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6th Annual Report

Volume 2

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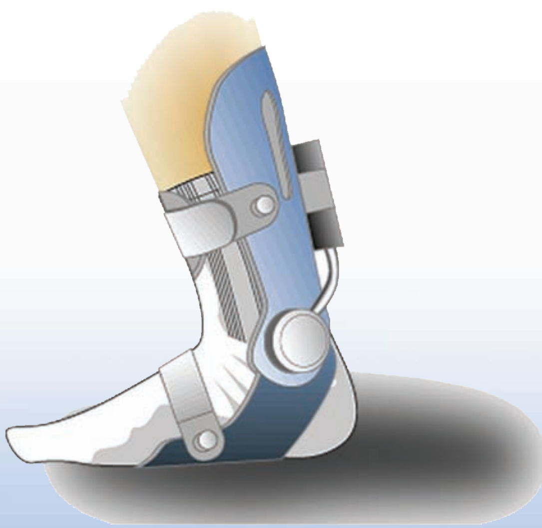

CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

University of Minnesota

Georgia Institute of Technology

Milwaukee School of Engineering

North Carolina Agricultural & Technical State University

Purdue University

University of Illinois at Urbana-Champaign

Vanderbilt University

Dr. Kim Stelson, Director

Dr. Perry Li, Deputy Director

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Project List: Center for Compact and Efficient Fluid Power (CCEFP)

RESEARCH PROJECTS

Thrust 1 – Efficiency

Project Name	PI / Institution / Sponsor
1A.1: Integrated Algorithms for Optimal Energy Use in Mobile Fluid Power Systems	Kim Stelson, University of Minnesota Andrew Alleyne, Univ. of Illinois at Urbana-Champaign
1A.2: Multi-Actuator Hydraulic Hybrid Machine Systems	Monika Ivantysynova, Purdue University
1B.1: New material combinations and surface shapes for the main tribological systems of piston machines	Monika Ivantysynova, Purdue University
1B.2: Surface Effects on Motor Start-Up Friction	Ashlie Martini, Purdue University John Lumkes, Purdue University
1D: Micro- and Nano-Texturing for Low Friction Fluid Power Systems	William King, Purdue University Eric Loth, Purdue University
1E.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor	Perry Li, University of Minnesota Thomas Chase, University of Minnesota
1E.2: High Speed On/Off Valves to Enable Efficient and Effective Fluid Power Systems	John Lumkes, Purdue University Monika Ivantysynova, Purdue University
1E.3: High Efficiency, High Bandwidth, Actively Controlled Variable Displacement Pump/Motor	John Lumkes, Purdue University Monika Ivantysynova, Purdue University
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	Perry Li, University of Minnesota Thomas Chase, University of Minnesota
1G.1: Tribofilm Structure and Chemistry in Hydraulic Motors	Paul Michael, Milwaukee School of Engineering Ashlie Martini, Purdue University
Advanced Energy Saving Hydraulic System Architecture for a Wheel Loader	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Advances in External Gear Machines Modeling	Andrea Vacca, Purdue University *Sponsors:* Casappa S.p.A.
Design of low noise emission internal gear machines	Andrea Vacca, Purdue University *Sponsors:* Confidential
Design of positive displacement machines for SCR automotive applications	Andrea Vacca, Purdue University *Sponsors:* MGI Coutier, France

Project Name	PI / Institution / Sponsor
Design, Simulation and Control of Hydraulic System Topographies with Integrated Energy Recovery	John Lumkes, Purdue University *Sponsors:* National Fluid Power Association
Efficiency Measurement on special axial piston pump	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	Perry Li, University of Minnesota Terrence Simon, University of Minnesota *Sponsors:* National Science Foundation
Fluid Efficiency	Paul Michael, Milwaukee School of Engineering *Sponsors:* Confidential
Hydrostatic Transmission for Wind Power Generation	Kim Stelson, University of Minnesota Brad Bohlmann, University of Minnesota *Sponsors:* Bosch Rexroth Corp., Eaton Corp., Racine Federated Inc. (formerly Hedland Flow Meters), Sauer-Danfoss, University of MN, IonE and IREE
Mechanical Implementation of Waved Surface and Waved Piston Technologies	Monika Ivantysynova, Purdue University *Sponsors:* Purdue Research Park Trask Funds
Modeling and Analysis of Swash Plate Type Axial Piston Pump (Interface)	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Optimization Environment for the Architecting of Micro-grids in Ultra Low Energy Communities	Christiaan Paredis, Georgia Institute of Technology *Sponsors:* United Technologies Research Center
PCA Mule- System Implementation and Testing	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Performance Prediction and System Control through Coupled Multi-domain Models: A Comparison Study	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Pump Dynamic Model Development	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Reliable Lightweight Transmission of Off-shore Utility Scale Wind Turbines	Kim Stelson, University of Minnesota Brad Bohlmann, University of Minnesota *Sponsors:* Eaton Corporation, Clipper Wind Power, UMN's Eolos Wind Consortium

Thrust 2 – Compactness

Project Name	PI / Institution / Sponsor
2A: Chemofluidic Hot Gas Vane Motor	Michael Goldfarb, Vanderbilt University
2B.1: Free-Piston Engine Compressor	Eric Barth, Vanderbilt University
2B.2 Miniature HCCI Free-Piston Engine Compressor	David Kittelson, University of Minnesota Will Durfee, University of Minnesota
2B.3: Free Piston Engine Hydraulic Pump	Zongxuan Sun, University of Minnesota
2C.2: Advanced Strain Energy Accumulator	Eric Barth, Vanderbilt University
2D: Multifunctional Fluid Power Components Using Engineered Structures and Materials	Vito Gervasi, Milwaukee School of Engineering Douglas Cook, Milwaukee School of Engineering
2E: Model-Based Systems Engineering for Efficient Fluid Power	Christiaan Paredis, Georgia Institute of Technology
2F: MEMS Proportional Pneumatic Valve	Thomas Chase, University of Minnesota
2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems	Robert Webster, Vanderbilt University Jun Ueda, Georgia Institute of Technology
Functionally Graded Metallic Lattice Components for Advanced Propulsion Components	Vito Gervasi, Milwaukee School of Engineering *Sponsors:* DARPA
Open Accumulator Compressed Air Storage Concept for Wind Power	Perry Li, University of Minnesota Terrence Simon, University of Minnesota *Sponsors:* University of MN; IonE and IREE
Precision Pneumatic MRI Compatible Robotic Surgery	Eric Barth, Vanderbilt University *Sponsors:* The Martin Company
Single-Channel Hybrid FES Gait System	Will Durfee, University of Minnesota *Sponsors:* National Institutes of Health (NIH)

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Project Name	PI / Institution / Sponsor
3A.1: Multimodal Human Machine Interfaces - The impact of operator interface on fuel efficiency	Wayne Book, Georgia Institute of Technology Steven Jiang, North Carolina A& T State University
3A.3: Human Performance Modeling and User Centered Design	Steven Jiang, North Carolina A&T State University Zongliang Jiang, North Carolina A&T State University
3B.1: Passive Noise Control in Fluid Power	Kenneth Cunefare, Georgia Institute of Technology

Project Name	PI / Institution / Sponsor
3D.1: Leakage Reduction in Fluid Power Systems	Richard Salant, Georgia Institute of Technology
3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems	Scott Bair, Georgia Institute of Technology
Adaptive Control for Oscillation Damping	Andrea Vacca, Purdue University *Sponsors:* CHN America, Inc.
Analysis of transmission noise sources	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Development of an Experimental Pressurized Thin-film Couette Viscometer and Consultation	Scott Bair, Georgia Institute of Technology *Sponsors:* Total Oil Company
Evaluation of the High Pressure, High Shear Stress Capability at Georgia Tech	Scott Bair, Georgia Institute of Technology *Sponsors:* Lubrizol Corp.
MRI-R2: Development of a Precise and High Speed Hydrostatic Dynamometer System for Research and Education in Automotive Propulsion Systems	Zongxuan Sun, University of Minnesota Kim Stelson, University of Minnesota *Sponsors:* National Science Foundation (NSF)
Shaft Pumping by Laser Structured Shafts with Rotary Lip Seals	Richard Salant, Georgia Institute of Technology *Sponsors:* University of Stuttgart/German Research Foundation; The Toro Company
Understanding and Reducing the Adverse Effects of Biodynamic Feedthrough	Wayne Book, Georgia Institute of Technology *Sponsors:* Caterpillar, Inc.; Bobcat; Deere and Company.
Water-removing filters and relative humidity sensors	Paul Michael, Milwaukee School of Engineering *Sponsors:* Confidential

EDUCATION AND OUTREACH PROJECTS

Project Name	PI / Institution / Sponsor
EO A.1 Interactive Exhibits Fluid Power	J. Newlin Jr, Science Museum of Minnesota
EO A.3 Multimedia Educational Materials	Alyssa Burger, University of Minnesota Kim Stelson, University of Minnesota
EO B.1 Research Experiences for Teachers (RET)	Alyssa Burger, University of Minnesota
EO B.2 Project Lead The Way	Will Durfee, University of Minnesota

Project Name	PI / Institution / Sponsor
EO B.3 Hands-on Fluid Power Outreach	Alyssa Burger, University of Minnesota Will Durfee, University of Minnesota
EO B.3a Hands-on Pneumatics Workshop	Will Durfee, University of Minnesota
EO B.3b Portable Fluid Power Demonstrator and Curriculum	John Lumkes, Purdue University Will Durfee, University of Minnesota
EO B.4 gidaa K12 STEM Programs	Alyssa Burger, University of Minnesota
EO B.4a gidaa K-12 STEM Camp	Alyssa Burger, University of Minnesota
EO B.4b gidaa odaangiina anaangoog (Shooting for the Stars) Robotics Program	Alyssa Burger, University of Minnesota
EO B.5: BRIDGE Project	Paul Imbertson, University of Minnesota Alyssa Burger, University of Minnesota
EO C.1 Research Experiences for Undergraduates (REU)	Alyssa Burger, University of Minnesota
EO C.2 Fluid Power OpenCourseWare	Will Durfee, University of Minnesota James Van de Ven, Univ. of Minnesota
EO C.3 Fluid Power Projects in Capstone Design Courses	James Van de Ven, University of Minnesota Will Durfee, University of Minnesota
EO C.4 Fluid Power in Engineering Courses	James Van de Ven, Univ. of Minnesota Will Durfee, University of Minnesota
EO C.5 giiwed'anang North Star Alliance	Alyssa Burger, University of Minnesota
EO C.6 Fluid Power Simulator	Will Durfee, University of Minnesota Christiaan Paredis, Georgia Institute of Technology
EO C.8 Student Leadership Council	Alyssa Burger, University of Minnesota Kim Stelson, University of Minnesota
EO C.9 Undergraduate Research Diversity Supplement (URDS)	Alyssa Burger, University of Minnesota
EO C.10 Graduate Research Diversity Supplement Program (GRDS)	Alyssa Burger, University of Minnesota Kim Stelson, University of Minnesota
EO C.11: Innovative Engineers	Paul Imbertson, University of Minnesota Alyssa Burger, University of Minnesota
EO D.1 Fluid Power Scholars Program	Alyssa Burger, University of Minnesota Linda Western, University of Minnesota
EO D.2 Industry Student Networking	Alyssa Burger, University of Minnesota
EO D.5 CCEFP Webcast Series	Alyssa Burger, University of Minnesota
EO D.6 Publication	Kim Stelson, University of Minnesota Linda Western, University of Minnesota
EO E.1 Evaluation	Paul Imbertson, University of Minnesota Alyssa Burger, University of Minnesota
EO Assoc Project: Zephyr Wind Power Teaching Training Workshop	Alyssa Burger, University of Minnesota

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Project 1A.1: Integrated Algorithms for Optimal Energy Use for Mobile Fluid Power Systems

Research Team

Project Leader: Prof. Kim Stelson, UMN; Prof. Andrew Alleyne, UIUC
Other Faculty: Prof. Perry Li, UMN; Prof. Monika Ivantysynova, Purdue
Graduate Students: Jonathan Meyer, UMN; Timothy Deppen, UIUC
Industrial Partners: John Deere, Parker, Caterpillar, Eaton

1. Statement of Project Goals

The goal of this project is to identify methods of regulating power generation and distribution in mobile fluid power systems that maximize the overall system efficiency and to demonstrate them on Center test beds. From previous Center-funded work in the study of energy management strategies (EMS), it was concluded that there is no single strategy that is optimal for all applications [1-6]. Therefore, the planned approach is to develop a toolbox of EMS design methods and decision algorithms that will identify the best design method for a chosen application. These algorithms will select the optimal design from the EMS toolbox based on a number of system attributes such as knowledge of duty cycle, ability to store energy, and problem constraints. In this way, the energy efficiency of mobile fluid power applications can be improved without compromising performance. The first Center test bed that will be targeted is the Hydraulic Hybrid Passenger Vehicle, Test Bed 3 (TB3), where the goal is to demonstrate a 100% improvement in fuel economy over a non-hybrid vehicle.

2. Project Role in Support of Strategic Plan

This project will attack energy management challenges at a very fundamental level. It will result in the development of an energy management toolbox and decision algorithms which together can be used to choose the design method best suited for a chosen application. Such a toolbox is critical to doubling the efficiency of fluid power within the hydraulic hybrid passenger vehicle and the general class of mobile fluid power systems (medium and heavy-duty trucks, buses, construction equipment, etc.).

3. Project Description

A. Description and explanation of research approach

This project explores how to achieve optimal energy usage in the general class of fluid power systems by (a) understanding when to use available power sources and (b) achieving smooth transitions between different modes of operation. Deterministic dynamic programming can be used to find the optimal behavior for an assumed drive cycle but cannot be used in real time. To design real time implementable energy management strategies that address both challenges, three methods are being studied: rule based, stochastic dynamic programming (SDP), and model predictive control (MPC). Each of these methods is being studied because each has unique advantages and disadvantages which make them better suited for different applications. These studies will include hardware in the loop (HIL) testing using an augmented earthmoving vehicle powertrain simulator (AEVPS) and the hydraulic hybrid passenger vehicle test bed. This will lead to the development of an EMS design toolbox that will be used with decision algorithms to choose the design method best suited for a given application.

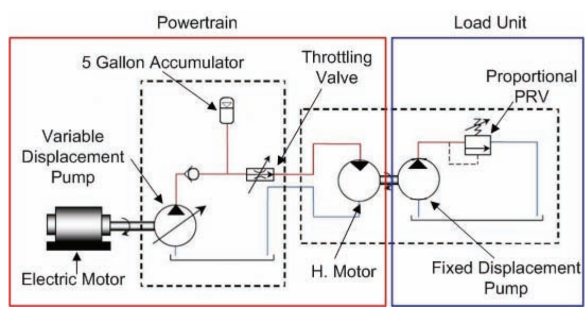

Figure 1: Schematic of AEVPS hydraulic circuit

With the integration of multiple research efforts within the CCEFP, the project team is able to study optimization of the powertrain architecture, multiple EMS design methods, and conduct simultaneous hardware-in-the-loop studies (using TB3 and the AEVPS), thus providing a much broader view of the energy management problem. Two of the major gaps being addressed are taking advantage of the hydro-mechanical powertrain architecture and developing an EMS toolbox that integrates the advantages of the rule-based, SDP, and MPC approaches. The hydromechanical configuration is more complex, but offers the potential for greater efficiency and performance. Also, while other researchers have focused on establishing the merit of a single strategy the project team recognizes that there is no single EMS design method that will give optimal performance for all applications. Rather, each design approach has its own unique advantages/disadvantages and a decision algorithm is needed to identify the optimal design approach.

B. Achievements

The focus of the past year has been to translate the rule-based, SDP, and MPC based EMS designs into physical systems using both TB3 and the augmented earthmoving powertrain simulator. The team has worked closely with TB3 to incorporate the three-tier control strategy being used on the test bed into our EMS models. The dynamic programming algorithm has incorporated this control structure to allow for seamless integration onto the test bed. TB3 has also provided the dynamic model they have developed for the redesigned hydraulic hybrid vehicle, thus allowing the project team to do experimentation in simulation and make refinements of the EMS before physical implementation on the test bed. For TB3, the team has determined the optimal behavior using dynamic programming and is developing a rule-based strategy. Concurrently, the AEVPS has been used to validate the model predictive control approach and dynamic programming has been used to design a rule-based strategy based on models of the AEVPS. Furthermore, a comparison of the robustness properties of the rule-based and MPC based EMS's in the context of the AEVPS is being done to formalize the decision algorithms.

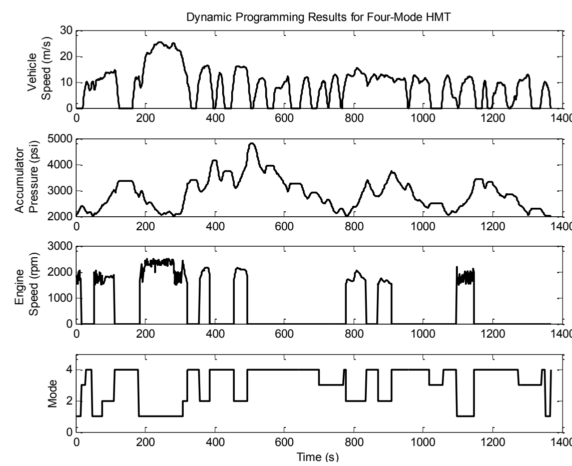

Figure 2: DP results for redesigned TB3 with mode and engine penalties

As a benchmark, a model of a non-hybrid vehicle was used over the Federal Urban Drive Cycle (FUD Cycle) and resulted in a fuel economy of 37 mpg. For this simulation a standard 6-speed transmission was used along with manufacturer's engine data. An optimal control strategy was then developed for a hydraulic hybrid vehicle using the architecture of TB3, an input-coupled, power-split architecture using two hydraulic units. The first unit, known as the torquer (pump/motor T) is connected to the output of the engine to control engine torque; the second unit, known as the speeder, (pump/motor S) is connected to the input of the planetary gear to control the output speed to the wheels. This configuration has the ability to operate in 4 distinct modes: hydro-mechanical (HMT), parallel, pump T only, and pump S only. Dynamic programming uses the engine power and operating mode as the control variables. This optimization technique can be used to derive a non-causal control strategy using Bellman's principle of optimality [5]. Experimental engine data was obtained for the engine, while manufacturer's efficiency data was used for the hydraulic units. To prevent rapid mode switching and engine cycling, a fuel penalty was added each time a mode change occurred or the engine was turned on or off. An optimal fuel economy of 95 mpg over the FUD Cycle was obtained. This shows that using a four-mode hydraulic hybrid vehicle could potentially double the fuel economy of a vehicle in urban driving situations by operating the engine more efficiently, utilizing regenerative braking to capture energy, and turning the engine off once enough energy is stored. The results are shown in Figure 2. The engine is off for much of the drive cycle, and the entire range of the accumulator is used. These results will be used to derive a rule-based strategy.

For the AEVPS a rule-based EMS was developed. To develop this strategy, dynamic programming was employed to first determine the global optimal behavior over the FUD Cycle. For this platform, the control inputs are the throttle command, pump displacement, and valve command. Figure 1 provides a schematic of the system architecture. Once the dynamic programming solution was obtained, the data was manipulated to determine if any correlation between the control variables and the states existed. After several iterations, a successful rule-based strategy was developed for the FUD Cycle. Motor speed and acceleration were used to develop a relation for the engine throttle, and the motor speed and downstream pressure were used for the swash-plate angle. The valve command was achieved using a PI controller to ensure tracking of the desired motor speed. The results from the rule-based strategy are shown in Figure 3. Excellent tracking of motor speed is obtained while using only 5% more fuel over the dynamic programming results.

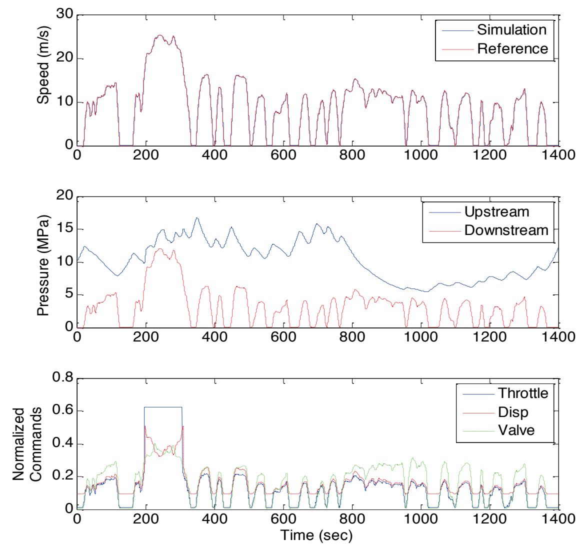

Figure 3: Simulated AEVPS powertrain response with rule-based EMS

In addition to the rule-based strategy, a discrete model predictive controller was also designed for the AEVPS using the same control variables. MPC is a finite horizon optimal control framework that uses a model of the system to express future values of the states in terms of previous control decisions within the prediction horizon. Through this transformation, the objective function can be restated as just a function of the control decisions. In this way, solving for the trajectory that minimizes the objective function over the prediction horizon reduces to solving for the optimal control sequence. The first element of this sequence is then applied to the system and the process is repeated at every discrete instance the control is updated. For a complete discussion of the control design see [3]. The MPC based EMS used about 10% more fuel than the dynamic programming results. The MPC formulation was also tried experimentally on the AEVPS system with the results shown in Figures 4 and 5. This shows excellent speed tracking to the reference trajectory and matches well with the results from simulation. Finally, a non-hybrid version of the AEVPS was simulated to provide a baseline result for hybridization. For the non-hybrid model the hydraulic hybrid powertrain was replaced with an ideal 3 gear transmission and a fuel consumption of 1.37 kg was observed over the FUD Cycle, 37% more than the optimal fuel usage for the hybrid setup.

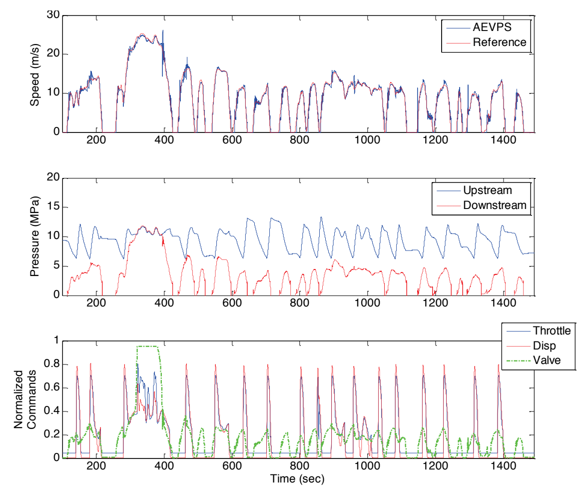

Figure 4: Experimental AEVPS powertrain response with MPC

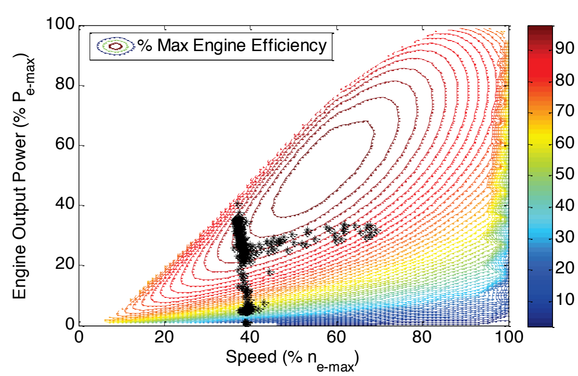

Figure 5: Experimental AEVPS engine response with MPC. Black dots are operating points and color bar indicates % maximum efficiency.

With the FUD Cycle results complete, a sensitivity analysis was performed to evaluate how the rule-based and MPC EMS's for the AEVPS in variation to drive cycle variation. For this analysis, 100 random drive cycles were generated whose transitions probabilities were identical to the FUD Cycle. The transition probabilities give the probability of the acceleration at the next time step given the velocity and acceleration at the current time step. A uniform random number generator is used to generate a number between zero and one. Using this and the transition probability matrix, the acceleration at the next time step is known. An example of a drive cycle generated using this method is shown in Figure 6. The random cycle shows a similar pattern to the FUD Cycle with both urban driving and a brief highway driving section. Using this technique, it is possible to study the performance of an EMS over many different drive cycles, each of which is representative of a certain driving situation (i.e. urban or highway). The rule-based and MPC strategies were simulated for each of the random drive cycles and compared to the non-hybrid simulation results. The results in Figure 7 show that the MPC exhibited much less sensitivity to variations in drive cycle. This agrees with the team's expectations since the rule-based strategy was tuned over one drive cycle and MPC uses no drive cycle information in its derivation.

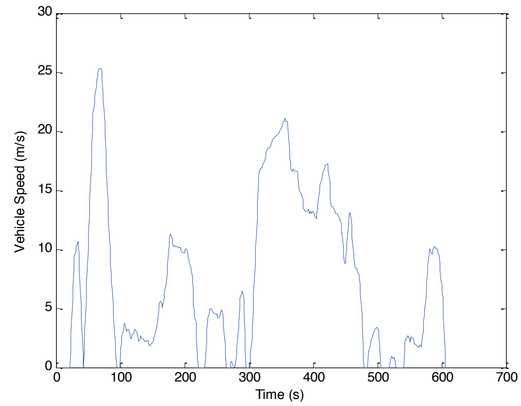

Figure 6: Random drive cycle

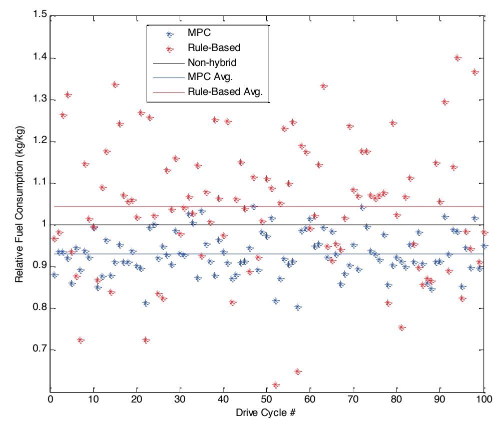

Figure 7: Simulation results for rule-based and MPC over random drive cycles

A similar sensitivity analysis was performed for model parameter variation. For this study 5 parameters were varied by ±10% in increments of 5% (cases 1-4: variable displacement pump flow gain, cases 5-8: upstream hose loss coefficient, cases 9-12: downstream hose los coefficient, cases 13-16: motor displacement and cases 17-20: vehicle viscous friction). The results in Figure 8 show that the two approaches are both robust to parameter variation with 10% changes in parameters yielding less than a 10% change in fuel consumption. In the future the team will validate the simulation results experimentally and study a SDP based EMS under similar uncertainty. These results will then be used in the formulation of the decision algorithm.

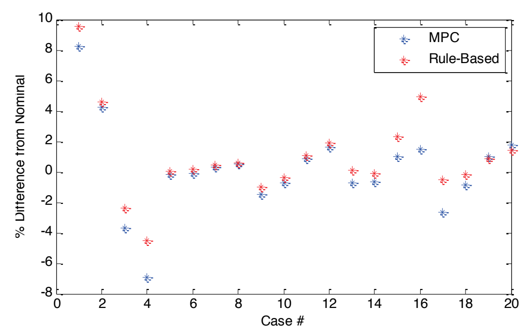

Figure 8: Simulation results for rule-based and MPC for parameter variation

Looking forward, the project team plans to cross-pollinate the lessons learned from work on TB3 and the AEVPS to develop a full energy management suite for both platforms. The plan is to have a rule-based strategy ready for TB3 and a SDP based EMS for the AEVPS by May 2012. A similar sensitivity analysis will be performed for SDP to compare drive cycle and model parameter variations to rule-based and MPC for robustness and performance. This will aid in the development of the decision algorithm for the EMS toolbox. Additional energy management strategy development will continue in future years. Furthermore, a large industry collaboration has been formed to better define the necessary capabilities of the EMS toolbox and decision algorithms. This collaboration will be used to develop the EMS toolbox and formalize the process of transferring control algorithms to industry members. In addition to robustness and performance, another characteristic that will be studied is the dependence on future knowledge of the drive cycle. Ultimately, the goal is to expand the EMS toolbox to consider other energy domains as well (electrical, mechanical, and thermal). This would enable the use of a single control toolbox to study a mechanical/electrical/hydraulic hybrid or other multi-domain power systems.

Expected Milestones and Deliverables

- HIL study of Rule-based EMS using TB3 (4/2012)
- Comparison Study of Rule-based, MPC, and SDP (5/2012)
- EMS toolbox (5/2013)
- Validation of toolbox on multiple industry owned systems (1/2014)
- Extension of toolbox to other energy domains (1/2016)

C. Member company benefits

Members will benefit from the development of a formalized framework for analysis and control synthesis of multi-mode powertrains.

D. References

1. Deppen, T. O., A. G. Alleyne, K. A. Stelson and J. J. Meyer, “Model Predictive Control of an Electro-Hydraulic Powertrain with Energy Storage,” Proceedings of the ASME Dynamic Systems and Control Conference, 2011

2. Deppen, T. O., A. G. Alleyne, K. A. Stelson and J. J. Meyer, “A Model Predictive Control Approach for a Parallel Hydraulic Hybrid Powertrain,” Proceedings of the 2011 American Control Conference, 2011.

3. Deppen, T. O., A. G. Alleyne, K. A. Stelson and J. J. Meyer, “Optimal Energy Use in a Light Weight Hydraulic Hybrid Passenger Vehicle,” to be published in Transactions of ASME, Journal of Dynamic Systems, Measurement and Control.

4. Meyer, J. J., K. A. Stelson, A. G. Alleyne and T. O. Deppen, “Power Management Strategy for a Parallel Hydraulic Hybrid Passenger Vehicle Using Stochastic Dynamic Programming,” Proceedings of the 7th International Fluid Power Conference, 2010.

5. Meyer, J. J., K. A. Stelson, A. G. Alleyne and T. O. Deppen, “Developing an Energy Management Strategy for a Four-Mode Hybrid Passenger Vehicle,” Proceedings of the 52nd National Conference on Fluid Power, March 23-25, 2011, Las Vegas, NV.

6. Stelson, K. A. And J. J. Meyer, “Optimization of a passenger hydraulic hybrid vehicle to improve fuel economy,” Proceedings of the 7th JFPS Symposium on Fluid Power. 2008.

Project 1A.2: Multi-Actuator Hydraulic Hybrid Machine Systems

Research Team

Project Leader:	Prof. Monika Ivantysynova, Purdue University, School of Mechanical Engineering, Dept. of Agricultural & Biological Engineering
Graduate Students:	Josh Zimmerman, Rohit Hippalgaonkar, Enrique Busquets, Jess Rose
Industrial Partners:	Bobcat, Caterpillar, Parker Hannifin, Moog, Husco, Sauer-Danfoss

1. Statement of Project Goals

The primary goal of the original project 1A.2 (from June 2006 through June 2010) was to develop system architectures and control methods for optimal power management in multi-actuator mobile hydraulic machines using displacement-controlled linear and rotary actuators. It was desired to demonstrate that at least 40% reduction of energy consumption for typical working cycles of multi-actuator machines compared to the state of the art of machines is achievable. This goal was met, and energy efficiency was doubled by implementing displacement controlled actuator circuits, demonstrated Test Bed 1 (TB1), the prototype displacement controlled excavator. An additional outcome was that reduction of cooler size was shown to be feasible while maintaining the same oil temperatures and performance, through introduction of the new displacement controlled architecture.

In June 2010, the project goals were redefined to investigate hydraulic hybrid architectures for multi-actuator machines and the potential for further fuel savings from these systems. A target of at least 50% fuel savings over the standard Bobcat excavator system is targeted for the test-bed. The research will include investigation of hybrid architectures and control methodologies for optimal hybrid power management which allow efficient engine operation through energy storage and engine load-leveling.

The new system design will also allow cost savings by downsizing the combustion engine. The hydraulic and electrical systems will be simplified by the development of methodologies for variable displacement “smart pumps” with improved swash plate controls and integrated electronics.

From 2012-2016, the project will focus on reducing production costs and introducing effective machine prognostics of highly efficient displacement controlled hydraulic machines. The new goals of the project are to investigate how production costs can be reduced by pump switching between actuators during machine operation, thus reducing the number of pumps installed in the hydraulic system and their sizes. Such concepts are important for large machines where the current design approach requires the installation of large pumps. Another goal is the development of effective machine prognostics concepts. These will allow for the prediction of impending failures thereby avoiding expensive machine breakdowns.

2. Project Role in Support of Strategic Plan

The project primarily addresses the efficiency barrier by developing new system concepts and control strategies for multi-actuator mobile machines. The project also addresses the compactness barrier since displacement-controlled systems allow higher operating pressures and a reduction of interfaces and components. The project will result in an excavator hydraulic system with hydraulic energy storage and integrated electro-hydraulic control hardware.

The project leverages past and current research in multi-actuator systems and on-road hydraulic hybrid vehicles in the project leader’s research group, while confronting barriers of efficient systems, control and energy management, and compact integrated systems.

3. Project Description

A. Description and explanation of research approach

Project 1A.2 focuses on improving the overall efficiency of mobile hydraulic machines with multiple linear and rotary actuators. Advances in system efficiency and improvements in effectiveness of the proposed technologies are obtained through:

1. Displacement-controlled (DC) actuator systems that eliminate control valve throttling losses.
2. Real-time control of power generation and transmission in order to maximize operating efficiency of diesel engine and hydraulic pumps.
3. Energy recovery from linear actuators, enabled by the use of displacement controlled circuits, without addition of energy storage.
4. Improving swash plate adjustment systems, through a novel design methodology.
5. Development of multi-actuator DC hydraulic systems with energy storage (DC hydraulic hybrid systems) to maximize energy recovery and reduce rated engine power.
6. Real-time control of power generation and transmission of DC hydraulic hybrid systems in order to maximize operating efficiency of diesel engine and hydraulic pumps.
7. Developing pump-switching architectures and control methodologies that will reduce the number of pumps required in multi-actuator DC systems, yet allow use of maximum number of actuator combinations.

Traditionally in multi-actuator machines using hydraulic actuation, one or two large hydraulic pumps transmit power from the engine. Control valves that are downstream of the pumps, arranged in series or parallel, are responsible for controlling actuator motion according to operator input. Such configurations incur energy losses since they throttle flow through the valves and additionally, do not allow energy recovery from aiding loads. Alternative system designs, such as displacement control, have already demonstrated improvements in efficiency, as was shown on TB1.

Hybrid vehicles have been studied for many years in the transportation sector and more recently there has been increasing interest in the hybridization of off-highway applications such as in construction, mining and agricultural machines. This is a result of rising fuel costs as well as more stringent emission regulations placed on the industry. Much of the focus has been on electric hybrid systems with Case, Kobelco and Komatsu having released hybrid construction equipment to the market. Little focus however seems to have been placed on purely hydraulic hybrid systems. In the second phase of the project, purely hydraulic hybrid configurations for multi-actuator machines have been investigated, while continuing use of displacement controlled actuation for the differential cylinders.

Thus, an additional opportunity for efficiency improvements in hydraulic hybrid multi-actuator systems is through leveraging additional flexibility in power management. Intelligent use of the accumulator will allow engine load-leveling and consequently more efficient engine operation compared to the non-hybrid case, while ensuring that performance requirements are met.

The state-of-the-art in hybrid power management techniques has evolved with hybrid architectures for passenger vehicles [1]. Rule-based approaches together with stochastic dynamic programming [2, 3], model predictive control [4, 5] and instantaneously optimal approaches have been employed in various passenger vehicle applications. Apart from rule-based [6-8] and instantaneously optimal strategies [9, 10], extensive research has not gone in to application of advanced control techniques for hybrid or non-hybrid architectures in off-highway machines and vehicles. These applications pose peculiar challenges such as faster cycles, shorter sampling intervals in which to apply the desired control techniques, together with more potential degrees of freedom.

Further, optimal control studies that generate dynamically optimal results have not been previously undertaken for off-highway applications. Formulation of the optimal control problem so as to be solved by dynamic programming was done as part of project 1A.2 in the period of reporting. This allows a method of benchmarking implementable control techniques, and a reference for designing simpler, rule-based techniques. Additionally, many designs can now be compared on an even keel, by using optimal control results for each. Thus optimal control can also be extended for optimal design of specific hybrid architecture.

B. Achievements

In addition to the achievements which will be listed in this section, a number of publications have resulted from the work on Project 1A.2. These publications are listed at the end of this document.

Achievements prior to the reporting period

- The DC hydraulic system is operational and was demonstrated by video at the CCEFP annual meeting on October 7, 2009 and in person to a delegation from Caterpillar on November 4, 2009.
- 40% fuel savings were demonstrated [11] at a Caterpillar facility in independent side-by-side testing of the prototype DC excavator and the standard Bobcat mini-excavator, in August, 2010 for an aggressive truck-loading cycle with loose soil.
- Through an optimal power management strategy [10], 56% fuel savings were demonstrated over the standard excavator system in September, 2010.
- Feasibility studies for the parallel hybrid excavator architecture were completed to demonstrate that more than 50% fuel savings over the standard valve-controlled excavator system, together with 50% engine downsizing, can be achieved without loss of performance of the working functions.

Achievements during the reporting period

Achievements during the reporting period include design of a novel hydraulic hybrid concept for multi-actuator DC machine systems, an optimal control study for such systems, analysis and replication of optimal results through an implementable, rule-based strategy and a design methodology for the swash-plate adjustment system for pump control. Methods and results for these topics are discussed briefly in the Test Bed report.

Novel Hybrid Excavator Architecture

Perhaps the easiest way to transition from a non-hybrid to a hydraulic hybrid configuration for multi-actuator machines is by addition of a pump on the engine shaft for charging or discharging of the accumulator, also known as the parallel hybrid architecture [12]. In the reporting period, a novel, series-parallel hybrid architecture (Figure 1) was proposed and filed for a patent, which entailed addition of energy storage capability for the DC excavator without addition of an extra pump. The fixed displacement motors that are used for the rotary actuators (and particularly the swing), are substituted with variable displacement, over-center pump/motors that allow capture of braking energy in both directions of motion, while the hydraulic accumulator is now placed between the pump originally supplying the swing motor and the new swing pump/motor.

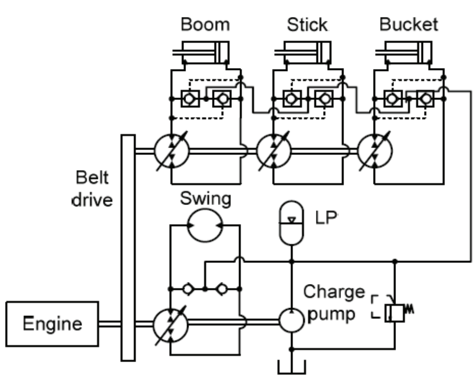

Figure 1: CCEFP Prototype DC Excavator

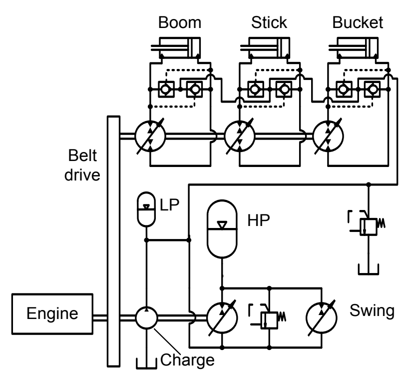

Figure 2: Series-Parallel Hybrid DC Excavator (Proposed)

As previously stated, one of the project goals is to be able to reduce the required engine power of the machine by 50%. A feasibility check was successfully performed [13], similar to the one for the parallel hybrid concept. Measurements from an aggressive, expert-operated truck-loading cycle (which was assumed to represent the upper limit of power requirements from the machine) were used to simulate the novel hybrid system with a downsized engine and a preliminary power management strategy, wherein the engine was operated at the maximum governed speed and maximum torque. These simulations also showed that both hybrid configurations can reduce fuel consumption by at-least 20% over the prototype DC system.

Optimal Control for Hydraulic Hybrid System

The optimal control problem was formulated and solved for the hydraulic hybrid (Zimmerman, et al. [14]), using dynamic programming (Figure 3). It was discovered that given cycle requirements, at any instant of time there are only two degrees of freedom (or two free controls), and two states that evolve according to these controls. The dynamic programming technique was then applied to this problem to generate optimal control histories and state trajectories.

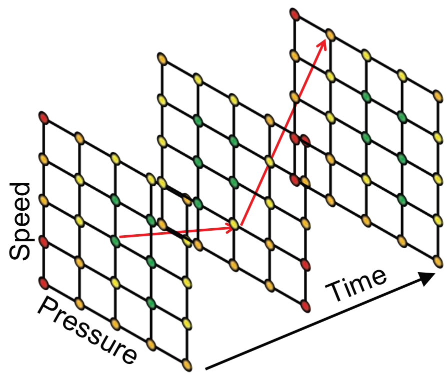

Figure 3: Dynamic Programmingor S-P Hybrid DC System

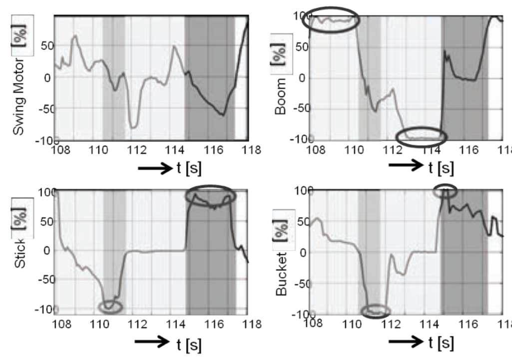

Figure 4: Optimal Pump Displacements

Numerous desirable trends were discerned from the optimal results. For example, the pumps on the engine shaft (or 'DC pumps') were kept at high displacements (Figure 4), and the DC pump with the maximum flow requirement was always kept close to 100%. The engine was thus maintained at the minimum allowable speed to meet these flow requirements while the accumulator was maintained above the minimum pressure to meet requirements on the swing. The storage pump and engine throttle act to keep the engine acting in an efficient region at minimum speeds.

Implementable Machine Power Management

An implementable rule-based strategy was derived to replicate the optimal trends. A set of rules had to be designed depending on the power requirements at the DC actuators and the swing motor to regulate the engine speed and accumulator state-of-charge [15].

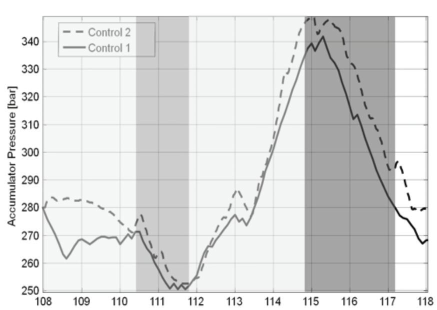

Figure. 5: Optimal and Rule-based Accumulator Pressures

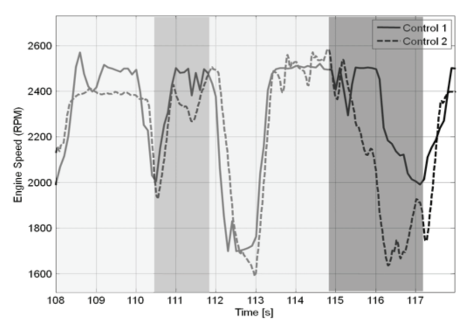

Figure. 6: Optimal and Rule-based Engine Speeds

As can be seen from Figures 5 and 6, the rule-based strategy replicates optimal trends reasonably well. The rule-based strategy will next be extended other typical excavator working cycles.

Design Methodology for Pump Adjustment System

A detailed hydraulic and kinematic model was developed for the simulation of the pump adjustment system. A new methodology was proposed for sizing the pump adjustment system (selection of valve flow gains, control pressure and control cylinder diameter) to satisfy requirements on pump response times, power and pump size. The work done [16, 17] provides a significant first step toward 'smart pumps' of variable displacement, wherein prototype pumps for displacement control will come with integrated adjustment system and electronics. Ultimately this will lead to reduced cost of bringing displacement controlled actuation technology to production.

Planned Achievements following the reporting period

- Design, modeling, simulation, and implementation of both hybrid and non-hybrid multi-actuator displacement-controlled architectures with pump switching
  - Deliverables:
    - Hydraulic circuit schematics with pump switching for 5-ton and 20-ton displacement controlled excavators both hybrid and non-hybrid (01/12/2012)
    - Multi-body dynamic and hydraulic co-simulation models of 5-ton and 20-ton excavators including engine, hydraulics, and machine structure (01/06/2013)
- Develop intelligent controls for handling pump switching transitions
  - Deliverables:
    - Optimal pump controls for pump switching transitions to minimize pressure transients resulting from opening and closing valves (01/09/2012)
- System prognostics design, study, simulation, and implementation
  - Deliverables:
    - Analyze proposed DC system architecture with pump switching in order to identify different system failure modes (01/12/2012)
    - Study the applicability of system diagnostics based on monitoring of thermodynamic system behavior. (01/03/2013)
    - Defined applicable diagnostics and condition monitoring methods (01/12/2012)
    - Simulated machine fault detection (February 2013)
    - Simulation results for all proposed prognostic concepts (August 2013)
    - Implemented and fully functional system prognostics (June 2014)

The proposed work will enable in the long term, the introduction of highly efficient displacement controlled hybrid systems to the market, especially for larger machines, by reducing production and operation costs. The project leverages past and current research in multi-actuator systems and off-road hybrid vehicles while confronting the barriers of efficient systems, control and energy management, and compact integrated systems. Further, system prognostics will make machine more effective by predicting failures using already installed sensors. The emphasis on reducing the cost of both operation and production is significant since cost has previously been a limiting factor in market acceptance of displacement controlled hydraulic systems.

C. Member Company Benefits

The results of project 1A.2 are directly transferable to industry and have already offered benefits to member companies. Some of these benefits include:

- The implementation of the technology developed in project 1A.2 onto Test Bed 1 provides a usable prototype that can be evaluated and tested by industry members. This saves them much time and money compared to if they were to build prototypes themselves in order evaluate the potential of displacement controlled hydraulic actuation systems.
- The results of this project have already shown that up to 40% fuel savings can be achieved, and potentially up to 50% fuel savings have been predicted in simulation over the standard excavator system. This would clearly be a benefit to OEM companies within the center.
- The improved efficiencies and potential for reduced engine power made possible by the technologies being developed in this project will help OEMs meet upcoming emission regulations under the Tier IV emissions standards.
- The improved efficiencies offered by the technologies developed in this project will reduce the cooling requirements for mobile machines saving cost and space for machine production.
- The work done toward improving swash plate adjustment systems for displacement controlled actuators will aid in reducing the cost of bringing the technology to production.
- Project 1A.2 has led to associate projects with multiple sponsors working with the Maha Fluid Power Research Center with a total funding amount of $1,310,000 since June, 2006.

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Project 1B.1: New material combinations & surface shapes for the main tribo-systems of piston machines

Research Team

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Industrial Partners:	Parker Hannifin, Sauer-Danfoss, Poclain Hydraulics, Caterpillar, Bosch Rexroth

1. Statement of Project Goals

The project goal is to discover the impact of material combinations and advanced surface shaping on the reduction of energy dissipation and the increase of load carrying ability of the lubricating gaps of axial piston machines. Studying the role of material properties in combination with gap micro geometry through a fully-coupled fluid-structure-thermal and multi-body dynamics simulation model for the piston cylinder interface will provide a better understanding of the complex physical phenomena of lubricating gaps performance and this knowledge will be used to propose new design solutions for the main tribological systems of axial piston machines.

2. Project Role in Support of Strategic Plan

The project addresses the efficiency barrier by providing a deeper understanding of axial piston machine lubricating gap behavior through the analysis of the impact of novel material properties and structured surface designs. Design optimization will be carried out using a computer model based approach coupling together for the first time the main machine lubricating gaps considering the main physical effects. Piston pumps form the heart of energy saving displacement controlled hydraulic systems and hydraulic hybrids. Both new system concepts have been proposed and developed in the CCEFP to drastically reduce energy consumption of current hydraulic systems in the transportation sector and other applications. After replacing throttling valves, the pumps and motors represent the main source of losses of these new hydraulic systems. The reduction of power loss of pumps and motors will also help to increase system pressure and to increase compactness of fluid power systems. The low efficiency and the lack of compactness are barriers for a breakthrough of hydraulic hybrids into automotive transmissions.

3. Project/Test Bed Description

A. Description and explanation of research approach

Swash plate type axial piston machines are widely used today in industry. The hydraulic systems in which these machines are placed require the units to operate under a wide range of operating conditions, necessitated by system performance requirements. Unfortunately, at the present time, there is only limited range of operating conditions where these machines are highly efficient. The sealing and bearing gaps separating the movable parts of the rotating group (piston, slipper, and cylinder block) form the most critical design element of piston machines. These gaps, as illustrated in Fig. 1, determine the achievable machine performance (speed, pressure, and maximum swash plate angle) and overall efficiency.

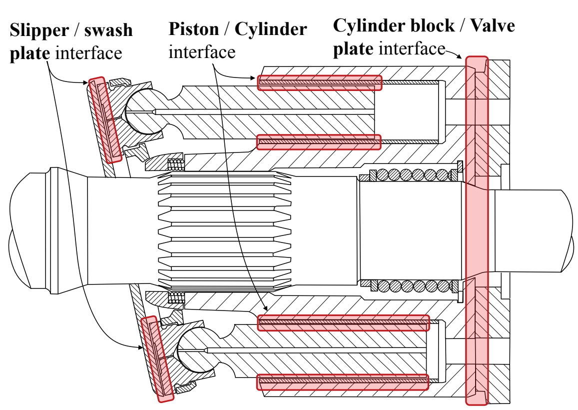

Figure 1: Swash plate axial piston machine cross section and identification of the three lubricating interfaces

The energy dissipated in the sealing and bearing gaps represents up to 90% of entire machine loss at low swash plate angles and up to 60% at maximum swash plate angles. The development of physical models which can be used to predict the energy dissipated in the gaps is fundamental to propose better gap designs, including novel material combinations and shaped surfaces. These innovative designs will lead to better machine performance and increased efficiency especially at low swash plate angles.

The physical effects occurring in the gap are complicated and interact with each other. To suggest improvements in gap design either through material combinations or surface shaping, the physical effects influencing the fluid film behavior must be accurately captured by the model. These effects include:

- Dynamic pressure in the fluid due to the hydrostatic and hydrodynamic effects
- Micro and macro motion due to dynamic loading and machine kinematics
- Deformation of the solid bodies due to the pressure load from the fluid
- Heat generation in the fluid due to the viscous shearing
- Heating of the solid bodies due to heat transfer from the fluid
- Thermal deformation of the solid bodies due to their heating

Each of these physical effects and the interaction between them must be captured by the pump model. This creates a complicated transient load fluid-structure-thermal solid body dynamics problem.

Due to very thin film thickness the flow in lubricating gaps of piston machines can be assumed to be laminar. By assuming an incompressible Newtonian fluid, neglecting inertia forces and the change of pressure with the gap height as well as the derivative of fluid velocity in direction of gap length and breadth, and assuming an ideal roughness of surfaces, the Reynolds equation can be used for description of laminar flow in narrow gaps.

B. Achievements

Achievements prior to the reporting period:

Baker and Ivantysynova investigated a circumferential micro-waved pattern on the valve plate surface (Fig. 2-a) using a non-isothermal fluid flow model in the gap, accounting for elasto-hydrodynamic deformation on the cylinder block [1]. The simulation model predicted up to 60% reduction of total power losses associated with the cylinder block interface when a circumferential pattern of 1μm amplitude was introduced. Testing on a prototype confirmed up to 10% improvement in overall efficiency of the pump.

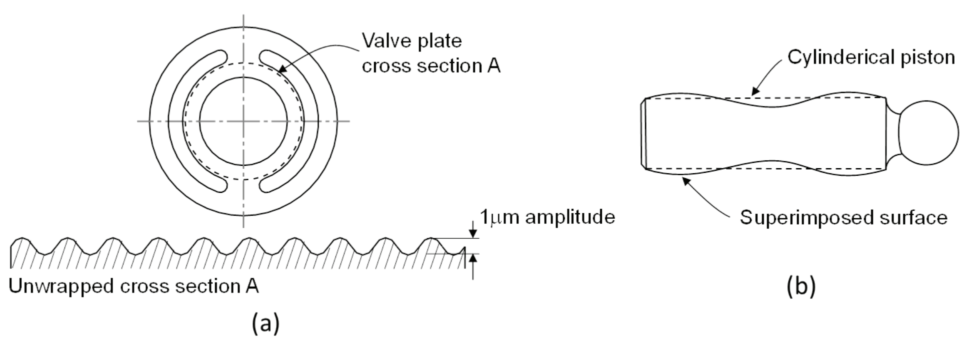

Figure 2: Cross section of an exaggerated waved valve plate (a) and axially waved piston (b).

Further simulation studies on the piston/cylinder interface showed the potential of waved surface shaping on the lubricating interfaces efficiency. In particular, the work of Garrett [2] focused on using a lubrication model of the piston/cylinder interface that did not consider the elastohydrodynamic or thermal effects to study the impact of introducing micro surface shaping on the piston. His work considered specifically the effects of an axially waved shape as illustrated in Fig. 2-b. The simulation study concluded that significant leakage and torque loss reduction were possible using an axially waved piston.

Although the work of Baker and Garret showed great potential for the use of micro-surface wave shaping, the models used to predict performance were dated. At the end of Garrett's work, only a simple first model of elastohydrodynamic was available for the piston cylinder interface. Later in 2009, development of thermal and structural analysis for the piston-cylinder interface was computed only considering a single 'wedge' of the cylinder block, and the solid bodies were meshed with a simplified algorithm that only allowed for simplified geometries. In 2010 this analysis of the piston-cylinder interface was extended to an entire rotating group by combining the separate wedges. This was a significant step forward in model complexity and ability to accurately model the real hydraulic machine. However, the mesh was still a simplified, structured mesh that did now allow for the direct use of CAD geometries, but rather parameterized values which were used to construct the complete mesh.

Achievements during the reporting period:

Piston cylinder interface

A novel non-isothermal fluid structure interaction model coupled with a multi-body dynamic simulation model that considers elastic surface deformation due pressure and thermal load has been verified experimentally for the piston cylinder interface. The new model represents a significant achievement both due to the complexity of numerical methods used and completeness in terms of physical phenomena considered. An overview of the piston cylinder modeling approach and coupling is given in Fig. 3.

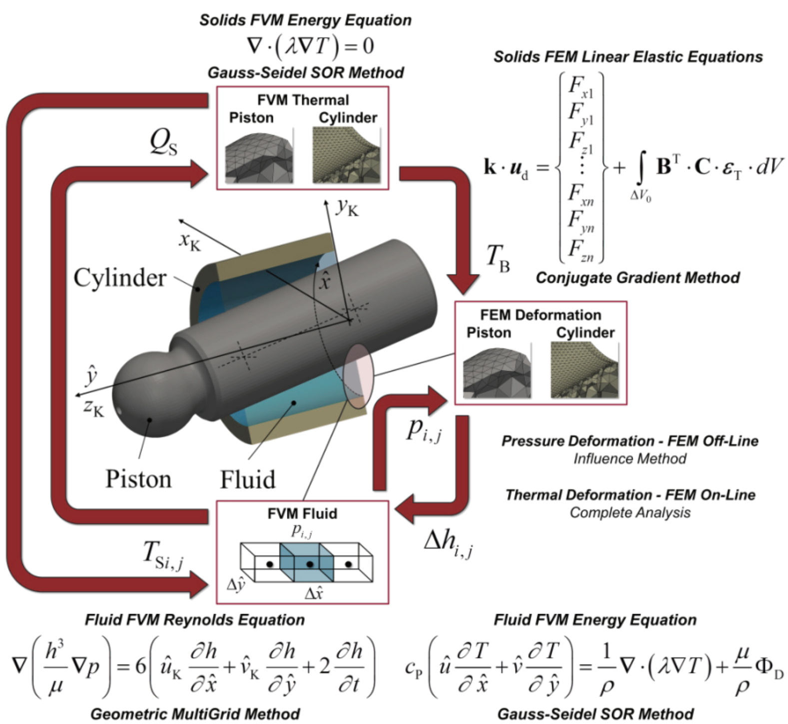

Figure 3: Flowchart of the multi-domain model.

This model has been validated against measurements taken from two specially developed test rigs, and used to discover the mechanisms enabling successful operation of pumps under high pressure as will be explained in the following three sections.

EHD test rig

The EHD test rig is a special test stand which allows pressure and temperature distribution in the fluid film between piston and cylinder to be measured under real operating conditions of a pump [4]. Measurements of the fluid film dynamic pressure field were taken for the first time using manufactured barreled piston with the shape used for the simulations. The comparison with measurements in Fig. 4 shows that the developed model is able to predict the temperature distribution as well as the absolute values with a high level of accuracy (additional results are reported in [18]). Determination of the fluid film heat fluxes is only possible when the fluid film geometry, temperature distribution, pressure field, fluid properties and piston micro-motion are correctly calculated.

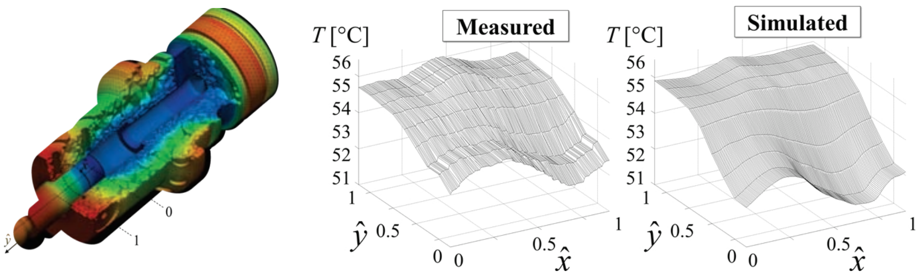

Figure 4: comparison of the measured and simulated temperature field in the lubricating film (EHD test rig).

<u>*Tribo test rig*</u>

The tribo test rig is a unique test stand which allows the friction force exchanged between piston and cylinder block to be measured [6]. A real pump has been modified and equipped with a hydrostatically balanced brass bushing, decoupled from the steel cylinder block (Fig. 5-a), which transfers the axial and circumferential viscous friction forces exerted on the bushing through a lever to a piezoelectric force sensor. The geometry of the actual piston and cylinder are precisely replicated (Fig. 5-b) and the measured displacement chamber pressure is used for non-isothermal fluid film flow, force balance and surface elastic deformation calculations. Numerical analysis has been performed to demonstrate the capability of the fully-coupled model to capture the viscous friction force behavior over one shaft revolution. A comparison between measured and simulated friction force is shown in Fig. 5. (Other operating conditions can be found in [18]).

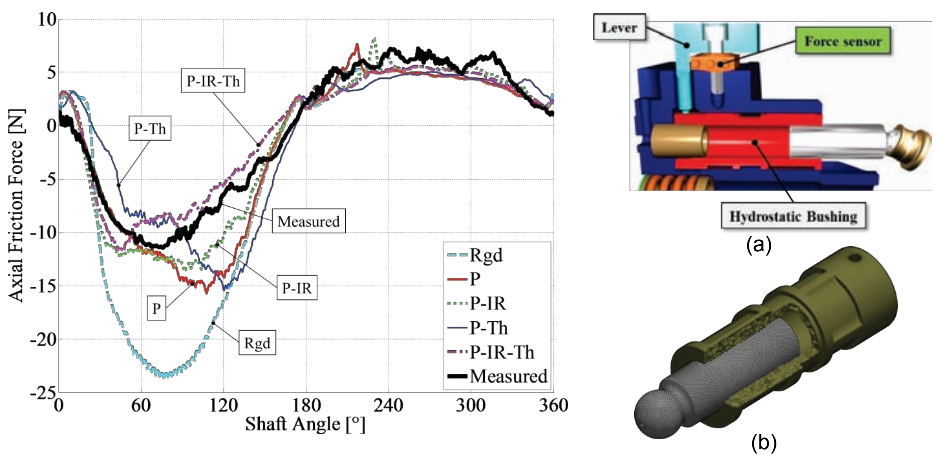

Figure 5: Friction force measurements and simulation
(a) Force sensor illustration (b) Discretization of the piston / cylinder geometry)

Three separate models have been run to evaluate the influence of the different types of surface elastic deformation on the final results. *Rgd* is a model considering non-isothermal fluid film flow with no fluid-structure and thermal interactions. In the model *P* the elastic deformation of the solid boundaries due to pressure is considered in addition to *Rgd* (elastohydrodynamic lubrication). Finally the model *P-Th* couples *P* with heat transfer analysis and thermal deflection of the solids (thermo-elastohydrodynamic lubrication). Figure 3 shows how the *P-Th* model can predict very precisely the measurements, especially when the advance Inertia relief (*IR*) constraint condition is applied to the boundary solids (*P-IR-Th*).

In conclusion, all the main parameters responsible of the interface performance (pressure, temperature and friction force) were measured and accurately predicted by the simulation model, which can be considered to be mature to assist in the digital prototyping.

A new discovery: How surface deformations enable high pressure operation of axial piston pumps
The numerical model was used to investigate brass bushings used in high pressure axial piston units [13]. It was found that thermal expansion due to energy dissipation in the fluid film can lead to major changes of the fluid film thickness and shape. For pumps using a brass bushing pressed into a steel cylinder, these thermal expansions introduce a wavy surface shape that helps improve the load carrying ability of the fluid film. This represents a major discovery, which explains why all pumps and motors working at extreme high pressures have to have a brass bushing in order to achieve a reliable operation and acceptable efficiency values. This discovery, together with the developed multi-physics model, forms the starting point for a new computational-based design approach. It will form a very important basis for the development of the next generation of highly efficient high pressure pumps and motors.

Slipper / swash plate interface
A semi-rigid numerical model of the slipper/swashplate interface was used to develop a design optimization methodology [19]. The goal of the optimization is to minimize average power loss over a number of operating conditions by allowing four geometrical parameters to change. To further reduce the computational burden of the optimization process, computationally cheap surrogate models were built using the Kriging method on top of the physical model described previously. An algorithm was then used on the surrogate model to find designs exhibiting minimum power loss. A human-in-the-loop refinement was used to enhance the accuracy of the surrogate modes in promising locations and further guide the optimization. Finally, an optimized design was found. Further work modeling the elastohydrodynamic effect in the slipper swashplate lubricating interface was published [20] and won a best paper award.

Planned Achievements following the report period

- Development of a new special test rig which enables direct measurement of the fluid film thickness in the slipper swashplate interface.
  - Deliverables:
    - Design of all test rig aspects, acquisition of components / electronics, and construction.
    - Completion of test rig construction and initial debugging and testing.
    - Complete measurement study using the test rig and comparison with simulation results.

- Investigation and development of a thermal model to predict pump and motor case temperatures under steady state operation.
  - Deliverables:
    - New pump thermal model methodology development.
    - Testing of axial piston pump to acquire temperature measurements for model validation.

- Digital prototyping case study to investigate various combinations of piston-cylinder material and design combinations.
  - Deliverables:
    - Deeper simulation study of the thermal waving effect in the piston-cylinder interface using the latest developed numerical models.
    - Digital prototyping of new material designs and proposal of best piston cylinder design.
    - Physical prototyping of a piston cylinder combination guided by the digital prototyping results and experimental testing. Deliverables include the physically prototyped part and a comparison of measurement results to simulated predictions.

C. Member company benefits

- Deeper and more comprehensive understanding of physical phenomena enabling successful operation of axial piston pumps and motors.
- Discovery of the impact of surface shaping and material properties on reliable pump and motor operation.
- Fundamental modeling of complex fluid structure interaction enabling further digital prototyping
- 10% overall efficiency improvement of an axial piston pump using surface shaping techniques demonstrated with prototype waved valve plate measurements.
- Preferential patent licensing options for waved pump lubricating surfaces
- Project 1B.1 research has led to seven associated projects on pump modeling with different member companies with a total investment of ~$1.1 million since 2006.

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Project 1B.2: Surface Effects on Motor Start-Up Friction

Research Team

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Industrial Partners:	Eaton, Parker, Toro, Poclain, Trelleborg

1. Statement of Project Goals

The goal of this project is to develop and experimentally validate a model for static friction to improve the start-up efficiency of hydraulic components. The resulting modeling tool will be the first experimentally validated start-up friction model that incorporates the real surface profile characteristics and lubricant effects. A successful project will result in a fundamental understanding of the relationship between characteristics of a component's interfaces and the friction it must overcome at start-up. The modeling tools and corresponding experimental test rig developed for the project will be used to evaluate existing and novel (e.g. textured) surfaces to improve start-up efficiency in fluid power machinery.

2. Project Role in Support of Strategic Plan

In the context of the CCEFP strategic plan, this project will contribute to overcoming the transformational technical barrier of efficient components. Many hydraulic motors exhibit extremely poor start-up efficiency, forcing OEM manufacturers to specify larger motors than necessary for normal operation, which in turn increases the overall cost and weight of the machines. This project will provide an understanding of the physical mechanisms underlying static friction which will lead to specific approaches for minimizing start-up friction. The research is relevant not only in terms of the start-up efficiency of fluid power applications, but also in terms of its fundamental focus on understanding static friction from a tribological perspective.

3. Project Description

A. Description and explanation of research approach

One of the challenges for equipment designed to operate intermittently is static friction. Static friction, the resistance to the onset of motion, results in large inefficiencies at start-up and often requires engineers to oversize machine components for the sole purpose of overcoming start-up conditions. Unfortunately, static friction is a physical phenomenon that is not yet well understood, particularly when dealing with complex, lubricated interfaces. Consistent parameter definitions and reproducible experimental methods are necessary to understand static friction and its dependence on material properties and operating conditions. Characterization of static friction is a critical step towards enabling machine interfaces optimized for improved start-up efficiency. In general, three approaches have been identified as alternatives to reduce static friction and improve performance: a) Reduce static friction by applying surface coatings, b) reduce static friction by modifying the lubricant and c) reduce static friction by studying and altering the surface [1]. This project explores the latter two of these approaches in this research.

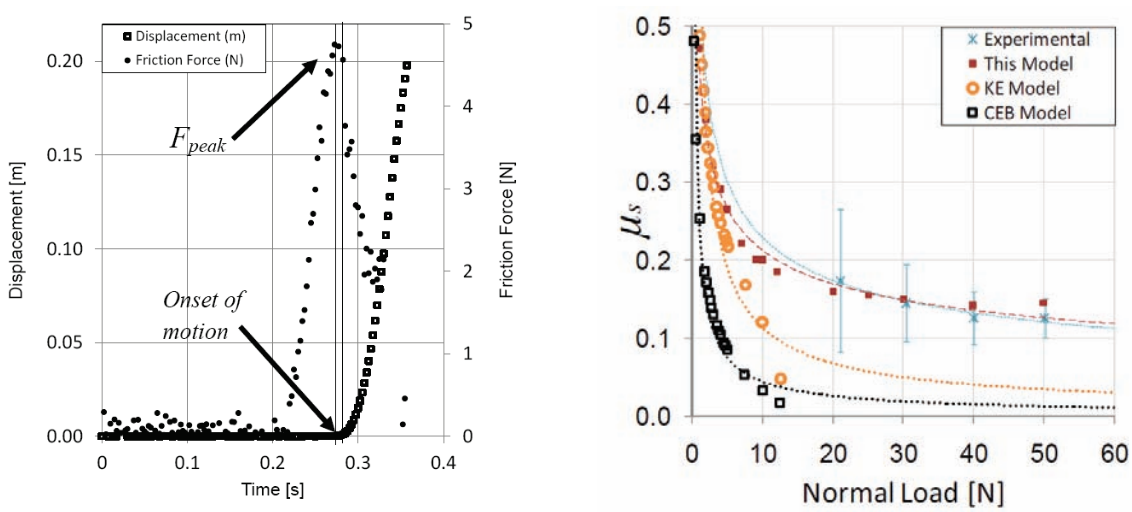
Static friction is typically quantified by the static friction coefficient, the ratio of the force required to initiate movement to the normal load. Researchers have used various experimental and model-based techniques to try to measure and understand the dependence of this parameter on material and operating conditions.

The following is a summary of experimental methods reported in the literature. One of the first approaches was the inclined plane in which a flat test surface is placed on top of a tilting flat surface, and the tangent of the angle at which the top test surface starts sliding is identified as the static friction coefficient [2-5]. In another early approach, a rotational device was used to measure both static friction and the deformation of test specimens under very light loads (~mN) [6]. More recently, static friction has been measured using an instrument referred to as the centrifugal friction apparatus which measures the friction between a block and a rotating disk [7, 8]. Static friction between flat surfaces at higher loads has been studied using instrumentation with hydraulic cylinders introduced as a clamping mechanism [9, 10]. Lastly, static friction of point contacts under light loads (~mN) has been measured using modified pin-on-disk instruments [11-13]. The applicability of previously reported experimental methods is limited by (i) restrictions on contact geometry, (ii) the range of accessible normal loads, and (iii) the ability to accurately determine the onset of motion. Perhaps the most significant limitation of nearly all previously reported methods for static friction measurement is their inability to accurately and consistently determine the onset of motion. Test standards to measure the coefficient of friction do not specify how this point should be identified [14]. Therefore, most studies utilize visual inspection or other indirect methods to determine when displacement begins and therefore at what point the static friction coefficient should be calculated.

The following paragraph summarizes model-based approaches for predicting static friction. Typical static friction models consider interfaces at the asperity level using statistically generated profiles to capture surface effects. The static friction coefficient is obtained as the ratio of the normal force input to the maximum shear force the material can withstand before sliding. The first models assumed elastic deformation of the asperities and used Hertz contact theory for predicting the contact area [15]. Later, a model accounting for plastic deformation was proposed [16]. Shortly after, a model including adhesive effects in metallic contact was proposed [17] and was later extended to incorporate lubricant adhesion [18]. Subsequent models focused on expanding the theories proposed in [16-23]. Unfortunately, nearly all of these models assume the surface profile can be represented by a statistical distribution of the asperity heights, which cannot capture the behavior of a real surface with scratches, grooves and deformations that are typical of surfaces in hydraulic components. In addition, most of these studies are focused on extremely small scale devices and so are based on assumptions that are not necessarily applicable to macro-scale components.

Thus, there are significant limitations in both the experiments and models reported previously to study static friction. Perhaps the most critical issue is that these limitations preclude direct comparison of model predictions with experimental measurements.

In this project both models and experiments were developed that address the issues described above. The experimental test rig is capable of handling multiple contact geometries, high normal loads, and will allow precise determination of the onset of motion. The model can incorporate real surface profiles into the calculation and is designed to capture the physics underlying static friction. In addition, the models and experiments were developed synergistically such that the model predictions can be validated by experiments, phenomena observed experimentally can be explained by reference to the simulations, and both can form the basis for reliable predictive models describing start-up friction.



(a) (b)

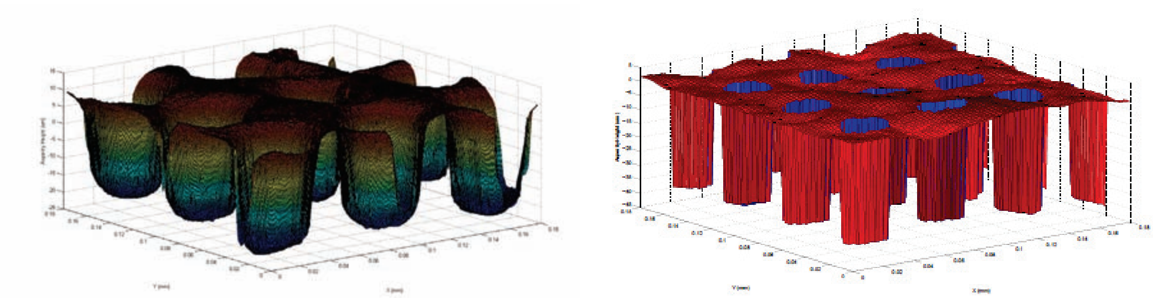
Figure 1: (a) Representative experimental measurement of the static friction coefficient at a 50N normal force. (b) Comparison of experimental static friction vs. load plot as measured experimentally and predicted using our model and two previously reported in the literature.

B. Achievements

Progress To-Date

During the first year of the project (2009) a model for static friction in dry point contact was developed and validated by comparison to experimental data reported in the literature. In the second project year (2010) an experimental test rig for static friction measurement was designed and built. The test rig was used to (i) validate the model for dry contact, (ii) study the effect of fluid material properties on static friction, and (iii) evaluate the performance of hydraulic oils formulated at MSOE. Details of the experimental rig and test conditions are available in [24] and [25]. Most measurements were taken for contact between a cylindrical roller from a geroler motor and a flat test piece. An example of the results of a single measurement is shown in Figure 1a.

The static friction coefficient for a metallic point contact over a range of loads is shown in Figure 1b. The star markers show the average value of the experimentally measured static friction, and the error bars represent the 95% confidence intervals of the measurements. The dotted line is a fitted curve of the form $\mu_s=c_1N^{c2}$ where c_1 and c_2 are regression fit constants. This functional fit has been used before by Hall [26] and has been seen to match experimental results by Etsion and Amit [11] and some of the results found by Archard [27] and Ibrahim [28]. The numerical model was run using the same material properties, geometry and loads of the experiment. Figure 1b shows predictions of the static friction coefficient using previously reported models (labeled CEB and KE in plot) and the present model. These simulations were performed for macro contacts past the plastic regime. To obtain these results, the normal load was varied between 1 N and 60 N. The KE model predicted values of the static friction for lower normal loads that are in agreement with the model proposed in this paper, but past 10 N the static friction coefficient prediction of the CEB and KE models falls off dramatically. This is because the previous models are unable to predict the static friction coefficient for contacts beyond the plastic deformation regime. Plastic deformation under our experimental tested conditions was estimated to occur at approximately 12 N. Based on this study, the team felt confident that the model was able to capture experimentally-measured static friction under a range of industrially-relevant loading conditions.



(a) (b)

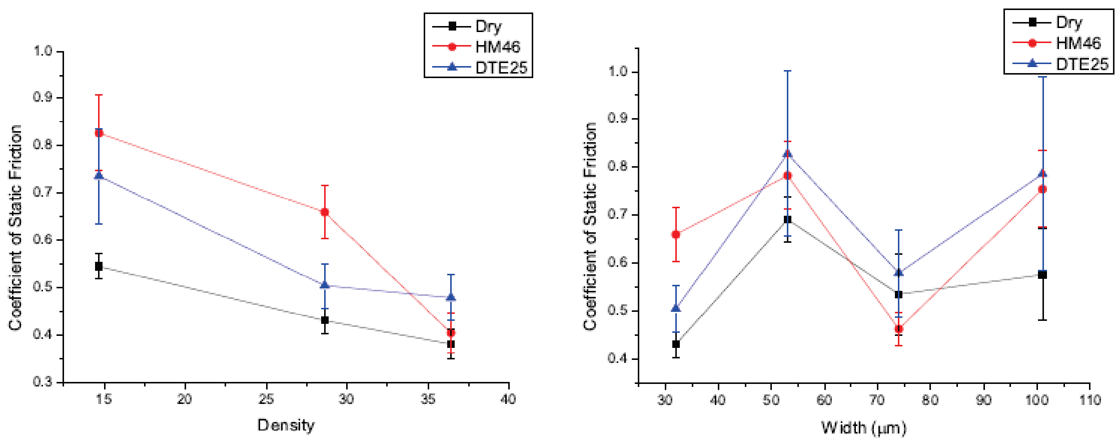
Property	Untextured	Textured	Artifical Texture
Ra (um)	0.91918	12.366	12.921
Rq (um)	1.1601	13.262	16.123
Peak to Peak (um)	9.1998	38.294	49.177
Sk	-0.2385	-0.5014	-2.2739
Ku	3.1620	1.4639	5.7115

(c)

Figure 2: (a) Profilometer scan of textured surface produced by project 1D. (b) Numerically generated textured surface. (c) Comparison of the statistical surface characteristics of the measured un-textured and textured surface and the artificially textured numerical surface.

Next, the focus turned to surface textures and their effect on static friction. Textured surfaces were obtained from Wm. King at UIUC for this purpose. A profilometer image of one such surface is shown in Figure 2a. To introduce textures in the model, we developed an add-on module that takes as input the dimple density, depth, and size and imposes a pre-defined texture on a measured un-textured rough surface. An example artificially textured surface is shown in Figure 2b. To verify that the generated surface patterns where consistent with those obtained from UIUC, we compared the statistical surface parameters and found them to be quite reasonable as shown in Figure 2c. Since the model had been validated, this capability can be used to explore the effect of various surface patterns before they are manufactured. The textured surfaces specifically manufactured at UIUC for this project were also directly measured. The key parameters that defined a texture, density and width, were varied systematically. All surfaces were then tested over a range of loads and with both dry conditions and two lubricated conditions.

The effect of lubricating fluid was also studied through collaboration with P. Michael at MSOE. The fluids used in testing were HM 46 and DTE 25, two ISO Viscosity Grade 46 antiwear hydraulic fluids. DTE 25 is a commercial antiwear hydraulic fluid that is produced by ExxonMobil formulated with a solvent-refined paraffinic mineral oil base stock. HM 46 is an experimental antiwear hydraulic fluid formulation that is formulated with a hydroisomerized paraffinic mineral oil base stock. In addition to differing in base oil composition, these fluids differ in antiwear additive chemistry. DTE 25 uses a zinc dialkyldithiophosphate antiwear additive while HM 46 uses a zinc-free or ashless antiwear additive that combines amine phosphate and sulfurized hydrocarbon chemistry to achieve wear protection.



(a) (b)

Figure 3: Experimentally measured static friction for dry and lubricated cases illustrating the effect of (a) dimple density and (b) dimple width.

Although a large amount of data was generated that is still being analyzed, Figure 3 shows two examples of the types of results have obtained. In Figure 3a it was observed that increasing dimple density decrease the static friction. In addition, this plot shows that, at least in the lower dimple density range, both fluids cause an increase in static friction. This observation, although somewhat counter-intuitive, is in agreement with previous static friction research such as that reported by Tian and Bhushan [29], who found that the presence of a thin film of lubricant increases the coefficient of static friction and that the magnitude of this increase is a function of lubricant film thickness increased. Figure 3b is an example of a study on the effect of dimple width. In this case the trend is not so straight-forward. It is clear that some widths are more preferable than others (for example, in this case 75 microns appears to have a beneficial effect), but there is not a monotonic relationship between dimple width and static friction. This and other trends have been observed and are currently being analyzed. In general, the plan is to use the model predictions to help guide the surface texture designs for optimal start-up friction and experimentally evaluate the performance of the resultant textured components.

Plans for Next Year

This project will be ending in May 2012.

C. Member company benefits

Based on this research, member companies will have access to a new theoretical understanding of how surface characteristics affect start-up friction as well as a numerical modeling tool that implements this theory. In practical terms, this work lays the groundwork for development of development of application-specific design tools for optimal start-up efficiency.

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Project 1D: Micro- and Nano-Texturing for Low-Friction Fluid Power Systems

Research Team

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Graduate Students:	Ashwin Ramesh
Undergraduate Students:	Courtney Engle
Industrial Partners:	Trelleborg, Eaton, Gates, Caterpillar, John Deere, Hoowaki

1. Statement of Project Goals

The goal of this project is to develop low-cost microstructured surfaces with significantly reduced coefficient of friction compared to surfaces with conventional surface finish. The project aims to design, fabricate and characterize the effect of micro-textures on lubricated surfaces that are suitable for real world fluid power applications. The focus is to enhance the performance of lubricated contacts by using micro-textures that lead to a significant reduction in the sliding friction between the surfaces compared to non-textured ones. The focus is also on low-cost scaling of these surfaces to sizes and shapes appropriate to the industrial applications.

2. Project Role in Support of Strategic Plan

The ultimate goal is to enable leak-free components with friction lower than state of the art. Such a technology would overcome current barriers to fluid power systems (efficient components, leak-free), and provide a transformational capability for future fluid power systems (efficient components). The technology will be validated through collaboration with industry and through application to the excavator and orthosis test beds. The work will also improve fundamental understanding critical to fluid power components.

3. Project Description

A. Description and explanation of research approach

Microstructures patterned onto mating surfaces can significantly reduce friction, adhesion, and wear [1-4]. Previous work by our group and others shows that micro-textured surfaces may offer significant advantages for fluid power including reduced friction and reduced leaks. The goal of the proposed research is to drive this technology to application within the fluid power industry by producing fluid power components that have lower friction and leakage compared to state of the art.

Until recently, the key technical challenge to realizing microtextured surfaces in fluid power applications has been the inability to manufacture microtextures on real surfaces at scale. Some published reports investigate sliding friction on micro-structured semiconductor surfaces [5], which are too brittle for use in a pump and cannot be scaled beyond a few inches. It is possible to fabricate microtextured steel using photolithography and chemical etching, [2], but this approach cannot be scaled to curved substrates or large areas. Finally, laser texturing has been considered for manufacturing micro-textures [1, 3, 4], but it is prohibitively expensive and can produce a very small range of texture sizes and shapes. The team's research on manufacturing micro-textures onto durable metal substrates overcomes these limitations [6, 7]. A standard industrial investment casting process that is modified to incorporate microstructures into the investment mold is used. The manufacturing approach can fabricate microstructures into very large surfaces of any shape, and the material can be any castable metal. Metal components including rods, shafts, bearings, and seals can also be post-processed. This manufacturing technology forms the basis for a company Hoowaki LLC, and in 2011 was recognized by the Society of Manufacturing Engineers with their award "Technologies that Will Change the Way You Manufacture." Figure 1 shows metal surfaces that demonstrate the ability to cast submicron structures into metal and on curved surfaces.

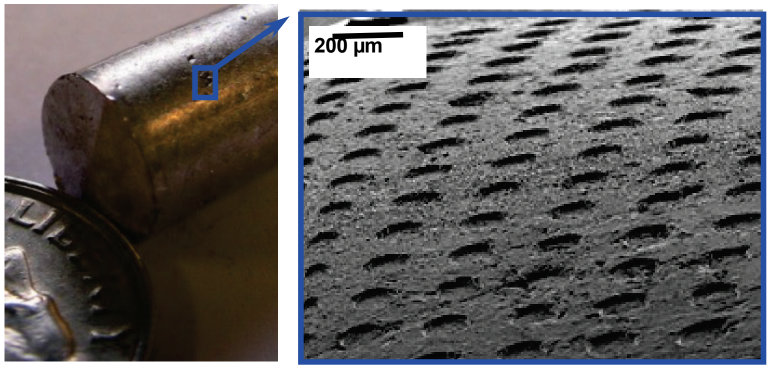

Figure 1: Metal surfaces fabricated with surface micro-textures. This surface is similar to a rod surface we will explore in the proposed research.

The second technical challenge to realizing microtextured surfaces in fluid power applications is the lack of engineering design rules. The optimal microtextures depend upon component geometry, operating speed and pressure, and fluid properties. There have been a few published reports that use simulations to select the optimal size and shape of microtextures [8, 9], but there is a lack of published research showing both computations and experiments. Over the last 1.5 years under CCEFP support, the team has performed both experiments and simulations to develop the first comprehensive approach to engineering microtextures for fluid power. There have been two major outcomes from this work: first, an experimentally-validated computational tool has been developed; and second, this tool has been used to design microtextures for several fluid power applications.

B. Achievements:

Microtextured surfaces decrease friction: Computational fluid dynamics (CFD) simulations to model fluid flow and friction between sliding surfaces have been performed. Figure 2 shows the computational regime which consists of two walls in relative motion, one of which is textured and the other is smooth. The velocity, gap thickness, fluid properties, pressure, and texture width, depth, and periodicity can all be defined within the simulation. Figure 2 shows a 2D calculation, although we have also performed 3D simulations and have found the results to be easily scaled from one to the other. The simulations were validated through constant load experiments in a commercial tribometer. The experiments tested textured steel surfaces that were manufactured using the techniques described above. The goal of these experiments was not to mimic fluid power conditions, but to validate the simulation. Figure 2 shows experimental and simulation results at 0.36 m/sec speed, 5.3 MPa pressure, 1.5 Pa-sec viscosity (gear oil), and 30% texture density.

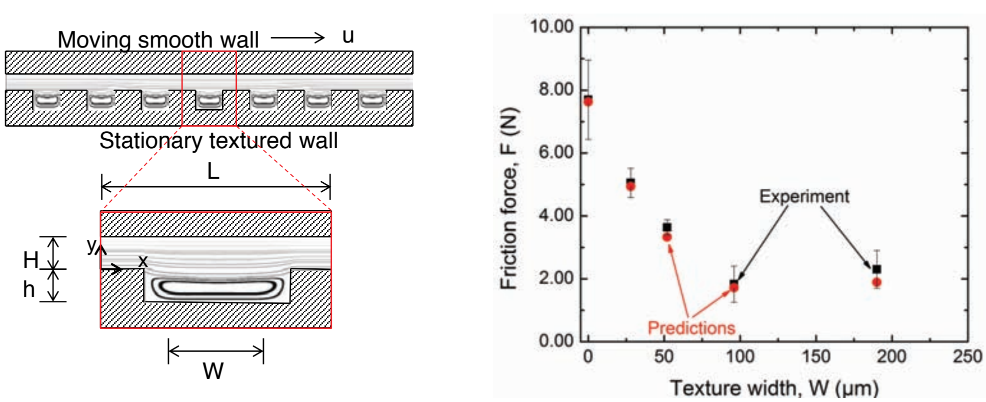

Figure 2: Left: computational regime which consists of two walls in relative motion, along with the key texture dimensions. Right: Computational and experimental results, showing friction force as a function of texture width.

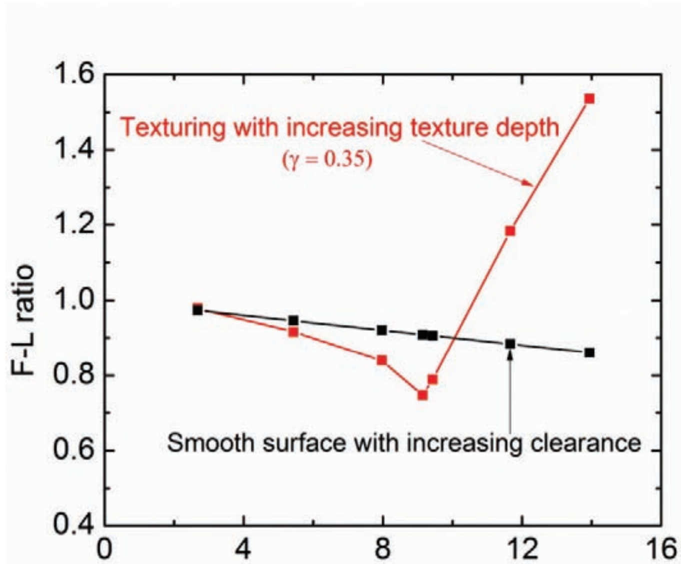

Figure 3: Comparison of the friction and leakage characteristics of smooth and textured surfaces. The F-L ratio is the ratio of friction decrease to leakage increase. For a range of parameters, the microtextured surfaces have clear benefits compared to smooth surfaces.

<u>Microtextured surfaces improve leakage:</u> There is a tradeoff between friction and leakage in any seal: it is always possible to increase the gap between mating surfaces to decrease friction. However, this gap increase also increases leakage. In order to directly compare textured and nontextured surfaces, we define the friction-leakage (F-L) ratio, which is the friction reduction (%) divided by leakage increase (%). When this ratio is greater than one, there is a net benefit. While this ratio is not the key design parameter in a fluid power system, it allows for clear performance comparison between different surfaces. Figure 3 shows the calculated F-L ratio for textured and smooth surfaces when velocity = 12 m/sec, viscosity = 1.5 Pa-sec (gear oil), and film thickness = 20 µm. For the microtextured surface, texture depth = 1-100 µm. When the gap thickness is increased between smooth surfaces, the F-L ratio slightly decreases, illustrating why this is not a preferred approach. When one surface is microtextured, there is a range of textures for which there is a significant benefit for both friction and leakage.

The team's work is being applied by other researchers within the Center. First, the team is working with Paul Michael at MSOE and Ashlie Martini at Purdue to texture and test hydraulic motor components. The preliminary tests show that microtextured rollers have more than 25% reduction in start-up friction compared to (untextured) rollers used today. Second, the team is working with Professor Perry Li at University of Minnesota to apply microtextures to a three-way valve. Simulations predict that microtextures applied to the valve will result in 30% friction reduction and 70% increase in leakage. The same friction reduction could be achieved by increasing the gap between untextured smooth surfaces, but the corresponding leakage increase would be 200%. If the microtextures were to be designed into the valve from the beginning, it would be possible to improve both friction and leakage relative to untextured surfaces. The microtextured device is currently being fabricated and tested. Third, microtextured surfaces have been designed for Trelleborg under a nondisclosure agreement. Trelleborg has fabricated these components – some have been tested with favorable results, and some components have yet to be tested. Overall, this activity has validated that microtextures can be applied to fluid power components and can improve their performance.

<u>Gerotor roller application</u>: Low efficiency in gerotor motors in the startup regime due to high static friction has been a major concern in the fluid power community. In this collaboration with Project

1.B2, this issue is being addressed by surface texturing the faces of the gerotor roller. Experimental and numerical work conducted in Purdue University has suggested a static friction reduction of up to 25% through surface texturing compared to untextured surfaces. The roller has micro-grooves parallel to its axis (Figure 4) and the cylindrical counter bodies have rectangular textures with width 50 µm in 100 µm spacing. These components will be tested for static friction performance in lubricated and unlubricated conditions.

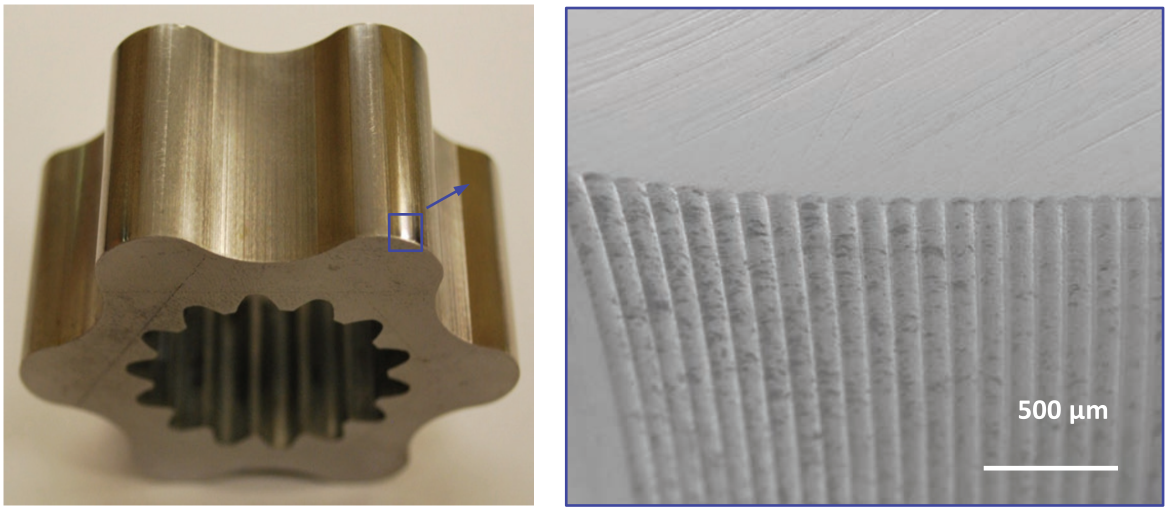

Figure 4: Microtextured gerotor roller (Project 1.B2). SEM image of the textured portion indicates rectangular grooves for reduced start-up friction.

<u>3-way valve application</u>: An important problem in fluid power systems is the trade-off between friction between the sliding surfaces and the leakage through those surfaces. In this collaboration with Project 1.E1, this issue is addressed in the rotary spool of an on-off valve by microtexturing the spool surface. The spool experiences friction due to rotation within a bearing sleeve and leakage across the lands due to a pressure gradient. The spool-bearing clearance is 20 µm and the Reynolds number for the flow is 0.5. The simulation was used to identify the best microstructure for this application and a design with grooves on the outer land and rectangular slots on the helical land predicts a friction reduction of 30% with 70% increase in leakage. Compared to the alternate method of increasing clearance, for the same friction reduction, the leakage increase would be 200%. The spool has been textured successfully (Figure 5) and is currently in the testing phase.

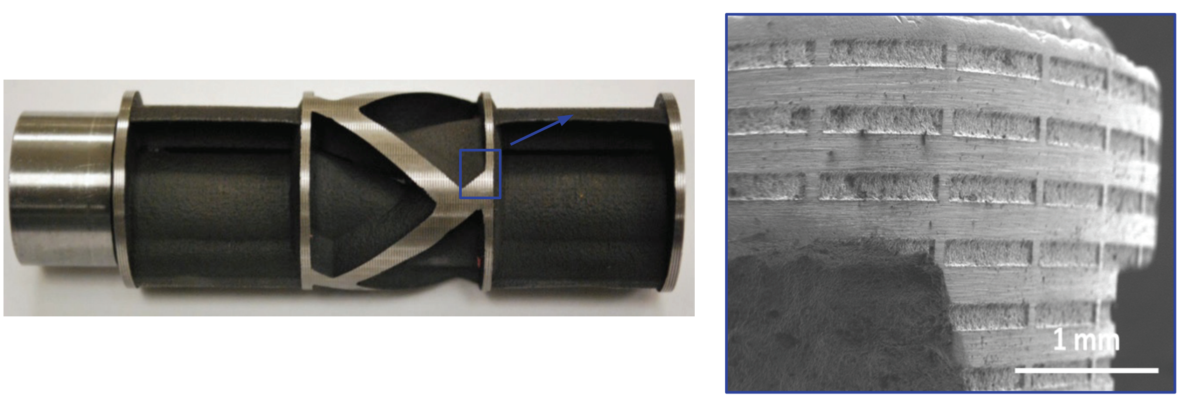

Figure 5: Microtextured rotary spool used as on on-off valve (Project 1.E1). SEM image of the textured portion indicates rectangular trenches for reduced friction and leakage.

C. Member company benefits

Friction losses are ubiquitous in the fluid power industry. Discussions have been initiated with several member companies (Trelleborg, Eaton, John Deere, Caterpillar, Gates) about this technology. Each company has a specific set of applications that do not necessarily overlap with one another. The goal is to be broadly useful to a range of these applications without becoming too narrowly focused on just one of them at this time.

In 2008, Professor King started a company, Hoowaki LLC, based on the technology shown in Figure 1. Several CCEFP member companies have already purchased microstructured tools from Hoowaki in order to accelerate the insertion of this technology. This CCEFP project aims to develop the design rules for the tools that they are acquiring.

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Project 1E.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor

Research Team

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Other Faculty:	Prof. Thomas R. Chase, University of Minnesota, Mechanical Engineering
Graduate Students:	Haink Tu, Rachel Wang, and Mike Rannow
Industrial Partners:	Eaton, Parker Hannifin, Sauer-Danfoss, and others

1. Statement of Project Goals

The goal of the project is to demonstrate high performance, efficient control of hydraulic power using on/off valves in a throttle-less manner. This goal will be met through the development of critical enabling technologies such as novel high speed rotary on/off valves that will be integrated into virtually variable displacement pump/motors (VVDPM) for demonstration on CCEFP test beds. In addition to the rotary spool valve approach studied in previous years, a newly proposed rotary valve based on a ring control element will be developed. This new ring valve has been conceived with the objective of improving valve efficiency at high pressure and high bandwidth operation by simplifying the valve flow path while simultaneously reducing the internal compressible volume. Prototype targets include 21-35MPa operating pressure, VVDPM system bandwidth in excess of 10Hz, and hydraulic valve efficiency greater than 85% at 50% VVDPM displacement.

2. Project Role in Support of Strategic Plan

Pulse-width-modulation (PWM) of hydraulic power using on/off valves is a potentially efficient control concept that is analogous to switched mode converters used in power electronics [1]. By pairing on/off valves with a fixed displacement pump or motor of any type, variable displacement functionality can be achieved with designs that are inherently efficient or compact but traditionally fixed. This project addresses the Center's efficiency goal by developing efficient pulse width modulated alternatives to inefficient throttling valves. It also addresses the compactness goal by enabling variable displacement functionality using compact, inexpensive fixed displacement components.

3. Project Description

A. Description and explanation of research approach

Current methods of controlling fluid power systems are either inefficient (throttling valve control) or expensive and bulky (mechanical variable displacement pump or piston-by-piston digital pump). The virtually variable displacement pump/motors (VVDPM) proposed in this project combine the strengths of traditional approaches by enabling throttle-less displacement control of compact, inexpensive fixed displacement pump/motors using a single on/off valve.

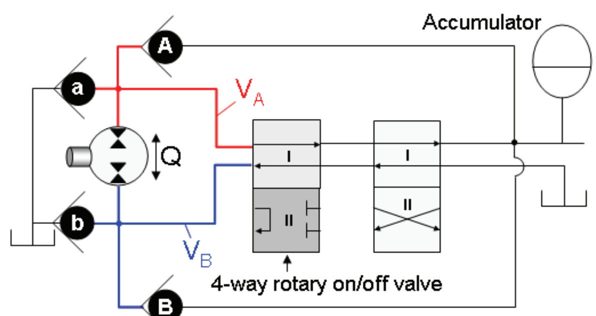

Figure 1: Hydraulic schematic of a VVDPM using a 4-way tandem rotary on/off valve. Check valves a and b prevent cavitation while check valves A and B reduce pressure spikes during transition.

One such VVDPM implementation based on a 4-way tandem on/off valve is shown in Figure 1. The VVDPM enables variation of the output flow or torque of a fixed displacement pump/motor by rapidly pulsing it between full output flow or torque (corresponding to on/off valve Position 1 in Figure 1), or letting the pump/motor idle (i.e. zero output flow or torque corresponding to Position 2). The ratio of full output to the total switching period is the duty ratio, which controls the mean output of the VVDPM.

The lack of high-speed on/off valves, which are the counterparts to electronic transistors, is a major challenge. These on/off valves must have large orifices to allow high flow at low pressure drop. They must have fast transitions to reduce the time when the valve is partially open. And, they must have the ability to operate at high PWM frequencies to reduce ripple and achieve high control bandwidth. A typical control valve consists of a linear translating element such as a spool or poppet. The element must be accelerated and decelerated rapidly to be used in PWM control. This requires large actuators, since power input is proportional to the cube of the PWM frequency.

Novel on/off valves that use continuous rotary motion to generate on/off switching are developed in this project. These rotary valves do not need to start and stop; therefore, the only power required is that to overcome friction (proportional to frequency squared). Moreover, in applications where the pump or motor shaft speed is fixed (i.e. constant flow rate through the valve), the rotary actuation power can be obtained by scavenging energy in the fluid stream without using an external actuator. The average response time and effective flow area for several commercial on/off valves and a few valves found in the literature [2, 3] are compared to the prototype rotary valve in Figure 2.

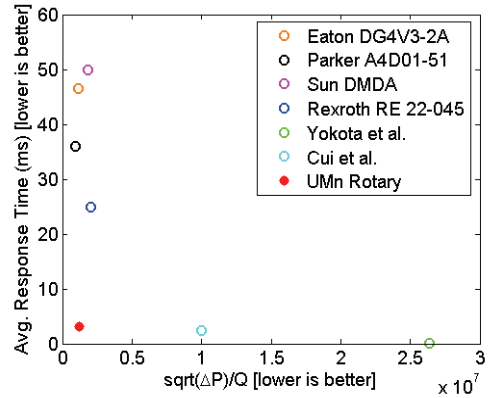

Figure 2: Effective flow area and response times of existing on/off valves

B. Achievements

The project team is developing two rotary valve prototypes that will be integrated into VVDPMs for demonstration on Test Bed 3 (TB3), the hydraulic hybrid passenger vehicle. The plan is to replace the speeder pump/motor of the vehicle, which is used for decoupling the engine speed from the wheel speed. The first prototype is based on the spool valve architecture that has been under development since the inception of the CCEFP. This architecture has evolved from a 3-way self-spinning design for the control of fixed displacement pumps to a 4-way tandem design for the control of pump/motors. The second prototype is based on a novel ring valve that was proposed a year and a half ago with the goals of improving valve efficiency in VVDPMs during high pressure, high PWM frequency operation.

Research during the previous reporting period showed that self-spinning was not an efficient actuation method when using the VVDPM as the speeder pump/motor on Test Bed 3. This is due to the large range of pump/motor shaft speeds and corresponding flow rates through the rotary valve (0-8400rpm or 0-82lpm) when the vehicle is driven over the combined EPA Urban and Highway drive cycles. In order to meet minimum PWM frequency requirements at low shaft speeds, excessive throttling is incurred at higher ones. An optimization case study based on analytic design equations showed that rotating the valve using an external actuator was a more efficient approach for this application. A two-degree-of-freedom rotating and translating drive mechanism for the valve spool was then designed and experimentally validated.

Achievements over the past year include: developing improved dynamic models of the VVDPM, performing simulations to compare VVDPMs with bent axis pump/motors in the TB3 Generation I vehicle, prototyping a VVDPM which utilizes a 4-way rotary valve, developing a controller for the 4-way rotary valve, and developing an alternative VVPDM which utilizes a novel 3-way rotary ring valve in place of the 4-way rotary valve. These achievements are described in order below.

The VVDPM is modeled using a two state model that captures the compressible oil dynamics seen by the two ports of the pump/motor (V_A and V_B in Figure 1). The model uses the optimized externally actuated rotary valve geometry. It has been simplified by assuming that the vehicle accumulator pressure is constant, neglecting line losses and ignoring the dynamics of the check valves. Simulated pressure profiles are presented in Figure 3 and the corresponding VVDPM pump and motor efficiency maps are presented in Figure 4 (which include the fixed displacement pump/motor losses based on a manufacturer provided map). Figure 3 shows that valve transition effects are not reduced by the check valves (a, b, A, B) during motoring as they are with pumping. To understand this, consider the pressure in volume V_B as the on/off valve switches from open to recirculation mode. When throttling arises due to transition of the on/off valve, the rotary inertia of the motor causes the pressure of the fluid in V_B to drop. Check valve B remains closed and check valve b will not open unless V_B drops below atmospheric pressure. A similar phenomenon occurs with check valves a and A in volume V_A.The result of the ineffectiveness of the check valves in reducing motoring transition effects is observed in the efficiency maps in Figure 4; motoring efficiency is lower at higher shaft speeds compared to pumping.

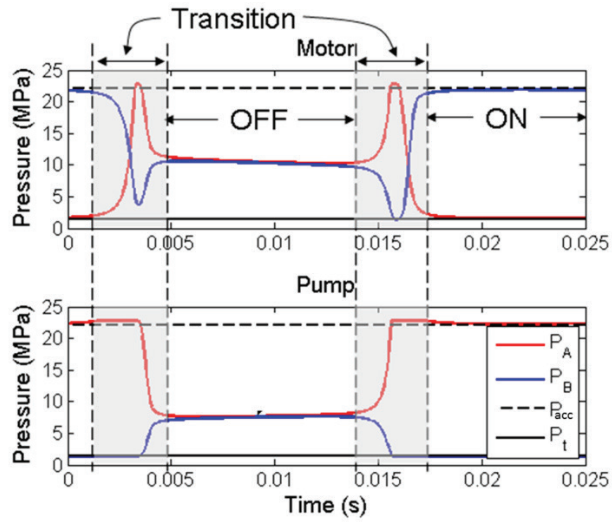

Figure 3: Simulated VVDPM pressure profiles showing ineffectiveness of check valves (a,b,A,B) in reducing transition spikes during motoring

Using the efficiency maps generated by the simulation, two case studies were performed to compare the VVDPM to the variable displacement bent axis pump/motors that are currently being used on Test Bed 3. In the first case study, the cycle efficiency of the two devices were compared based on speeder pump/motor operating points (speed, torque) and displacements that were optimized for a variable displacement bent axis pump/motor. The optimization was performed using an efficiency map that was provided by the manufacturer of the bent axis unit that may or may not include actuation power losses. Actuation power, however, is included in the VVDPM numbers. In this scenario, the variable bent axis pump/motor achieved a cycle efficiency of 88%. The VVDPM achieved a valve cycle efficiency of 83% and an overall cycle efficiency of 77%. Breaking up the VVDPM overall cycle efficiency into motoring and pumping reveals that the cycle motoring efficiency is 76% compared to a cycle pump efficiency of 81%. The following conclusions can be drawn from these results: first, the lower motor cycle efficiency is a consequence of the efficiency drop off at high shaft speeds due to transition losses as seen in Figures 3 and 4. Second, since the optimally sized variable bent axis pump/motor displacement is 15.1cc (for 21MPa accumulator pressure) and the displacement of the fixed pump/motor that will be used with the rotary valve is only 9.8cc, the VVDPM is forced to run non-ideally at higher speeds because the operating points were optimized for the variable bent axis unit.

In the second case study, the speeder operating points over the EPA drive cycle were optimized for the VVDPM. The displacement of the VVDPM was also optimized by scaling the simulated efficiency maps in Figure 4. The pump/motor displacements and cycle fuel economy for three cases are presented in Table 1. If only the speeder pump/motor is replaced with a VVDPM (middle column), the impact on cycle fuel economy is negligible (-.6%). Notice that the optimal VVDPM displacement for

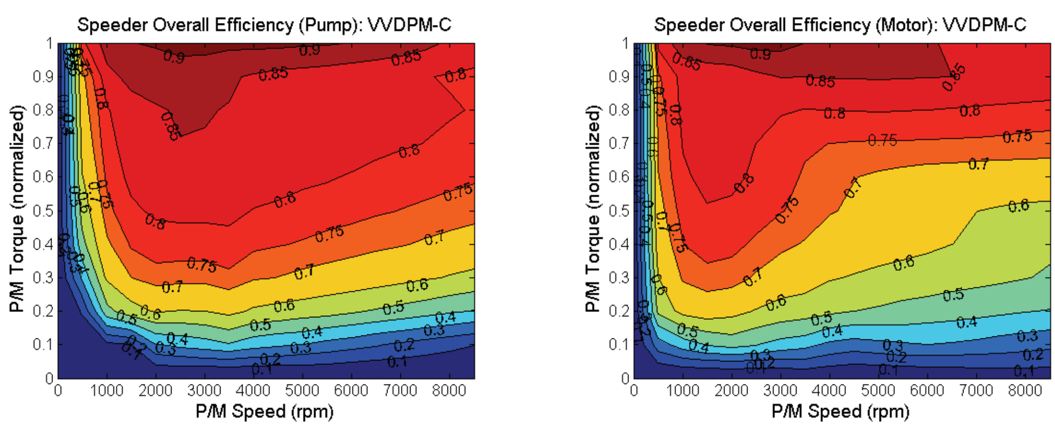

Figure 4: Overall VVDPM efficiency maps for pumping (left) and motoring (right). Includes losses from the fixed displacement pump/motor based on a manufacturer-provided map.

this case is 22.4cc instead of the 9.8cc unit that will be used on the prototype (also used in the first case study). If both pump/motors on the test bed are replaced with VVDPMs (right column), the fuel economy decreases by 5%. This result is most likely due to the variable bent axis torque unit's higher and more constant efficiency which allows more flexibility in placing the speeder operation in the VVDPM's sweet spot if only one pump/motor is replaced. Even replacing only one variable unit can potentially yield savings in vehicle cost. In addition, more flexibility exists in choosing the optimal displacement since there is typically a larger selection of fixed pump/motor displacements and architectures available.

	Variable bent axis	Speeder VVDPM	VVDPM
Torquer	12.0cc	13.1cc	15.3cc
Speeder	15.1cc	22.4cc	19.9cc
MPG	65.6	65.2	62.3

Table 1: Test Bed 3 fuel economy over combined EPA Urban and Highway drive cycles. All displacements are optimal.

Significant progress has been made this past year toward the development of a prototype VVDPM to validate the operation, analysis, and efficiency of the 4-way rotary valve. All prototype components were sized taking fatigue into account where applicable due to the high frequency, high amplitude pressure fluctuations experienced by PWM systems. All major components, including an updated driving mechanism, have been quoted and are in the process of being manufactured. Figures 5 and 6 show the prototype valve spool and sleeve. The spool is cast from 316 stainless with secondary machining by MSOE and the sleeve was CNC machined from 4150 pre-heat treated alloy steel for improved fatigue life. One major design challenge for the prototype was the custom housing needed to reduce the internal dead volume between the fixed-displacement pump/motor and the rotary valve. Minimizing this volume is important in order to reduce compressibility losses, which are significant at high pressures and PWM frequencies. The initial housing design combined a thick walled section containing the sleeve, as required to obtain adequate fatigue strength, with a thin walled section for the pump/motor interface. However, no manufacturer submitted a bid to fabricate this part. Splitting the part and redesigning sub-components for machining instead of casting produced an affordable, buildable prototype. The new housing further reduces costs with its modular design; it will also be used with the prototype ring valve.

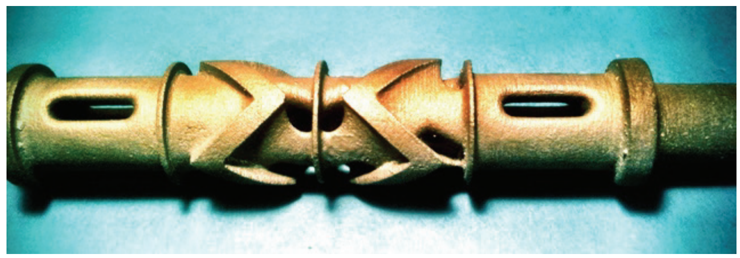

Figure 5: Cast 4-way rotary valve spool prototype from MSOE

Figure 6: CNC machined 4-way rotary valve sleeve prototype

The axial controller for varying the duty ratio of the rotary valve using the external driving mechanism has been improved. The valve's duty ratio determines the VVDPM's mean output flow or torque [15]. The external driving mechanism's axial degree-of-freedom is controlled by modulating the pressure within a control chamber that is acted on by a return spring. A passivity based nonlinear controller has been developed that uses a novel pressure dependent fluid compressibility model to define the compressible fluid energy term. The new controller reduces the effort required to tune the feedback gain compared to a traditional backstepping nonlinear controller. The new controller also allows a smaller feedback gain which is insensitive to measurement noise.

The new controller and drive mechanism can achieve full stroke duty ratio variation of the VVDPM in less than 50ms using a pilot pressure of 1.3MPa.

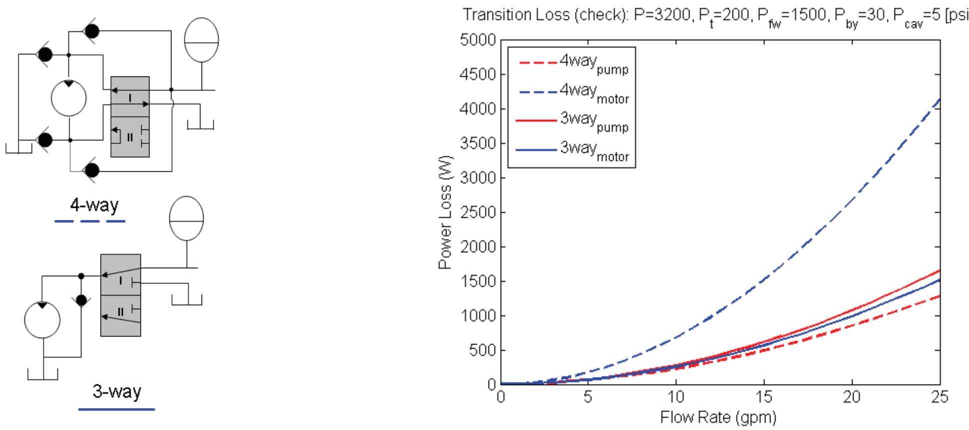

Figure 7: 4-way and 3-way motoring circuits (left) with corresponding transition losses (right). The dotted blue trace is the motor transition loss for the 4-way circuit and the solid blue trace is the loss for the 3-way circuit.

The remaining effort in the past year has been to refine and develop the ring valve concept. Due to the high motor transition losses observed in the 4-way rotary valve, the ring valve was redesigned as a 3-way valve. Figure 7 compares motoring transition losses between the 4-way and 3-way circuits. The analysis shows that check valves can be used effectively in the 3-way motoring configuration to reduce transition losses to the same level as pumping. Another benefit of the 3-way ring valve is that it eliminates the need to seal both the ID and OD of the original 4-way ring valve embodiment. This significantly reduces both valve friction and leakage.

A traditional disadvantage of 3-way on/off valves is that the directional control valve needed for 4-quadrant VVDPM operation is located in the switched volume between the on/off valve and the pump/motor. This added volume contributes to compressibility losses. However, the ring valve allows the on/off valve to switch between pulse-width-modulating ports A or B of the pump/motor, which makes it possible to relocate the directional valve outside of the switched volume. Other notable circuit modifications to the 3-way ring valve included reducing the valve length from 5 sections to 3 sections by replacing two check valves with pilot-to-open valves. Additional progress made on the ring valve includes an analytical loss analysis that can be used for optimization and preliminary CAD models. Finally, an initial CFD analysis of the ring valve was done that led to geometry improvements that reduced the pressure drop in the valve by 17% without increasing the switched volume.

Over the next 5 years, after the current generation of rotary valves has been experimentally demonstrated, the technology should be expanded to other applications such as virtually variable displacement linear actuators, transformers, and multi-circuit systems. Studies should also be performed to evaluate the impact of high frequency flow and torque ripple on vehicles and other systems as well as component life such as hoses, connectors, and fittings. Noise is also a potential concern that should be investigated in detail. References [4]-[18] have been published to date (in chronological order); references [13]-[16] were published during the reporting period.

Expected Milestones and Deliverables

The prototype 4-way tandem externally driven spool valve is targeted for initial testing by April 2012 with bench testing complete by May 2012. Implementation onto Test Bed 3 will begin during the summer of 2012. Concurrently, the ring valve prototype will be finalized and sent out for prototyping by the end of April 2012. Prototypes should be available for testing by the end of May 2012.

C. Member company benefits

Member companies will benefit from the development of innovative on/off valve architectures, new digital control and estimation algorithms, design insights, high frequency hydraulic sensing techniques, and an expanded knowledge of applications.

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18. Rannow, M. and Li, P., “Soft Switching Approach to Reducing Transition Losses in an On/Off Hydraulic Valve" (under review)

Project 1E.2: High Speed On/Off Valves to Enable Efficient and Effective Fluid Power Systems

Research Team

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Graduate Student:	Shaoping Xiong
Undergraduate Student:	Yichen Li
Industrial Partners:	Parker Hannifin, Eaton, Husco, Moog

1. Statement of Project or Test Bed Goals

The *goals* of the project are to research and develop advanced multi-domain models and increase the theoretical understanding of high speed digital hydraulic valves, experimentally validate the models, and apply the results to design valves in support of CCEFP projects and related digital fluid power applications. Digital valves will be implemented into several CCEFP projects and test beds to facilitate and validate the use of high speed on/off valves as enablers of efficient and effective fluid power systems.

The fundamental problem is the highly non-linear coupling between the electrical actuator, mechanical system friction in moving components, and fluid dynamics (flow forces and viscous friction). Project metrics will be achieved if, using the tools developed and dissemination during the course of this project, high speed digital valves are successfully modeled, simulated, tested, and implemented in related center projects and test beds.

2. Project or Test Bed Role in Support of Strategic Plan

This project supports the efficiency thrust and the compactness thrust of the strategic plan. The efficiency thrust is supported through the use of on/off valves to reduce metering losses in typical fluid power systems, increase the bandwidth and control of existing components, and to enable new, more efficient, fluid power components and systems. Compactness is achieved by the development of high speed positive sealing digital valves capable of operating at higher than standard pressures. Also, as hydraulic systems are made more efficient, they inherently become more compact due to reduction in size of the prime mover, cooling systems, hoses, and fittings. An understanding of the interaction between the electrical, mechanical, and hydraulic systems has enabled accurate models to be developed and combined with larger system models for the optimization of system efficiency, operating pressure, and dynamic response. Successful completion of this project will have a significant impact on the ability to develop and implement the control strategies proposed in Project 1E.3 as well as the feasibility of that project. Project 1E.2 will benefit test beds 1 and 3 though high bandwidth control actuators, digital pump/motors, and virtual variable displacement pumps (VVDP similar to Project 1E.1).

3. Project/Test Bed Description

A. Description and explanation of research approach

Understanding and analytically describing the non-linear coupling and impact of fluid dynamics (flow forces), electromagnetic transients, leakage flows, and mechanical deformations and friction in high speed switching valves enables fluid power systems with improved efficiency and effectiveness (meterless switching control, digitally controlled pump/motors, virtually variable displacement pumps, new system topologies, and improved control bandwidth for existing components). This work is an important and complementary component to the other ongoing work in the center. By providing fundamental understanding about the operation and implementation of high speed on/off valves, other researchers can study how the use of such valves impact their efficiency (component and system) and effectiveness (compactness, noise, reliability, etc.).

The valves considered in this project are axisymmetric positive contact sealing. In most conventional systems, as working pressure is increased, efficiency tends to decrease due to increased leakage and compressibility losses. It becomes increasingly difficult to seal using sliding surfaces (i.e. spool overlap and kidney/valve plates) and positive contact sealing surfaces are preferred at higher pressures to minimize leakage losses. One example high pressure application, pumps, usually rely on check valves in place of kidney valve plates and in doing so become fixed displacement unidirectional machines. High pressure, high speed on/off valves can enable a high pressure pump/motor to become variable displacement and bidirectional if the actively controlled valves replace the check valves such as in Project 1E.3. This has benefits in the compactness thrust and urban vehicle test bed since high pressure and high efficiency hydrostatic transmissions become possible. Although positive contact seat type valves are preferred for minimizing leakage and tolerance requirements, the geometry of the seat leads to potentially large flow forces that make them difficult to actuate directly using electromagnetics, which saturate at a much lower equivalent pressure. New and innovate valves designs are needed that minimize the effects of the flow forces while retaining (or improving) the dynamic capabilities of switching type valves. Some work is addressing this issue through pressure balancing ports within the moving poppet [9].

There are four basic areas where fundamental science is being applied in this project. Past research has shown that numerical calculations do not accurately predict the magnitude and effects of steady state and dynamic flow forces [8]. Because of this, CFD analysis is used to allow a more accurate description of these forces [22] and the results will be used to construct a reduced order analytical model accurate enough for and capable of being embedded into a systems level model. Electromagnetic transients, as seen in high frequency eddy currents, affects the transient force of the actuator [5, 17]. Effects of eddy currents can be reduced with novel driving methods (peak & hold shaping, momentary reversed currents, and minimization of magnetic diffusion time constants). Area three includes the mechanical dynamics, impact forces, and contact sealing models. The combination of high pressures coupled with high switching speeds has the potential to negatively affect the reliability and lifespan of high speed valves. Finally, the behavior of the fluid is also important at the higher pressures and high switching speeds. This aspect of the project will be supported by other work within the center and is necessary to complete the system model of switching valves.

To address, study, and find solutions to these issues, a simulation model and the underlying theoretical models have been developed and utilized to generate new design concepts for optimized switching valves. The theoretical models include improved modeling of flow forces through CFD analysis and enhanced understanding of how flow forces affect the high pressure performance of the valve, especially at high switching speeds and the addition of new accurate lumped parameter electromagnet modeling techniques describing eddy current effects, magnetic fringing and leakage, and effects of nonlinear material properties captured using a nonlinear material data. The capabilities are not specific one particular valve configuration and the simulation toolbox resulting from this work can be used to quickly design and simulate the flow characteristics and dynamic response characteristics for nearly any axisymmetric seat type valve actuated by electromagnetic actuators.

B. Achievements

A new prototype bi-directional check valve (BDCV) has been experimentally tested to validate the design and simulation models. The prototype was also incorporated into Project’s 1E.3 single piston pump/motor test stand. Experiments were conducted that demonstrated the various operating modes of the test rig. For each experiment the testing conditions were:

- Piston motion actuation mechanism: sinusoidal pattern
- Piston speed: 550strokes/min
- Stroke length: 22mm
- Inlet pressure: ≈14bar
- Outlet pressure: ≈42bar

The results from this single piston pumping testing can be seen in Figure 1. From these experimental results, the BDCV has been demonstrated to be capable of enabling multiple operating modes of digital pump/motors.

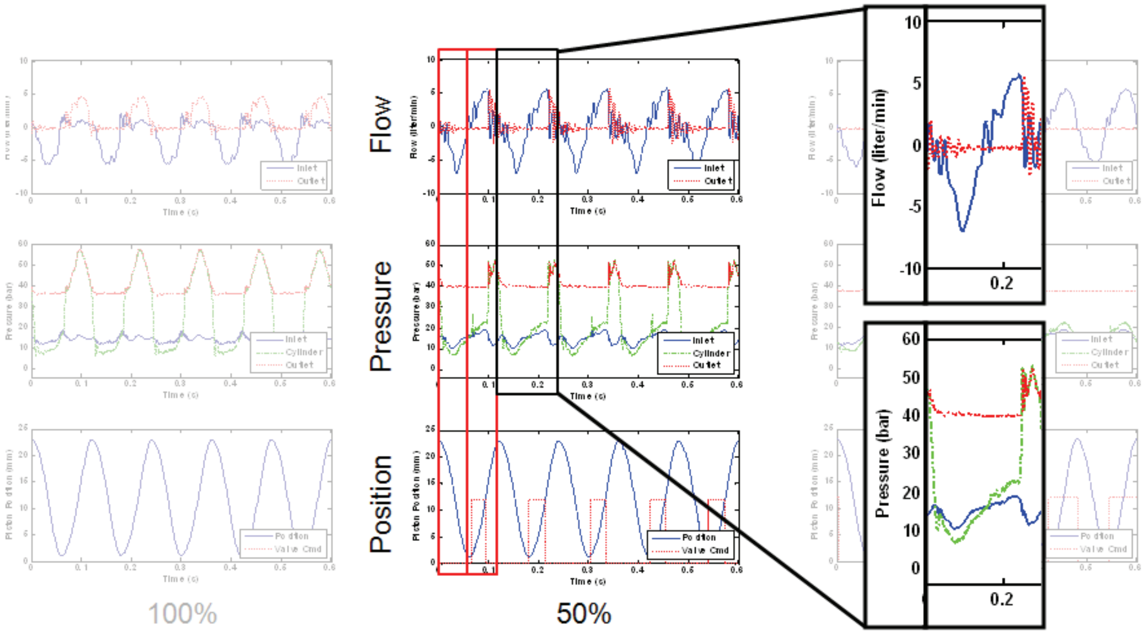

Figure 1: single piston pumping test results

In addition to the experimental testing, modeling and simulation was completed on the BDCV. A multi-physics domain model for BDCV system was built up utilizing a lumped parameter method (Matlab Simulink & Simscape) and a finite element method (COMSOL). Both Simulink model and COMSOL model were used to simulate a BDCV steady state pressure-flow test. The simulation results in reference to measurement results are shown in Figures 2 and 3. As seen in the results, the measurement and simulation plots match well, but more so for the COMSOL approach.

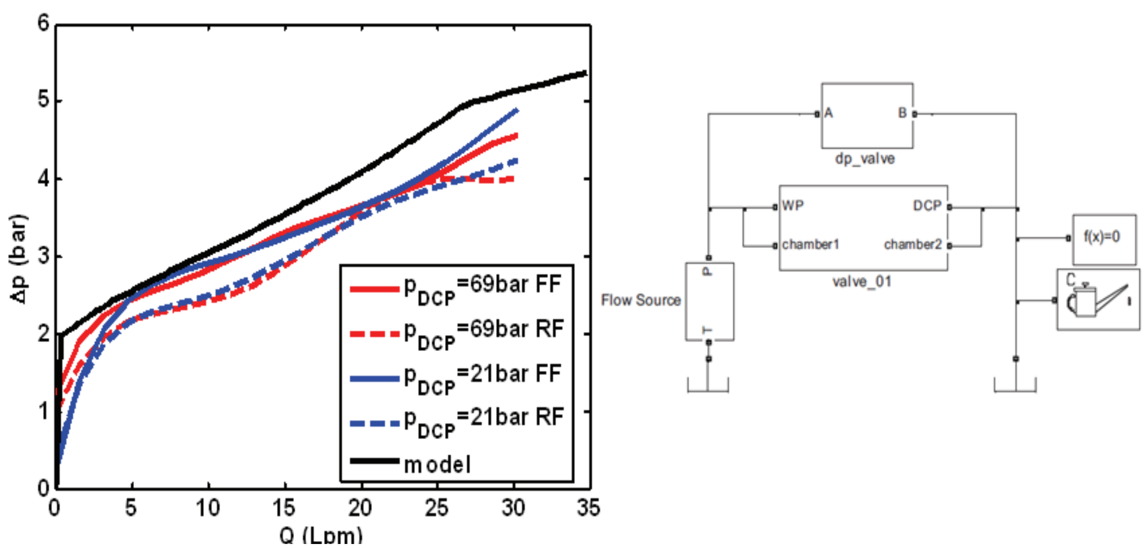

Figure 2: BDCV steady state simulation results (Matlab Simulink)

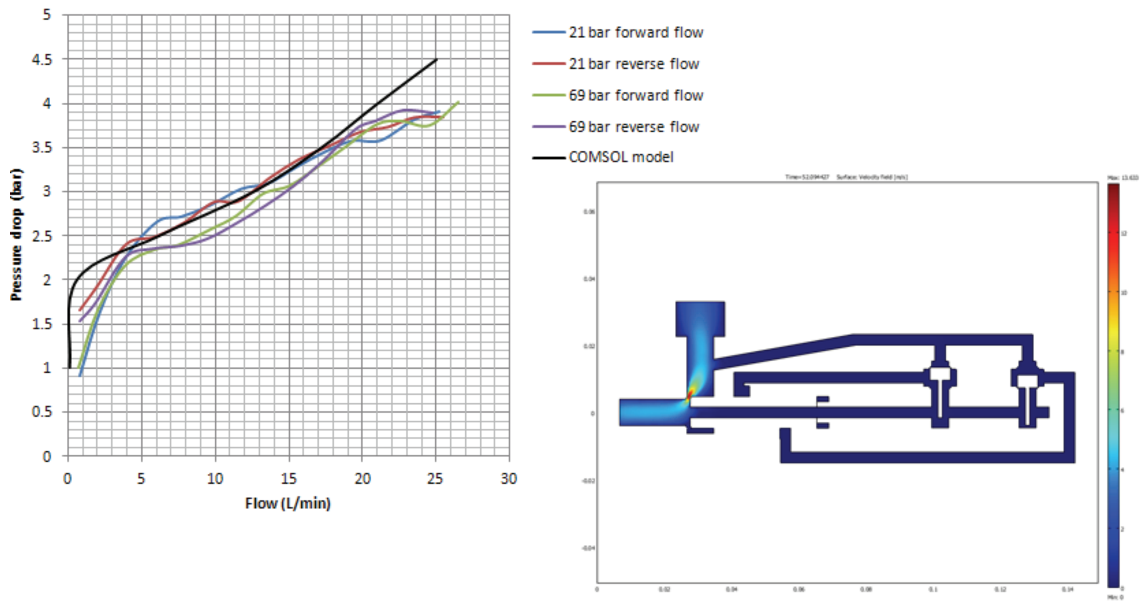

Figure 3: BDCV steady state simulation results (COMSOL)

A single piston 100% pumping system equipped with two prototype BDCVs and simulated utilizing a COMSOL model (Figure 4). The results from this are shown in Figures 5 & 6. For the flow rate, the simulation and experimental measurement results match well, demonstrating that the BDCV is capable of operation in a digital pump/motor application. Also, the COMSOL simulation successfully captured the back flow effects, which is important for being able to use the simulation tool to minimize the negative effects.

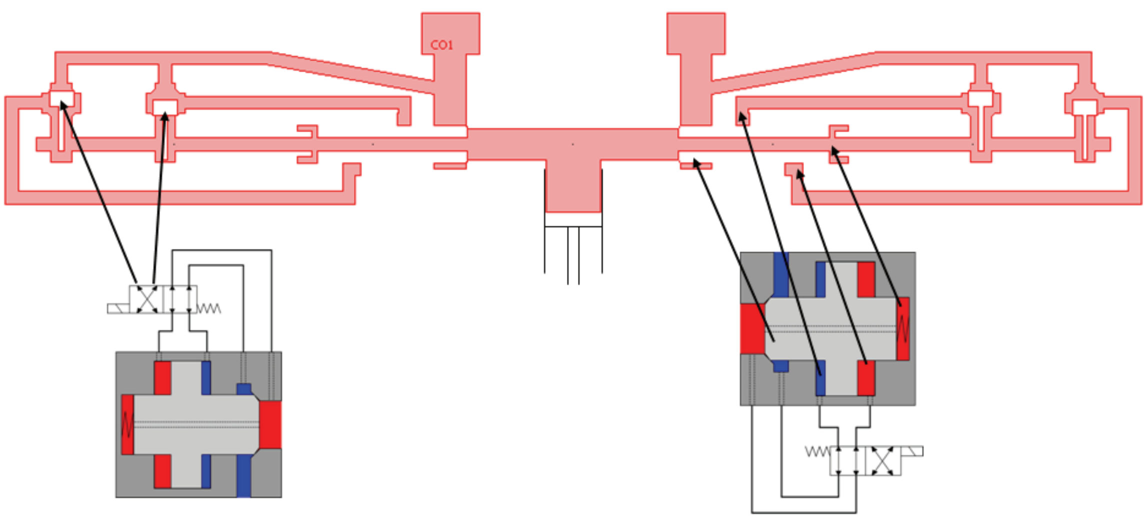

Figure 4: COMSOL model for single piston 100% pumping system

The system pressure simulation results do a good job of predicting what was measured in the lab. Referring to Figures 5 and 6, it can be observed that the differential pressure between the displacement chamber port and working port triggered the motion of main stage poppet valve of BDCV indicating passive checking feature of BDCV during 100% pumping system.

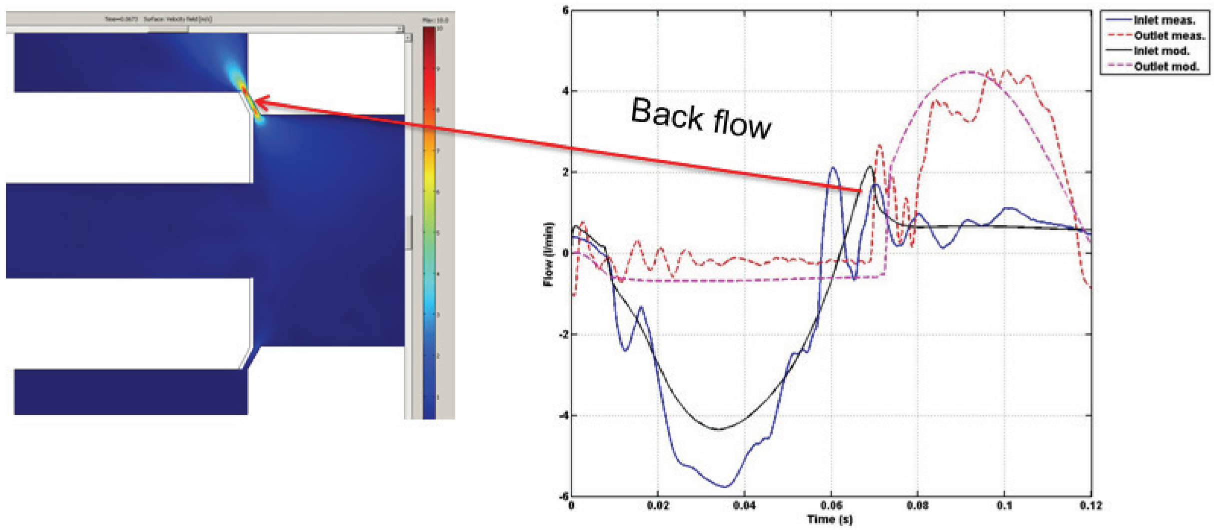

Figure 5: single piston 100% pumping flow rate results

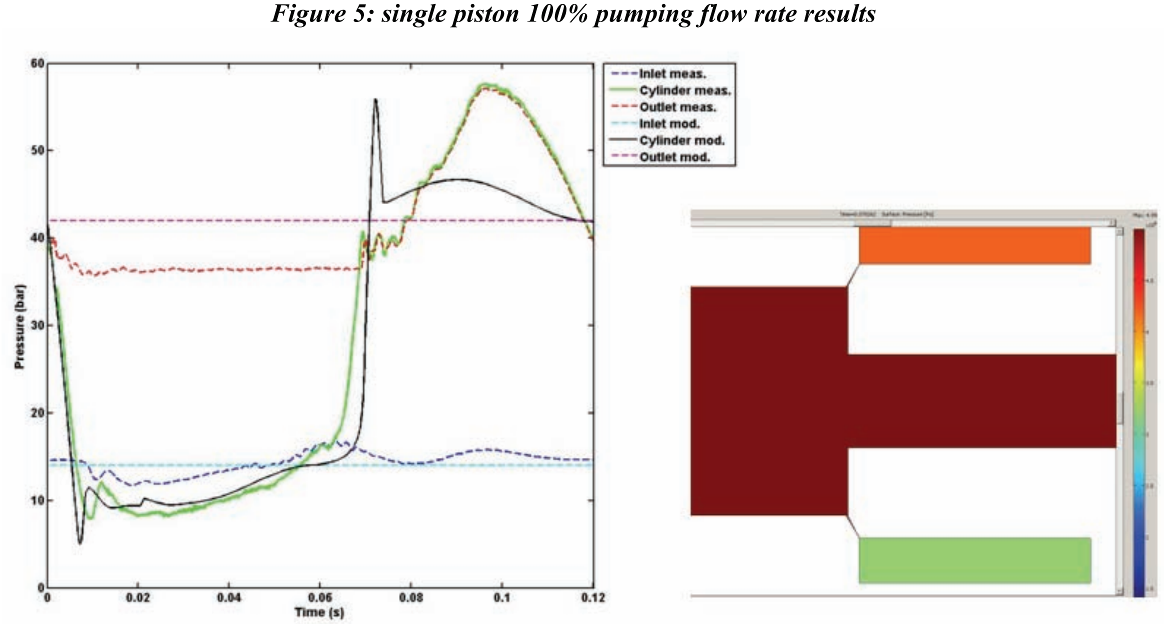

Figure 6: single piston 100% pumping system pressure results

A leakage test on the prototype BDCV was also conducted and it was found that there was a 0.4L/min leakage rate at the main stage and 2.0L/min at the pilot stage. To achieve lower leakage rate and more compact valve package, a new valve design was designed. The available COMSOL multi-physics modeling tool will be utilized to evaluate the new design as well as other high speed switching valve designs like piezoelectric actuated valve.

C. Member company benefits

This project has benefited CCEFP projects and member companies by providing new tools, enabling new projects, and designing optimal electrical signal driving profiles for on/off valve designs. It indirectly benefits member companies through its role as an enabling technology for other CCEFP projects. The work in this project has led to a provisional patent filing and the technology is accessible to industrial members.

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Project 1E.3: High Efficiency, High Bandwidth, Actively Controlled Variable Displacement Pump/Motor

Research Team

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Industrial Partners:	Eaton, Parker Hannifin, Poclain, Sauer-Danfoss

1. Statement of Project Goals

The goal of the project is to develop a hydraulic pump/motor that replaces the valve plate with actively controlled high speed on/off valves connected to each cylinder. The coupled dynamic model of the hydraulic pump/motor developed during this project is crucial to facilitate the development of the pump/motor. Unit displacement is electronically controlled by on/off valve timing, not by a swash plate or other typical means. Pump/motors of this design can have increased efficiency due to reduction of friction, leakage, and compressibility losses as well as increased displacement control bandwidth [1, 4, 8, 12, 16, 18]. Supporting tasks include using the model to characterize and predict pump/motor efficiency, define the dynamic response and flow requirements of on/off valves required to provide significant improvements in efficiency and dynamic response over traditional pump/motors, simulate different operating strategies and characterize the effects on pump/motor efficiency (valve timing effects, partial fill methods, etc.), and to experimentally validate the model, design, and operating strategies. For experimental validation a prototype pump/motor will be built and tested.

2. Project Role in Support of Strategic Plan

The project will overcome a major system efficiency limitation in the fluid power industry by providing high bandwidth and efficient four quadrant pump/motor. This will be accomplished by providing an accurate simulation model to predict the effects of using actively controlled on/off valves to replace the valve plate timing in hydraulic pump/motors, and leveraging results from Projects 1E.1 and 1E.2 on high speed valve designs. The variable displacement pump/motor will maintain high operating efficiencies at lower displacements, be capable of four quadrant operation, and exhibit high operating bandwidths. Improving pump/motor efficiency, particularly at lower displacements and throughout four quadrant operation will strengthen existing markets and enable new markets by improving efficiency and effectiveness. A project outcome is the construction and testing of a prototype to validate the concepts developed in years one and two of the project. The project directly supports the CCEFP goals of improving efficiency in existing fluid power applications and expanding the use of fluid power in the transportation sector to reduce fuel consumption.

Two test beds within the center will directly benefit from the outcomes of this project. The hydraulic hybrid vehicle, where pump/motors operate in all four quadrants and at reduced displacements, will experience significant fuel economy increases with increased pump/motor efficiency. The displacement control excavator also requires high efficiency units since all power is delivered (or recovered) hydraulically using pump/motors. Also, the high bandwidth aspect of this project will help to improve the operator feedback and enable high speed motions (bucket “shaking” to dislodge material, etc.).

3. Project Description

A. Description and explanation of research approach

A longstanding difficulty with current state-of-the-art variable displacement pumps and motors is reduced efficiencies at partial displacements. This is the result of several factors: as displacement decreases the output power decreases, compressibility losses increase, and friction and leakage losses remain approximately constant. In addition, because in a traditional unit valve plate timing is geometrically defined as a function of shaft rotation, optimal timing is difficult to obtain over the full range of operating conditions (speed, pressure, direction, and displacement).

The challenge is to decouple the valve plate timing and provide for the ability to continuously vary the opening and closing geometries and timing as a function of real time operating conditions. Additional benefits that come with decoupling the ports include the ability to explore new operating strategies (partial fill, adaptive adjustment of noise and efficiency design tradeoffs, etc.) and increased pump/motor displacement control bandwidth.

The innovation for this project involves applying fundamental science and latest design and simulation tools to provide insight on the interacting dynamics and accompanying tradeoffs associated with independently and actively controlling the port timing for each piston in hydraulic axial or radial piston pump/motors. The project is developing fundamental insight into the design tradeoffs for actively controlled pump/motors and will provide these tools to industry. Actively controlled pump/motors as focused on in this project are more likely to be successful than past attempts because of several reasons 1) electronic and sensing capabilities have progressed significantly in the past decade, 2) new fundamental knowledge has been gained in the area of pump/motor design [6, 11] and can be used in this project, 3) computational power and simulation tools are allowing for coupled multi-domain system models to be optimized, 4) the high cost of energy is making component efficiency an important consideration in operating costs, 5) previous and ongoing research on high speed on/off valves is providing the enabling technology, and 6) the CCEFP provides a unique critical mass of researchers, industry, and resources to successfully overcome the barriers.

The fundamental research barriers occur at the intersections of different physical domains represented during the short (< 1ms) transitions between high and low pressures, and the valves opening and closing. As the references make clear, the concept of actively and independently controlling the valve plate areas through the use of high speed valves is not new [1, 8]. What will allow the barriers to be overcome through this project is the ability to accurately model the interactions between the different physical domains and design the components to act as an optimized system capable of meeting the metrics of the project. In addition, the advanced electronics required to implement such a system have only recently become available at the processing speed, reliability, and cost levels needed. Even if the simulation and experimental results demonstrate improved performance, many practical challenges still remain. Reliability and redundancy of key components (valves and sensors) are critical when considering possible failure modes, electronics and sensors must be robust and embedded on the pump/motor to be competitive with existing units, new packaging options should be considered since the pump/motor valves are now independently controlled and not geometrically constrained, and new system level operating strategies could be possible with "smart pumps" containing embedded microprocessors and the ability to adapt to different load requirements.

B. Achievements

Project 1E.3 made important progress in several key areas. There has been continuing and valuable collaboration with Project 1B on understanding the internal losses within the pump and with Project 1E.2 on high-speed valves.

Figure 1 shows the efficiency of flow-diverting and flow-limiting versus the typical valve plate type unit during motoring. The valve area throttling loss, piston cylinder leakage, and compressibility are modeled in these results as reported by Merrill [12]. With a complete simulation model of a digital pump/motor, different configurations and component tolerances and specifications can be analyzed for an in-depth understanding of advantages, disadvantages, and tradeoffs of the digital pump/motor technology.

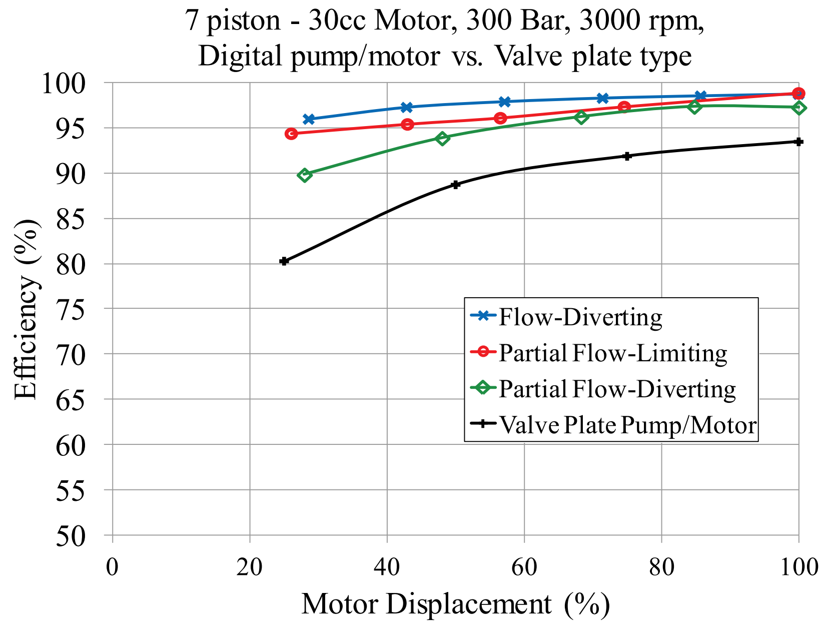

Figure 1: Efficiency comparison between different digital pump/motor operating strategies and typical valve plate unit

Figure 2 provides a breakdown of the losses as a percentage of theoretical power. A novel bi-directional check valve that was developed in collaboration with Project 1E.2 would only have electrical losses at partial displacement and no electrical losses at 100% displacement. However, when using typical off-the-shelf direct acting valves, there will always be electrical losses during all modes of operation.

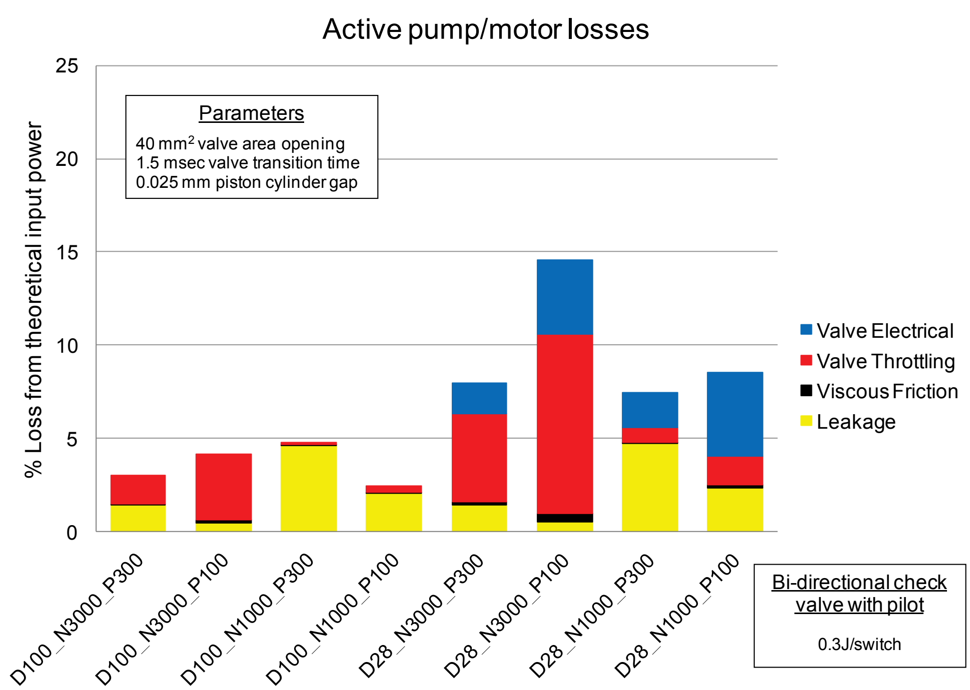

Figure 2: Flow-diverting strategy with bi-directional check valve

While continuing to collaborate with Project 1E.2 for developing high-speed on/off valves that will enable efficient pump/motor operation at speeds of 3,000 rpm, a parallel development path was taken to ensure that Project 1E.3 can continue to progress and be successful. Findings from earlier center research in Project 1E.2 were leveraged to improve the performance of off-the-shelf on/off valves. Implementations of peak-and-hold turn-on strategies and reverse-current turn-off strategies were used to drive poppet sealing cartridge valves sized for the three-piston digital pump/motor prototype. Figure 3 shows the effect of differential pressure on the delay time (t_{10}) and the transition time (t_{trans}) for a normally closed, poppet sealing cartridge valve. The valve has a 12V solenoid, but is pulsed for 5ms at 50V to apply the peak. The high initial voltage serves to overcome inductance lag. A period of high current, the peak, serves to overcome eddy current lag and to generate high magnetic flux levels across the air gap [2]. The resistive losses are reduced after the transition by maintaining a lower hold current. At low differential pressure, this off-the-shelf valve can shift from closed to open with approximately 1ms transition time with a total shift time of approximately 5ms. Note the consistency of the delay time with respect to pressure. During operation of the digital pump/motor, valves will be shifted when the differential pressure is minimized.

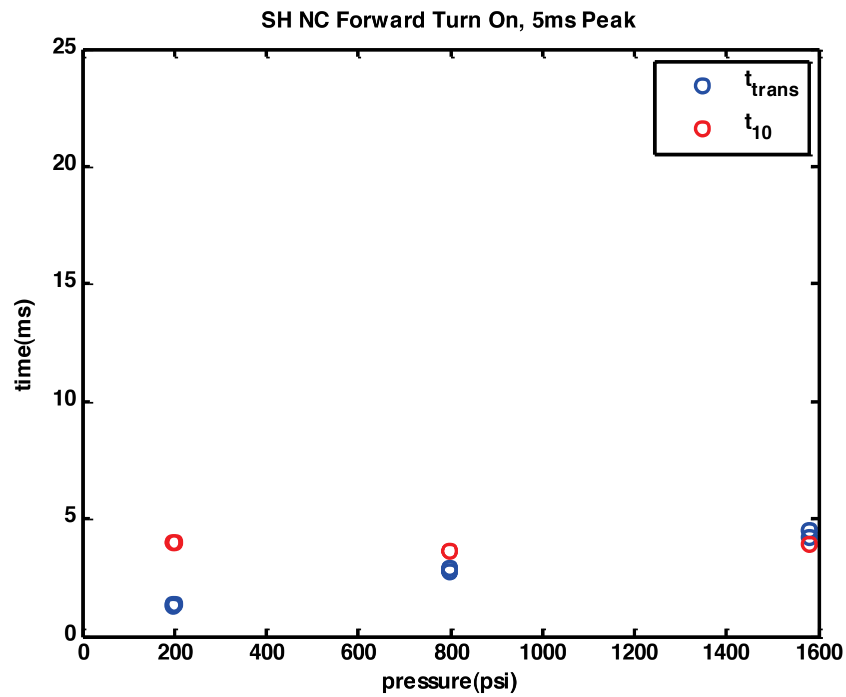

Figure 3: Turn on time vs. differential pressure

Figure 4 shows the three-piston digital pump/motor test stand. The crosshead mechanism of a three-piston, in-line CAT pump is used with custom valve blocks to accommodate six poppet-sealing on/off cartridge valves. The CAT pump is advantageous due to the modular design and the in-line crosshead mechanism. The modular design separates the unit crankcase from the working fluid and allows the displacement chamber block to be interchanged. The in-line crosshead mechanism does not require the pistons to bear side loads, accommodating the use of lip seals at the piston/bore interface and reducing fabrication costs through wider machining tolerances. Three additional cartridge check valves provide over pressure protection for the individual displacement chambers. The stand will operate with a regenerative hydraulic circuit to minimize power and heat rejection requirements.

Figure 4: Three-piston digital pump/motor test stand

The future work for Project 1E.3 includes an in-depth simulation study and optimization for multi-chamber pump/motors and expanded experimental validation in the laboratory. With a 7 piston pump/motor model completed and initial multi-piston pump/motor experimental testing currently under way, the focus will be on utilizing the model for control strategies studies and optimization, and an expanded focus on validating these experimentally, along with the effect of operating strategies on efficiency and noise.

With the completion of the multi-piston digital pump/motor test stand, experimental testing is in progress and will utilize the various operating strategies to achieve variable flow with a digital pump/motor. With the results from the multi-piston pump/motor test stand, implementation on Test Bed 1 (Excavator) and/or Test Bed 3 (Hydraulic Hybrid Vehicle) with a properly sized pump/motor unit will commence. This will showcase the system efficiency improvements that a high efficient, high bandwidth pump/motor component would contribute.

C. Member company benefits

This project has and will continue to benefit CCEFP member companies by providing new digital pump/motor design tools, on/off valve designs, and digital pump/motor operating strategies for further development and commercialization by member companies. It indirectly benefits member companies through its role as an enabling technology for other CCEFP test beds. Industry partner involvement will be critical while developing the appropriate performance metrics, benchmarking current products, and involvement will be necessary to build (or supply from existing) the various components and sub-assemblies (pumps, valves, sensors, etc.) and help with the fabrication and testing.

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Project 1E.4: Piston-by-piston control of pumps and motors using mechanical methods

Research Team

Project Leader:	Dr. Perry Li, Mechanical Engineering
Other Faculty:	Dr. Thomas Chase, Mechanical Engineering
Graduate Students:	Mike Rannow, Chad Larish, Meng Wang, and Haink Tu
Industrial Partner:	Sauer-Danfoss

1. Statement of Project Goals

The goal of this project is to develop simple and efficient strategies for controlling hydraulic power transformation machines (i.e. pumps, motors, or transformers) on a piston-by-piston basis. This project will focus on creating a variable displacement pump/motor that can meet or exceed existing designs in peak efficiency, and demonstrate a shallower drop off in efficiency as the displacement is decreased. By utilizing a two degree of freedom rotary valve, the expected efficiency benefits of piston-by-piston control will be achieved with a control mechanism that is simpler and more cost effective than alternative research approaches.

2. Project Role in Support of Strategic Plan

The need for efficient hydraulic components is listed as a transformational barrier for the fluid power industry. The development of high efficiency variable displacement pump/motors is essential to overcoming this barrier. A pump or pump/motor that is more efficient than current technology is essential for realizing practical hydraulic hybrid powertrains in both on-highway and off-highway vehicles. The key element to the new design described here is a single rotary valve, which replaces multiple solenoid valves used in competing designs. This valving strategy has the potential to be more compact and less costly than current approaches, while maintaining high efficiency.

3. Project Description

A. Description and explanation of research approach

Most hydraulic systems contain one or more devices to transform rotary mechanical power into hydraulic power or vice versa, such as a pump, motor, or transformer. In order to reduce power losses in throttling valves, these devices are often designed to have a variable displacement. In existing state-of-the-art designs, the efficiency of variable pumps and motors dramatically decreases as the displacement is decreased. This is a significant barrier to the creation of efficient hydraulic systems. The drop off in efficiency is caused by the fact that the dominant power losses, primarily leakage and friction, do not decrease as the output power is decreased. The majority of variable pumps and motors are bent-axis or swashplate type piston machines and their displacement is varied by changing the stroke length of the pistons. In this approach, high pressure is applied to all pumping pistons, regardless of the displacement. As a result, some of the leakage paths and friction losses remain constant. A significant amount of research has been done to understand and model the leakage and friction losses that occur in pumps and motors, with the goal of reducing the magnitude of these losses. However, the issue of high power losses at low displacements has not received significant attention until recently.

A new approach to improving the efficiency decrease at low displacements is the piston-by-piston variation method. Research was initiated at the University of Edinburgh and has continued with the start-up company Artemis Intelligent Power. It has produced a method of reducing the displacement of a radial-piston device by disabling individual pistons when not needed [1, 2]. This so-called piston-by-piston approach has been demonstrated to significantly improve the efficiency of hydraulic machines at low displacements. The Artemis design is based on two electronically latched check valves to enable or disable each piston. When a piston is disabled, high pressure fluid is not applied to it, removing the leakage and some of the friction losses associated with that piston. Thus, a portion of the losses will scale down with displacement. With separate valves controlling the fluid in and out of each piston, the constant losses associated with the valve plate are also eliminated.

While the latching check valves have advantages over other types of valves with respect to actuation power and ideal timing for pumping, they present challenges for creating a motor. Project 1E.3 is developing an approach that moves away from the latching check valves and incorporates actively switched valves to improve the control flexibility [3, 4]. While the piston-by-piston control approach has significant potential to reduce power losses, it relies on multiple high-speed, electronically controlled valves per pumping piston, which can increase cost and reduce reliability.

In Project 1E4, piston-by-piston displacement variation will be achieved with a single control input, in the form of a two degree of freedom rotary on/off valve. This project leverages knowledge gained in the design of a similar rotary valve for Project 1E.1 [5-11]. With this approach, a rotary spool valve that can translate axially will enable or disable the desired number of pistons to vary the displacement of the machine. Some advantages of using a mechanical control method are: simplicity; only a single control input (the axial position of the rotary valve) is needed, robustness and cost; it does not require solenoids and wires and current drivers for each piston, low actuation power; the rotary valve does not need to be accelerated/decelerated, repeatability; the valve is mechanically coupled to the drive shaft ensuring repeatable timing, and contamination resistance; significant torque is available to spin the valve through contaminated oil. The approach has the disadvantage of reduced control flexibility in the mechanical mechanism. However, this is anticipated to have only a slight effect on the overall efficiency.

In the initial phase of this project, a study of the losses associated with a variable displacement pump/motor was conducted to demonstrate the potential of piston-by-piston variation to reduce losses. The models used in this study will help guide the design of a pump/motor which demonstrates rotary valve enabled piston-by-piston displacement variation. The design and construction of the pump/motor will be carried out with assistance from an industry champion (Sauer-Danfoss), who has agreed to donate prototype parts.

B. Achievements

Achievements in 2011 consist of: confirming the feasibility of the proposed design through modeling, deciding between constructing the rotary valve as a direct acting valve or a pilot valve, deciding whether to design a pump or a pump/motor as a concept demonstration prototype, performing a detailed simulation of the valve system to resolve its sizing, and beginning the mechanical design of the prototype. These achievements are described in order below, followed by a description of a plan to complete the project.

The initial phase of this project consisted of examining how the losses in a variable displacement pump/motor scale with displacement, in both conventional and piston-by-piston approaches. The goal of this phase was to demonstrate the feasibility of the approach and define the magnitude of the potential energy savings. The results of this analysis are shown in Figure 1.

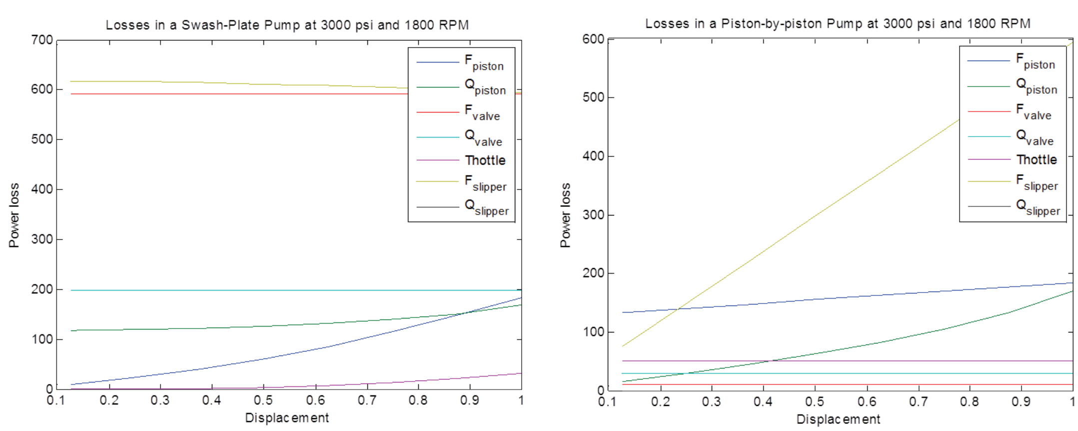

Figure 1: Losses in a swash plate (left) and piston-by-piston (right) pump

The models used to generate this comparison were designed for a pump having the size of the expected prototype (52 cc) and are based on a combination of first-principles modeling and measurements of physical parameters from literature or existing components. This is not intended to be a high-fidelity study of the losses in a pump/motor, which is a project unto itself [12]. However, the trends of the losses with displacement are clear.

In the piston-by-piston method, the piston friction and throttling losses remain higher as displacement is decreased due to the constant piston stroke. However, the rest of the losses decrease faster than the swashplate losses due to the removal of pressure from the unused pistons. Fortunately, the losses that are high in the piston-by-piston approach are relatively small when compared to the worst swashplate losses. The key benefits of the piston-by-piston approach are: the reduction of swashplate friction with displacement and the reduction in valve plate friction and leakage by using valves to control each piston. This removes the tradeoff between sealing and load bearing that exists in a typical valve plate.

The prototype parts supplied by an industry champion did not have hydrostatically balanced pistons, which would reduce the swashplate friction, but add an additional leakage path. In order to create a valid comparison it was assumed that neither the piston-by-piston nor the swashplate device had hydrostatically balanced pistons. The combination of the losses in Figure 1 is shown in Figure 2.

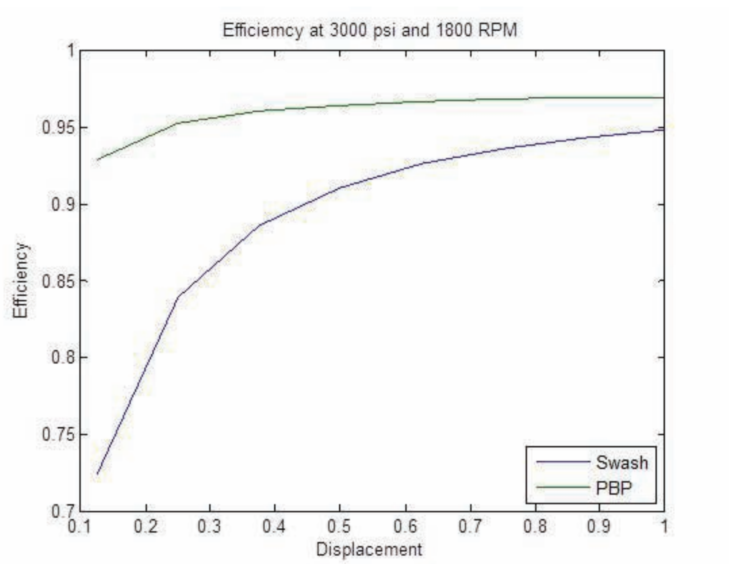

Figure 2: Efficiency comparison between a swashplate and a piston-by-piston pump

Figure 2 shows the potential improvement from a piston-by-piston variation approach. Note that neither model includes losses due to compressibility, throttling in transition, bearing or churning losses. The transition and compressibility losses are accounted for in a more detailed model of the piston-by-piston method, but they are heavily design-dependent, so a valid comparison is difficult to derive.

Once the loss scaling model was complete, several design choices had to be made to enable a dynamic model of the piston disabling mechanism to be created. The concept for the project was to use a rotary valve to control the pistons. However, two alternative designs were possible: the rotary valve could control the main piston flow, or it could act as a pilot stage. Several design concepts were derived, modeled, and analyzed in order to decide between these two alternatives. After comparing the leakage, throttling loss, transition time, actuation power, and complexity, it was decided that the rotary valve would serve as a pilot stage which drives another valve for each piston.

The initial plan for this project was to create a variable displacement pump, and use that as a starting point for a variable displacement pump/motor. However, during the concept selection phase, it was determined that the pump solution did not pose a significant challenge nor provide much opportunity to solve problems that would benefit the design of a pump/motor. Thus it was decided that the project would focus exclusively on designing a 4-quadrant pump/motor.

A dynamic model of the valve mechanism was created (see Figure 3), which was used to analyze the transition and compressibility losses of the proposed design. Using this model, parameters were adjusted to create a design that is expected to have throttling, compressibility, transition, leakage, and actuation losses that are significantly less than the modeled valve plate losses. Nevertheless, these improvements comprise only a fraction of the overall expected piston-by-piston benefit.

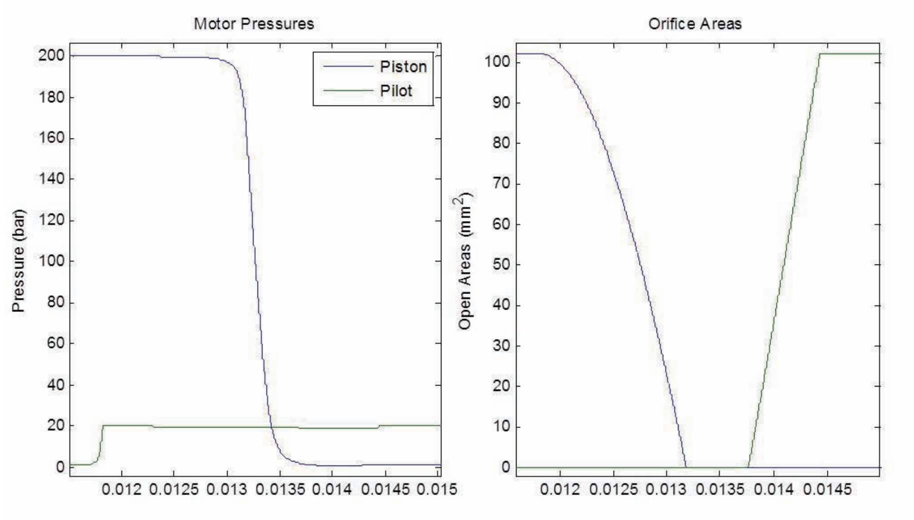

Figure 3: Modeled dynamic response of the piston pressure (left) and control valve areas (right)

With the dynamic model complete, the mechanical design of the pump/motor was begun. The detailed design is still in progress, with an anticipated completion of March 2012. Once the mechanical design is complete, computational fluid dynamics (CFD) analysis will be performed to verify the anticipated throttling losses. Following completion of the CFD, the prototype will be built and tested, which is scheduled for early summer 2012. The prototype will be tested for efficiency and dynamic performance, and if the results are promising it will be demonstrated on Test Bed 3, the Hydraulic Hybrid Passenger Vehicle. At that point the original project plan will be complete. If the efficiency tests are promising, the next step will be to contact member companies to gauge the interest in further developing the technology. A logical next step for this research is to investigate whether the approach can be extended to a piston-by-piston transformer.

Milestones

- Analyze piston disabling strategies (complete)
- Determine how swash plate and piston-by-piston losses scale with displacement (complete)
- Generate and analyze valve architectures (complete)
- Model selected mechanism to predict losses and dynamic performance (complete)
- Complete mechanical design of the pump/motor (3/12)
- Analyze flow paths using Computational Fluid Dynamics (4/12)
- Construct prototype (6/12)
- Test efficiency of the pump/motor (7/12)

C. Member company benefits

Member companies will benefit from the analysis showing the potential of piston-by-piston variation, by demonstrating a potential avenue for efficient product development. This will be enhanced by a successful demonstration of an efficient piston-by-piston pump motor.

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Project 1G.1: Tribofilm Structure and Chemistry in Hydraulic Motors

Research Team

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Graduate Students:	Kelly Burgess, Hassan Khalid, Meghan Miller and Chuck Ziemer
Undergraduate Students:	Brian Blazel, Brittany Hauser, and Rebecca Ruechel
Industrial Partners:	Afton Chemical, ExxonMobil, Parker Hannifin, Poclain Hydraulics, RohMax USA, Sauer-Danfoss, Shell Oil

A. Statement of Project Goals

The research objective of this project is to improve fluid power efficiency by systematically investigating tribofilm structure and chemistry in hydraulic motors. From our previous investigations we have concluded that hydraulic motor efficiency can be improved by enhancing boundary lubrication conditions. [1, 2] This conclusion is based upon correlations between motor efficiency tests and friction measurements in simple bench-top tribometers. We propose to bridge the gap between the performance of fluid power components of complex geometry and the fundamental understanding of tribology by studying the structure and chemistry of boundary films formed in motors. Improvements in boundary lubrication conditions are expected increase the minimum hydraulic motor starting efficiency by 10-20% without compromising the efficiency of other fluid power components.

B. Project Role in Support of Strategic Plan

This project addresses the efficiency barrier by identifying how tribofilm structure and chemistry affect starting torque and low-speed friction in hydraulic motors. Understanding this relationship will make possible the formulation of hydraulic fluids that improve motor efficiency. This is of strategic importance within the CCEFP because low-speed motor efficiency often determines the minimum displacement (size) and operating pressure of mobile hydraulic equipment. In order to bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power components, this investigation will be conducted in coordination with the elastohydrodynamic research of Prof. Bair (Project 3D.2), the surface texturing research of Prof. King (Project 1D), and the static friction research of Prof. Martini (Project 1B.2). Integration of Test Bed 3 (TB3) will be coordinated with Prof. Chase.

C. Project Description

A. Description and explanation of research approach

There is a gap to be bridged between the fundamental understanding of tribology and the performance of fluid power components of complex geometry. This project targets this gap by investigating the fluid properties that influence friction and tribofilm formation. In previous research we determined that boundary friction, thin-film traction, and pressure-viscosity fluid properties influence hydraulic motor efficiency under low-speed, high-torque (LSHT) conditions. [1] Significant improvements in mechanical efficiency were demonstrated:

- *Geroler, Improvement over baseline – 11%*
- *Radial Piston, Improvement over baseline – 6%*
- *Axial Piston Improvement over baseline – 17%*

Boundary friction coefficient, as measured in a High Frequency Reciprocating Rig (HFRR), was found to correlate with hydraulic motor efficiency. [2, 3] HFRR has also proven useful in evaluating diesel fuel lubricity in high pressure fuel pumps. [4] Translating bench-top tribometer measurements to full-scale equipment presents a number challenges. Boundary friction is affected by a myriad of interacting factors including load, entrainment velocity, surface topography, metallurgy, and lubricant chemistry. Even with these parameters defined, it is difficult to replicate real tribological contacts in a benchtop tribometer due to local contact geometries, temperatures, and time dependencies. [5] Characterizing the tribochemistry presents its own set of challenges.

The tribochemistry of boundary lubrication is the subject of numerous studies. Tysoe and Kaltchev proposed that friction reduction from boundary lubrication additives corresponds to the formation of Langmuir-Blodgett monolayer films. [6] Spikes characterized common zinc-dithiophosphate reaction films as thick, rough, iron and zinc phosphate-based coatings. [7] Devlin posited that friction reduction can be achieved by reducing the thickness and roughness of boundary additive films [8]. Jahanmir pointed to a reduction in the free energy of the surface as an explanation for film formation in terms of physical chemistry. [9] These fundamental tribological perspectives are founded upon experimental results produced in relatively simple tribological systems. Project 1G.1 seeks to bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power components by characterizing the boundary films formed within hydraulic motors.

In order to study the nature of the boundary films formed in hydraulic motors, prototype hydraulic fluids will be evaluated in the low-speed high-torque dynamometer shown in Figure 1. Parker Hannifin, Poclain Hydraulics and Sauer-Danfoss have supplied orbital (geroler), cam-lobe, and bent axis motors for the research project. Two motors of each type were provided, along with extra rotating groups. The prototype fluids will be evaluated in the HFRR as well as each hydraulic motor. Motor tribofilms will be evaluated via Energy Dispersive X-Ray Spectroscopy. HFRR specimens will be evaluated via surface profilometry, atomic force microscopy and EDX spectroscopy.

Figure 1: Low-speed high-torque dynamometer

B. Achievements

In Phase 1 of Project 1G.1, prototype hydraulic fluids were evaluated in orbital (geroler), cam-lobe, and axial piston motors under low-speed and starting conditions in accordance with the ISO 4329-1 and ISO 4392-2 standard test methods. Through collaboration with S. Bair, A. Martini, and M. Devlin (Afton Chemical) it was determined that the hydraulic fluid with the lowest pressure-viscosity coefficient and lowest static and boundary friction coefficient (HEES46) minimized mechanical losses at startup and at 1 RPM. [1] Test results for phase 1 are shown in Figure 2.

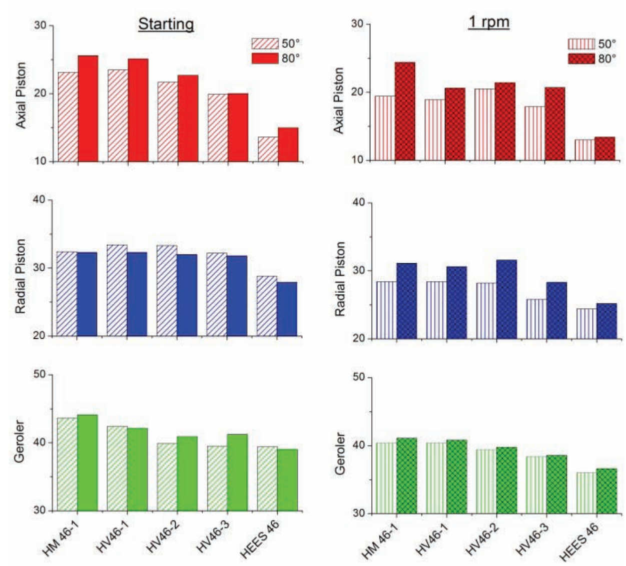

Figure 2: Torque loss during starting (left) and at 1 rpm (right) measured at 50°C and 80°C for geroler, radial piston, and axial piston type hydraulic motors.

Based upon these results, a new project will be initiated in December of 2012 in the Generation I Test Bed 3 vehicle. A HEES-46 synthetic biodegradable ester will be compared with the HV 46-1 shear stable high viscosity index hydraulic fluid which serves as the baseline oil for the vehicle. The new vehicle dynamometer will be utilized for these tests. Thus, Phase 1 of Project 1G.1 will culminate with efficiency testing in TB3.

Parker Hannifin, Poclain Hydraulics, and Sauer-Danfoss have supplied orbital (geroler), cam-lobe, and bent axis motors for Phase 2. The efficiencies of these motors have been measured with ashless and zinc-containing hydraulic fluids. The boundary lubrication film formed by the ashless antiwear additive has been analysed via EDX. Surface analysis for the zinc-containing fluid is underway.
A series of experiments have been conducted to elucidate the kinematic behaviour of a geroler motor and observe tribofilm formation under controlled condition. In the geroler motor, torque is generated by

driving a shaft-mounted 8620 steel rotor in an epitrochodial orbit against 52100 steel vanes mounted in a 65-45-12 ductile iron stator as shown in Figure 3. Contact pressure between the rotor and the vane varies with shaft orientation. Modeling predicts that contact pressure can exceed 3 GPa. [10]

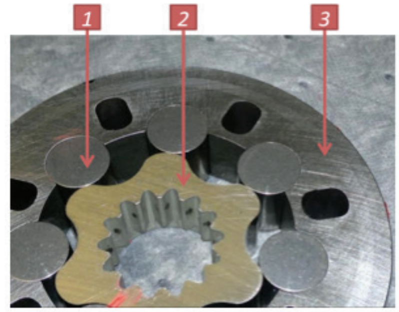

Figure 3: Vane (1), rotor (2) and stator (3) in geroler motor

In order to prepare tribofilms for analysis, new rotating groups were installed in two TG240 motors. Each motor was started 1000 times with the shaft locked at a fixed orientation. In one case the fluid temperature was maintained at 25ºC and the other 80ºC. The test fluid contained a phosphorus-based ashless antiwear additive. Upon completion of testing, the motors were disassembled, rinsed with heptane, and inspected with a JEOL JSM-5800LV Scanning Electron Micrlandscape (SEM). This microscope was equipped with a ThermoElectron Nanotrace Detector for performing Energy Dispersive X-ray Spectroscopy (EDX) to allow chemical analysis of the tribofilm. EDX analysis revealed that higher temperatures created thicker tribofilms on the steel surfaces, as shown in Figure 4. [11] These results are consistent with tribochemical film growth theory and for the first time demonstrate the formation of tribofilms by hydraulic fluid additives in motors.

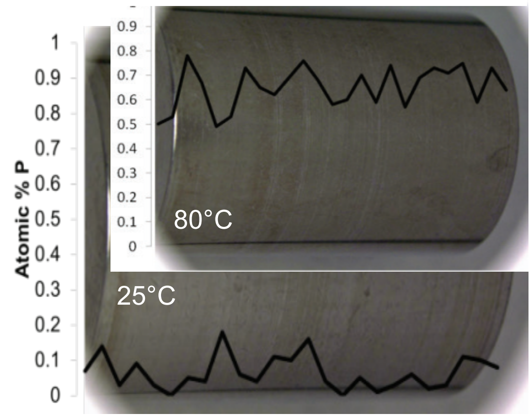

Figure 4: Atomic % phosphorus after 1000 starts. The overlay displays the approximate position of the EDX analysis results across the face of the vane; 25 measurements were made on each roller

HFRR tests were conducted on the experimental fluids in order to investigate the nature of tribofilms produced by hydraulic fluids; load 4N, frequency 20 Hz, amplitude 1mm, duration 1 hour, metallurgy 52100 steel. The test fluids were a simple Group III base oil plus a) zinc dialkyldithiophosphate (ZDDP) and b) amine phosphate (ashless) antiwear additive. The HFRR friction coefficients for the zinc-based fluid were lower than those of the ashless oil. These friction levels considerably higher than observed with the optimized fluids in Phase 1.

Property	Parameter	Ashless	ZDDP
Friction Coefficient	70°C	0.166	0.152
	100°C	0.162	0.148
	130°C	0.158	0.144
Surface Roughness	Rpk (µm)	0.451	0.679
	Rvk (µm)	0.543	0.585

Table 1: HFRR friction and roughness measurements

Wear scars produced on the HFRR specimens were evaluated by surface profilometry and atomic force microscopy (AFM). As shown in Table 1, the ZDDP-based fluid exhibited a higher reduced peak height (Rpk) and reduced valley depth (Rvk) roughness. Atomic force microscope (AFM) images of HFRR wear scars were produced in tapping mode with a silicon probe. The edge of wear scars produced by the ZDDP-based fluid exhibited a raised edge due to material displacement as shown in Figure 5. The relative roughness of the ZDDP and ashless surfaces was consistent with the observations of previous investigators. However we have concluded that the HFRR conditions were too severe and the rough surfaces that were produce are ill-suited for AFM analysis. Testing will be repeated at a reduced load in an effort to link these fundamental tribological measurements to motor performance.

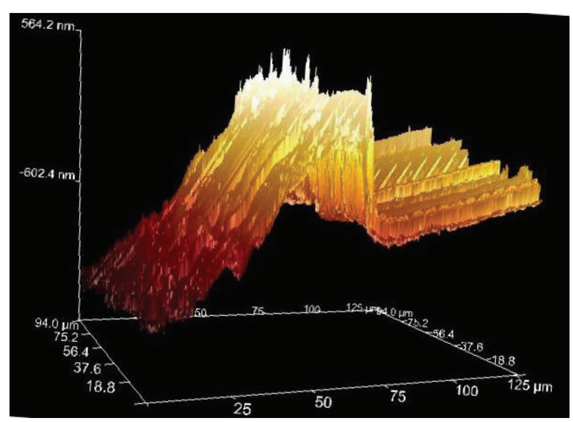

Figure 5: Tapping mode image of wear scar (inset) produced by the ZDDP-based fluid

In addition to providing controlled conditions for the tribofilm investigation, the 1000 start test identified areas of the rotor that experience high load conditions at startup. Scuffing was observed on the rotor surface in the red area highlighted in Figure 6. Scuffing wear is the result of friction, which reduces the mechanical efficiency of the motor. Wm. King of UIUC (Project 1D) has developed advanced methods for modeling and constructing microstructured surfaces that significantly reduce friction. Experimental and numerical work by A. Martini of Purdue (Project 1B.2) demonstrated static friction reductions up to 25% may be achieved through microstructure surface texturing. A rotor with optimized microstructure has been fabricated by Prof. King's group (Figures 7 and 8). The surface textured rotor will be incorporated into a new Parker Hannifin TG240 geroler assembly and evaluated in the low-speed high-torque dynamometer. Parker agreed to provide at least one additional motor for comparison. Testing is scheduled for April-May 2012. Dynamometer testing will provide data that is necessary to bridge the gap between the performance of motors and the fundamental tribological models developed at UIUC and Purdue.

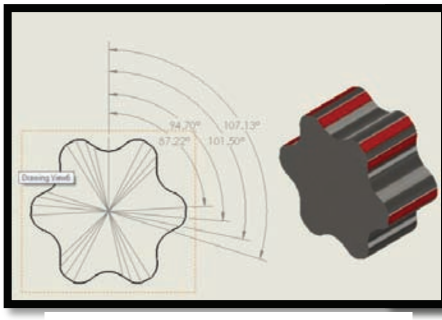

Figure 6: Scuffing on the rotor in the area highlighted in red.

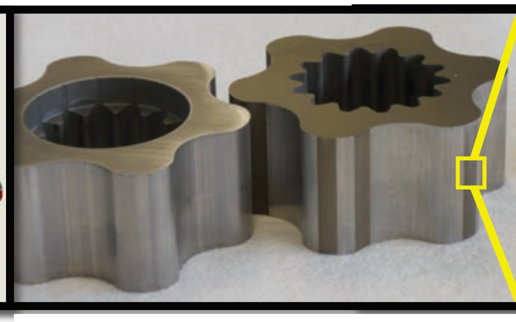

Figure 7: Un-textured and textured rotor

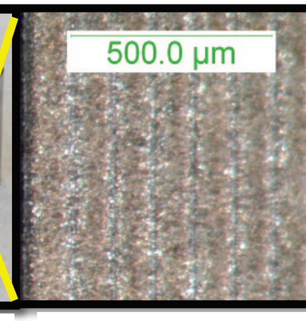

Figure 8: Magnified view of textured surface

Near-term Goals
In the next 6 months the textured rotor will be evaluated, EDX analysis will be completed, and HFRR tests will be performed under less severe conditions.

Long-term Goals
In June of 2012, Project 1G.1 will transition to Phase 3. In Phase 3 we will study the relationship between *system-wide* efficiency and the compressibility, traction, and shear-thinning characteristics of hydraulic fluids. Through collaboration with other CCCEFP investigators, this project will bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power systems. Future milestones are shown in Figure 9. In the long term, this project will make possible the development of models for selecting energy efficient fluids that are based upon hydraulic system architecture, duty cycles, and the underlying tribological conditions.

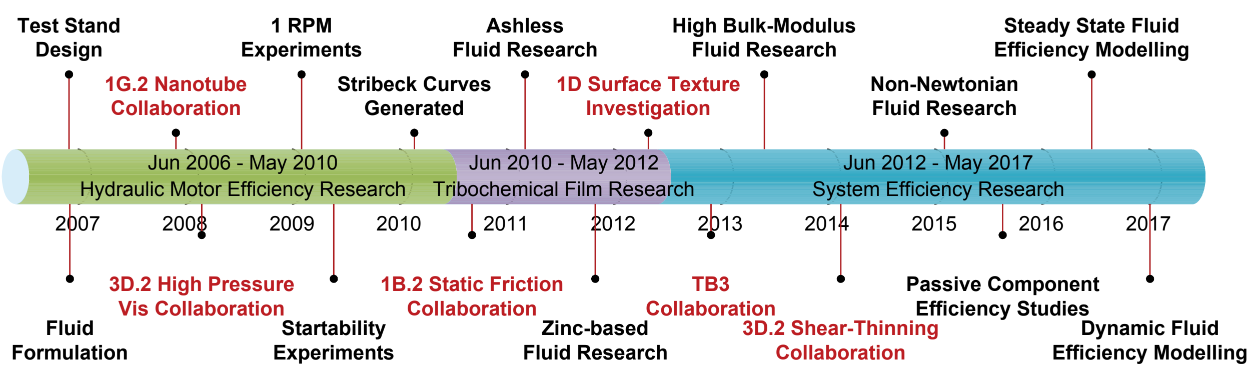

Figure 9: Project timeline with major research milestones. Collaborative efforts are highlighted in red.

Phase 3 Task List

- Convert pump from EH to manual displacement control and install new instrumentation. Develop controls and DAQ to test efficiency under a wider range of conditions. (3 months)
- Define test matrix, select materials, and formulate prototype hydraulic fluids for an orthogonal study of compressibility, traction, and shear-thinning effects on system efficiency. (3 months concurrent)
- Conduct high pressure compressibility and shear-thinning experiments at Georgia Tech. Conduct benchtop thin-film friction studies at industrial partners. (3 months)
- Conduct dynamometer experiments with reference fluid and prototype fluid for TB-3 to establish baseline efficiency values. (3 months concurrent)
- Conduct dynamometer experiments on prototype hydraulic fluids to probe the effects of fluid compressibility, shear stability, and thin film friction on hydraulic system efficiency (12 months)

Milestones

- Expansion of dynamometer capability to measure system efficiency (Q3 2012)
- TB-3 fluid formulation and characterization (Q4 2012)
- Dynamometer testing of prototype fluids (Q1 to Q4 2013)

C. Member company benefits

This project was conceived in collaboration with hydraulic motor manufacturers, additive formulators, international oil companies and other university researchers. Through collaboration, we will be able to discover the fundamental properties of the boundary lubrication layer required to reduced friction in motors and translate that technology into practical application. The discovery of correlations between bench-top tests and *system wide* efficiency will make possible the systematic development of new fluids that increase the productivity and efficiency of hydraulic machinery. Since conversion to an energy efficient hydraulic fluid often does not require a modification of the hydraulic system, this technology can immediately benefit the existing equipment of member companies and their customers.

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Project 2A: Chemofluidic Hot Gas Vane Motor

Research Team

Project Leader: Prof. Michael Goldfarb, Mechanical Engineering, Vanderbilt University
Graduate Student: Jason Mitchell, Vanderbilt University

1. Statement of Project Goals

The goal of this project is to develop, demonstrate, and characterize the performance of a monopropellant-powered vane motor for use in high bandwidth actuation of a hydraulic pump. The initial research involved the development of the motor, which had a target for continuous power in excess of 1000 W/kg. This is approximately five greater than rare-Earth magnet brushless electric motors. The second phase of the project focuses on the integration of the motor into a closed-loop-controlled throttle-less hydraulic actuator to provide compact hydraulic power for small-scale fluid-powered systems, such as compact robots. The project also aims at implementing the technology in a human-scale robot, specifically in Test Bed 4, the compact rescue crawler test bed. If successful, project 2A will enable the use of high power density fluid-power actuators in these human-scale robots and thus will contribute directly to the fulfillment of the Center's vision.

2. Project Role in Support of Strategic Plan

Project 2A supports the Center's goal of developing compact fluid powered systems. It aims at providing a means of efficiently powering and controlling human-scale fluid-powered systems. The chemofluidic hot gas vane motor provides unique features that make it particularly appropriate for these types of applications. For example, it is not subject to the wall quenching or scavenging problems found in conventional small-scale internal combustion (IC) engines. In addition, unlike an IC engine, it can provide bidirectional, high-bandwidth motion and high torque at zero speed (rpm). As such, the motor can be used for throttle-less actuation, therefore bypassing the fluid heating and inefficiency problems that occur in those engines. Further, the liquid propellant that powers the device is not flammable, the motor can be easily started and stopped to reduce fuel consumption, does not require air (i.e., can be used underwater or in space), and has completely safe reaction products (i.e., can be used indoors).

3. Project Description

A. Description and explanation of research approach

Challenges in the development of the motor include friction, thermal expansion, and sealing. These issues are being addressed by model-based design, experimental assessment, and design iteration. The extent to which these issues can be mitigated will determine the promise of this technology. With regard to throttle-less control, the challenges include achieving a competitive closed-loop bandwidth and achieving sufficient closed-loop positional accuracy in the presence of Coulomb friction and a non-collocated control structure. These issues can be improved via nonlinear and model-based control techniques, but at some point provide a fundamental limitation on control performance.

B. Achievements

<u>Achievements prior to the reporting period</u>

Several prototypes have been designed, fabricated, and tested since the start of the project. The most recent motor prototype was experimentally shown to provide a power density of 790 W/kg. This compares favorably to a good, brushless electric motor which has a power density of approximately 160 W/kg.

Since the project began in June 2006, the investigators have developed multiple iterations of the vane motor. Three of the experimentally characterized prototypes are shown in Figures 1-3, and the performance data corresponding to these prototypes is given in Table 1. The project objectives for the motor power density and continuous torque were 1000 W/kg and 0.5 Nm, respectively, which were originally chosen to be five times better than state-of-the-art rare-earth magnet brushless DC motors. As indicated in Table 1, the vane motor prototype V2.6 (and V2.7) achieved of power density of 790 W/kg and a maximum continuous torque output of 0.7 Nm (see Figure 4). The prototype achieved 79% of the power density target and the torque target was exceeded.

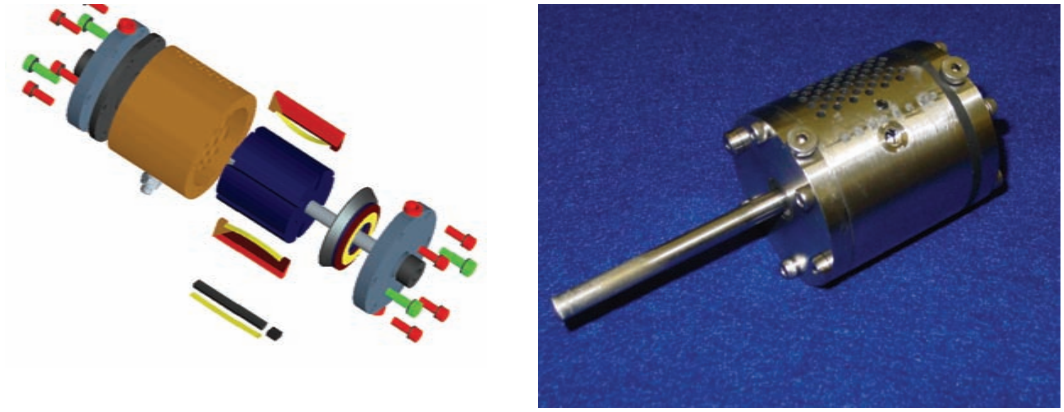

Figure 1: Version V1 vane motor prototype

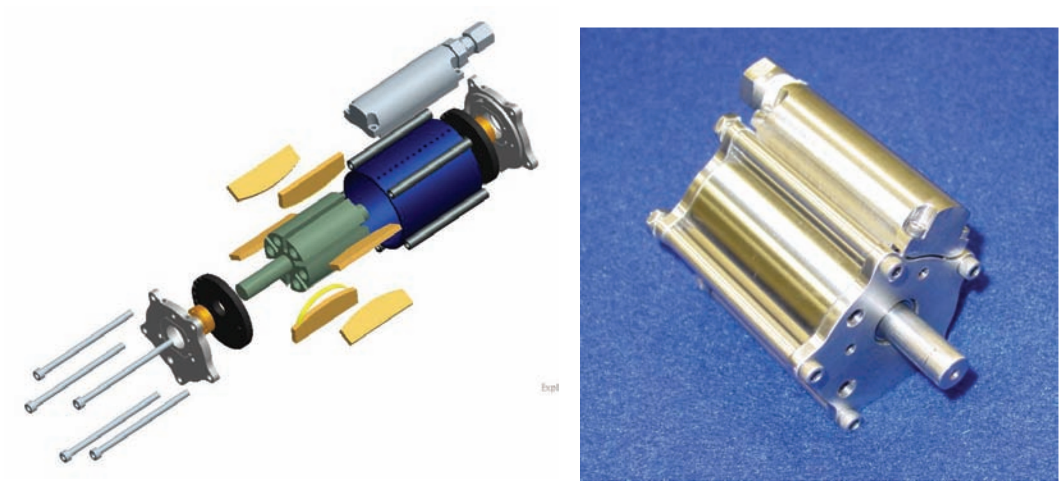

Figure 2: Version V2.1 vane motor prototype

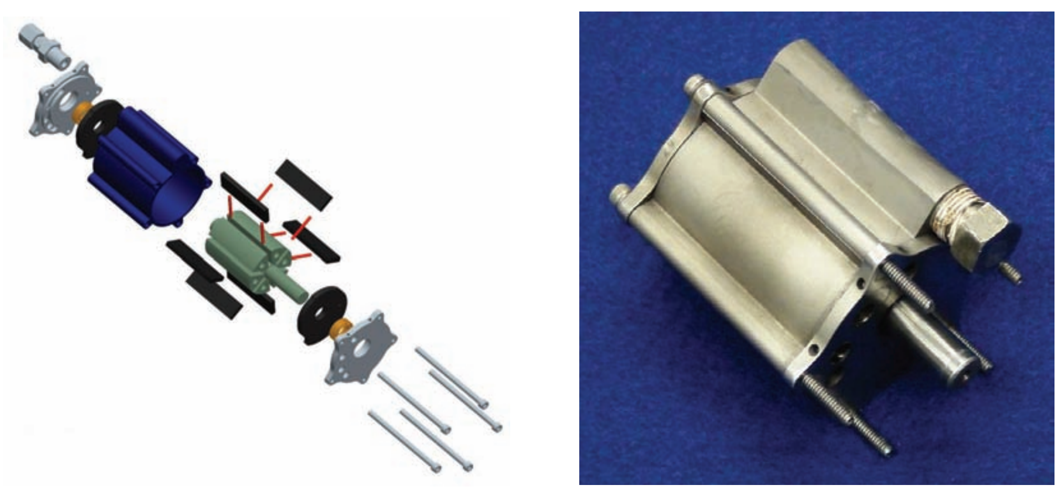

Figure 3: Version V2.7 vane motor prototype

Motor	V1	V2.1	V2.7
Motor Mass	785 g	366 g	366 g
Expansion Ratio	~13	~17	~17
Rotor Mass	225 g	112 g	112 g
Max Vane Area (A)	.1375 in^2	.3438 in^2	.3438 in^2
Max Vane Lever Arm (L)	1.45 in	1.25 in	1.25 in
A x L	.1994 in^3	.4297 in^3	.4297 in^3
Max Speed	3400 rpm	8000 rpm	11000 rpm
Max Measured Power	130 Watts	235 Watts	290 Watts
Power Density	180 W/Kg	644 W/Kg	790 W/Kg

Table 1: Performance characteristics of vane motor prototypes

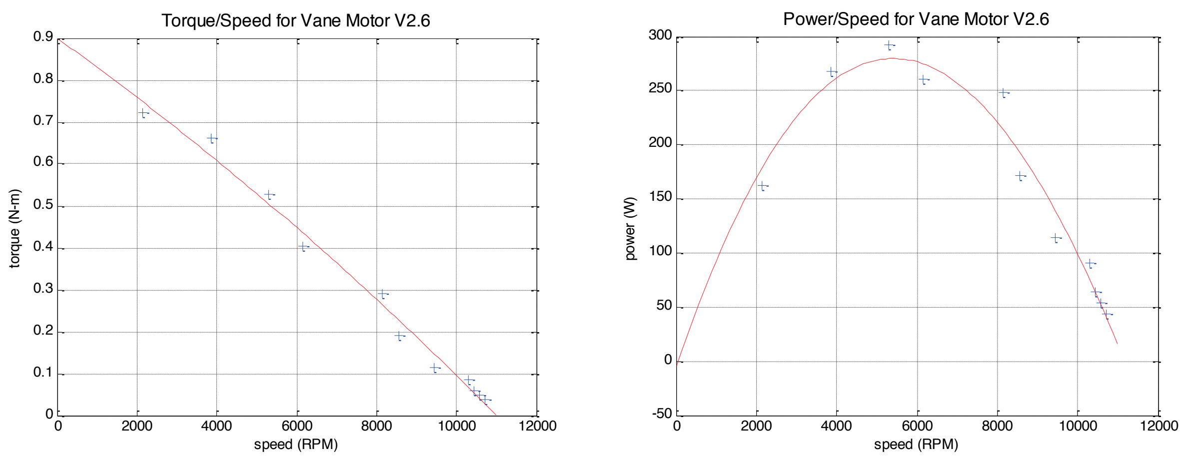

Figure 4: Torque and power curves for vane motor prototype V2.6

The version V2.7 motor prototype was tested on an efficiency test stand. For these experiments, thermocouples were placed on the catalyst pack, the motor body, and in the exhaust flow; the flow rate of the propellant was measured; the brake was controlled to maintain a constant speed; and the brake torque and shaft speed were recorded. Based on these measurements, the motor running with a 70% solution of hydrogen peroxide was shown to have an efficiency of 2.4% at steady-state operation, which is 32% of Carnot efficiency for the 70% peroxide solution. In order to achieve higher efficiency, the motor must be run with a higher percentage peroxide solution. An 80% concentration enables a significant gas expansion ratio prior to vapor condensation. The adiabatic decomposition temperature of 80% peroxide, however, is 920°F, compared with 450°F for 70% peroxide. Although efficiency measurements were attempted with 80% peroxide solution with the V2.7 motor prototype, the motor seized after approximately 30 seconds, due to thermal expansion of the rotor. It became clear that a new version of the motor designed to operate with an 80% peroxide solution would need to be built.

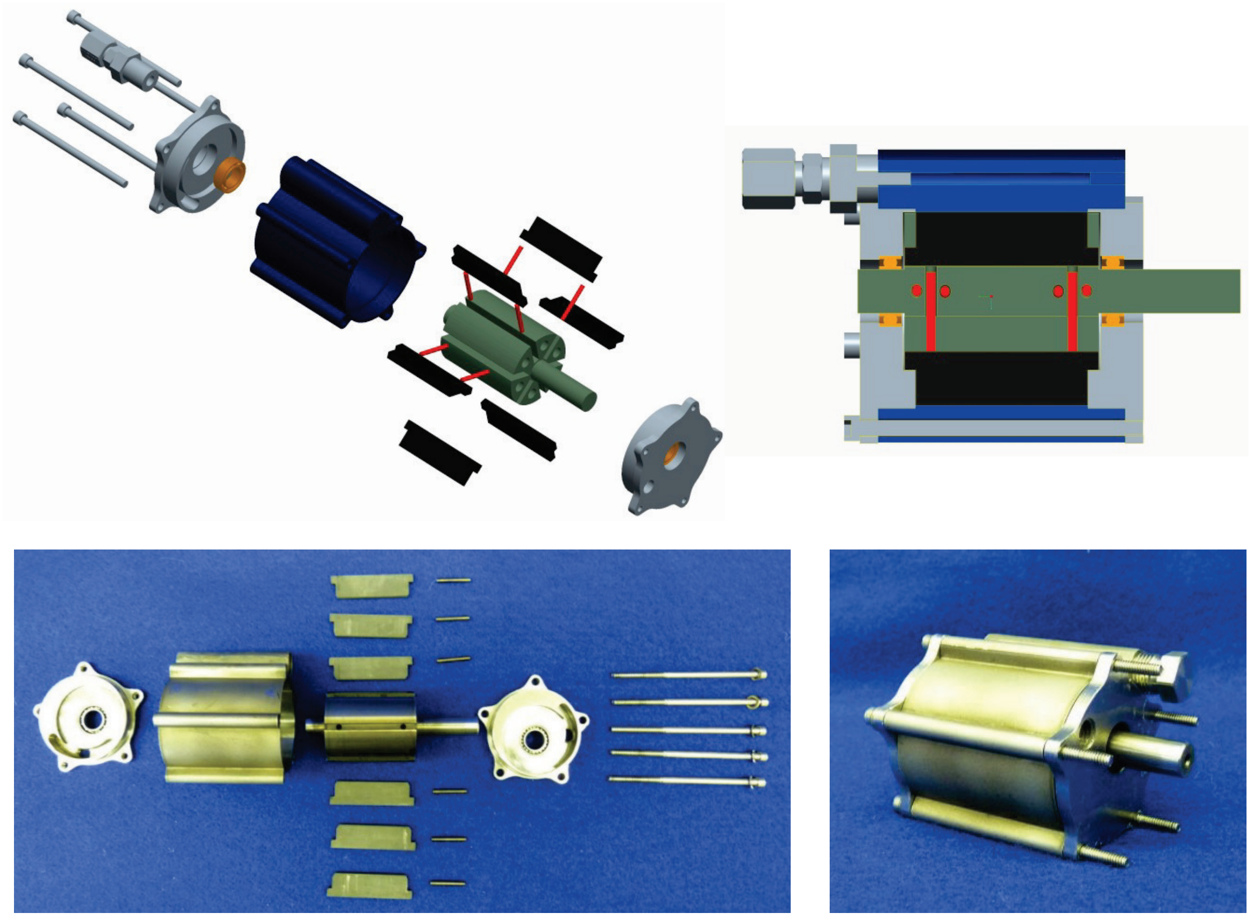

Figure 5. Version 2.10 of the vane motor designed to accommodate 80% peroxide

The latest research focused on design revisions to the vane motor to enable continuous operation of the motor with 80% peroxide and to approach the 16% efficiency indicated by the experiments with 70% peroxide. Three new versions of the motor were fabricated and tested, but after 18 months of work we have not been able to achieve continuous operation with 80% peroxide.

<u>Summary of research plans for the next two years</u>
We believe that the geometric requirements of multiple surface close-sliding-fits, together with significant thermal expansion, coupled with the absence of a lubrication system, renders this a research project that is not consistent with the resources of the Center. Therefore, work on Project 2A was stopped at the end of Year 5.

C. Member Company Benefits

If successful, the project would have provided a compact power source for hydraulic machines and could provide whole new potential markets for the member companies.

Project 2B.1: Free-Piston Engine Compressor

Research Team

Project Leader:	Prof. Eric Barth, Vanderbilt University, Mechanical Engineering
Graduate Students:	Mark Hofacker, Chao Yong
Undergraduate Students:	Menge Sun

1. Statement of Project Goals

The project goal is to develop a dynamic model-based design framework for a novel compact high energy density pneumatic power supply applicable to untethered fluid-power applications. This is achieved by modeling, designing, building and testing a free-piston engine utilizing spark-ignited fuel that is specifically load matched to the task of compressing air. Target metrics for the device include 100W average continuous output power in the form of 80 to 150 psig compressed air, a dry weight of 1.5 kg, energy density greater than 1500 kJ/kg, and a small footprint. This device will be integrated into the Compact Rescue Robot, Test Bed 4, by the end of 2012. Fundamental research will result in a generalized design method for the exploitation of free-piston engine dynamics for optimizing the efficiency and power density of the energetic conversion and transduction processes between chemical stored energy, kinetic energy of the free-piston, compression and pumping work, and stored pneumatic potential energy. This model-based design methodology takes a combined system dynamic and thermodynamic perspective that uniquely addresses the role of dynamic elements and effects seen to have a larger role in free-piston engines than more standard kinematic engines. Correspondingly, a generalized control methodology for free-piston engines will be formulated and applied.

2. Project Role in Support of Strategic Plan

This project contributes mainly to the compactness thrust. The compactness is achieved both due to the high gravimetric energy density of the driving fuel and the compact configuration of the engine which favors dynamic “linkages” over larger kinematic ones. This project will contribute to the Center’s goal of breaking the barrier of low energy density power sources for untethered devices. Additionally, given that an adequate level of overall efficiency is required to break the energy barrier and provide an order of magnitude increase in energy density over conventional technology, this project also has some crossover with the efficiency thrust of the Center.

3. Project Description

A. Description and explanation of research approach

The need for an effective portable power supply for human-scale robots has increasingly become a matter of interest in robotics research. Current prototypes of humanoid robots show significant limitations in the capacity of their power sources in between charges. Given the low energy density of state-of-the-art rechargeable batteries, operational times of these systems in the 100W range are restrictive [7]. This limitation becomes a strong motivation for the development and implementation of a more adequate source of power. Moreover, the power density of the actuators coupled to the power source needs to be maximized such that, on a systems level evaluation, the combined power supply and actuation system is both energy and power dense. Put simply, state-of-the-art batteries are too heavy for the amount of energy they store, and electric motors are too heavy for the mechanical power they can deliver, in order to present a viable combined power supply and actuation system that is capable of delivering human-scale mechanical work in a human-scale self contained robot package, for a useful duration of time [8].

The total energetic merit of an untethered power supply and actuation system is a combined measure of 1) the source energy density of the energetic substance being carried, 2) the efficiency of conversion to controlled mechanical work, 3) the energy converter mass, and 4) the power density of the actuators. With regard to a battery powered electric motor actuated system, the efficiency of conversion from stored electrochemical energy to shaft work after a gear head can be high (~50%) with very little converter mass (e.g. PWM amplifiers); however, the energy density of batteries is relatively low (about 350 kJ/kg specific work for Li-ion batteries after the gearhead), and the power density of electrical motors is not very high (on the order of 50 W/kg), rendering the overall system heavy in relation to the mechanical work that it can output. With regard to the hydrocarbon-pneumatic power supply and actuation approach presented here relative to the battery/motor system, the converter mass is high and the total conversion efficiency is shown to be low. However, the energy density of hydrocarbon fuels, where the oxidizer is obtained from the environment and is therefore free of its associated mass penalty, is in the neighborhood of 45 MJ/kg, which is about 2 orders of magnitude greater than the energy density of state of the art electrical batteries. This implies that even with poor conversion efficiency (e.g., one order of magnitude less than battery/motor systems), the available energy to the actuator per unit mass of the energy source is still at least one order of magnitude greater than the battery/motor system. Additionally, linear pneumatic actuators have approximately an order of magnitude better volumetric power density and a five times better mass specific power density [11] than state of the art electrical motors. Therefore, the combined factors of a high energy-density fuel, the efficiency of the device, the compactness and low weight of the device, and the use of the device to drive lightweight linear pneumatic actuators (lightweight as compared with power comparable electric motors) is projected to provide at least an order of magnitude greater total system energy density (power supply and actuation) than state of the art power supply (batteries) and actuators (electric motors) appropriate for human-scale power output.

The free piston engine compressor presented in this summary serves the function of converting chemically stored energy of a hydrocarbon into pneumatic potential energy of compressed air. More specifically, it extracts the energy via combustion of a stoichiometric mixture of propane and air, and the combustion-driven free piston acts as an air pump to produce the compressed air.

The use of free piston engines for compressors is not a new idea. In fact, the first free piston machine designed by Pescara in 1928 was used as an air compressor [14]. Free piston engine compressors were used through the mid-twentieth century, such as the Junkers-designed compressor used in German submarines [13]. Other applications for the technology were investigated, such as gas generators for use in automobiles [10, 17] and small power plants. However, the lack of adequate sensing and control technology led to the free piston engine being largely abandoned after 1960 [9]. Modern electronic controls available today have led to a second generation of free piston engine research. Most of this research, however, uses free piston engine technology for hydraulic pumps [1, 6] and small-scale electrical power generators [2, 3, 4], not as air compressors. An extensive review of both early free-piston engine compressor and gas generator applications as well as the recent resurgence in research in free piston hydraulic pumps and linear alternators has been conducted [12].

Despite free piston devices having been studied in the past, none of these previous designs explicitly featured what is perhaps the main advantage of a free piston, its capability to offer a dominantly inertial load. Although it is widely recognized that the inertial load presented by a free-piston can be used advantageously to influence the thermal efficiency, previous research fails to explicitly exploit this feature through design. The main focus of the work in this project is to exploit through design the fact that a free piston can present an inertial load to the combustion pressure, and as a result, desirable operational characteristics can be obtained, such as high efficiency, low noise, and low temperature operation. The fundamental research barrier preventing this is a lack of tools regarding the design of “dynamic engines”. What is needed is a model-based design approach that combines the system dynamics and thermodynamics that are more intimately coupled in a free piston engine than a traditional kinematic engine. Methodologies associated with system dynamics and controls are not typically applied to engine design, and this research provides an opportunity to formulate: 1) the dynamic analysis of such engines in light of exploiting the intermediate kinetic energy storage of the free piston, and 2) a synthesis method for the design of free-piston engine devices that have a load tailored for certain applications, such as pumping hydraulic fluid, compressing air, and other outputs, while also being “shaped” to benefit the combustion cycle for efficiency, power density, control and/or other metrics. Additionally, this work aims to demonstrate that a free piston compressor stands as a strong candidate for a portable power supply system for untethered human-scale pneumatic robots.

B. Achievements

Funded by the CCEFP, Riofrio, et al [15, 16] designed a free piston engine compressor specifically for a lightweight untethered air supply for actuation of traditional pneumatic cylinders and valves, using hydrocarbon fuels as an energy source. The piston, acting as an inertial load, converts the thermal energy on the combustion side of the engine into kinetic energy, which in turn compresses air into a reservoir to be used for a pneumatic actuation system. This early work verified some of the notions of the idea irrespective of device design.

A second device by Riofrio et al [16], a free liquid-piston compressor (FLPC), was designed using a liquid trapped between elastomeric diaphragms as a piston. The liquid piston eliminated the blow-by and friction losses of standard piston configurations [16]. This device incorporated a combustion chamber that was separated from an expansion chamber. Once the high pressure combustion gasses were vented into the expansion chamber, PV work was converted to inertial kinetic energy of the piston. The separated combustion chamber kept air/fuel injection pressure high prior to ignition for efficient combustion, and allowed for air/fuel injection that was decoupled from power and return strokes of the engine cycle. The separated combustion chamber and the high pressure injection of both air and fuel allowed for an engine devoid of intake and compression strokes. Achievements included: 1) Experimentally validated dynamic model of the pressure dynamics due to combustion, combustion valve inertial dynamics, expansion chamber pressure dynamics, compressor chamber pressure dynamics, reservoir pressure dynamics, 2) Experimental characterization of prototype I efficiency (2.03% overall efficiency from chemical potential to stored pneumatic potential energy in the reservoir – the target metric is 3.25%) and power (52 watts – the target metric is 100 watts), 3) A design-based diagnosis of prototype I led to a number of quantified design tradeoffs and conclusions for subsequent designs, 4) Prototype II (FLPC) was designed, has a much smaller footprint than prototype I, and incorporated design changes to overcome the inadequacies of prototype I, 5) A full dynamic simulation of prototype II was used in its design to size and scale with respect to design tradeoffs between desirable effects and losses, 6) The formulation of a “virtual dynamic cam” framework was initiated as a generalized method for the control of free-piston and dynamically dominant engines without a kinematic index (crankshaft).

In Willhite and Barth [18], a dynamic model of a free liquid piston that exploits piston geometry to produce a high inertance was developed for use in a free piston engine compressor. It was shown that for the size scale targeted, advantageous piston dynamics can be achieved with a reduced piston mass compared to a rigid piston design. A schematic of this new design is shown in Figure 1. A patent on this device was filled in 2010. Modeling work on the former separated combustion chamber prototype revealed certain energetic losses associated with the fast dynamics of the piston motion. Following from this motivation, the concept of inertance was exploited to slow the dynamics of the piston motion while concomitantly reducing the mass of the piston. It was shown that a high inertance liquid piston with a mass of 0.414 kg has the equivalent dynamic response of a 12.5 kg liquid piston of uniform cross sectional area. It was also shown that the required “inertance tube” section of the high inertance liquid piston exhibits manageable viscous losses for the geometries considered. Finally, the dynamic response of the high inertance liquid piston resolved significant issues when incorporated into a free-piston engine compressor device. These issues are: 1) valve sizing, 2) complications associated with a separated combustion chamber, and 3) a balanced engine.

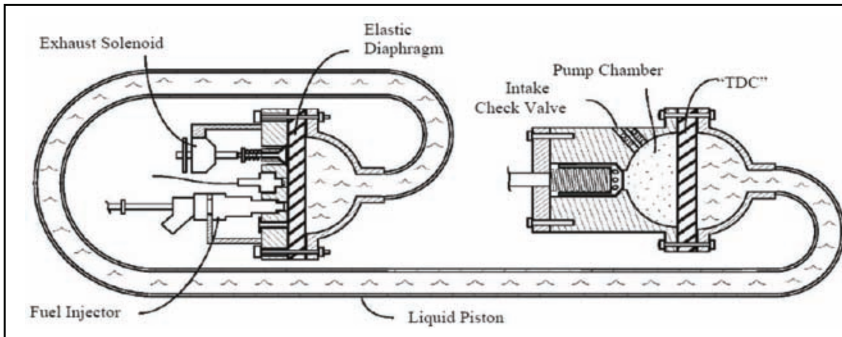

Figure 1: Schematic of HIFLPC at effective TDC.

Willhite and Barth [19] focused on accurately modeling the liquid piston diaphragm stiffness, injection valve capacity and dynamic response, and pump check valve dynamics. A discussion of the implications of these parameters on the overall FLPC design and performance was also presented. The aim of this modeling was to enable an optimization of overall system performance. In Willhite and Barth [20], an optimization of piston dynamics to achieve performance goals of the High Inertance Free Liquid Piston engine Compressor (HI-FLPC) was presented. Simulation studies were conducted to optimize liquid piston dynamic characteristics for overall system performance, and the results were discussed.

Willhite, et al [21], the first part of a two-part journal paper submission, presented detailed component and system modeling. An inertance-based dynamic model for the liquid piston was developed, validated, and incorporated into a system model of the device. Critical model parameters for components and subsystems of the model were experimentally characterized independently for use in the system model. Simulations were performed that support the effectiveness of the liquid piston dynamics on overall performance of the HIFLPC. Specifically, the piston provides a desirable load against combustion, and its kinetic energy is well-matched to drive the compressor load. The companion paper [22], presented the design and experimental evaluation of a full prototype of the High Inertance Free Piston Engine Compressor. A model-based design for a high inertance liquid free piston engine compressor was developed. An experimental prototype of the device was fabricated and experimentally evaluated. Consistent operation of the device was achieved, and efficiency and power output of the device as tested were assessed. Test data was used to validate the dynamic model developed for the device. Model-based studies investigated the effect of varying liquid piston dynamics on overall system performance. The transduction efficiency from chemical to pneumatic potential in the reservoir was measured to be in the range of 3.45-6.63%. These significant results suggests that pneumatic systems using the HIFLPC as a power source would exhibit system energy densities comparable to, if not better than, the best electromechanical systems. Combined with the inherent advantages of pneumatic actuators over DC servomotors, devices like the HIFLPC position pneumatically actuated systems as an attractive option for human-scale, untethered robotic systems. The virtual cam control methodology was applied to the HIFLPC prototype in [24].

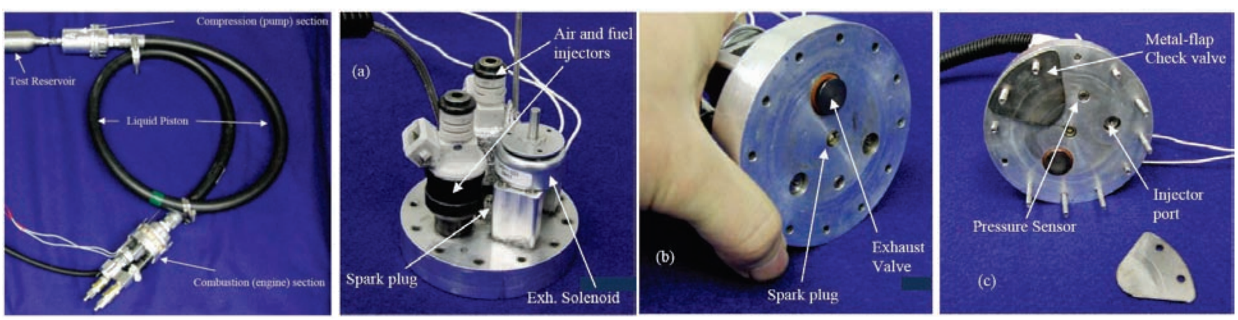

Figure 2: Experimental prototype of HIFLPC. Shows entire device (left), (a) combustion head top, (b) combustion head interior, (c) combustion head with injection check valve

To achieve higher pressures, increase efficiency, lower weight, and decrease vibration, a redesign was started in September of 2011. A computer render of the compressor alongside a photograph of the fabricated hardware is shown below in Figure 3. Many components are constructed using stereolithography which dramatically lowers the total weight and allows for intricate, strong, and compact components. The unique figure-8 arrangement of the liquid piston contributes toward self-balancing the device to reduce vibrations and eliminates the need of opposing cylinders. The compressor is controlled with a micro-computer and compact, efficient electronics. The next version of this device will be demonstrated in May 2012 and will feature on board electronics and seamless titanium tubing to lower hydraulic friction, improve efficiency, and further reduce weight.

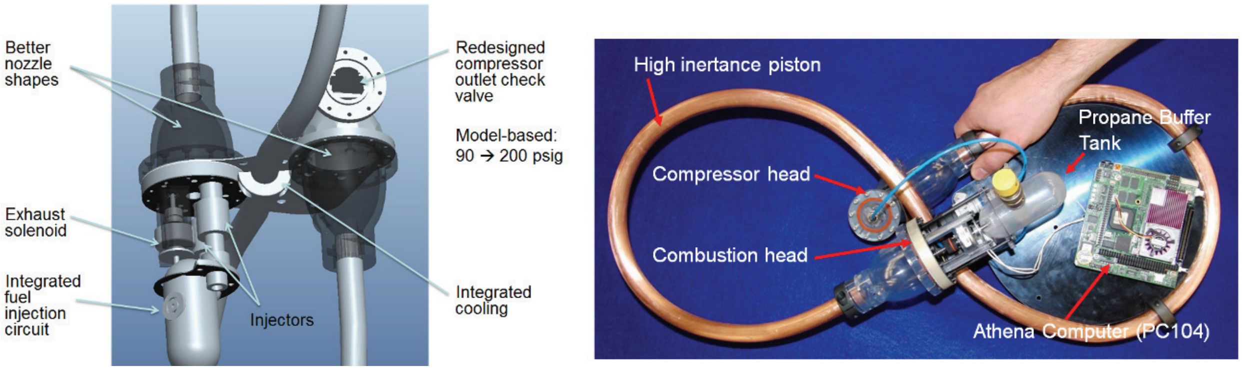

Figure 3: (a) CAD drawing of design, (b) High inertance free piston compressor hardware with self balancing figure-8 design

This engine has been instrumented and tested at a component level. Although the closed loop controller has not yet been implemented (at the time this report was written), open loop control has given promising results shown below in Figure 4. The plan is to implement the completed engine on the Compact Rescue Robot (Test Bed 4) in May 2012.

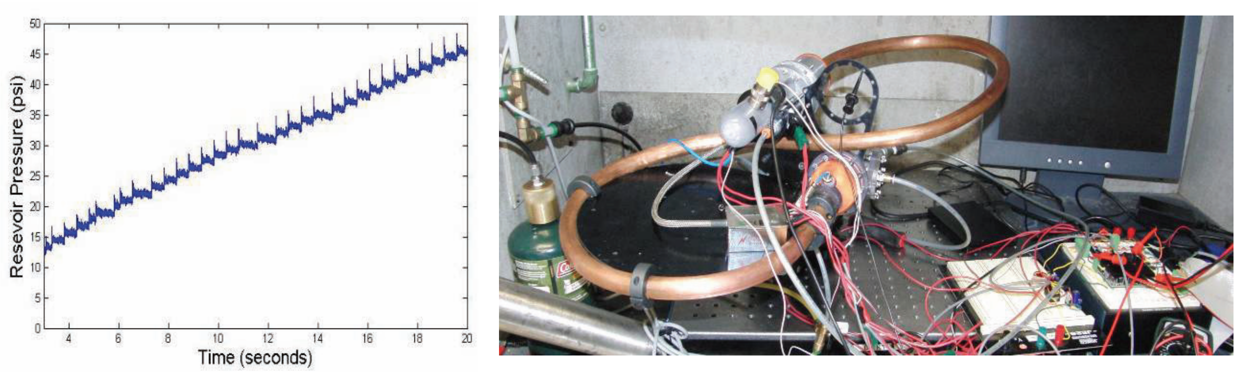

Figure 4: Preliminary performance results showing the increasing reservoir pressure as the engine operates (left). The engine has been instrumented and is controlled using low power and compact electronics (right).

Expected Milestones and Deliverables (Project ends in May 2012)

The project is on track with previously set milestones and deliverables. Recently fulfilled milestones and planned future milestones are listed below.

- Milestone 1: High Inertance Prototype (HIFLPC) Completed *DONE*
  - Task: Unloaded tuning *DONE*
  - Task: Constant load energetic characterization *DONE*
- Milestone 2: HIFLPC Energetically Characterized at Ideal Conditions *DONE*
  - Task: Full model experimental validation *DONE*
  - Task: Injection controller for varying loads (reservoir pressures) *DONE*
  - Task: Energetic Characterization over operating envelope *DONE*
- Milestone 3: Controlled Prototype Energetically Characterized *DONE*
- Milestone 4: Design Compact Rescue Crawler ready prototype (FIGURE-8) *DONE*
- Milestone 5: Stand-alone Power Supply System Completed (3/31/12)
  - Task: Ship to Georgia Tech, work with Georgia Tech to resolve any issues
- Milestone 6: Power Supply Fully Characterized on Test Bed 4 (5/31/12)

C. Member company benefits

Some interest has been expressed in using a version of the engine/compressor for portable handtools and leafblowers.

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Project 2B.2: Miniature HCCI Free-Piston Engine Compressor

Research Team
Project Leader: Prof. David Kittelson, Mechanical Engineering, University of Minnesota
Other Faculty: Prof. William Durfee, Mechanical Engineering, University of Minnesota
Graduate Student: Lei Tian

1. Statement of Project Goals

This project has two goals. The first goal is to generate new knowledge about the science and engineering of homogeneous charge compression ignition (HCCI) free piston engine-compressors suitable for tiny power supplies for small scale fluid power systems. This goal builds on preliminary work which investigated novel small free-piston engine-compressors operating in glow-plug combustion mode. The second goal is to design, build, evaluate and deliver a tiny, high-efficiency air compressor that delivers approximately 10W of cold compressed air and runs on clean-burning dimethyl ether (DME) fuel. The engine-compressor will be suitable for Test Bed 6, the Portable Pneumatic Ankle Foot Orthosis.

2. Project or Test Bed Role in Support of Strategic Plan

This project supports the CCEFP goal of "developing new fluid power supplies that are one to two orders of magnitude smaller (10 W-1 kW) than anything currently available". It also supports the CCEFP vision of revolutionary new portable and wearable applications of fluid power that operate in the 10 to 100 W range, including human assist devices. A major barrier to these new applications of fluid power is the lack of a compact, light, high energy density source of pressurized fluid. This project addresses this barrier with an internal combustion free-piston engine compressor that will be more compact, lighter in weight and run longer than current pneumatic supplies that use a battery, electric motor and air pump.

3. Project/Test Bed Description

A. Description and explanation of research approach

The approach for the development of the engine compressor is based on an integrated program of testing and modeling. The design of prototype engines is based on mathematical modeling which is supported by testing of components from a very small conventional engine, and testing of prototypes themselves. With the experimental results, appropriate models with fitted parameters can be chosen to better simulate the engine, which in turn will guide the design and optimization of further generations of prototypes. These optimizations will include improvements in compactness and efficiency as well as reductions in emissions, noise, and heat rejection.

B. Achievements

<u>Overview of Previous Achievements</u>

The project started September, 2008. In the last reporting period (Feb. 2009 – Jan. 2010), the general concept for the free piston engine compressor was developed. Modeling the design was conducted, and an overall engine compressor model was built in a MATLAB SIMULINK application.

To model the miniature free-piston engine compressor, various components were experimentally tested to help with model calibration and validation, including check valve response, blow-by leakage, friction, scavenging process and combustion process [1]. An overall model for the engine compressor was constructed based on the experimentally fitted and verified sub-models using the MATLAB SIMULINK tool. With the SIMULINK model, the starting and operation can be simulated with all sub-models in place. With all the inefficiencies modeled, the overall engine compressor model predicted that at steady state operation it would outputs 17.6 W of cooled compressed air at an overall efficiency of 4.6% (From fuel lower heat value to cooled compressed air energy).

The overall model was used to examine factors the influence engine compressor performance. Trade-offs between leakage and friction were evaluated to determine the optimum operating speed of the engine. At lower speed, leakage and heat transfer loss are higher. However, mechanical efficiency drops with increasing speed. This trade-off can be evaluated in the overall engine compressor model and the engine's optimum operating range was predicted to be between 100 and 150 Hz.

A prototype was fabricated during last reporting period. The prototype suffered alignment and friction problems and did not manage to operate in free-piston mode.

Achievements in the current year (Feb. 2011-Jan. 2012)

Prototype Gen II fabricated

Major design revisions were made compared to the last prototype, and the updated Generation 2 design and fabricated free-piston engine compressor prototype are shown in Figure 1. The entire engine compressor package is about 12 cm long with 12.5 mm engine bore size, and weights 260 grams. Various unique design features ensured alignment of components, and minimal friction while maintaining good sealing. This engine was designed to run autonomously in a narrow speed-load range, which is appropriate for charging the reservoir, without any active control of the free piston motion and ignition timing. This is in contrast to full scale conventional free-piston engines that employ active control 4 including the rebound energy regulation for controlling engine compression ratio [2, 3] and engine frequency modulation [4]

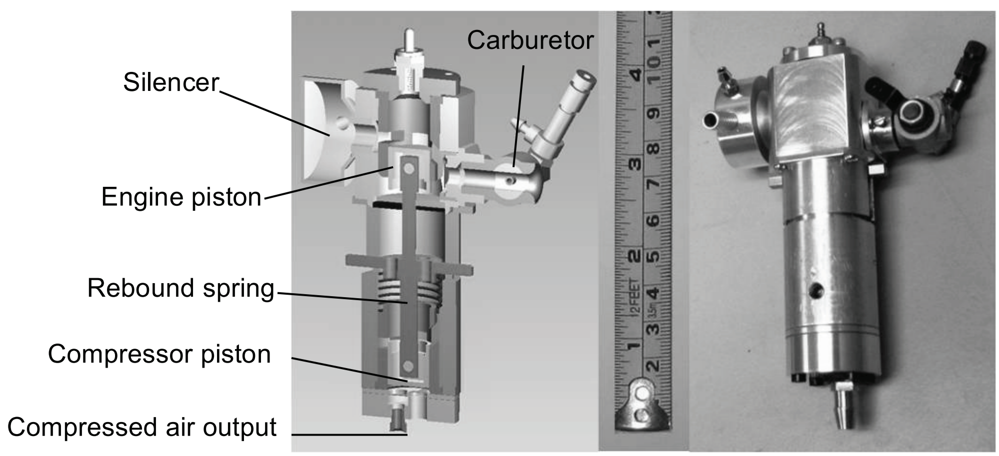

Figure 1: Free-piston engine compressor design cutaway and prototype

Running of engine compressor prototype

A test stand was built for experimental testing of the prototype. A high speed laser triangulation sensor was used to measure piston position, and a pressure transducer was used to measure combustion chamber pressure. The compressor output was connected to a 530mL air tank through a check valve to prevent leakage back into the compressor.

To start the prototype, the starting handle was pulled by hand to compress the rebound spring. After the pistons reached its bottom most position and the spring was fully compressed, the handle was released to initiate the first cycle. The piston position and in cylinder pressure during starting up are shown in Figure 2. The first two combustion events were weak, reaching peak pressure of about 15 bar, just enough to push the pistons past the exhaust port open (EO) position at 10.17mm. After the piston was beyond position EO in the first cycle, scavenging occurred and supplied the engine with fresh fuel air mixture for the next cycle.

The prototype pressurized a 530mL air tank from 2.4 bar to 6.7 bar in 38 seconds. As the pressure in the air tank rose, the compressor output pressure also rose. This is equivalent to increasing the stiffness of a spring-mass system, and as a result, the engine operation frequency increased from 108Hz to 124Hz. This result fit the model prediction.

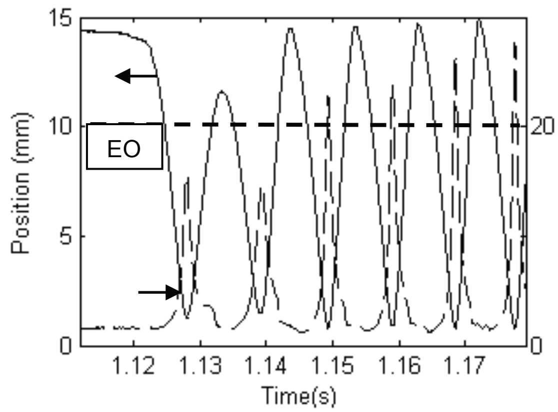

Figure 2: Experimental data of miniature free-piston engine starting up

The energy stored in compressed air can be calculated by amount of work it can do if expanded to atmosphere pressure adiabatically. From the energy stored in the air tank, the output compressed air equivalent power was estimated to be 5 W. The low efficiency of converting the 48 W indicated output of the engine to 5 W of compressed air output was due to leakage in the compressor, compressing heating effect and friction in the engine and compressor.

<u>*Piston motion analysis*</u>
In a crankshaft engine, piston motion is mechanically restrained by crankshaft and connecting rod. As the crankshaft rotate, energy converts among mixture expansion energy, crankshaft and flywheel kinetic energy and shaft work. However, in a free-piston engine the process is more complicated as the motion of pistons is determined by forces and energy balance, instead of by mechanical constraint.

Position-velocity diagram was used to analyze the motion of the free pistons, as shown in Figure 3. The dashed line in the diagrams is the position of the piston bumping into a rubber bumper. As the piston travels beyond that line, the kinetic energy of the piston and connecting rod are lost in the collision. The speed of piston at that collision point is a good indication of how much energy is wasted due to bumper collision. During start up, the engine compressor was running at no load since the hose connected to the compressor output was not at pressure. As a result, in Figure 3, after the

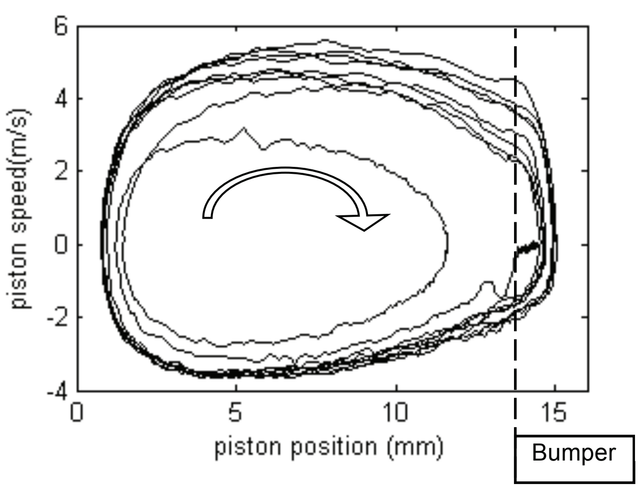

Figure 3: Piston position-speed diagram of 9 consecutive cycles at engine starting up

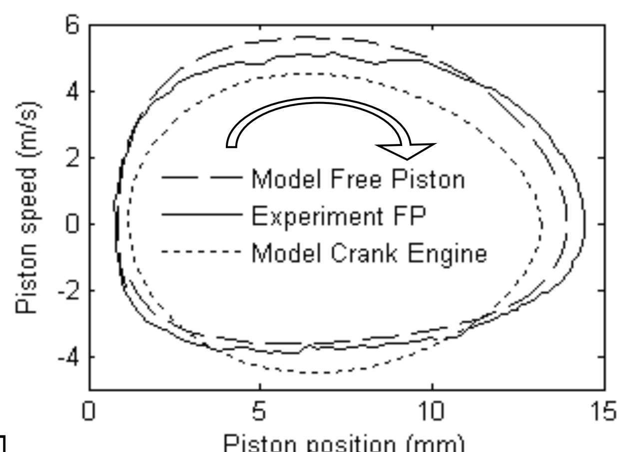

Figure 4: Piston position-speed diagram of a typical cycle of experimental data at steady state running, compared with modeling result of free-piston engine and modeling result of a crankshaft engine

engine entered steady state running from starting up, almost all energy from engine output was lost in bumping into the bumper, which was about 0.4 J per cycle. After the compressor was operating in nominal output pressure (4.5 bar) much less energy was wasted in bumper collision as shown in Figure 4. Figure 4 also shows a comparison among piston-speed traces, from modeling of free-piston engine compressor, a typical cycle of free-piston engine experimental test data, and modeling of a crankshaft engine. Free-piston engine traces are distinct from crankshaft engine trace as the pistons are free from kinematic constraint of crankshaft and connecting rod. The modeling of the free-piston engine predicts the trend correctly and fits generally well with experimental data, indicating that our model can capture the dynamics of the free piston. However, due to assumptions made to enable engine zero dimensional modeling, especially as simple scavenging and combustion models were used, the model prediction and experimental data do not match.

<u>*Combustion analysis*</u>

The experimental test data of pressure volume diagram of the free-piston engine is shown in Figure 5. The cycles were consistent, with some variation in pistons TDC position and pressure trace during combustion and expansion processes. The pressure volume trace of our free-piston engine compressor differs considerably from its crankshaft engine counterpart. The crankshaft engine data was from experimental test of a same size crankshaft engine which utilizes the same engine cylinder and glow plug ignition system.

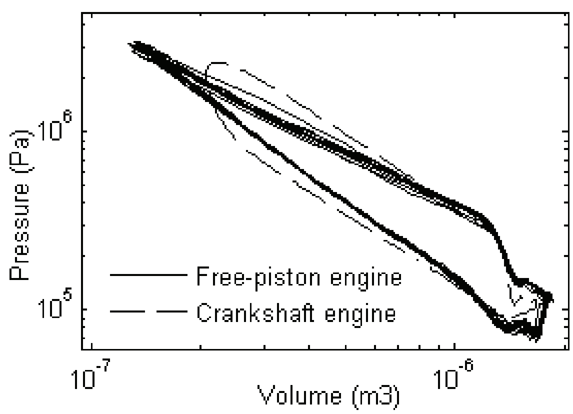

Figure 5: Pressure volume log-log diagram for 12 cycles in free-piston engine compressor prototype, compared with a crankshaft engine

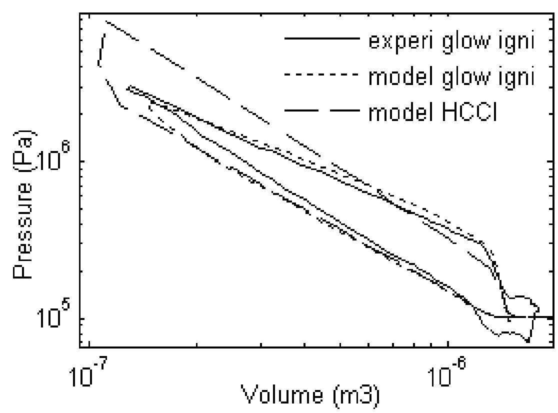

Figure 6: Pressure volume diagram for glow ignition free-piston engine model prediction, HCCI free-piston engine model prediction and a typical cycle's experimental data

Figure 5 shows that in the free-piston engine prototype combustion continued throughout the expansion process, while combustion in the crankshaft engine is centered about the top dead center, resulting in a wedge shape and a bar shape pressure volume log-log diagram respectively. This can be explained by the nature of the free-piston engine. After the mixture ignites in a crankshaft engine when the piston was around top dead center, the piston is held there by the crankshaft and connecting rod. In a free-piston engine the mixture also ignites around top dead center position, however, at that position the rebound spring is not exerting much force on the pistons since it is not compressed, and the compressor is not doing work since it is still in the end of intake stroke. As a result, without the mechanical restraint of crankshaft and connecting rod, the free pistons rapidly retract from the top dead center, outpacing the mixture combustion process.

An internal combustion engine achieves highest possible thermal cycle efficiency if combustion happens instantaneously at top dead center, as in an ideal Otto cycle. The combustion of the crankshaft engine shown in Figure 5 was close to that ideal. In contrast, the free-piston engine heat release took a considerable amount of time and was not at fixed volume as the ideal cycle

Implementation of HCCI should increase cycle efficiency in a free-piston engine. Aichlmayr, et al [5] realized HCCI in a small 3 mm cylinder, and high speed camera images showed that the HCCI combustion process duration was less than 60 μs. If HCCI is implemented in this free-piston engine, the entire combustion process will happen around TDC, yielding high thermal efficiency. This was also confirmed by the engine compressor model. Modeling HCCI in the free-piston engine compressor is shown in Figure 6, which features a steep rise of in-cylinder pressure due to fast heat release. The model predicts the efficiency of glow plug ignition to be 25% and HCCI to be 41%. Part of the efficiency gain is caused by the higher compression ratio (12.3 for HCCI cycle versus 9.0 for glow plug ignition cycle), while the rest is due to more optimum heat release. The model predictions on cycle efficiency are higher than the experimental value because the model simplifies the heat release process and charge properties.

In summary, in the last year an engine compressor prototype was developed and successfully operated in free-piston mode, compressing air up to 6.5 bar (94 psi). Experimental test data were compared with the simulation model and verified that the model is able to predict key engine compressor characteristics. Experimental results showed the heat release process in the free-piston engine compressor prototype was not optimal and pure HCCI combustion mode has good potential to improve efficiency.

Expected milestones and deliverables

Task 1: Second generation prototype optimization for better efficiency

- Leakage in prototype compressor will be reduced by investigation into better component design to optimize lubrication and sealing. The engine compressor design will also be optimized so that less energy is wasted in pistons colliding into the rubber bumper.
    - Timeline: 4 months (Mar. 2012 – June 2012)
    - Deliverable: Optimized operating engine.

Task 2: Engine compressor integration into PPAFO

- The engine compressor prototype will be integrated into TB6, the Portable Pneumatic Ankle Foot Orthosis (PPAFO) as compressed air power supply. Mounting, heat dissipation and insulation, vibration and emission issues will be considered and optimized.
    - Timeline: 12 months (May. 2012 – April 2013)
    - Deliverable: A optimized running engine compressor integrated to an AFO

Task 3: Pure HCCI implementation

- As the modeling and experimental results indicating potential efficiency benefit of HCCI combustion versus current glow plug ignition, it will be implemented in the prototype. The prototype will be optimized for higher compression ratio which is needed for HCCI.
    - Timeline: 6 months (Jun. 2012 – Dec. 2012)
    - Deliverable: Free-piston engine compressor prototype operating on pure HCCI

Task 4: Three dimensional CFD modeling

- The engine compressor will be modeled in 3D dimensional CFD software FLUENT. It will be useful in understanding miniature engine scavenging and combustion processes.
    - Timeline: 5 months (Mar. 2012 – July 2012)
    - Deliverable: 3D modeling tool of the engine compressor

C. Member company benefits

CCEFP member companies can use this technology to expand their product offerings and increase the size of the fluid power market.

D. References

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Project 2B.3: Free Piston Engine Hydraulic Pump

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Post Doc: Ali Sadighi
Graduate Students: Ke Li, Michael Koester
Undergraduate Student: Julian Jones
Industrial Partners: Ford Motor Company, Individual Project Champion: John Brevick

1. Statement of Project Goals
The research goal is to provide a compact and efficient fluid power source for mobile applications (10 kW-500 kW). Specifically this project will investigate the design, modeling and control of a free piston engine driven hydraulic pump.

2. Project Role in Support of Strategic Plan
The project will address two transformational barriers as outlined in the ERC strategic plan: compact power supply and compact energy storage. This is achieved by proposing a hydraulic free-piston engine, which stores energy in hydrocarbon fuel and convert it to fluid power in real time according to the power demand, as the main power unit for on-road vehicles or off-road heavy machineries.

3. Project Description
A. Description and explanation of research approach
Background and Motivation
For mobile applications including both highway vehicles and mobile heavy equipment, fluid power is currently generated using a crankshaft-based internal combustion engine (ICE) with a rotational hydraulic pump. The main drawbacks of this configuration are its relatively low efficiency and complex design of both the ICE and the hydraulic pumping system due to the dynamic operating requirements. The flexibility and efficiency of the ICE would increase significantly if variable compression ratio control can be achieved during the engine operation. Different variable compression ratio mechanisms have been proposed [1-3]. However, those technologies are subjected to the complicated mechanical constraints and the response time limits of the actuation system. An alternative approach is to supply fluid power using a free-piston engine (FPE) with a linear hydraulic pump. An FPE offers the flexibility for variable compression ratio control by eliminating the crankshaft, therefore enables advanced combustion cycles, such as low-temperature combustion, which provide better fuel economy and less NO_x emissions [4-7]. Other advantages of this approach is its simpler design with fewer moving parts, resulting in a compact engine with low maintenance costs and reduced frictional losses. The schematic diagram of the hydraulic free-piston engine we are investigating is shown in Figure 1(a). Combustion in the right cylinder will push the inner piston to the left and outer piston to the right, which will compress the gas in the left cylinder and generate high pressure fluid in the inner hydraulic chamber. Similarly combustion in left cylinder will return the inner piston to the right and outer piston to the left.

Free-piston engine driven hydraulic pump can be designed with three different architectures: single piston, opposed piston, and opposed chamber arrangement [8-9]. Single-piston architecture is simple and relatively easy to operate. Opposed-piston architecture is self-balanced, therefore produces no vibration. The opposed chamber arrangement offers higher power density and therefore a compact design. A single piston hydraulic FPE was reported to have power output of 17 kW, and indicated efficiencies of nearly 50% [10-11]. A synchronization method for an opposed piston hydraulic FPE has been proposed, which combines an electronically controlled hydraulic rebound and a mechanical spring system in [12]. The authors demonstrate engine operation with varying power outputs. The indicated efficiency was shown to be almost constant throughout the power range. The first-cycles experimental results of an opposed-chamber hydraulic FPE with no closed loop feedback control was reported in [13], and a PID and feed forward engine control is proposed thereafter based on simulation in [14]. The major technical barrier for bring FPE to mass production is the large cycle-to-cycle variation, especially during transient operation. Specifically, the compression ratio of the FPE cycle is mainly dependent on the dynamic coupling of the in-cylinder gas dynamics, the load and the piston

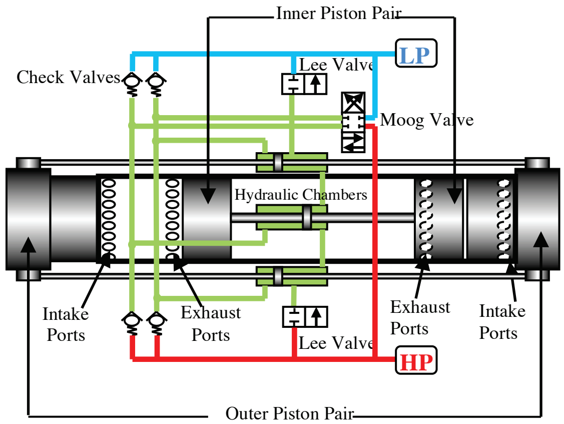

Figure 1(a): Schematic of the Free Piston Engine Driven Hydraulic Pump

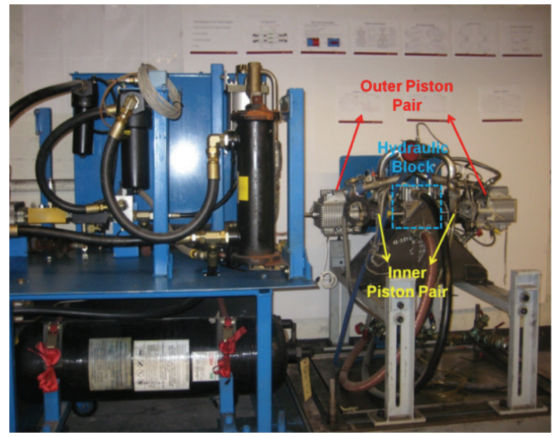

Figure 1(b): Free Piston Engine-Driven Hydraulic Pump

motion. For a free piston engine with 100-mm stoke and 5-mm clearance at the top dead center, a 1% variation of the piston motion (1mm) will results in a 20% variation in the compression ratio, which will further affect the combustion performance. This imposes a huge challenge on the robust and precise engine operation control. The current FPE control methodologies which are primarily calibration based show a limited success and mainly apply to the single piston FPE. Therefore, systematic active controls and design optimization that can precisely regulate the engine operation are needed [15-17].

Research Approach

To address the above challenges, we propose to investigate the two fundamental technical barriers of the free piston engine driven hydraulic pump. One is the seamless coordination of the combustion and the fluid power. The other is the design optimization of the system. To support the proposed research, our industrial partner Ford Motor Company has donated a free piston engine driven hydraulic pump to the University of Minnesota. Figure 1(b) shows the picture of the system.

Real-time Control of the Combustion and Fluid Power

For conventional IC engines, the crankshaft is the mechanism, which brings the engine back to normal if misfire occurs. However, for opposed cylinder FPEs, the combustion and the piston dynamic are heavily dependent on the conditions from last cycle. In other words, a misfire in previous cycle would results in engine stall. In the research being done in this project, an active controller acts as a virtual crankshaft that would force the piston to follow the reference trajectory using the high-pressure fluid stored in the accumulator if abnormal combustion occurs. The piston/pump motion is periodic with respect to the position of its stroke. If the operating frequency is fixed, the piston motion is also periodic in time [8]. Given the periodic nature of the free-piston engine motion, the advanced controller employed here is of robust repetitive type [29], which is capable of tracking any periodic reference signal with known period. A key feature of repetitive control is its extremely fast convergence rate of the tracking error due to its high feedback gains at desired frequency locations [18-21].

Not only the virtual crankshaft can guarantee a stable operation, it will also regulate the engine to run at maximum efficiency. With a mechanical crankshaft, the piston trajectory is fixed and is independent from engine speed and load. Thus, there are limited means for optimizing the engine efficiency. However, with the virtual crankshaft, the piston trajectory can be varied in real time by altering the reference signal. Optimal trajectories will be determined for the engine under various frequencies and load conditions, so that the engine would always run at its maximum efficiency.

Design Optimization of the Free Piston Engine Driven Hydraulic Pump

To increase system controllability as well as efficiency, we will investigate alternative designs for the free piston engine driven hydraulic pump. First, digital flow control approach will be studied and simulated to assess its effectiveness in improving the performance of the HFPE. Currently, check valves as shown in Figure 1(a) are used to enable suction of fluid from the low-pressure reservoir and pumping it to the high-pressure reservoir. Despite its simple and reliable design, this approach introduces some limitations on the operation of the HFPE under different scenarios. This limitation arises from the fact that these valves are passively controlled by the pressure difference between up and down stream and could not be actively adjusted. To overcome this limitation and provide further flexibility in the operation of the HFPE, we propose to replace the check valves and the servo valve with high speed digital on-off valves. System simulation will be conducted to investigate the feasibility of this approach. Second, we propose to control the intake and exhaust process with an electro-hydraulic camless valve actuation system [22-25] enabled by the on board high pressure fluid. This technology is capable to regulate the mixture of the fresh charge and the residual gas on a cycle to cycle basis and is critical to realize optimal combustion phasing control.

B. Achievements

The research team has been conducting research on an opposed-piston opposed-cylinder hydraulic free-piston engine (Figure 1) donated by Ford Motor Company. Prior to the reporting period, comprehensive physics-based models have been constructed [26]. The simulation results have provided us with new insights into the engine performance under different loading conditions.

During the reporting period, a novel methodology for stability analysis of the HFPE has been developed, which predicts the stability of the engine operation at specified operation points in a systematic manner [27]. Furthermore, different FPE architectures have been studied. Specifically, we compared an FPE with a linear alternator with an FPE coupled with linear hydraulic pump [28]. One of the main milestones during this period was the successful development and implementation of an advanced piston motion control system for the hydraulic free-piston engine [29]. To conduct experiments and collect data, several engine sub-systems were installed. This included a driver for Moog and Lee valves. The lubrication system was built for both inner and outer piston pairs. A displacement transducer, pressure transducer and thermocouples were connected to the combustion chamber and hydraulic chamber, and were properly conditioned and calibrated.

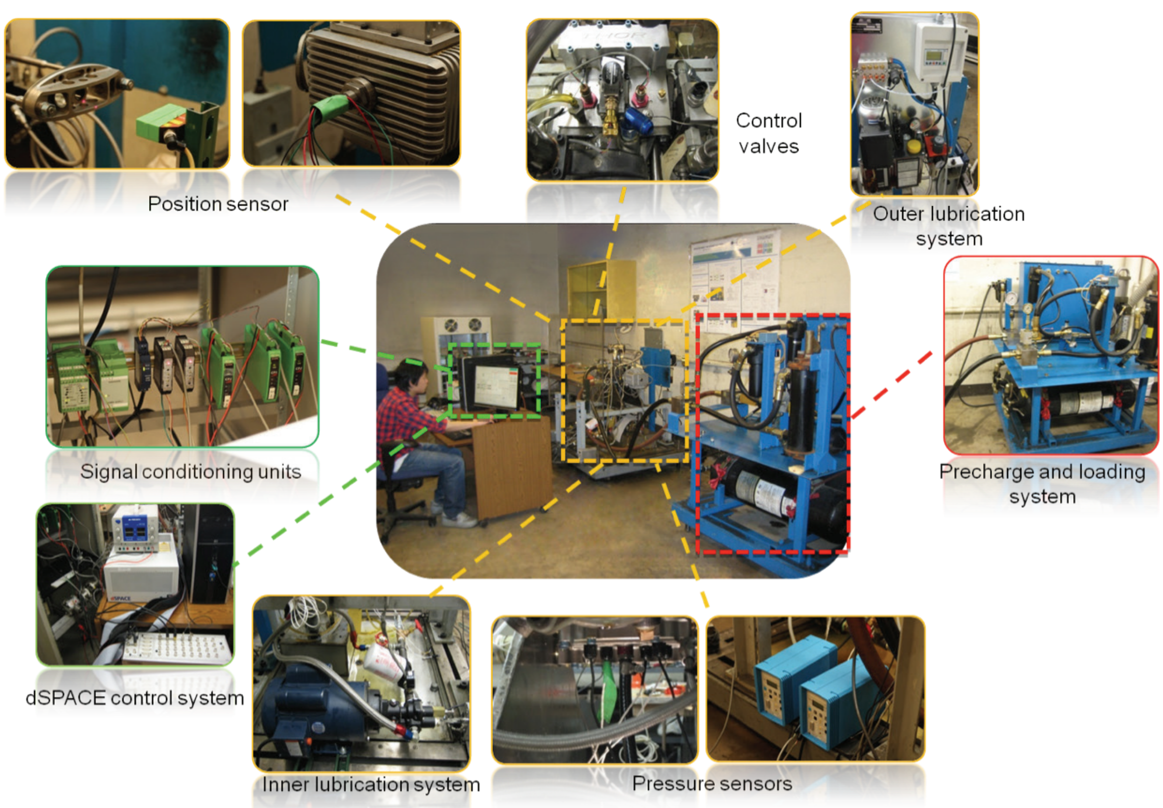

Figure 2: Test cell set-up of the HFPE and its subsystems

A dSpace system that realizes real-time control was setup and connected to the sensors and actuators. The engine and hydraulic setup have been disassembled and diagnosed to get ready for testing. Figure 2 shows the test cell set-up of the hydraulic free piston engine with its subsystems.

A proportional control was first implemented, then system identification was conducted that a series of sinusoidal signals with varying frequencies were sent to the Moog valve. Based on the recorded piston displacement, by utilizing Matlab system ID toolbox, a linear model was developed that was used for the advanced control design. The precise tracking performance of the robust repetitive controller during engine motoring is shown in Figure 3(a). The pressure trace in the cylinder is illustrated in Figure 3(b).

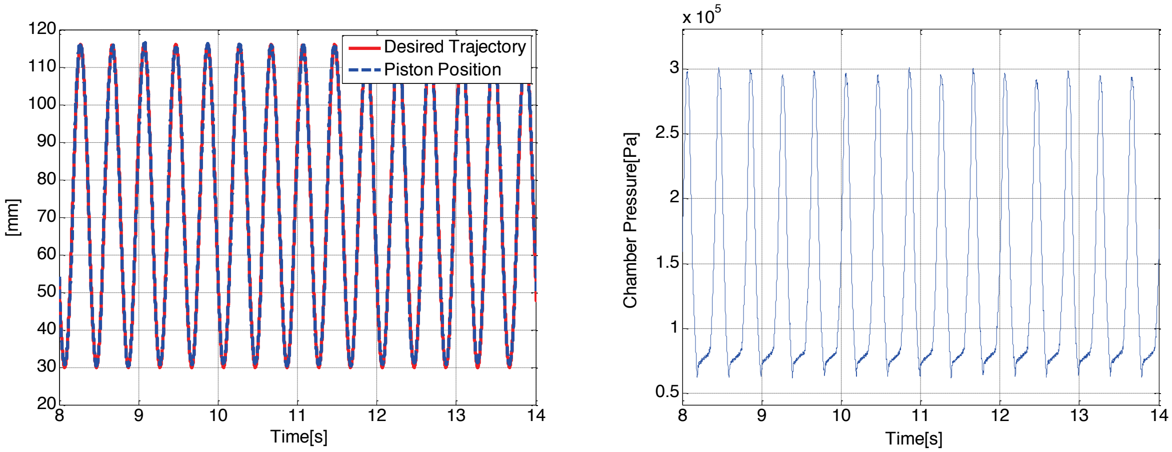

Figure 3: (a) Tracking performance of the repetitive controller. (b) Pressure trace in cylinder.

By utilizing the virtual crankshaft, we are able to motor the engine at various compression ratios. Figure 4 shows the cylinder pressure trace at two different compression ratios.

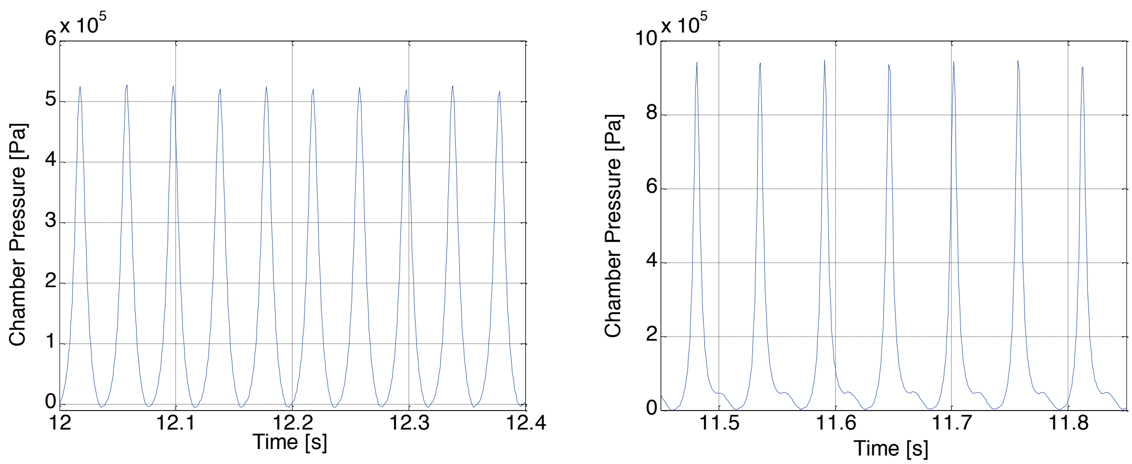

Figure 4: (a) Pressure trace in cylinder at CR = 3.5. ***(b) Pressure trace in cylinder at CR = 6.***

Plan for the Next 5 Years

The breakthrough in the precise piston motion control of the HFPE [29] could create an enormous opportunity for the use of this technology in on-road vehicles and off-road heavy equipment. However, further research is necessary to demonstrate reliable operation of the HFPE under various loading conditions. The recently-developed piston motion control methodology will be applied to control the output hydraulic power of the HFPE by coordinating the combustion process and the fluid power generation. Specifically, we will first design a control system for regulating the piston motion as well as the engine output power (see Figure 5). Second, we will utilize the "virtual crankshaft" to optimize the engine operation by designing desirable piston trajectories, which result in the best cycle efficiency under various loading conditions. Third, the developed system will be fully tested at various loading conditions and benchmarked against crankshaft-based ICE driven pump system.

Digital flow control approach will be studied and simulated to assess its effectiveness in improving the performance of the HFPE. In this approach, the check valves are replaced by digital on-off valves which could be actively controlled to achieve certain operational objectives. Also, by employing well known pulse width modulation (PWM) techniques, the flow rate could also be adjusted. This digital hydraulic design could replace the servo valve for the engine startup to further reduce system cost.

Based on the above proposed work and to further explore the applications of the HFPE, we are proposing a flexible testing platform to emulate on-road or off-road vehicles powered by the HFPE. Such a platform allows us to investigate various energy management strategies to achieve the most fuel-efficient operation for the hydraulic free-piston engine powered vehicle. To do this, comprehensive physics-based models of various components of the vehicle as well as environmental conditions are used to create a virtual vehicle interacting with the HFPE.

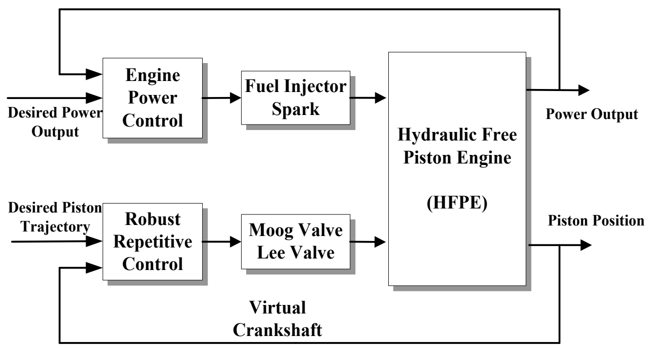

Figure 5: HFPE active control architecture

Milestones and Deliverables

- Task 1: HFPE test under various loading conditions
  - Deliverables:
    - Motoring and combustion tests with virtual crankshaft (5/31/2013)
    - HFPE tests and benchmarking against conventional ICE (11/30/2013)
- Task 2: Digital flow control
  - Deliverables:
    - Simulation results of the HFPE with digital flow control system (10/31/2012)
    - New HFPE design with digital flow control system (11/30/2012)
- Task 3: HFPE-in-the-loop emulation platform
  - Deliverables:
    - HFPE-in-the-loop test platform for on-road or off-road vehicles (3/31/2014)
    - Optimized operational conditions for HFPE for different applications (5/31/2014)
- Task 4: Series hydraulic hybrid vehicle implementation
  - Deliverables:
    - Vehicle design (11/31/2014)
    - Series hydraulic hybrid vehicle prototype (5/31/2016)
    - Test drive and benchmarking against other hybrid vehicles (11/31/2016)

C. Member company benefits

The project will benefit the member companies in three areas. First, this project will provide a new fluid power source for series hydraulic hybrid vehicles. Several member companies have active programs for series hydraulic hybrid vehicle, and if successful, the free piston engine driven hydraulic pump will offer higher efficiency, lower emissions, and better modularity. Second, this project will also benefit member companies by offering a modular and efficient fluid power source for off-highway mobile equipment. Third, this project will help attract automotive companies to join the Center.

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Project 2C.2: Advanced Strain Energy Accumulator

Research Team

Project Leader: Prof. Eric Barth, Vanderbilt University, Mechanical Engineering
Graduate Students: John Tucker, Richard Whitney
Industrial Partners: Bosch-Rexroth, Gates Rubber

1. Statement of Project Goals

The research objective of this work is to extend the current state of knowledge in the use of strain energy storing materials for the engineering design of compact energy storage devices. Specifically, this project seeks a low cost, low/no maintenance, high energy density accumulator primarily targeted toward a fluid powered automotive regenerative braking system (hydraulic hybrid). This project will focus on extending the energy storing capabilities of accumulators for the specific purpose not of flow smoothing, but of storing large amounts of hydraulic energy with an energy density appropriate for applications such as regenerative braking in passenger vehicles. The envisioned high energy density accumulator will be appropriate for either series or parallel hydraulic hybrid vehicles. The metric for success of the project will be an experimental prototype capable of storing up to 200 kJ of energy (3500 lbs at 35 mph) at a peak power of 90 kW (35 mph to zero in 4.5 second) in a package of acceptable weight and volume for a compact to midsized passenger vehicle (accumulator system energy density >10 kJ/liter). This metric will enable implementation in a passenger vehicle for city driving. Additional significant benefits of this research potentially include solutions to more traditional accumulator problems including cost, pre-charge issues, and fluid contamination from gas diffusion through the bladder.

2. Project Role in Support of Strategic Plan

This project will contribute to the Center's goal of breaking the barrier of a lack of compact energy storage. The task of designing new compact energy storage devices is central to the Center's vision of "significantly reducing energy consumption" by "enabling the migration of fluid power to passenger cars". As identified in a recent NSF site visit, compact energy-dense storage solutions are critical to the success of this migration. This project addresses the knowledge level of this goal (explore new energy density concepts) by seeking a design to provide the enabler (improve energy density of storage mechanisms) and ultimately the needed system capability (reduce size and weight of FP systems to work in passenger vehicles) for this important goal [4]. This project will be demonstrated on the Hydraulic Hybrid Passenger Vehicle Test Bed, TB3.

3. Project Description

A. Description and explanation of research approach

This project seeks to investigate, design and experimentally implement a compact energy storage accumulator via strain energy in materials not traditionally utilized in existing accumulators. A control strategy and control laws for regulating power flow will be formulated and implemented. Concerns regarding the efficiency of the hydraulic pump/motor will be out-of-scope and left to researchers in the efficiency thrust.

Hydraulic accumulators are energy storage devices commonly used to provide supplementary fluid power and absorb shock. One particularly interesting recent application of these devices is regenerative braking. Although a theoretically appealing concept, hydraulic regenerative braking (HRB) is difficult to implement due to some major inherent weaknesses of conventional accumulators.

The primary weakness of spring piston accumulators that prohibits them from being used in HRB is their low gravimetric energy density. Using linear analysis, spring steels and titanium alloys have a gravimetric energy density of around 1-1.5 kJ/kg [1]. Consequently, in order to store enough energy to bring a mid-sized 4-door sedan (mass=3500 lb (1590 kg)) to rest from 35 mph (15.65 m/s), the accumulator spring would have to weigh somewhere from 130 kg to 195 kg. In automotive manufacturing, where minimizing vehicle weight is vital, including such a heavy component would be largely impractical.

Gas bladder accumulators and piston accumulators with a gas pre-charge (PAGPs) use gas for energy storage and, therefore, are much lighter than their spring piston counterparts. In these accumulators, a gas, separated by a bladder or a piston, occupies a certain volume of a container which is otherwise filled with an incompressible fluid. As fluid is forced into this container, the gas inside the separated volume is compressed and energy is stored in the thermal domain (kinetic theory of gasses). Such accumulators are subject to two serious drawbacks: 1) inefficiency due to heat losses, and 2) gas diffusion through the bladder into the hydraulic fluid. The drawback of inefficiency via heat loss is mild, but the gas diffusion issues gives rise to high maintenance costs associated with "bleeding" the gas out of the fluid often.

With regard to inefficiency, if the energy stored in the compressed gas of such an accumulator is not retrieved soon, the heat flow from the gas to its immediate surrounding results in much less energy being retrieved. Pourmovahed et al. showed that with as little as 50 seconds passing between gas compression and expansion, a piston-type gas accumulator's efficiency can fall to about 60% [1]. Several methods to mitigate these heat losses have been proposed. For PAGP, one promising method involves placing an elastomeric foam into the gas enclosure. This foam serves as a regenerator by absorbing the heat generated during gas compression, and returning it to the gas when the latter expands. According to Pourmovahed, "the insertion of an appropriate amount of elastomeric foam into the gas enclosure…[can] virtually eliminate thermal loss" [2]. Incorporation of elastomeric foam has shown how accumulator efficiency can be vastly improved through slight modification. However, this modification still does not solve the maintenance issues associated with gas diffusion.

The purpose of this research is to investigate a new method of energy storage in a hydraulic accumulator by using strain in an elastomer as the mechanism for energy storage. An elastomeric bladder or other deformable shape will be designed and tested for its capacity to store and return energy by stretching in response to a hydraulic fluid being pumped in and out of it. This approach presents a new and unconventional method which aims to simultaneously avoid the susceptibility to heat losses and gas diffusion inherent to gas pre-charged accumulators, while attaining a higher gravimetric energy density than that of metallic spring piston accumulators. This design fundamentally avoids the gas diffusion problem given that the pressure gradient between gas and hydraulic fluid is opposite of that of a gas charged accumulator. Additionally, the design pursed will be advantageous due to low cost, relative simplicity and good manufacturability.

Material Selection

The selection of an appropriate energy storing material for the design of the high energy-density accumulator requires: 1) a high volumetric energy density, 2) a high gravimetric (or mass specific) energy density, 3) the ability to absorb and release the targeted power efficiently, 4) the ability to store the targeted energy efficiently for a duration on the order of minutes. A promising candidate energy storing class of materials includes elastomers such as polyurethane, nitrile rubbers, polyisoprenes, and natural rubber. Material data shows polyurethane as possessing an order a magnitude better volumetric energy density than steels (springs), and two orders of magnitude better gravimetric energy density than steels (Cambridge Engineering Selector, 2008). Polyurethane's high elongation percentage (500% to 700%) allows for a straightforward accumulator design that directly stretches the energy storing material without utilizing a transformer to scale pressure and displacement. Polyurethane also exhibits a fatigue strength of 5000 psi at 10,000,000 cycles (Cambridge Engineering Selector, 2008). Research results to dates have yielded the selection of an elastomeric material with an experimentally measured energy density of 15 kJ/l and an efficiency of 81-84%. It is worth noting that this commercially available material was not specifically engineered for this purpose. The material properties database cited above indeed show much higher capacities. An elastomer expert at ExxonMobil has confirmed that such a material can be engineered with a similar or lower hysteresis. Sample polyurethanes can be evaluated based upon their volumetric energy density as well as their hysteresis properties. These properties can be combined into one single property by calculating volumetric energy density based only off of the energy returned in a hydraulic cycle, as opposed to energy stored.

Scientific and Engineering Research Goals

Scientific discovery: expand the field of knowledge of fundamental strain energy storage mechanisms in materials not traditionally considered for high energy density energy storage (e.g., elastomers and composites).

Engineering discovery: utilize new fundamental models/understanding of high energy density energy storage for the design of a viable and cost effective hydraulic hybrid; ultimately expand the capabilities and application domain involving energy storage (contributing to the goal of hydraulic ubiquity)

B. Achievements

Achievements before February 2011

A volumetric system energy density upper bound was placed on a hydraulic accumulator system. This upper bound is equal to the working pressure. For a 5000 psi system, this is 34.5 kJ/liter.

A low pressure prototype demonstrated the following. Nearly constant pressure behavior was measured upon charging and discharging the bladder. A pre-strained region of the bladder near the fill port induced a “rolling” behavior along the inside of the shroud. An 85% round trip efficiency was measured for the latex bladder used. A hyperelastic finite element model revealed the need to distribute material loading to optimize strain energy storage in the material.

Using material data obtained from CCEFP member company Gates Rubber (NBR 6212), the stress-strain curve of the material showed a theoretical material energy density of 33 kJ/l. Accounting for the hydraulic fluid, this would result in a system energy density of 17 kJ/l. FEA modeling revealed a material energy density of only 4 kJ/l and a resulting system energy density of 3.6 kJ/l. Further investigation into the model revealed an effective transmission ratio between wall thickness of the bladder and the held hydraulic pressure of the fluid inside the inflated bladder. The thinner the wall, the better the strain was distributed in the material, but the lower the hydraulic pressure in the bladder. This fact necessitated a change in the bladder geometry from the original shape in order to utilize the full material energy density while keeping the hydraulic pressure high. A geometry was needed that could maximally and uniformly strain the material (as seen in the thin wall limit) to maximize material energy density, while concomitantly keeping a high hydraulic pressure. In fact, a geometry needed to be found that could achieve arbitrarily higher hydraulic pressures than maximum material stresses.

Shown below are several design drawings from the patents from this project submitted thus far. This project has generated 3 PCT (international) patent applications and 1 US provisional patent (held jointly with Georgia Tech) that will likely be converted to a full US or PCT application by March 2012. This project is currently in license negotiations with a major automotive OEM.

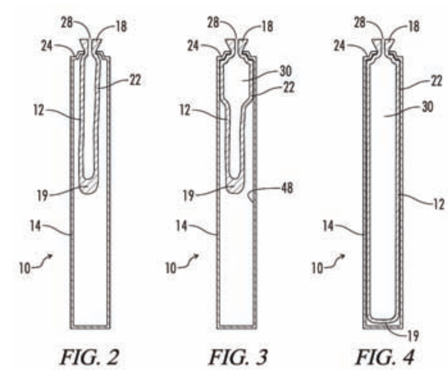

Figure 1: Original PCT patent application

Figure 1 shows the original “balloon in a shroud” concept with a thick-walled elastomeric, closed-end balloon inflates with admitted hydraulic fluid. As with a balloon-animal balloon, it inflates radially and then axially and produces a nearly flat P-V curve.

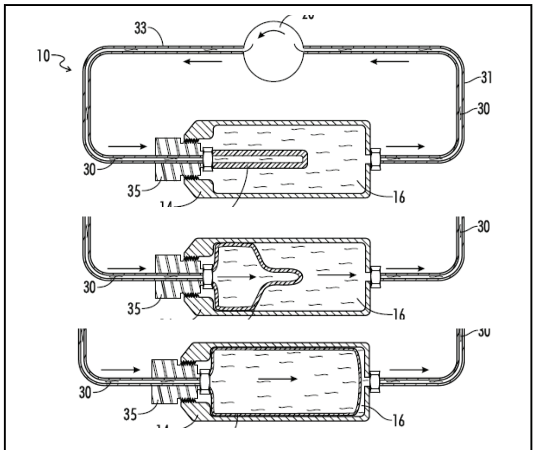

Figure 2: Integrated Reservoir PCT application.

Figure 2 shows the “integrated-reservoir” concept where the low pressure side of the balloon is assigned the role of

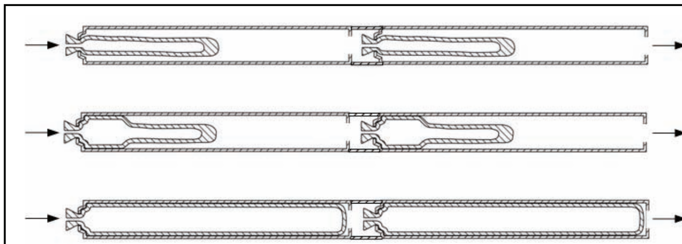

Figure 3: Series configuration to multiply pressure. Provisional patent filed with Georgia Tech.

low-pressure reservoir. This has the effect of doubling the system volumetric energy density over gas-charged accumulators as the same volume is utilized for two roles.

Figure 3 shows the "series configuration" where multiple bladder/shroud units are ganged together to increase the fluid pressure (common flow in the language of bond-graphs). This allows the fluid pressure to exceed the maximum localized material stress experienced.

Achievements in this reporting period

Much of the work during the reporting period was focused on a concept we call the "distributed piston accumulator" because of its energy storage dependent cross sectional area. The Distributed Piston Accumulator configuration exhibits "inverse ballooning." Figures 4 and 5 show this configuration and the associated Continuous Perimeter Clamp used to grip the elastomeric member at the ends. As will be explained below, this configuration: 1) more fully utilizes the material (thereby achieving a higher energy density) by eliminating radial strain gradients experienced in the balloon configuration, 2) exhibits a P-V curve that is similar in shape to the balloon configuration (due to an axially propagated "inverse ballooning" similar in function in keeping a relatively constant pressure), and 3) enables the fluid pressure to be a multiple of the maximum stress in the material through a designable ratio of the exposed piston area to the unstretched cross sectional area of the elastic member. This concept encompasses the features of the first three "balloon" concepts into a single device (series configuration not necessary) with a more easily manufacturable elastomeric shape.

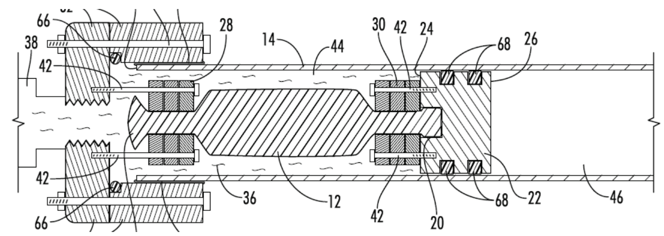

Figure 4: Distributed Piston Accumulator PCT patent application.

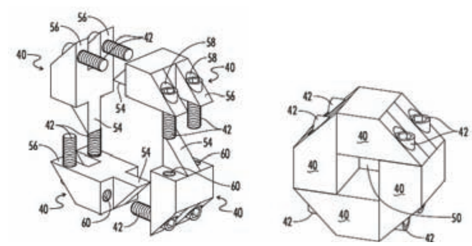

Figure 5: Continuous Perimeter Clamp claimed in the Distributed Piston Accumulator PCT patent application.

A number of elastomeric materials display hyperelastic expansion behavior. Configured in the correct geometry, this physical characteristic allows these materials to possess PV curves that resemble ideal energy storage (maximum area under the curve for a given maximum pressure) much closer than the PV curves of traditional gas pre-charged accumulators. Previous work has revealed that the "balloon" concept exhibits a nearly flat P-V curve after the initial radial expansion. While this was desirable, further investigation revealed two limitations. First, as the wall thickness of the balloon increased, the strain gradients in the radial direction became more severe. This has the effect of limiting the effective strain energy density of the material given that not all of the material is fully utilized (some is at its maximum yet other areas are not). A second limitation was that the hydrostatic pressure inside the balloon could not be larger than the maximum local stress experienced in the material. This lead to the series configuration such that the hydrostatic pressure could be made to exceed the maximum allowed material stress, but at the expense of increased interstitial fluid volume.

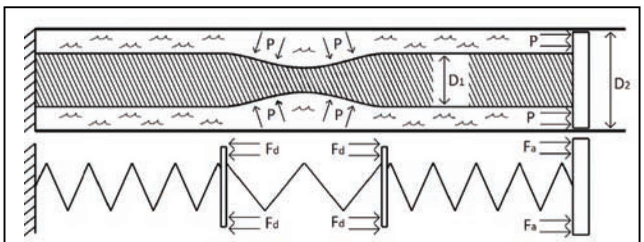

Figure 6: The mechanism of "inverse ballooning".

The distributed piston accumulator design shown in Figure 6 was recently developed to overcome the limitations of the "ballooning" accumulator design. It consists of an elastomeric member attached to and stretched by a piston. A photograph of an experimental prototype is shown in Figure 7. This new design is capable of 1) a relatively flat P-V curve, and 2) achieving a higher hydrostatic pressure than the maximum stress experience in the material by a designable multiple. Figure 6 shows the mechanism of this inverse ballooning. As hydraulic fluid is pumped into the device, the pressure pushes on the exposed annular area of the piston. The tensile force is then distributed over the original cross sectional area of the material as engineering stress. In this manner, the stress induced in the material is the hydrostatic pressure multiplied by the ratio of the annular area to the material cross sectional area. For a large material cross section and a small annular area, the hydrostatic pressure can be many times that of the material stress. This is important given that elastomeric materials with high energy densities do not possess allowable stresses much over 3000 psi (under that of common hydraulic systems). This pressure amplification factor will allow such materials to be used in a single simple stage (as opposed to a series configuration). A second non-intuitive feature arises that provides a flat P-V curve. As the material stretches, if any one point along the axis of the material becomes thinner than the rest, the pressure-induced axial force components along that "dent" cause the material to thin more, which in turn causes more of a dent. The dent gives rise to an increased distributed area that continues to localize the effect. This is similar to the balloon-animal constant-pressure effect. In this case it has a similar effect of "rolling out" the material so that the pressure upon extension remains mostly flat. Figure 7 shows an experimental setup with the distributed piston accumulator. Figure 8 shows a comparison of tensile and hydraulic loading of a distributed piston elastic member. As can be seen, the curve is flattened. This picture becomes more pronounced if actual strain as opposed to engineering strain is considered in the tensile loading case.

Figure 7: Experimental Prototype of the Distributed Piston Accumulator loaded into a hydraulic cylinder (piston rod provided only for measurement of displacement). Elastomeric member shown with cylinder casing removed. Inset shows clamping schemes.

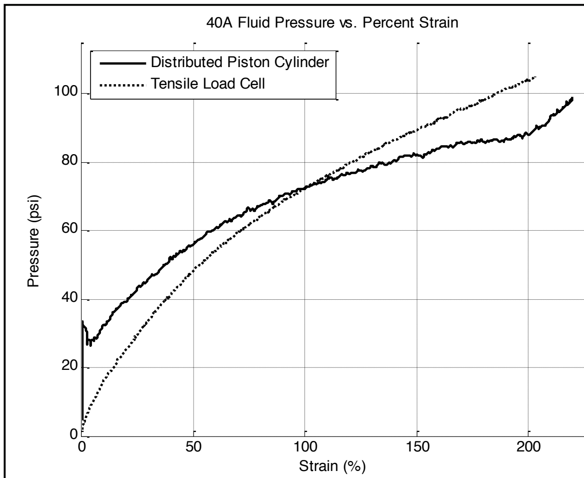

Figure 8: Distributed piston member in pure tension and hydraulic pressure in a cylinder

<u>Expected Milestones and Deliverables</u>

- Hardware in the Loop simulator (3/15/2012)
- High Pressure Distributed Piston Accumulator (DPA) (4/1/2012)
- Characterize DPA (5/1/2012)
- Model DPA (7/1/2012)
- Redesign and fabricate DPA with lessons learned (1/1/2013)
- Fabricate DPA unit(s) to be tested on TB2 (3/1/2013)
- Coordinate with UMN and begin to install DPA in TB2. (4/1/2013)
- Metrics measured on TB2 (5/15/2013)
- Final Evaluation (5/31/2013)

C. Member company benefits

The results of this project will provide an alternative to current hydraulic accumulators that has a higher energy density, presents a simple configuration, has inexpensive material costs, is easy to manufacture, is leakless, is safe, requires no pre-charging, and does not possess problems of gas diffusion into the hydraulic fluid as with gas accumulators. Member companies Gates Rubber and Bosch/Rexroth are formally engaged in this project. We are in early discussions with Bosch/Rexroth regarding licensing of the intellectual property.

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Project 2D: Multi-Functional Fluid-Power Components Using Engineered Structures and Materials

Research Team

Project Leader:	Douglas Cook, Applied-Technology Center, MSOE
Other Faculty:	Prof. Subha Kumpaty, Program Director, MS Engineering, MSOE Vito Gervasi, Applied-Technology Center, MSOE Prof. James Mallmann, Physics & Chemistry, MSOE
Graduate Students:	Samuel Newbauer, Gunnar Vikberg
Undergraduate Students:	Devin Pettis, Adam Leslie, Toni Borel (REU)
Industrial Partners:	Orbitec (associated project), Parker

1. Statement of Project or Test Bed Goals

The goal of Project 2D is to characterize the structural-thermal-acoustic coupling of three of the five unit-lattice structure types identified earlier to allow for the design of passive, noise-reducing, heat-managing, fluid-power components, i.e. multi-functional components using meso-scale meta-materials. Structural-acoustic and thermal-structural couplings will be defined through virtual testing; and, physical, non-destructive testing will be conducted for validation of the couplings. An additional goal is the inclusion of thermal-energy storage, recovery and conversion for improved component and system efficiencies.

When Center-wide budget cuts, that reduced our budget by ~20% from that proposed, Project 2D was directed to research only the thermal-management aspects of the lattice structures; so, in collaboration with Test Bed 6 and Project 2B.2, minimal-mass, heat-dissipating/-shielding components for the portable, powered, ankle-foot orthosis (PPAFO) were to be designed, analyzed and fabricated in Year 6. While the Rev. 2 PPAFO is near the one kilogram target, the maximum output torque is much lower than desired. Increasing torque output will require a combination of higher pressure, improved efficiency and a larger actuator (greater mechanical advantage); therefore, thermal management and structural optimization are critical, regardless of the final choice for portable power generation. For the mini-HCCI (Project 2B.2) to be integrated, a suitable engine operating temperature must be maintained, such that it can run for one hour, continuously. Additionally, this active orthosis must be safe and quiet to garner acceptance from the end-user. The FDA mandates a maximal contact temperature of 41°C for medical devices [16]. Component integration, heat dissipation and noise reduction through multi-functional component design will address these challenges.

Future goals are to apply this multi-functional design methodology to other components and systems, on Center projects and test beds, and those being developed by industry, including aerospace and medical.

2. Project or Test Bed Role in Support of Strategic Plan

Project 2D addresses the transformational barrier of efficient components by integrating mass reduction, thermal management and noise reduction into the design of fluid-power components, minimizing the need for peripheral components or systems to achieve these functions. The fluid-power technical barriers of efficient systems, safety, quietness and containment (leak-free) are also addressed by extension.

Hydraulic pumps and motors have already been demonstrated to carry significant amounts of "dead weight." With additional considerations for multi-functional components, i.e. heat-dissipating and noise-reducing, efficiencies would be improved; and, noise would be mitigated. Cooler operating temperatures of these devices also result in longer life for their components, and even the hydraulic fluid. Efficient pumps and motors, if not light and quiet, are certainly beneficial to the goals of Test Beds 1 & 3, as well. Likewise, mass reduction and thermal management afforded by custom, multi-functional components will benefit Test Bed 4.

3. Project/Test Bed Description

A. Description and explanation of research approach

Fluid-power technology's competitiveness/market penetration, despite high theoretical volumetric and gravimetric energy/power densities, is significantly hindered by; the lack of efficient commercial components and the levels of noise generated. Fluid power struggles to compete with electronics due to dead weight, poor energy management, highly-modular design and noise. The result is average fluid-power-system efficiencies of only 40%. The industry must develop the equivalent of three-dimensional integrated circuits if it is to successfully compete. This is the innovation required.

The challenges are then thermal and noise management, while also considering total mass and size. Heat must be effectively removed from the components and working fluid to maintain maximum efficiency throughout the operation period (an efficiency issue), and shielded from end users to prevent injury (an effectiveness issue). Excessive noise levels prevent the use of fluid-power components and devices in personal assistive devices or passenger vehicles due to the resulting discomfort of the user (an effectiveness issue). Add-on components or systems to mitigate these issues increase mass and volume of the system, hindering performance of mobile systems (a compactness issue).

Commercial heat sinks are limited by fabrication limitations and generally do not bear significant structural loads, resulting in dead weight. Topology optimization has been applied to profiles of extruded geometries to determine the optimal load-bearing and heat-dissipating structure, under active cooling, for gas turbine engines [18]. This optimization was simplified by axial symmetry and minimal degrees of freedom. Research has also been conducted for “open-cell” load-bearing lattices as heat sinks, for forced convection [9] and conductance [17]. This research will complement this prior work through multi-directional, geometry-dependent characterization of the selected unit-lattice structures for the definition of a load-bearing thermal-management structure of minimal required mass.

In addition to thermal management, cellular materials are also used for noise suppression. Polymeric foam is a ubiquitous example; however, this material, primarily, absorbs the energy through cyclical mechanical loading of the polymer. The low stiffness and conductivity also significantly limit their application for load bearing and heat dissipation, respectively. Carbon and metal foams are much stiffer and more thermally conductive than their polymer counterparts [20]; but, tailoring of their properties to meet a specific application is exceptionally difficult. An engineered lattice can be optimized to meet the structural, thermal and noise-suppression [2, 6] requirements, and fabricated via additive manufacturing methods. This also allows for the integration of other component geometries into the lattice structure, such as the outer case of a pump, motor, actuator, valve, etc.

The innovation proposed is then the coupling of the structure’s stiffness requirements for bearing loads, leveraging the structure-characterization work completed in Years 1-4, with the lattice-spacing requirements for filtering noise and effectively dissipating heat through natural convection, within a fully-integrated lattice structure. Figure 1 shows a conceptual sketch of such a lattice that integrates the mini-HCCI engine into the Test Bed 6 orthosis structure, while also dissipating the waste heat of combustion and providing noise suppression for the engine. This approach provides significant design advancements because three functions are integrated into a single structure. It must be noted, however, that in this coupled system, not all functions can be fully optimized: trade-offs are necessary.

Phase-change materials are already used in medical devices for managing thermal energy [16]; and, are also being considered for advanced latent-heat-energy storage systems in solar-heating units [11, 12]. They can be integrated into the thermal-management structures being developed here, as well.

Figure 1: (Left) Concept of the mini-HCCI engine with an integrated noise-filtering and heat-dissipating structure. The structure also bears mechanical loads, so it can be integrated into the structure of the Test Bed 6 PPAFO. (Center) Conceptual model of the integration into the PPAFO. (Right) Conceptual model of a belt-worn structure that contains the engine's temperature, while also protecting the wearer and reducing noise.

The primary barrier to the development of this technology is the lack of available software that can effectively couple the FEA data with design software, and export the final fabricatable design. The closest offering is the Scan & Solve® plugin for Rhinoceros®; but, it failed to process a small, simple lattice. Several proposals have been submitted over the last four years, to various organizations, to procure funding to develop such software, to no avail. Presently, we are working with four separate software packages to design, analyze, populate and process the geometries. This will all be combined and automated in future work, allowing for significantly more time to consider alternative designs. Two aerospace companies, outside the Center, have recently expressed interest in working with MSOE to realize this software.

Another barrier is the minimum feature size that can be fabricated. One millimeter is the current threshold for MSOE's hybrid fabrication process. This can be pushed to one-half millimeter by copper cladding a nylon lattice, but sacrifices strength.

B. Achievements

Achievements prior to February 2011

- ✓ Unit-lattice structural characterizations [3, 10]
- ✓ Software algorithms for automated structure generation [3, 19]
- ✓ Preliminary optimizations of fluid-power components [3, 10]
- ✓ Functionally-gradient metal-matrix composites
- ✓ Preliminary characterizations of lattice unit cells for acoustic attenuation – REU 2010 – "sonic crystals" vs. viscous damping vs. Helmholtz resonance [1]

Achievements this reporting period

Experimental comparative study

The first achievement since the last reporting period was the design and fabrication of an engineered structure that could maintain a contact temperature below the "pain threshold" (the target at the time) of 43°C for 25W of waste heat - the presumed amount to be generated by the mini-HCCI. As reported in the 2011 NSF Site Visit, and several conferences [4, 5, 13], the engineered structure performed better than an off-the-shelf cylindrical block of aluminum foam, and an equivalent-mass finned heat sink of the same copper-aluminum alloy (Moldstar 22®). The engineered structure was the only one to achieve the targeted surface temperature past 5W of waste heat, and remained below the pain threshold up to ~25W of waste heat.

Unit-lattice characterizations

Effective-conductivity characterizations were completed for three unit-lattice types, and their diameter-dependent relations were derived [5].

Internal natural convection
Investigations into the role of lattice-cell and structure-through-flow convective currents in the performance of the final lattice design were conducted for improved mass and size optimization of the lattice. Cellular convection provides little contribution when the structure is much more conductive than the fluid; but, when the cells are large enough, chimney-like flow can develop through the structure. Depending on the design goal, this may be promoted or blocked by structure-type selection and sizing.

Structure-generation scripting
Without support for our previously-proposed direct-structure-generation software, scripts were written for Rhinoceros® to generate structures semi-automatically using the three unit-lattice types, from manually-defined iso-surfaces. This is generally limited to extruded curves, at present (Figure 2).

Thermoelectric energy recovery
The 2011 REU participant, Toni Borel, conducted a preliminary investigation into the use of thermoelectric generators for recovering waste heat, comparing their efficiency, size and cost to that of micro-turbines. While the micro-turbines are several times more efficient, the commercially-available thermoelectric generators are significantly less expensive; and, new materials may allow them to outperform the micro-turbines. One potential application is to provide electrical power to UMN's MEMS pneumatic valve from the mini-HCCI's waste heat, improving system efficiency and reducing required battery capacity.

50W mini-HCCI thermal-management structure
The mini-HCCI is projected to generate 50W of waste heat, in close proximity to the orthosis wearer. A section of the structures shown in Figure 1 has been re-designed to safely dissipate this heat and maintain reasonable engine temperatures (Figure 2). The structure is quite large (~19cm wide) relative to the orthosis. Phase-change materials and forced-convection cooling are being considered as complementary means of maintaining lower temperatures; but, their added mass is likely prohibitive. Efficiency improvements in the power generation are critical.

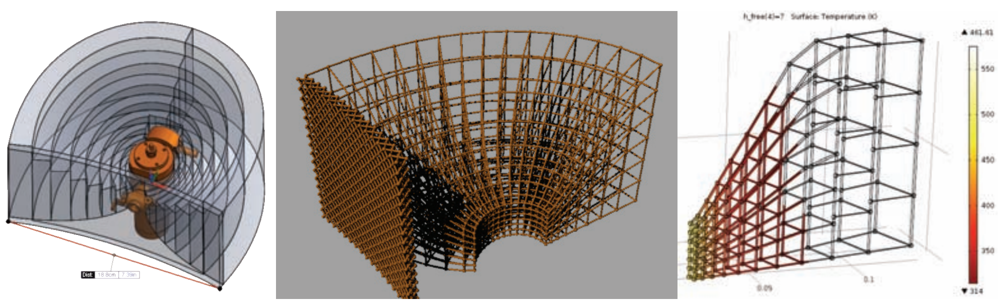

Figure 2: (Left) "Bulk" model of mini-HCCI thermal-management structure for preliminary sizing. (Center) Lattice representation of half of the bulk structure with the same layer-wise effective conductivities. (Right) FEA of structure section showing effect of 7W/(m^2*K) natural convection on the temperature profile.

Custom TB6 Actuator:
Using Test Bed 6's funding, MSOE had previously developed a custom pneumatic actuator and, over the last nine months, MSOE has once again been involved in its continued development. In May, 2011, MSOE requested the return of the actuator from UIUC, after a year of use rendered it inoperable. MSOE quickly re-seated the valves, and installed a newly-designed, lower-mass, silicone-over-molded nylon rotor, to make the actuator operational once again [http://www.youtube.com/watch?v=ucdiqBRUxLI]. To handle the torque requirements of the orthosis in operation, a stainless-steel rotor was then cast, and molded over with silicone. Concepts for higher torque production, closer to 75N-m, using 1MPa (~150psi) CO_2 tanks, have also been developed.

Expected milestones and deliverables

- ✓ Geometry-dependent effective-conductivity relations defined (October 31, 2011)
- Geometry-dependent structural-acoustic relations defined (October 31, 2011)
  - Project 2D was directed not to continue this effort in the middle of Year 5, due to a budget cut. Bongiorno has reported his preliminary REU efforts in this regard.
- Fabrication of nine pistons for fluid-borne testing (February 15, 2012)
  - Project 2D was directed not to continue this effort in the middle of Year 5, due to an excessive budget cut.
- Integrative TB6 structure for the mini-HCCI engine installed (February 28, 2012)
  - One structure has been fabricated in nylon and another design is nearly ready to be fabricated in nylon, clad with copper. There were delays in getting the mini-HCCI engine's specific target heat rates and operating temperatures to properly size the structure.
- Integrative TB6 structure performance testing complete (May 31, 2012)

Plans for the next 5 years

- Efforts to metal-plate additively-manufactured polymer structures, to simplify fabrication and reduce weight, have begun. This approach will be compared to the solid-metal designs.
- Energy-balance analyses will be conducted to determine the efficacy of forced-convection cooling of a structure, relative to natural convection, including consideration for mass and volume.
- This structure-design methodology will be modified to allow for the optimization of thermoelectric energy recovery. Valves and sensors, for example, can be powered with this recovered energy.
- Multifunctional structures will be developed for other, larger components & sub-systems, within the Center, and outside.
- Inclusion of, and optimization for, phase-change materials for superior thermal management, as well as the coupling with thermoelectric generators for controlled energy recovery.
- The PI proposed in this last round of funding to develop a high-efficiency pneumatic system for TB6, replacing the mini-HCCI engine and rotary actuator, that will demonstrate the potential for the approach to fluid power system design. Employing energy harvesting, as well as thermal energy storage, recovery and conversion, the system has a targeted efficiency of 60%. It is also expected to run for one hour on just 5g of butane. This system will also be applied to Test Bed 4, and other "walking" fluid-power machines outside the Center.
- As originally proposed, the structural-acoustic relations will be derived for the three unit lattices; and, noise-reducing structures will be integrated into the pistons of fluid-power pumps and motors.
- The direct-structure-generation software will be developed to expedite the design and evaluation of components and systems.

C. Member company benefits

As Herzog & Neveu of Rohmax found in their experiments with cartridge valves, the efficiency of fluid-power systems is dependent on the relative temperatures of the fluid and components to the reference temperature, ~35°C [8]. Inclusion of engineered structures and materials in the design of fluid-power components for thermal management can increase component efficiencies by more than 20% by passively maintaining temperatures, at or near the reference, throughout the entire system, not just at the add-in chillers, etc. Running at lower temperatures will also extend the longevity of the hydraulic fluid and fluid-power components, minimizing operating and maintenance costs.

Since heat generation can be mitigated through surface treatments, oil additives, etc., safety may be a more important aspect of thermal management than efficiency gains. As discussed in

Section 1, the FDA mandates a maximal contact temperature of 41°C for medical devices that humans are in contact with [16]. We have demonstrated experimentally that we can maintain a safe contact temperature for up to 25W of waste heat with our small structure; and, our analyses show that our larger structure can safely dissipate 50W. Any member companies interested in production of personal-assistive devices, rescue machines, etc. will benefit from this design methodology that has been developed.

Of course, the ultimate goal is multi-functional integrated design – reducing weight, while also passively managing heat and mitigating noise, through structure design. Achieving these meso-scale meta-materials will be of greatest value to the CCEFP member companies, particularly in their competition with electric-based alternatives. High-performance and/or multi-functional component design concepts will be shared with the Center, generally as intellectual property. The interested member companies can tailor the designs for their specific needs, either on their own, or through associated projects. Members having their own concepts may also work with Project 2D to develop them, through associated projects.

Parker Hannifin has gained insight resulting from the structural optimization of their pump, but their greater concern is noise reduction. Toward this end, quiet pistons, etc. using lattice structures will be investigated. These benefits, however, are not specific to Parker as they are shared confidentially with all members interested in the intellectual property.

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Project 2E: Model-Based Systems Engineering for Efficient Fluid Power

Research Team

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Industrial Partners:	Deere & Co., Phoenix Integration, NoMagic

1. Statement of Project Goals

The goal of the project is to significantly reduce the time and effort required to formulate and solve systems engineering problems for compact and efficient fluid-power systems. To achieve this, analysis knowledge about fluid-power components from multiple disciplinary perspectives and multiple levels of abstraction will be captured and organized in a modular, object-oriented knowledge repository using a standardized language (Systems Modeling Language, SysML) and synthesis knowledge about fluid-power systems will be captured in the form of model transformations. A systems engineering method and software framework will be developed in which the synthesis and analysis knowledge from the repository is used to explore efficiently and comprehensively large spaces of system architectures with the goal to improve the compactness and efficiency of fluid-power systems while balancing other system objectives such as effectiveness, cost, and reliability.

2. Project Role in Support of Strategic Plan

The project provides a method and software framework to support the comprehensive and efficient exploration of integrated system architectures. This will enable the integration of the fluid-power subsystem with structural subsystems (compact integration and distribution barrier) and enable the comparison between different system architectures for achieving desired system-level tradeoffs (system integration inefficiency barrier). The framework could also enable the evaluation of the impact of introducing new component technologies (component efficiency barrier) or higher pressures (high pressure operation barrier) on system-level performance.

3. Project Description

A. Description and explanation of research approach

<u>The Problem</u> With the advent of electronic control, fluid-power systems have become increasingly integrated and multi-disciplinary in nature and the number of potential system architectures has exploded. With new demands on compactness, efficiency, and effectiveness, system engineers need to explore new system architectures that provide adequate tradeoffs across these conflicting objectives. The main barrier that needs to be overcome is one of complexity: a very large amount and variety of knowledge is necessary to synthesize and analyze promising system architectures. Unless this knowledge is managed well, the cost of acquiring, validating and applying this knowledge will limit significantly our ability to increase the functionality and performance of future fluid-power systems. To overcome this barrier, a systems engineering framework is required consisting of model repositories, algorithms for instantiating and linking these models, and algorithms for selecting appropriate models at each step of the design process.

The corresponding research question is: How should one represent, store, retrieve and use knowledge efficiently and effectively in support of the design of fluid power systems?

<u>Past Work</u> The need for a systems engineering framework for fluid-power systems has been recognized before with initial work by Krus et al. [1, 16-18] at Linköping University, Tilley et al. [4, 5, 8, 10, 24, 25, 29] at the University of Bath, and da Silva et al. [6, 7] at the Federal University of Santa Catarina (Brazil), with more recent work by Pedersen [23] at Aalborg University and Schlemmer et al. [27, 28] at the Technical University of Aachen. In this related work, the focus has been on traditional optimization approaches with a model of the objective at a single level of abstraction, sampled by the optimizer as a black box model, implemented in an imperative (rather than declarative) programming language. In addition, the work has focused almost exclusively on the modeling of the fluid power aspects of the system with only a few efforts allowing for seamless integration with other disciplines (e.g., structural mechanical, thermal, electrical, controls). Finally,

the past work either focused on optimization of the sizing parameters of a specific architecture, or used expert systems to guide the selection of a feasible architecture. The efficient exploration and optimization of system architectures has not been addressed.

A new approach In this project, the approach for realizing a systems engineering framework for fluid-power systems is based on the formal, declarative representation of knowledge. By capturing the knowledge formally, it can be more easily reused, allowing the cost of capturing and modeling the knowledge to be amortized over many re-uses. In addition, by representing the models in a declarative form (i.e., an implementation-independent formalization of the mathematical relationships), the models can be transformed, combined, and symbolically manipulated to create and solve system-level models that are larger and more comprehensive than could be practically achieved otherwise.

The systems engineering framework being developed is illustrated in Figure 1. It consists of three layers that can be considered separately or in an integrated fashion: The top layer addresses the generation and topological analysis of different fluid-power circuit configurations, the second layer sizes the components within a given circuit configuration based on algebraic models, and the third layer optimizes the components (under uncertainty) based on detailed dynamic simulations. Such a layered approach allows one to use resources efficiently by only performing more detailed analyses if the performance predictions obtained in a previous layer are sufficiently promising. The framework relies on formal representations in the Systems Modeling Language (OMG SysML™) to represent the problem definition, the libraries of fluid power components, and the analysis models that characterize these components from different perspectives and at different levels of abstraction (both as algebraic and as differential-algebraic models). By capturing this information and knowledge formally, it can be transformed in an automated fashion using model transformations.

B. Achievements

In the past year, research has focused on the top two layers of the framework in Figure 1 — that

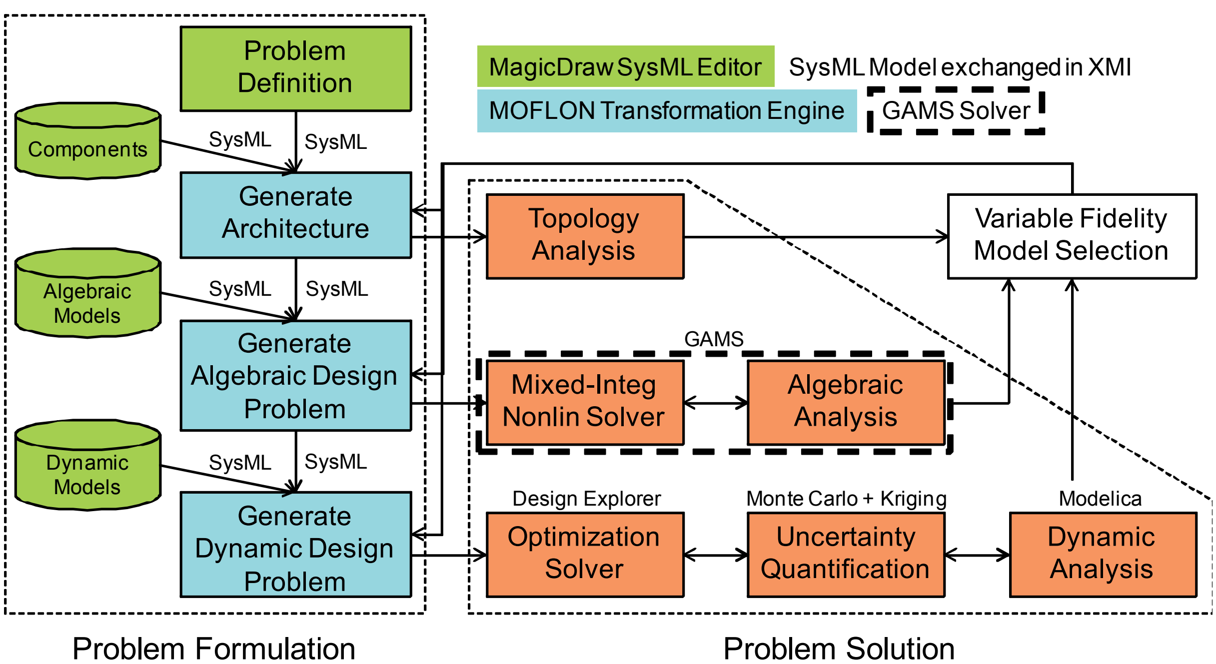

Figure 1: An overview of the proposed three-layer systems engineering framework

is a combined focus on system architecture exploration with initial (approximate) component sizing. By combining these two levels, the most promising system architectures can be identified which will then be further analyzed and optimized in two subsequent steps: detailed component sizing through the use of Mixed Integer Non-Linear programming, and robust optimization including dynamic and uncertainty considerations. In addition, a variable fidelity optimization algorithm has been developed which allows the combining of models at different levels of fidelity and different levels of accuracy to solve global optimization problems efficiently. The algorithm is called Value-Based Global Optimization (VGO).

<u>Synthesis of System Architectures</u>*:* From the components available in the model repository, a very large number of different circuit topologies can be configured. To design a good hydraulic system, algorithms that explore this very large space of system architectures efficiently need to be developed. Three different approaches have been investigated: design grammars [15], Markov Logic Networks (MLN) [26], and Mathematical Programming [30]. The goal was to determine which of these three approaches best unites optimization efficiency with the ease of expressing the domain knowledge. Through analysis and experimentation with the three approaches, it was concluded that Mathematical Programming is the best approach — it provides the best trade-off between the ease of expressing the domain knowledge (in repositories of linearized component models), and exploring the design space efficiently. The approach consists of three parts: 1) the design problem is defined in a formal model in the SysML language; 2) the SysML model is transformed into a corresponding Mixed Integer (Linear) Programming (MIP) problem; 3) the MIP problem is solved using the CPLEX solver in the AIMMS tool.

In the first step, the system design problem is defined in SysML. This includes in a first instance a definition of the space of alternatives: Which (generic) components can be used? How many of each component can be used? How can the components be connected to each other? Second, we model the individual requirements, such as force and velocity requirements in each operational phase, but also the overall value model which expresses who low-level attributes are rolled up into a top-level value objective.

In the second step, a model transformation algorithm combines the problem definition with the domain-specific models for the individual components into a MIP. This is the most significant intellectual contribution of the project. In this transformation, both the knowledge of MIP problems and of the fluid power domain are included to encode as effectively as possible, the domain knowledge into (piece-wise) linear constraints. This is non-trivial because the same problem can be encoded in many different ways and depending on the encoding, the solution time can vary by several orders of magnitude. To make the problem solve efficiently, we have judiciously taken advantage of the special constructs existing in state-of-the-art MIP solvers (such as CPLEX). For instance, Special Ordered Sets (SOS2) are used in a λ-formulation [2] to linearize the non-linear characteristics of hydraulic pumps.

In the final step of our approach, the MIP problem is solved using the IBM CPLEX solver available in the Mathematical Programming tool called AIMMS [3]. Such Mathematical Programming solvers efficiently explore the entire space of alternatives by analyzing and taking advantage of the mathematical structure of the problem, by branching and bounding or reducing the discrete search tree, and by repeatedly and efficiently solving very large linear programming sub-problems.

In an example problem for the design of the hydraulic circuit for an excavator, the space of system architectures included approximately 10^{12} configurations, the objectives and requirements were transformed into 7147 constraints on 2175 variables. The guaranteed global optimum for this problem was identified by the CPLEX solver in about 12 hours on an Intel i7 2.8GHz processor. Note that the global optimum of the mathematical problem does not necessarily correspond to the globally optimum design alternative, but even considering the linearization approximations, the MIP approach will determine the most promising system architectures which can then be analyzed in more detail using the additional layers in the framework in Figure 1.

Detailed sizing optimization under uncertainty: The result of solving layers 1 and 2 in Figure 1 is a promising architecture with reasonable component sizes. To refine the solution further, a more detailed (and hence more costly) analysis is required. Similar to the model transformation approach used to generate algebraic models, a model transformation approach is used to generate system level dynamic models. This is possible thanks to the port-based, object-oriented nature of the Modelica language [9]. A Modelica library for fluid-power systems has been developed [22] and a mapping from SysML to Modelica to enable the automated generation of system-level models [11, 12]. The computational cost of such dynamic simulations can be significant, especially when combined with uncertainty quantification. Therefore, an algorithm was developed that uses a value-of-information metric to decide which analyses to perform at each step in the optimization/design process. The algorithm is called Value-Based Global Optimization (VGO).

The approach is based on approximating Gaussian process (kriging) models combined with incremental search-space sampling based on a value of information metric. To incorporate models at multiple levels of fidelity, and hence improve the speed/cost of optimization [19, 20], we have extended the kriging modeling approach [21]. Traditional kriging models are interpolation methods. To support multi-fidelity modeling, the kriging method has been adapted to allow for fitting (rather than interpolating) an approximate model based on samples with only limited accuracy and for which the accuracy may vary from one sample site to the next. In the algorithm, the surrogate model for the objective function has the following structure: $y = F^T\beta + \varepsilon + \varepsilon_m$, where $F^T\beta$ is a regression model, ε is the difference between the true objective and the regression model, and ε_m is the error between the true objective and a prediction from one of the (multiple accuracy) simulation models. As compared to traditional kriging modeling, it is the addition of the ε_m term that allows for multi-fidelity fitting. Both ε and ε_m are represented by Gaussian processes. They are assumed to have a static correlation structure that reflects that the errors, ε_m, if originating from different simulation models, are uncorrelated with each other and are also uncorrelated with the regression error, ε. The VGO approach is different from the seminal work by Kennedy and O'Hagan [14] in that this correlation structure simplifies the maximum least-squares estimation and does not impose the constraint that high-fidelity models can only be sampled at points where low-fidelity models have already been sampled. An implementation of this algorithm has been developed in Matlab (see Figure 2) and its performance was compared to the previous state-of-the-art, namely, the EGO algorithm (Efficient Global Optimization) [13]. The computational experiments show that for a suite of randomly generated global optimization problems, the VGO algorithm finds a solution of the same quality as EGO with a reduction in computation cost of 78%. This is due to the fact that VGO can perform a broad exploration of the optimization space using an inexpensive low-fidelity model, and only use a costly high-fidelity model in the most promising areas near local optima and ultimately near the global optimum.

Next Steps

Both components of the project (architecture exploration and variable-fidelity optimization) have reached significant milestones – the algorithms developed by the students, Alek Kerzhner and Roxanne Moore, have been implemented, tested, and compared to competing approaches. Both students are therefore in the final phases of their research and will be defending their PhD theses in April. We have therefore decided that this is a good point to end this project and there will be no continuation project in Year 6.

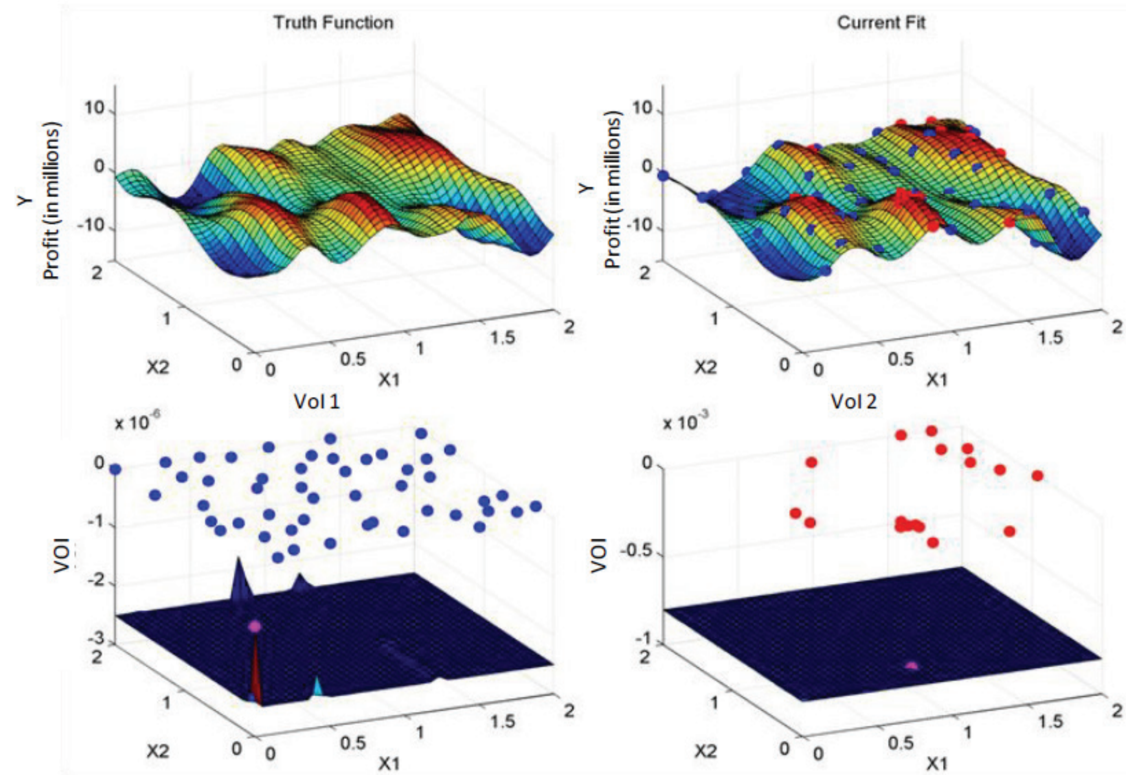

Figure 2: A step in the Value-Based Global Optimization (VGO) algorithm. The true objective function (left top) is in each optimization step approximated using a kriging model (top right). Based on the uncertainty in the kriging predictions, the most valuable sample is determined for either a low-fidelity (bottom left) or high-fidelity (bottom right) model. You can see that the Value-of-Information metric leads to a broad exploration of the design space using the low-fidelity model, combined with local refinement in the most promising areas using the high fidelity model.

C. Member company benefits

The proposed systems engineering framework will improve the ability of member companies to explore different system architectures when integrating fluid-power sub-systems into large systems engineering efforts. By formally and unambiguously capturing the system semantics in SysML, the approach provides all the benefits of a Model-Based System-Engineering approach including requirements management, traceability, functional decomposition, behavioral modeling at multiple levels of abstraction, and management of testing and validation.

D. References

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Project 2F: MEMS Proportional Pneumatic Valve

Research Team

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Graduate Student: Nebiyu Fikru
Industrial Partners: Enfield Technologies, Parker Hannifin Corporation and Bimba Manufacturing

1. Statement of Project Goals

The goal of this project is to create an efficient miniature proportional valve for controlling air flow in pneumatic systems based on Micro-Electrical Mechanical Systems (MEMS) technology. The valve is intended to operate at pressures up to 7 bar (700 kPa / 100 psi) with a flow rate of at least 25 slpm when operated at a pressure of 6 bar venting to 5 bar in the fully open state. Actuation efficiency is equally important to fluidic efficiency and the goal is to be able to hold a normally closed valve in the fully open state with an actuation power of 5 milliwatts. The target envelope of the valve is 4 cm^3.

Microvalves currently available in the marketplace can only deliver flow on the scale of milliliters per minute. The new valve will be able to provide macro scale flow while maintaining compactness, efficiency and low leakage. This will be achieved by a unique parallel architecture. The hardware design will be supported by models that can correctly predict the actuator behavior and fluid flow phenomena.

2. Project Role in Support of Strategic Plan

This project has breakthrough potential for the Center's mission of creating efficient components. The project's goal of 5 milliwatts of actuation power represents a three order of magnitude improvement over most commercially available pneumatic valves. The project also contributes to the mission of creating compact integrated systems, as another goal is to create the smallest valve available with the specified flow rate. Furthermore, the project will push the boundaries of reducing leakage through MEMS-type valves. Overcoming these barriers is helpful to advancing the feasibility of the Ankle-Foot Orthosis in Test Bed 6, as well as opening many other new potential applications for pneumatic systems.

3. Project Description

A. Description and explanation of research approach

The concept of the MEMS proportional valve is introduced by reference to a visualization of the potential valve architecture, as shown in Figure 1. The valve is a one way normally closed proportional valve. The foundation of the valve is a port plate. The port plate includes a matrix of through holes or orifices. The plate is placed in line with a pneumatic tube or channel. The air or other pneumatic working fluid flows freely through all holes in the fully open state. The fully open pressure drop is equal to the resistance through all the holes in parallel.

Each through-hole is equipped with a pallet valve. Figure 1 shows each valve cantilevered off of a simple straight arm, although alternative embodiments are also possible. The arms serve as actuators: the pallets are opened and closed by bending the arms. Bending is achieved by varying the strain in the material which constitutes the arms. An elastomeric material is deposited around the orifices to act as a valve seat and reduce leakage.

The flow capacity of a valve is determined by its effective orifice size. Therefore, MEMS based valves with macro flow capacity must have effective orifice sizes which are equivalent to non-MEMS based valves. For example, Enfield's LS-V05s (Table 1), currently used in TB6, has a maximum aperture area of 5 mm^2.

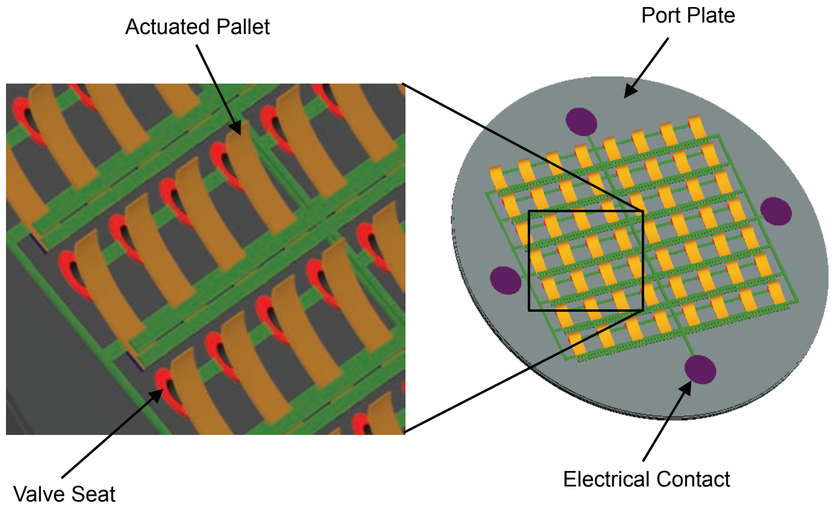


Figure 1: Visualization of a MEMS proportional pneumatic valve

Unfortunately, microactuators cannot overcome the force imposed by pneumatic fluid passing through a single orifice of this size. However, dividing a single orifice into hundreds or thousands of parallel orifices enables decreasing the force on each actuator, so the actuator size can be reduced to the MEMS scale. The resulting valve is compact and lightweight. Exploiting MEMS batch fabrication methods also enables the valve to be fabricated at low cost.

The pallet actuators are connected in parallel and common electrical contact nodes are used to supply electric current to power them. Proportional control of the flow can be obtained in either of two forms using the architecture suggested in Figure 1. First, all pallets can be partially opened by the same amount simultaneously. Second, a variable fraction of the valves can be fully opened. The second option requires wiring banks of actuators independently.

The state-of-the-art in miniature pneumatic valves is summarized in Tables 1 and 2. Table 1 reviews non-MEMS-based miniature valves. None of these valves approaches the power consumption nor size of the proposed valve. Table 2 reviews MEMS based valves. Note that the flow rate capacities of the MEMS based valves proposed to date are two orders of magnitude smaller than the conventional valves. The maximum operating pressure is also typically much lower for the MEMS based valves.

Only one valve in the literature shares some features of the valve proposed here [1]. That valve also utilizes an array of cantilevered actuators which are deformed using a single layer of PZT. However, the actuators do not act as pallets sealing against a port plate. Rather, the cantilevers protrude into rectangular slots in the port plate from opposite sides of the slots so that the tips of

Manufacturer	Model	Volume Envelope (cm^3)	Maximum Inlet Pressure (bar)	Flow Rate (slpm) for 6 bar venting to 5 bar	Power Consumption (W)
Enfield Technologies	LS-V05s	71	10	125	3.6
Clippard	EVP Series (0.04” dia)	26.4	3.45	20.4	2.3
Parker-Hannifin	HF Pro	28.4	3.45	35	2
IQ Valves	Standard PFCV	395	9.3	280	6

Reference	Volume Envelope (cm^3)	Maximum Inlet Pressure (bar)	Flow Rate (lpm)	Power Consumption (W)
Chakraborty et al. [2]	1	1.79	0.9	
Fazal and Elwenspoek [3]	1.4	4	0.25	< 1
Pourahmadi et al. [4]	1	1.03	0.5	1.1
Lisec et al. [5]	1	1	0.7	1
Kim et al. [1]	< 1	0.01	$0.12x10^{-3}$	< 1

Table 2: Flow rate capacities of MEMS based valves

the undeformed cantilevers almost touch, blocking most of the flow area of the slot. Deflection of the cantilevers causes the gap between their tips to increase, which is used as the flow regulating mechanism. This architecture leads to significant leakage and limits the valve to low pressure applications.

No MEMS based valve is available to replace traditional general purpose non-MEMS based valves. Almost all MEMS based valves have been designed for a specific micro-scale application such as lab-on-a-chip systems [6], drug delivery [7], refrigeration [8], or micropropulsion [9].

B. Achievements

Accomplishments since January 2011 include publishing a literature review paper, selecting an actuation strategy, establishing analytical models, constructing a concept demonstration prototype, constructing and commissioning an ISO compatible test stand, testing the parallel orifice concept, designing a learning prototype MEMS valve, and initiating the design of the first prototype fully featured MEMS valve. These accomplishments are described in order below.

An extensive literature review paper on MEMS pneumatic valves was presented at the 2011 National Conference on Fluid Power [10]. An actuation strategy for the new MEMS valve was selected based on this paper. All possible actuation strategies were considered, including piezoelectric, thermomechanical, electrostatic, electromagnetic, and a variety of exotic schemes. The piezoelectric and electrostatic strategies appear superior to the alternatives based on efficiency and speed of response. Of these two possibilities, piezoelectric offers an advantage by way of force capacity at the scale of the MEMS valve. In particular, Lead-Zirconate-Titanate (PZT) outperforms most alternative piezoelectric materials by a factor of 20 or more, so PZT has been selected as the material of choice for the actuators.

Basic static deflection and force models have been established for the actuator. In addition, a continuum fluid model for compressible flow has been adapted to estimate flow rate capacity of the valve. While all models to date are simple, they are adequate for rough sizing the MEMS valve geometry.

A “meso-scale” concept demonstration prototype valve has been designed and fabricated and is currently under test (See Figure 2). The foundation of this valve is a single 35 mm x 13 mm x 3 mm piezoelectric bender, fabricated from PZT, that can be purchased commercially. While the prototype is much larger than the intended MEMS-scale device, the working principle of the valve is the same as the final MEMS valve. Its large size enabled fabrication using conventional machining rather than specialized MEMS processing, thereby making it available on a short time scale. Early testing revealed that the valve is capable of controlling a flow of 14.5 slpm for a pressure drop of 6 to 5 bar, which is 58% of the goal for the final MEMS valve. The actuator required under 1 milliwatt of power to cycle it, revealing the breakthrough energy savings that may be possible with a MEMS scale PZT-based device. The power specification for the final valve was reduced from 1 watt to 5 milliwatts, a three order of magnitude reduction, as a result. A position sensor on the meso-scale device is being installed so that the flow rate can be determined as a function of position to better understand the valve's flow properties.

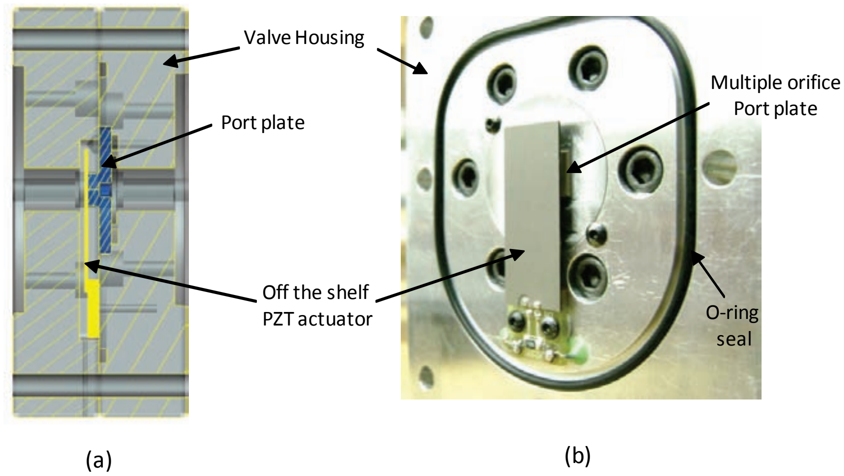


Figure 2: Meso-scale prototype (a) Solid model and (b) Fabricated valve

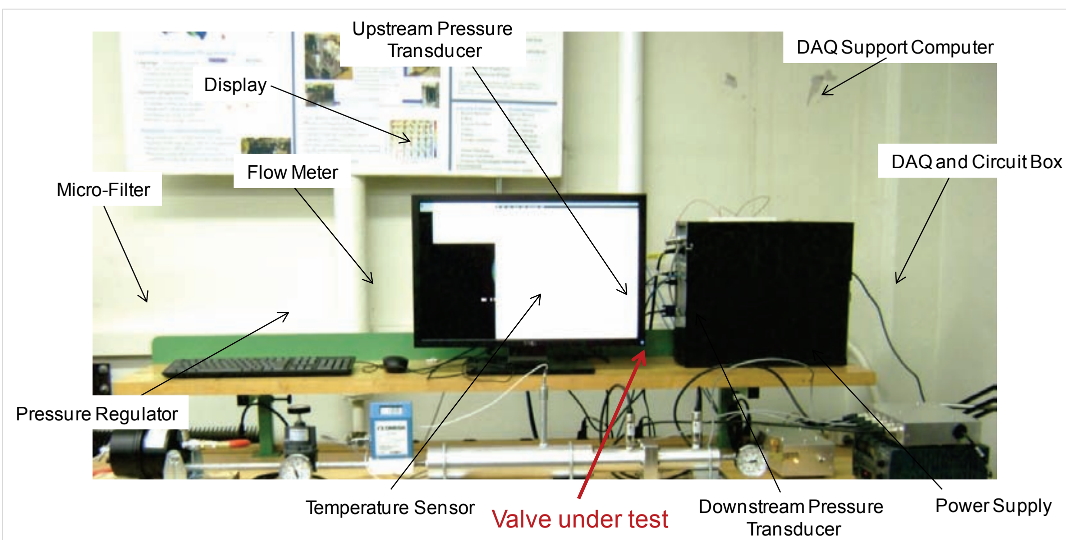
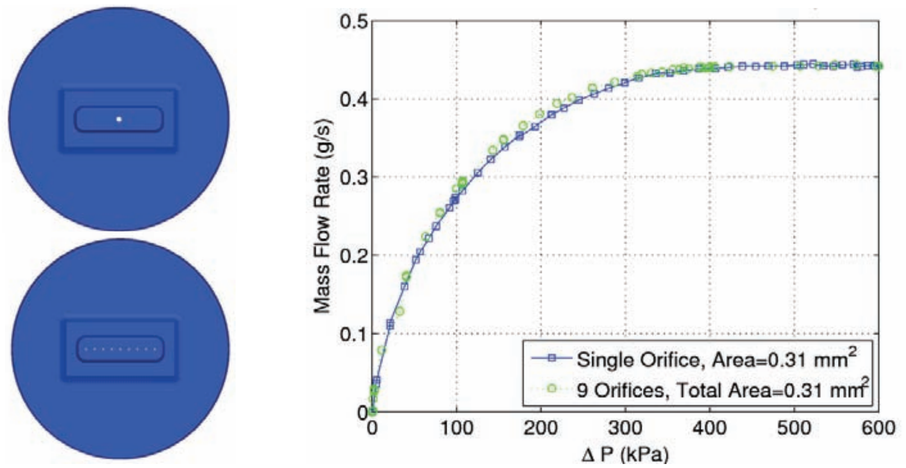


Figure 3: Test Stand for meso- and MEMS-scale valves

A test stand for evaluating the performance of both the meso-scale and MEMS scale valves has been designed, constructed and commissioned (see Figure 3). The stand conforms to international standard ISO 6358 [11]. It is equipped with a state-of-the-art data acquisition system.

A question arose in project reviews as to whether replacing a single orifice with multiple smaller orifices would lead to increased pressure drop. To address this concern, two port plates were fabricated. One has single orifice of diameter 635 μm and the other has 9 orifices of 210 μm diameter. The effective orifice area of the two port plates is equal (see Figure 4(a)). The test stand illustrated in Figure 3 was utilized to compare the flow characteristics of the two port plates. The results demonstrate that the flow behavior of the two valves is nearly identical (see. Figure 4(b)). Choked flow occurs for both port plates at a downstream to upstream pressure ratio of 0.48.

Originally, the plan was to fabricate the MEMS valves entirely at the University of Minnesota's Nanofabrication Center, but PZT cannot be processed at that facility. In addition, the team has been unable to locate a domestic company capable of fabricating PZT on a MEMS device. Fortunately, the Pennsylvania State University's Nanofabrication Lab can perform the MEMS device fabrication steps which involve processing PZT and the MEMS valves will be fabricated by PSU under a sub-contract.



(a) (b)

Figure 4. (a) Port plates and (b) Mass flow rate Vs Pressure drop of the two port plates

Due to the challenging nature of fabricating the MEMS valves, the fabrication of the first valve is being done in two steps. First, simple actuators will be fabricated apart from complete valves. The actuators will include a single layer of PZT on a passive substrate. This device is called the "unimorph actuator". Successful fabrication of the PZT will be validated by measuring deflection of the actuators. Once successful actuator fabrication is confirmed, the first full featured MEMS valve will be fabricated, which utilize two layers of PZT. At present, the fabrication of the unimorph actuator is roughly half completed and a draft design for the full featured valve is complete.

Plans for the next year include: completing the testing of the meso-scale valve, completing the fabrication and testing of the unimorph actuator, fabricating and packaging the final MEMS valve, demonstrating the MEMS valve operating as a proportional valve, integrating the final MEMS valve with the TB6 Ankle-Foot Orthosis, and developing improved sealing strategies for the next generation MEMS valve. Longer term goals consist of developing improved flow models of the MEMS valves and exploring the effect of contaminants in the fluid stream on the valve.

Revised Major Milestones:

- Unimorph actuator completed – March 2012
- Meso-scale valve tested – April 2012
- MEMS valve fabricated and packaged – June 2012
- Proportional controller demonstrated - July 2012
- First MEMS valve integrated into TB6 – August 2012
- Improved sealing strategies developed – May 2013

C. Member company benefits

CCEFP member companies can benefit from this research in three ways. First, the valve constitutes a new concept for constructing miniature pneumatic valves with significant market potential. Second, developing the valve provides an opportunity for member companies to become familiar with MEMS fabrication techniques, which are likely to play a growing role in valve manufacturing technology. Third, new modeling strategies will be developed which are applicable to micro-level flow devices.

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Project 2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems

Research Team

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	Colin Andrew, Sana Ali, Brandon Witt, Georgia Tech
High School Teachers (RETs):	Gabe Sterling, Sean Donnelly, Vanderbilt
Industrial Partner:	Martin Companies, Charlie Martin, CEO

1. Statement of Project Goals

The research goal is to extend fundamental understanding of the unique characteristics of fluid power that enable precise machines to withstand intense magnetic fields. Toward this end, the project will develop compact systems where cylinders, valves, and sensors are no longer independent entities assembled together, but are a single integrated system that can be manufactured simultaneously. Magnetic Resonance Imaging (MRI) compatible devices are the perfect focusing application for this research. In surgery MRI provides exquisite soft tissue resolution, but robots are required to effectively make intraoperative use of this information. In rehabilitation, functional MRI (fMRI) offers the unique ability to visualize brain activity during therapy. Fluid power is an essential enabler in both contexts, because traditional electromagnetic actuators fail (or cause artifacts in) intense magnetic fields. This research will open an entirely new industry to fluid power: Medicine (~1/6 of the Gross Domestic Product of the USA).

2. Project Role in Support of Strategic Plan

We aim to break the Major Technical Barriers relating to 1) Compact integrated systems (by designing systems where valves, cylinders, and sensors are not separate entities), and 2) making fluid-power systems safe and easy to use (new force sensors will ensure human safety when interacting with machines in an MRI). Furthermore, we will break a Transformational Barrier by applying fluid power in medicine. This precisely aligns with the CCEFP vision "of transforming and fully exploiting fluid power into a compact, efficient and effective source of energy transmission." Full exploitation requires new directions within the center, and fluidic energy transmission is the only effective way of transmitting energy during imaging in an MRI.

3. Project Description

A. Description and explanation of research approach

Toward achieving necessary compactness, the project determines fundamental engineering principles whereby compact fluid power systems can be manufactured as integrated devices rather than a collection of assembled components, which can lead to compactness and performance advantages compared to traditional assemblies. The project explores control of MRI compatible pneumatic systems; line dynamics and the nonlinearities intrinsic to pneumatic control make this an interesting theoretical problem.

Intraoperative image guidance, and particularly use of MRI images which have far better soft tissue imaging capability than other modalities, has the potential to fundamentally change the fact that the success of any modern surgery relies entirely on the experience, memory, spatial reasoning, judgment, and hand-eye coordination of the surgeon. To break this barrier and move surgical accuracy beyond the limits of human skill and perception, what is needed is real-time image feedback during surgery, combined with precise machines able to accomplish the surgeon's objectives accurately. Such feedback can 1) enable the surgeon to visualize the position of instruments in relation to sensitive subsurface blood vessels, nerves, tumors, etc., before incisions are made, and 2) enable the robot to directly position a tool at a desired target specified in a medical image. Both of these capabilities have the potential to make surgery safer and to improve clinical outcomes by enhancing the accuracy of treatment delivery. MRI is a key enabler of this due to its unique ability to clearly show soft-tissue boundaries and structures which are not visible in other imaging modalities. This makes fluid power essential – it is the only viable technology that can transfer energy to actuate machines without the adverse interference effects associated with by the intense magnetic fields required by MRI or interfering with the imaging itself. MRI is also safer than other imaging modalities like CT, which use ionizing radiation.

Magnetic resonance imaging is one of the most useful methods available to study neuromotor functions, evaluate rehabilitation therapies, and perform image-guided interventions and surgeries. Functional MRI (fMRI) is a new technique that can observe brain activity by measuring blood flow in a certain area. Research on brain-hand coordination in fMRI is an emerging area. Actuation and sensing technologies that can be used in MRI/fMRI would provide a wide variety of applications and research opportunities such as studies on neuroplasticity after stroke, somatosensory and motor functions, and sympathetic nerve activity during motor task learning. The study requires non-magnetic, compact, low-noise, highly accurate haptic interfaces with pneumatic actuators. The strong limitation in the selection of materials requires methodologies to design, develop, and analyze mechanical systems that can be used in fMRI. To achieve accurate sensing in fMRI, we have developed a new design method based the distribution of strain energy [1, 2] that mitigates the hysteresis in the structure and improves the signal-to-noise ratio of sensing. The team has investigated the pneumatic line dynamics and delay.

In summary, the research groups at Vanderbilt, Georgia Tech, and MSOE are working collaboratively to build a hardware and software “library” of MRI compatible fluid-powered sensors, actuators, and control methods, applying them to image-guided surgery and rehabilitation, sharing information about novel sensors and actuators, and jointly developing control methodologies.

B. Achievements

<u>MRI-compatible Actuators and Surgical Robots</u>

<u>Identification of Specific High-Impact Surgical Application/System Concept</u>: This year epilepsy treatment was identified as the specific initial clinical application of the system. The minimally invasive robot will provide a potentially curative treatment for the large number of epilepsy patients (50 million worldwide) [4]. Currently, medicinal treatment is ineffective for 15-40% of epileptic patients [4] and the only option is open brain surgery to remove the hippocampus, a structure deep in the brain where seizures originate. To achieve the same treatment effect without surgery, we plan a needle-based approach to deliver thermal therapy using an interstitial acoustic ablation probe. To deliver this therapy accurately, reproducibly, and efficiently, real time imaging and robotic assistance will be used to achieve precise, conformal ablation (see Figure 1). The position of the ablation probe tip is spatially controllable via a robotic steerable cannula; electronically controllable because the ablation probe contains an array of piezoelectric elements that permit both radial and axial control of ultrasonic, and hence thermal energy deposition. Real-time image feedback is provided by MRI images, enabling precise targeting of the desired structure, and image-based thermometry for real-time thermal therapy monitoring during intervention.

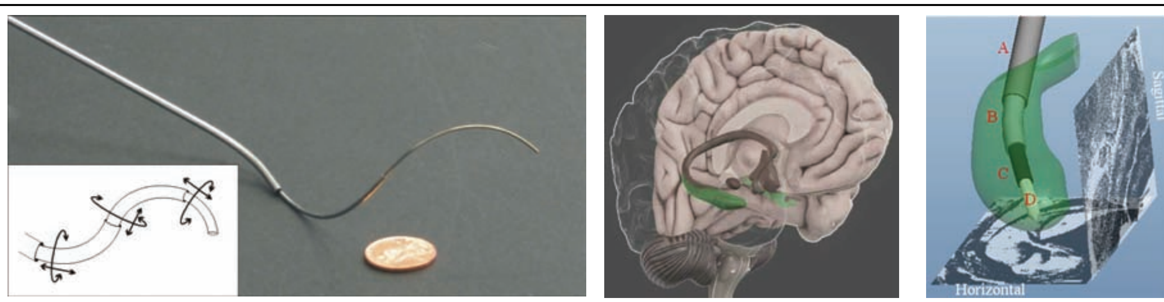


Figure 1: (Left) A concentric tube steerable needle. This device is controlled by translation and rotation of component tubes at their respective bases as shown in the inset line drawing.
(Center) A picture of the brain showing the hippocampus (green structure near the center of the head).
(Right) Illustration of the ablator tip positioned in the hippocampus, with two projection MRI image views.

Fabrication of MRI Compatible Robot Prototypes: Several prototypes of MRI compatible robots were constructed and tested this year. The robot shown in Figure 2 is capable of controlling 6 degrees of freedom (the axial translations and rotations of three tubes in a concentric tube robot), and is completely pneumatically controlled feedback from both optical encoders and pressure sensors. As shown in the figure, a modular concept has been pursued so that additional tubes can be added if desired. Rod locks were included for safety. General design objectives were small size with minimum friction to improve control precision. Each steerable cannula tube is translated via an acrylic plate supported by two plain linear bearings. Two carbon fiber guide rods support all three sliding plates. Each of the two curved elastic tubes rotates via one pneumatic actuator and transmission mounted to its respective acrylic plate. The reciprocating motion of the piston-cylinder is converted to rotation using a timing belt and pulleys. Images of a standard Alzheimer's Disease Neuroimaging Initiative (ADNI) phantom with the robot in the MRI scanner were collected and sent to Raforninn, Inc. for analysis. They exhibited zero geometric image distortion (result within scanner calibration limits). MRI compatibility was tested by placing the robot in a MRI scanner during imaging. No image quality degradation was apparent, and no robot components were heated excessively.

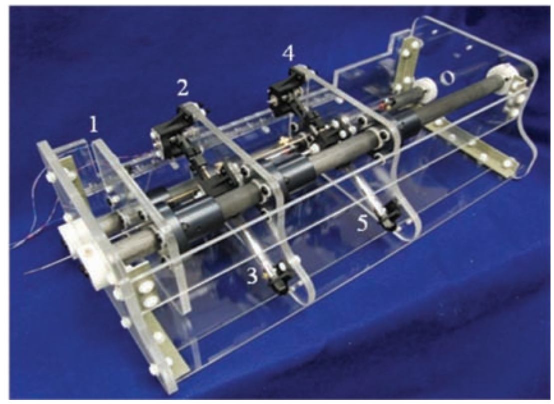


Figure 2: Modular pneumatic robot prototype able to control three tubes to deliver the steerable needle into the human brain in the MRI.scanner. Five Degrees-of-freedom are shown with 1, 2, and 4 being translational and 3 and 5 being rotational.

Nonlinear Control Results: A high precision nonlinear controller for the pneumatic actuators has been developed [5]. Experimental results show a steady-state error with mean 0.018 mm and max 0.028 mm, with max overshoot of 0.371 mm. The controller for each actuator requires one 4-way spool valve, two pressure sensors, and one optical encoder. The pressure sensors and valves are located 3 meters away in a Faraday Cage to eliminate any measureable image effects, and are connected to the robot only through plastic air lines. In recent experiments since publication of [5], we achieved a maximum error of 0.005mm (encoder resolution).

Initial Image Guidance Results: To begin to solve the problem of aligning the robot's coordinate system with the imager's coordinate system (the "registration problem"), initial in-scanner targeting experiments using a 6 DOF piezoelectric robot in collaboration with Greg Fischer's group at Worcester Polytechnic Institute were pursued. The MRI compatibility of the robot was evaluated in a 3 Tesla MRI using standard prostate imaging sequences with an average signal to noise ratio loss of less than 2% during actuator motion. The accuracy of the active cannula tip position was evaluated first in benchtop trials using an external optical tracking system with RMS error of 1.00mm. Three phantom insertions in an MRI scanner showed that cannula trajectories that agreed with kinematic models with RMS tip error of 0.61-2.24 mm. These accuracies are promising, but additional experiments are needed to establish statistical significance. These image guidance results are accepted for publication in [6].

fMRI-compatible Sensors and Haptic Device

Non-magnetic haptic interface: Figure 3 shows an overview of a 1-DOF haptic interface. A pneumatic cylinder produces bidirectional movement of an end-effector that interfaces with a subject in MRI. The pneumatic actuator is remotely controlled by pressure valves located in a control room. A force sensor is attached to one end of the handle that measures the force produced by the device. A rotary encoder, attached to the device through a pulley, measures the linear displacement of the pneumatic cylinder. The main research aim is to develop MRI-compatible sensors for this interface and understand the characteristics of the integrated system under closed feedback control through long pneumatic lines. The assembled haptic interface will be used in an

MRI gantry (e.g., the Siemens MAGNETOM Trio 3T at the GT/GSU Center for Advanced Brain Imaging that proves a space of 142 cm (length) x 60 cm (diameter) for a subject to lie down in the space). The displacement sensor utilized in this project is an assembly of a rotary encoder and a plastic wheel that follows the relative displacement of the surface in contact. Since the displacement sensor does not have to be close to the area of imaging, commercial rotary encoders could be used. The resolution of current displacement sensor is 0.028 mm which can be increased by adding a gear box between the wheel and the encoder if necessary.

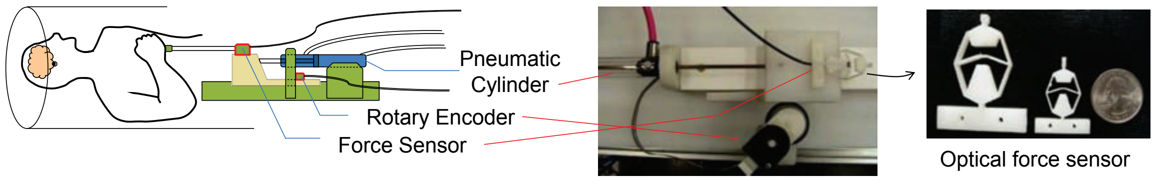


Figure 3: Pneumatically driven MRI-Compatible Haptic Interface [3]

The goal is to build a fully MRI compatible sensor that is compact and highly accurate for a fluid-powered haptic interface. Fiber optic extrinsic sensor technologies are considered to be suitable for this project. Among different fiber optic sensing methods, reflective sensing by light intensity measurement is implemented. Although that type of sensing involves sub-millimeter assembly procedures it is highly sensitive. The sensing principle shown in Figure 4 is adopted. To use the same fiber as the source and the receiver, and to eliminate the instability in the light source, a 2x2 coupler is used in the circuitry. This design reduces the number of fibers attached to the device and facilitates the cable management in the MRI room. A numerical approach for fiber to mirror light transmittance has been initiated.

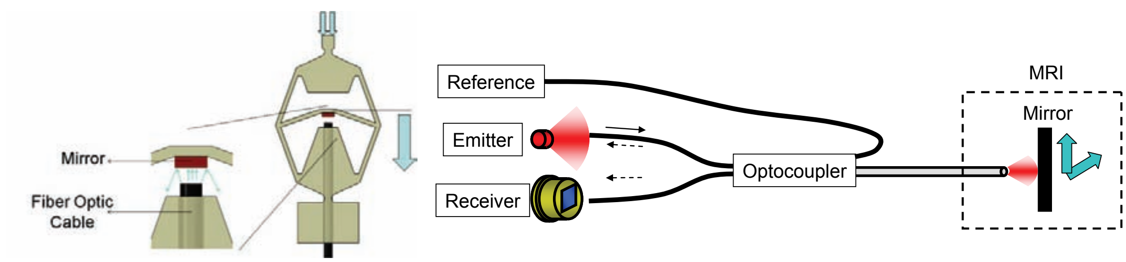
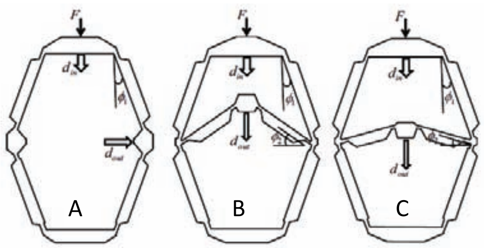


Figure 4: Sensing Principle in MRI (Left) Light, transmitted by a fiber, passes through a fiber-mirror inter-face. The returning light is measured by a photodiode; (Right) Deformable structure of the sensor

Mechanical design based on strain energy: The team designed a displacement amplification mechanism (DACM) which is compact and convenient for sensing tasks in a limited volume. The aim was to suppress the hysteresis problem with these DACM units and further improve the resolution of the reflective sensing technique (see Figure 5). The displacement of the top portion is amplified by the mini-link in the middle where the mirror is attached facing to the fiber. The amplification ratio is raised, its ability of decoupling is enhanced and it is made easier to assemble to fiber optic cable. The structure is decided to be made of Acetal regin (DuPont Delrin) for its high MRI-compatibility and relatively low hysteresis characteristics. The range of measurable force was adjusted to meet the maximum force created by a pneumatic actuator that we are planning to use. A newly designed force amplification mechanism improves the resolution of force sensing, and obtained a force resolution of 0.06N by effectively reducing the hysteresis due to plastic deformation. A force feedback controller has been implemented on an integrated haptic device. The scientific contribution of this work is that it was indicated that the sensitivity of a compliant mechanism could be traded for a lower hysteresis i.e. higher repeatability. Although it may fail to improve the sensitivity, a DACM could be targeted to achieve high repeatability in a sensor.

MRI-compatibility test: The sensing unit was brought to an MRI machine (Siemens Trio 3T) in the Center of Advanced Brain Imaging. The effect of the sensor on the image quality was analyzed by comparing the images of the PHANTOM device with and without the sensor in the imaging room.

First, the sensor was placed in zone 2 and then the sensor was placed in the middle of the area of interest (zone 1). The distortion due to the force sensor is analyzed by taking the difference between related images. As a preliminary analysis, the differences in the images were calculated as the ratio of total pixel value of difference in images with respect to total pixel value of the reference image. The sensor, made of Delrin, caused only 1.6% of change in the image, showing sufficient MRI-compatibility of the sensor.



Model	Strain Energy (mJ)	Hysteresis	Sensitivity (mm/N)	Overall Quality
Basis Mechanism	2.313	0.135	0.227	1.682
Sample A (Modarate Amplification Mechanism)	0.971	0.046	0.281	6.109
Sample B (High Amplification Mechanism)	0.802	0.036	0.204	5.667

Figure 5: Basis mechanism (Left), sample A moderate (amplification mechanism, in the middle), sample B (high amplification mechanism, on the right). Table shows the independent parameters which define the amplification factor of the manufactured samples. Sample B shows the highest performance that is equivalent to a resolution of 0.06N (c.f., approx. 1 N for the Basis mechanism).

Pneumatic line transmission delay: The delay of air pressure control could potentially destabilize the closed-loop control. The team confirmed that the delay is approximately proportional to the length of tubing. However, the response time depends on the air pressure. A response delay of 0.5 s was observed for a pneumatic line whose length is 30 feet operated under 30 psi [3]. Future work includes the development of a robust feedback controller that achieves satisfactory performance under a large delay of air pressure control due to the use of long hoses between the MRI laboratory and control room.

Plan for next 5 years

The miniature integrated fluid-power systems developed in this project can be applicable broadly within the center to projects where size and weight of components must be minimized, including the quantitative evaluation of Test Beds 4 and 6 using fMRI. PIs Webster and Barth have already begun collaborating with Dr. Joseph Neimat, a neurological surgeon, for clinical insight and guidance of the surgical robot project. PI Ueda plans to start collaborating with physiologists and physical therapists (e.g., Drs. Shinohara and Wheaton in Applied Physiology at GA Tech who have extensive functional MRI experience at the GT/GSU Center for Advanced Brain Imaging) so that project results can seamlessly be transitioned to clinical settings. Results will also be applicable to PI Ueda’s stroke rehabilitation robot project in collaboration with the University of Tokyo Hospital, Japan, a project supported by another NSF grant. The PIs will continue to seek external funds in the areas of biomedical and rehabilitation engineering, neuromuscular physiology, and clinical studies from one or two major funding agencies such as NSF (e.g. the NSF Research to Aid Persons with Disabilities (RAPD) Program), NIH, NASA, and DoD.

Thus, significant future funding is expected on both surgical applications (likely from NIH) and rehabilitation applications (from NIH or other funding agencies). This is expected to significantly contribute to the Center’s graduation strategy, as the investigators establish a self-sustaining center of excellence in medical fluid power that will continue beyond the duration of the ERC itself.

C. Member company benefits

Among the CCEFP member companies, some valve and actuator companies (including Enfield Technologies) have an interest in this project. In addition, Martin Companies, Acoustic MedSystems, and Panasonic Corporation (ActiveLink, Panasonic’s in-house venture company) have agreed to support the project. PI’s Webster and Barth have started a collaboration with Acoustic MedSystems and submitted a NIH Phase I SBIR proposal on the surgical robot. This collaboration will be leveraged into a Phase II proposal with the endpoint being a product brought to market. The Martin Companies also remain interested in commercial potential of this technology, and PI Barth will continue to explore ways that it might be leveraged in their business.

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Project 3A.1: Multimodal Human Machine Interfaces - The impact of operator interface on fuel efficiency

Research Team

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Undergraduate Students	Michael Valente
Industrial Partners:	Caterpillar, John Deere, HUSCO International, Bobcat, Sauer Danfoss

1. Statement of Project Goals

This project will establish the relationship between the user interface and fuel efficiency for a relevant range of dynamic system behaviors. The interfaces used will incorporate both traditional and experimental interface devices and sensory modalities. Prediction of the relative performance of interface approaches will be enabled for a range of applications. Implications for usability will be addressed through collaboration with researchers at NCAT.

2. Project Role in Support of Strategic Plan

Fluid power devices will be used more effectively, thereby reducing working time and hence the energy consumption (efficiency barrier). New and existing devices will be able to safely perform their intended functions under human direction without undue workload on the operator (safety and human machine interface barrier).

3. Project Description

A. Description and explanation of research approach

Fluid power applications potentially range from huge mobile excavators to compact wearable tools for home use. In most of those systems, human operators directly interact with machines. The necessary communication between humans and machines directly impact system performance [1]. Coordinated control and other more intuitive interfaces have been shown to reduce operator errors and speed up completion time. However, the impact of intuitive operator interfaces on fuel efficiency is unknown. This research will compare how fuel efficient operators are with a standard versus a novel HMI. It will also examine the differences based upon the type of machine (pump or valve controlled) and the characteristic behaviors that may be inherent or imposed on these differences.

Traditional human machine interfaces often rely solely on the visual modality as a path of communication between humans and machines. However, when operator's workload is heavy, the number of channels that are available for communication between the operator and the machine become more and more crucial. In practice, the visual modality or seeing, and the audition modality or hearing are the most commonly used. Other modalities through which the machine can send information to the human include feel (sense of pressure and its variations) and proprioception (the body's awareness of its own geometry and forces).

The challenge before us is the multiple criteria for evaluating the performance of a fluid power system: energy efficiency, productivity, user acceptance, accuracy of motion, safety, etc. The improvement of one of these metrics has a consequence on the others. It is possible to quantitatively measure energy efficiency as is proposed here, while usability is a more qualitative issue but one which must be simultaneously evaluated. The expertise of NCAT researchers have already started to address this issue and their contribution will continue to be essential.

Another challenge for some scenarios is that the operating environment is extremely complex and not readily controlled for testing. Georgia Tech has created an excavator simulator which minimizes the variation between test runs and will be further augmented to include operator motion as well as tested on TB1 at Purdue. Concepts will be reinforced with simulation and physical verification on the compact rescue robot, TB4.

B. Achievements

This summary of center work does not cover work completed under 3A1 at NCAT on human modeling. Those results will be covered in Projects 3A3 and 3E.

<u>Simulation based studies of interfaces</u>: In order to be able to quickly interchange and test new HMIs or iterations thereof, an excavator simulator has been constructed that simulates the mechanical and hydraulic dynamics of test bed 1 in its current pump-controlled state with the environment. The Bobcat Company donated an excavator for the operators to sit in while controlling the simulation.

The simulator is composed of three modules – the HMI interface, the dynamics simulator, and the graphics simulator. Each of these modules was specifically written in blocks so that they could be easily modified for future use. The simulator and modified versions thereof have been used at Georgia Tech and North Carolina A&T and have proved their robustness.

To complete the excavator simulator, a more extensive excavator-soil model was developed. Previous soil simulations have only examined trajectories and soils where the soil can only exert a force on the bucket less than the force exerted on the soil by the bucket (i.e. loose sand).

A test with 26 subjects was run on the simulator. The subjects used the joysticks in a standard state of the art input mode and used the Phantom in a position control mode to remove soil from a trench. The results from using each device were compared and presented in a paper at the FPNI PhD Symposium. The Phantom device was found to be 81% faster at removing soil from the trench and 18% more energy efficient for removing a unit volume of soil from the trench. Additionally, a webcast was held with members of four member companies represented to discuss the testing and results.

Four new input modes were added to the excavator simulator. Previously the joysticks could only be used in joint velocity mode, which is the current state of the art. The two new velocity control modes allow the operator to move in either the world frame (a frame fixed to the tracks of the excavator) or in the operator frame (a frame that rotates with the cab). The other input modes developed were world and operator frame velocity control modes for the Phantom. The same control module was used, but the commands were read in from the Phantom.

In addition to changing the software to reduce the number of computers, many other changes were made to increase the versatility and ease of use of the software. With data from TB1, a fuel map was created that allows the simulator to calculate the fuel consumption of the excavator instantaneously and cumulatively. Now a fuel amount can be calculated, and from that a calculated dollar amount of the savings provided by new HMIs. Also, additional code has been added that allows data recorded from TB1 to be read in as either joystick commands or swashplate commands. This enabled the comparison of the simulator to TB1 for model validation.

Finally, much effort and research was invested in deciding what aspects of HMI should be explored next. Several ideas have been formulated on energy saving control schemes and more intuitive interface devices. Members at Georgia Tech teleconferenced with representatives from several Caterpillar departments on the usefulness and feasibility of some proposed research topics.

During the past year, new hand controllers have been developed to realize the benefits of the position control as discussed above while addressing some of the challenges of employing a position control device on a real machine. Some examples of the challenges are operator fatigue, need for sensors to measure joint positions, and the inability of the operator to let go of the joystick without causing machine motion. Six different hand controller prototypes been constructed. Four of these controllers were tested in a brief pilot study. All of the controllers tested in the pilot study use position control of the boom, arm, and bucket and rate control for the swing. The results of the pilot study helped to select two controllers for a full study to compare their performance with a standard state of the art controller. This study is getting under way this week with 24 subjects taking part. The study is making use of the excavator simulator that has been upgraded so that the cab physically swings along with the simulation. A separate hand controller prototype that uses conventional joint flow commands but is kinematically similar to the excavator arm will be the focus of a future study to be perform later in spring 2012. This prototype was built through significant modification of a donated Sauer Danfoss joystick. It offers a potentially more intuitive interface to conventional joysticks without the need of any sensors and with little to no additional operator fatigue compared with the current state of the art.

The user studies performed with these hand controllers will provide valuable information towards future research. Regardless of the results of the study, modifications will be made to the designs of the hand controllers. If the hand controllers do not perform well, future work will involve improving the design to compensate for observed inadequacies and to evaluate at a theoretical level what significant design changes relative to the Phantom controller caused the reduction in performance. Assuming positive results from the studies, further improvements to the hand controller designs will be made in terms of comfort and robustness. An example of a potential modification that will likely be explored is the addition of friction to the joints of the position control hand controllers to enable the user to let go of the hand controller without causing unwanted machine motion. These hand controllers will be tested on TB1 to demonstrate their effectiveness in operating a real machine. In addition we will explore the possibility of commercializing the hand controllers through filing of a patent or patents. Long term future work will involve incorporating automation and haptic feedback. As an example of automation, an operator could specify a maximum depth for a trench and the machine would prevent the operator from digging below that preset depth. Haptic cues will be explored as a way to transmit important information to the operator. This will not be limited to coordinated forces but will focus more on the transfer of information, potentially through the use of vibratory cues. Vibratory cues have been demonstrated to provide intuitive information without the need for extensive hardware modifications [2].

To test the viability of the Phantom interface on production machines, the Phantom interface was tested both on and off TB1. Although the testing was only preliminary, it showed the viability of the Phantom interface for excavators in the field. It also demonstrated that biodynamic feedthrough is indeed an issue to be addressed. The week spent on site with TB1 laid the foundation for in depth experimentation during the upcoming year by standardizing both the software and hardware interfaces between the Phantom (and future hand controllers) and TB1.

Several improvements were made to the TB1 simulator [3, 4]. The swing motor of the operator workstation was connected to an external pump and custom encoder attached to the cab so that the cab of the simulator now servos to the same position as the onscreen arm. This greatly improves the realistic feel of the simulator and also provides some motion feedback so that the effects of biodynamic feedthrough on different hand controllers can be studied, at least in part. A “ghost arm” was added to the simulator that displays either a wire-frame or transparent arm overlay of the commanded arm position. The ghost arm also has the option of leaving a trail of ghost arms (similar to the “tail” option of a computer mouse) that show the path that the real arm will follow to reach the ghost arm, or commanded position. The effectiveness of displaying a ghost arm is being measured in an ongoing experiment using simple 1- and 2-D video games. The results from this experiment will be used to formulate the experiment that tests the effectiveness of the ghost arm on the TB1 simulator.

Five simple video games were designed to test how position control, position control with a ghost, and rate control compare for five task (1- and 2-D tracking, 1- and 2D point-to-point motion, and path following). Thirty subjects participated in this study. The data collected has not been fully analyzed, but it has been shown that for both point-to-point motion tasks the rate controller easily outperforms the position controller. However, the position controller with a ghost performs slightly better than the rate controller. After the data from this test is fully analyzed, new control laws will be proposed to improve on the current performance. The video games will be played with the new control laws to determine how performance changes. The best controllers will be implemented on the TB1 simulator along with the ghost arm to test their effectiveness. [5]

The future work of this project will be to determine if matching feedback with operator intent will improve operator performance. The current video game test will conclude in March, and the data will be analyzed to compare operator performance for each controller for each task. The types and costs of the errors will be enumerated. New control algorithms will be proposed that aim to eliminate or mitigate these errors, and a second round of video game test will measure the effectiveness of the algorithms at accomplishing this goal. The best of the control algorithms will be used for a test using the TB1 simulator. Operators will also perform different tasks (point-to-point motion, tracking, path following) with different controllers (position control, velocity control) under different task conditions (obstacles, bandwidth of the machine, etc.) to measure how different task factors influence the operator's intent. Unlike previous work, this research will compare the fuel efficiencies of different human-machine interfaces as well as time efficiencies. The TB1 simulator graphics will be modified to display on a 3DTV, which will be mounted on the simulator, replacing the current 2DTV. The feasibility of using a ghost arm for tele-operation will be investigated by displaying the arm with 3DTV technology.

Blended Shared Control: Previous work in Project 3A.1 resulted in a framework for a type of control we termed Blended Shared Control (SC). Blended SC allows the operator to cede authority to the machine to modify (either directly or indirectly) the original velocity commands such that the resulting motion results in a lower-cost task completion. This requires a three-part structure. First, the operator's intended task (e.g. slew left 60 degrees and raise boom 1 m) is inferred based on present and prior inputs. Second, the optimal control input for this task is computed subject to the constraints of the machine dynamics and the inferred task specifications. Third, the original operator input is combined with the optimal command in a manner which attempts to guarantee that the resulting command results in a lower-cost task execution.

Initial experiments on a single-DOF system showed Blended SC reduced task completion time when compared to manual control [6]. Then the concept of Blended SC was extended to multi-DOF hydraulic actuators, such as the industry-standard excavator (TB1). We introduced a model that expresses cyclical excavation tasks as a sequence of piece-wise monotonic motion primitives. Thus, we have the capability to predict an operator's intended task (essentially, the relative displacement of each of the actuators) from the parameters of the motion primitives, which are learned online using an approach based off of recursive least squares [7]. Further, for each motion primitive, there exists a closed-form optimal solution based on a refined kinematic excavator model that includes the single- and multi-functional flow constraints that dominate an excavator's steady state response. [8] The Blended SC algorithm is responsible for steering (either through direct modification or indirect cues such as haptic or auditory feedback) the operator's original input command towards the optimal input.

The initial research of Blended SC culminated in the Summer of 2010 with an experimental study. Over thirty operators (including experts and novices) completed a number of "excavation-like" tasks using the virtual excavator test bed developed by Mark Elton. The effects on task completion time of Blended SC and conventional manual control were studied. The results showed that excavation productivity is up to 15 percent greater using Blended SC compared to manual control with no electronic assistance. A brief overview of the experimental results will be presented at a major industry conference in Spring 2011 [9], and further research write-ups are now being prepared.

Aaron Enes completed his PhD on this topic at the end of 2010 and currently works for Lincoln Laboratories in Cambridge, MA.

Adaptive Robust Control of Variable Displacement Pumps: A direct pump displacement controlled actuator control algorithm fit for engineering practice with fewer limiting assumptions was proposed. A dynamic compensation solution to improve tracking performance is also proposed. A new test stand designed for displacement controlled actuator has been built up to verify the control strategy and the compensation results. More specifically:

(1) Singular perturbation theory was introduced to hydraulic control to simplify control design and make the results a better fit for practical applications [10]. A full state controller is plausible but not advisable in the practice since the integrated system requires not only the control efforts but also controller itself have higher bandwidth. I t turns out that an adequate controller design can neglect the highest system natural frequency while maintaining system stability and performance using singular perturbation methods. The result is published in the IEEE/ASME Transactions on Mechatronics [11].

(2) There are always some uncertainties in the hydraulic machines, e.g. varying loads of excavators; the classical adaptive control approach cannot converge to such varying parameters unless there is no measurement noise. However, measurement noise is inevitable in the practice. We are using recursive least squares method to keep system parameters errors to the minimum thus ensure system stability [12]. Furthermore, a simplified algorithm was applied to decrease controllers' calculation periods that make the algorithm is more fit for real time control.

(3) A new hydraulic test stand has been build up to verify the proposed algorithms. The trajectory tracking performance has been improved and the pressure oscillations (a common problem in the direct pump control) have been lessened. Experiments were conducted to validate simulation results. The circuit not only ensures the circuit itself stability, and preserves the high energy efficiency of the traditional circuit. Furthermore, a tracking compensation can be issued by the controller to improve the dynamic response of the cylinder. Part of results culminated in a paper published by the Journal of Dynamic System, Measurement and Control [13].

To deal with measurement noise and parameter convergence rate, an adaptive control algorithm with recursive least squares has been proven and validated by the experiments. The square root algorithm has been implemented to increase the controller computation efficiency and stability.

Discrete time control is popularly applied in hydraulic control systems, however, it is difficult to achieve desired trajectory tracking except some extreme cases. A hybrid control algorithm has been developed and validated by experiments. The algorithm can be naturally combined with the result (3) and, at same time, ensure the system can achieve desired trajectory tracking.

Longke Wang defended his PhD thesis in May, 2011. His research was tested in his absence on TB1 but time did not permit full tuning of the algorithms in the period of the two day visit. The success of the technique on the GT test bed could not be duplicated. Dr. Wang currently works for Parker Hannifin.

C. Member company benefits

The most interested and affected companies are the equipment builders in CCEFP. This includes John Deere, Caterpillar, and Bobcat. Caterpillar has attended our webcasts regularly and has a very active industry champion. Deere, Bobcat, Sun, MTS Systems and Sauer Danfoss have donated equipment that has enabled the studies to be as realistic as possible. HUSCO has been invaluable in critiquing the progress on pump displacement control. Parker assisted in testing a proposed circuit on TB4 at Purdue. Special thanks to Rollin Christensen for his assistance in securing and mounting the experimental circuit on TB4.

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Project 3A.3: Human Performance Modeling and User Centered Design

Research Team

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Undergraduate Students:	L. Levin and B. Handshaw
Industrial Partners:	Seth Redenbo, Caterpillar

1. Statement of Project Goals

The goal of the project is to develop an integrated human performance model that can address both cognitive and physical perspectives simultaneously in complex fluid power (FP) systems where human operators interact with the machines, and to use user centered design approach to develop human machine interface for selected fluid power systems (test beds) that are user-centered, safe, easy and comfortable to use.

2. Project Role in Support of Strategic Plan

This project studies the effectiveness of human operators when interacting with fluid power systems. It supports one of the key thrust areas of the center – effectiveness research thrust. In fluid power systems where human operators interact with the machines, the overall effectiveness of the system depends on the effectiveness of the human operator performance. This project presents a new framework to integrate cognitive and physical models of human performance for a fluid power system. A case study using the excavator test bed has been conducted to validate the integrated model and provide design suggestions for other complex fluid power systems. Specifically, the interaction between operator and the machine were studied to assess the overall system effectiveness. With regard to any revision or a new design of a fluid power system interface, a user centered design approach is recommended so that end users are involved in the design process from the very early stage and ensures the interface will be easy, comfortable, and safe to use, and consequently, will be more effective.

3. Project Description

A. Description and explanation of research approach

Human performance plays a significant role in complex systems. With the advancement of fluid power technology, fluid power systems today can provide a wide range of functionalities, and yet they might not achieve their full potential if the human operator cannot perform at their best.

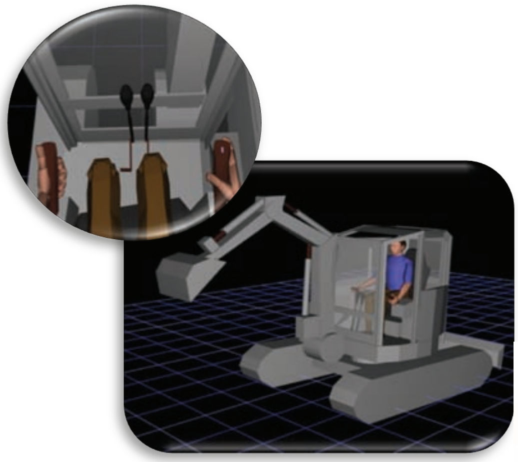
Research efforts in complex fluid power systems are exciting and promising. Unfortunately, very little research has been done on the human-machine interface of those fluid power systems. In fact, many complex fluid power systems are still manually controlled, requiring excessive amounts of energy, intense task concentration, high skill level, and decision-making capabilities on the part of the operator of the equipment. Operators need to interact with machines more effectively to accomplish the desired tasks. Unfortunately, the complex interactions between the operator and the system due to these requirements can often lead to errors and misunderstandings, and consequently degrade the overall system performance despite the fact the machine performance has advanced. Machines cannot accomplish complex tasks by themselves; they require a human operator.

Human performance deals with the physical and cognitive limitations of humans and has been widely used in aviation, automobile, military, medicine, and other industries. However, only limited research has been conducted in the area of complex fluid power systems. A control approach that integrates both physical and cognitive human performance is very important for those complex fluid power systems. Unfortunately, those that study human performance in fluid power systems, often concentrate on either the physical or cognitive part of the performance, failing to take into consideration the interaction between the two. The project has defined the following sequential approach to develop a user interface (UI) that facilitates integrated human performance:

1. Define levels of human performance: environment, system, human, and task
2. Define performance states
3. Differentiate Cognitive and Physical Functions
4. Categorization of metrics and extraction of performance variables
5. Link of performance variables
6. Select modeling tools to support the framework
7. Integrate performance models
8. Implement the framework
9. Applying the framework to appropriate fluid power systems

The integrated performance representation consists of four primary areas: human centered factors which serve as the basis for human performance assessment, a functional relationship which connects cognitive and physical performance, discrete-event simulation tools to realize (link) the integration process, and model output to provide a comprehensive representation of performance. The representation initiates with the key human centered factors from which performance metrics will be used as a subset to classify performance variables. From each performance metric, variables are linked through a functional relationship integrating cognitive and physical performance. Both the cognitive and physical aspects of performance will then be assessed in human performance modeling tools. Simulation with both tools will result in output capable of creating an integrated performance representation. The cognitive tool will be used to simulate the performance and human processes such as attention, perception, decision making; whereas, the physical tool will be used to extend the model to consider physical performance factors such as anthropometry, biomechanics, and movement. With the use of both tools, the human, system, and environment will be represented. Benefits of integrating internal models of cognitive function and external models of physical function can result in insight being gained on human performance in terms of operator responses and the cognitive constraints that guide behavior. More importantly, an understanding of the interaction of physical and cognitive components as well as the influences of tasks, strategies, and responses in human behavior will be gained. With proper application, the framework can lead to more accurate simulation models. Integrative models that are both predictive and computational to simulate cognitive and physical functioning will yield in more realistic representations and accurate predictions of human performance. Moreover, the framework can be used to overcome the past challenges of modeling human behavior, identify system vulnerabilities, aid in the proposal of system redesigns, and foster alternate methods for reaching the desired performance.

The integrated framework provides the required guidelines for developing human performance models that account for cognitive functioning and physical behaviors in relation to a variety of factors that shape human performance. A major contribution of the integrative framework is that it closes the gap between independent performance models to enhance the knowledge of how human performance occurs. It also improves modeling techniques by developing a new approach to modeling human processes with complex systems. The framework provides a structured blueprint that can be usefully utilized to model, analyze, record, and potentially improve human performance. Also, this framework identifies major types of knowledge that is required to increase the understanding of human performance and model integration. Such knowledge includes an understanding of performance at various levels, knowledge of the states and functional components of human performance, acknowledgement of the interactions that produce operator behaviors, and the correlation between cognitive and physical factors of human performance. Further understanding of these types of knowledge provide a major opportunity for using the developed framework to analyze human performance as well as work tasks and operations to improve, evaluate, and select more efficient processes and systems.



ANOVA-2x2x2 Factorial Design for Completion Time.

Source	DF	Type I SS	Mean Square	F-Value	Pr > F
Control	1	514,680.7	514,680.7	4.3	0.0378
Environment	1	6,111,726.0	6,111,726.0	51.4	<0.0001
Control*Environment	1	109,603.0	109,603.0	0.9	0.3374
Integration	1	10,784.7	10,784.7	0.2	0.7634
Control*Integration	1	729.1	729.1	0.0	0.9376
Environment* Integration	1	9.3	9.3	0.0	0.9930
Control*Environment* Integration	1	1.5	1.5	0.0	0.9972
Error	792	94,195,692.6	118,934.0		
Total	799	100,943,227.4			

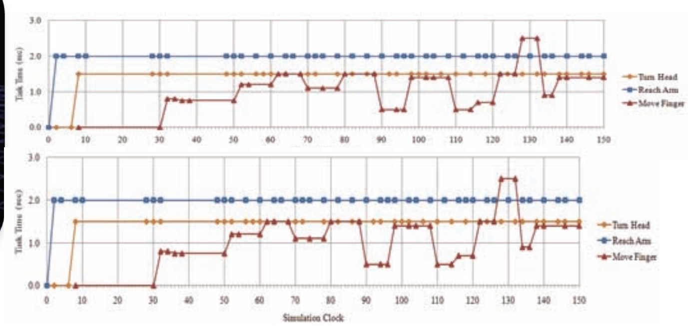


Figure 1: A case study

The integrated human performance modeling framework has been applied to a fluid power case study involving a hydraulic excavator controlled by a human operator performing routine excavation processes to remove earthen materials within a typical construction environment (Figure 1).

This study allows for the simultaneous examination of the influences and effects of physical and cognitive factors both individually or combined on human performance. Tasks were studied with regard to the system's design and function as well as the cognitive and physical tasks employed by the human operator to attain work goals; thus, reflecting the degree of detail necessary to comply with the framework's structure. A 2 (hydraulic and electronic) x 2 (soil and gravel) x 2 (non integrated model and integrated model) factorial design was used in the experiment to assess the framework. Micro Saint and Jack were selected as simulation tools to model human performance. The successful implementation of the framework on the excavator indicates that it can be expanded to other complex fluid power systems where operator interacts with the machines.

B. Achievements

Achievements prior to February 2011:

- Developed an integrated framework for modeling operator performance in complex FP systems (2008-2010).
- Conducted a pilot study on excavator operator performance with the integrated model (2010).
- Conducted empirical studies using various developed Jack models (physical model) for the rescue robot operators (2010)
- Conducted an empirical study using eye tracking to assess the effectiveness of the trust instrument for human robotic interaction (2010)
- Conducted a usability study to evaluate the haptically controlled excavator simulator in Georgia Tech (2010).
- Developed a conceptual model for a user interface suite that interfaces the pneumatic-power ankle-foot orthosis (PPAFO) with clinicians and patients (2010).

Achievements in this reporting period:

- Conducted an empirical study on excavators using the integrated human performance modeling framework (Spring 2011)
    - A thorough task analysis was conducted on excavators
    - A 2x2x2 factorial design was used with control type (hydraulic vs. electronic), environment (soil vs. gravel), and model (non-integrated model vs. integrated model) chosen as the independent variables and task completion time and workload as the dependent variables.
    - Four cognitive models were developed for each control-environment combination using Micro Saint.
    - Four physical models were developed for each control-environment combination using Jack.
    - Four integrated model were developed linking Physical model (Jack) and Cognitive model (Micro Saint) for each control-environment combination.
    - Simulations were run based on the experimental design and data were collected.
    - Conducted statistical analysis on the data collected from the empirical study using both univariate and multivariate statically analysis.
    - Empirical results verified that the integrated model performance was statistical better than the non-integrated model.

- Conducted an empirical study to assess the conflict between multiple modalities of excavator operators – Spring 2011
    - Three research questions were formulated: (1) Does conflict exists between sensory modalities (auditory, visual, and haptic) in the haptic-controlled excavator interface? (2) Are these conflicts significant enough to have an impact on the performance of operator-excavator interaction? (3) Do operators struggle to coordinate their hand-eye movement? If they do, how would this affect the efficient operation of the haptic-controlled excavator?
    - A haptic-controlled excavator simulator along with eye tracking device (Tobii) was used in this experiment.
    - Representative tasks were selected based on the findings of task analysis that was completed in previous research.
    - This study was approved by the IRB at NCA&T.
    - Task completion time, number of scoops and number of drops, eye tracking data such as fixation count and length, and NASA TLX subjective workload data were collected.
    - Both visual inspection and statistical analysis were conducted on the data collected.

- Conducted an empirical study to investigate the effect of haptic force feedback on excavator operator performance and analyzed results – Summer and Fall 2011
    - Conducted a pilot study to categorize force feedback to three levels: low, medium, and high.
    - An empirical study was performed based on the results from the pilot study and addressed the following two research questions: (1) Does different force feedback affect operator performance? (2) What is the optimal range of force feedback values that yield best operator performance?
    - A completely randomized design was used with force feedback level being the independent variable with four levels (none, low, medium, high) and task completion time, number of scoops required to fill a bin, number of scoops dropped outside a bin, and accuracy rate being the dependent variables.
    - A simulated excavator connected with a haptic device (PhanTom) was used in this experiment.

- Both pilot study and empirical study were approved by the IRB at NCA&T.
- Statistical analysis was conducted on the data collected.

- Developed clinician centered prototype interface for AFO - Fall 2011
  - Gathered feedback from clinicians and other stakeholders
  - Visited Georgia-Tech to meet with Physician
  - Reviewed literature & UIs related to therapeutic robot rehabilitation and serious gaming
  - Determined available resources for UI development
  - Designed Mock-up UI

<u>Plans for the Next Five Years</u>

- Conduct an empirical study to assess the auditory feedback on operator performance
- Conduct studies of fatigue on operator performance in fluid power systems
- Develop a feedback control system representation of human-excavator model Develop quantitative models for multimodal human excavator interface
- Identify the human subsystems in the human-excavator model
- Develop a transfer function for each component of the human subsystem
- Use Massaro's Fuzzy Logical Model of Perception (FLMP) to develop a transfer function for signal/cue perception and integration
- Develop a forward and closed loop transfer functions for human-excavator model
- Implement and validate models in MATLAB
- Develop (revise) a multimodal human excavator interface
- Conduct usability evaluation on revised human excavator interface.
- Develop a prototype for the clinician-PPAFO interface
- Develop protocols for usability evaluations of the prototype

<u>Expected Milestones and Deliverables</u>

- Case study using the excavator test bed to investigate the effect of auditory feedback on operator performance.
- A multimodal human excavator interface.
- A testable working prototype for the clinician-PPAFO interface

C. Member company benefits

The integrated human performance model can be applied to investigate operator performance for any complex fluid power systems where operators interact the systems to understand operator performance before any changes done to the system, allowing them avoid expensive and tedious prototype/mockup, and thereby saving companies time and money. In addition, as we demonstrated in our research, companies can use UCD approach improve their design process and by doing so, they can receive higher customer satisfaction, and reduce training/maintenance cost.

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Project 3B.1: Passive Noise Control in Fluid Power

Research Team
Project Leader: Prof. Kenneth A. Cunefare, Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Graduate Students: Nicholas E. Earnhart, Kenneth A. Marek
Undergraduate Students: Michael Walsh, Chandana Ramitha Edirisinghe, Stephanie Moertl
Industrial Partners: Michel Beyer, Eaton Corporation

1. Statement of Project Goals

The aim of this project is to improve noise control in fluid power systems by passive means. Excess noise is a problem not only for the attractiveness of existing products, but also as a barrier for entry of fluid power into new markets and technologies. This project seeks passive solutions to the reduction of noise and vibration by means of integrating engineered compliant materials into existing components and technologies. The use of compliant materials is expected to help reduce the size of noise control devices for fluid power.

2. Project Role in Support of Strategic Plan

The reduction of noise and vibration is a core enabling technology for Goals 2 and 3 in the Center's Strategic Action Plan. For the Hybrid Passenger Car (TB3), noise and vibration reductions are crucial to mass acceptance of the hybrid technology by the public. Noise can not only be a harmful to hearing and impair communication, but can increase mechanical fatigue and reduce component life. Increasing demands on quality make the need for noise reduction a priority for designers. Developing compact and effective noise control solutions is even more important for Goal 3: Portable, Untethered Human-Scale Applications. The limitations on noise output are drastically more stringent for devices to be worn on the body or used in the home compared to industrial applications. Reducing fluid power-related noise and vibration is crucial to supporting the Center's goal of enabling new markets for fluid power.

3. Project Description

A. Description and explanation of research approach

Excess noise is an ongoing issue in fluid power systems. Noise needs to be controlled not only to meet regulatory standards, but also to meet the expectations of customers and consumers. Fluid-borne noise is generated by pumps and can couple to structures, causing vibration and air-borne noise. The high speed of sound in hydraulic fluid, coupled with the low fundamental frequencies of pumps results in wavelengths of fluid-borne noise that are much longer than the practical size of common noise control components.

The current technology of reducing fluid-borne noise involves both the use of pressurized, gas-filled bladders for adding compliance to fluid power systems as well as integrated design features addressing such noise sources as cavitation and structural vibration. Pressurized bladders are used in commercially-available in-line silencers (one such silencer is used as a benchmark in this research) and in accumulators which act as low-pass filters.

As reported previously, the research approach in this project is unique in its application of a voided, engineered, compliant lining to noise control devices for fluid power systems. There are a number of patents for noise control devices that reference voided polymer materials [1, 2], however, there does not appear to be any product on the market exploiting these patents, nor is there material in the literature. Theoretical models may be found in the literature for annular air silencers [3] and for hydraulic silencers using flexible plates [4] but none currently addresses annular, compliant-lined hydraulic silencers. Other devices such as Helmholtz resonators and Quincke tubes have been studied but are not found in practice as their size is typically too large for practical application (however, it is our understanding that small, bellows-style resonators are a not-uncommon device on fuel injection systems; but such are not used in fluid power applications). Helmholtz resonators have been studied extensively for air; one notable study for a fibrous-lined resonator was performed by Selamet. [5] A number of studies have evaluated Helmholtz resonators for hydraulic systems, but none have been found that incorporate a lining. [6-9] Devices known as tuning coils act as ¼-wavelength resonators and are common in power steering systems. A patent for a tuning coil was first issued in 1967 [10],and they were studied in the literature in the mid-1990s. [11, 12]. Quincke tubes act as ½-wavelength resonators and were evaluated in some of the same literature. Aside from separate noise control components, fluid-borne noise may be abated by integrated design features. For example, changes to the geometry of axial-piston pumps and the use of relief ports in valve plates. [13-15]

A major barrier in reducing the size of noise control devices for fluid power lies in the properties of the material used in their construction. The material must be significantly more compliant than the working fluid, yet remain compliant while under hydrostatic pressure. Coupled factors include the sound speed and loss factor; a low sound speed is related to reflection losses from the impedance change at the inlet and internal reflections, while the loss factor is the variable governing energy dissipation. In addition, capturing all these factors in a predictive model for a given device is also a key to tailoring the material properties and device geometry to a given application. The microvoided urethane used in this research shows significant promise with respect to these aspects.

B. Achievements

Effort over the course of the year focused on improvement of the modeling for lined device, upgrade to the test rig with respect to the pressure capability, and initiation of patent and commercialization activities. Concerning the model, a significant modification was implemented for the in-line silencer. While still based on the approach of Xu, et al. [3] the liner component of the model was extended to include shear waves. The incorporation of such wave types, in addition to the compressional waves of the original model, significantly improved the mode fit to experimentally obtained data, as depicted in Figure 1. The model was also extended to permit analysis of the transmission loss of hydraulic hoses.

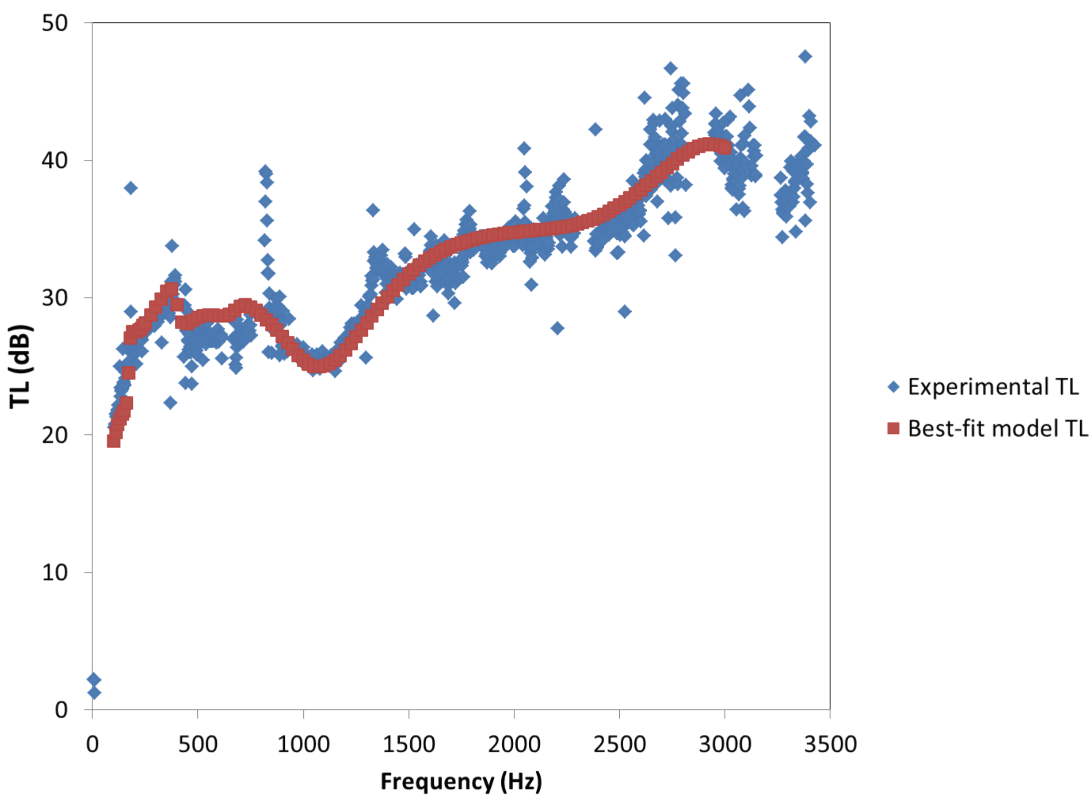

Figure 1: Improved fit to experimentally obtained transmission loss data through extension of model to include shear waves in the elastomeric liner. Shear waves contribute below 1000 Hz.

Continued work examined the performance of a lined Helmholtz resonator where the lining was configured either as a cylinder or as an annular section with a cylindrical hollow down its axis. The two liners had different volumes of the voided polymer; the cylinder had more volume than the annular configuration. Considering the volume alone, the compliance of the cylindrical volume should have been greater than that of the annular configuration, and should have had the lower resonance frequency; however, as depicted in Figure 2, the resonance behavior was actually opposite what was originally expected. Subsequent detailed analysis revealed that the annular configuration was inherently more compliant than the solid cylinder due to geometric configuration, explaining the observed behavior. This finding will be exploited in future designs of devices. Other work involving the Helmholtz resonator focused on the performance of liners with different material compositions, compositions designed to have lower and higher critical pressures. These efforts did yield benefits in terms of materials that stayed compliant to somewhat higher pressures.

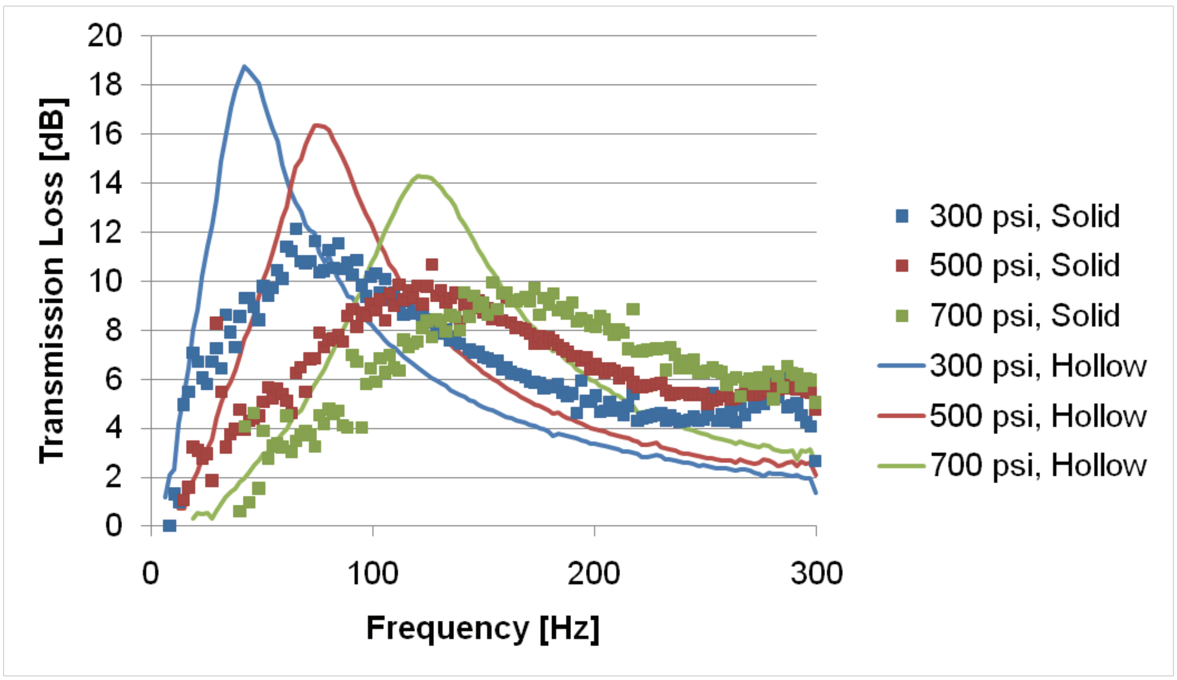

Figure 2: Transmission loss for prototype Helmholtz resonator at with solid vs. annular-hollow.

An upgrade to the pressure capability of the test rig was made possible by an equipment donation from one of the industry sponsors. Transmission loss tests on prototype devices at pressures up to 3000 psi indicated that the material does continue to stiffen with increasing pressure. The tests also permitted the estimation of the effective bulk modulus of the material, as depicted in Figure 3. It was determined that further material development effort was outside the pre-commercialization scope of the project.

Additional work related to this project, but peripheral to the main thrust of work, included exploration of the supporting experimental test rig and the related ISO standard. The work identified a weakness in the current test method for instances when there are particular phase matching conditions in the upstream and downstream sections, which tend to correlate to resonance conditions in these sections. A paper is under development on this topic.

Finally, the work has led to a separate research contract with one of the Center's industrial sponsors to develop an optimized accumulator configuration in a particular application.

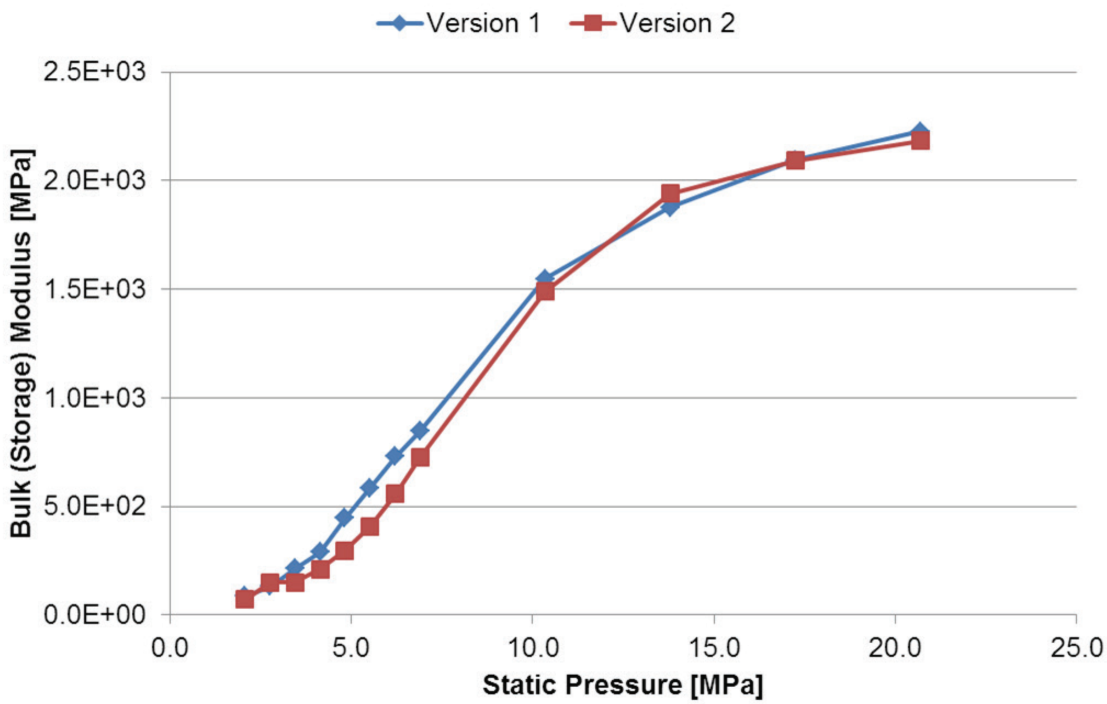

Figure 3: Bulk modulus for two material compositions; "Version 1" with a lower critical pressure, "Version 2" with a higher critical pressure.

Three conference papers were presented during the reporting period [16-18], one at the 52nd National Conference on Fluid Power, one at the SAE Noise and Vibration Conference, and one at Noise-Con 2011. One presentation was made at the 162nd meeting of the Acoustical Society of America. One archival publication was accepted by the International Journal of Fluid Power [19].

Due to the numerous developments, four patent disclosures that pertain to this technology were filed with the Georgia Institute of Technology's Office of Technology and Licensing (seven patent disclosures were filed in 2010). Extensive patenting and commercialization discussion with industry partners were initiated during the report period. This activity is reflective of the perception within Industry and the Center that the technology developed in this project has advanced to the point where it is appropriate to transition to technology transfer, as well as development toward commercialization. As such, future work on the material and devices developed to date will not be supported directly through the center, rather such would be pursued through industrial or commercialization support.

A potential future area of development leveraging the knowledge developed to date in this project is applicable to digital valving concepts currently under consideration within the center and within industry. The use of digital valving for fluid power applications leads to strong pressure transients within a system, transients that can be much larger than the pressure ripple from pumps. The pressure fluctuations in such systems may be an absolute barrier for adoption of the technology, despite the very high energy savings that would otherwise be gained through its use. Further, the load pressure can vary significantly over relatively short time scales, such that the common noise control devices optimized for a specific load pressure will no longer be appropriate. We have proposed a concept embodying a functionally-graded, locally saturating silencer concept to address these issues. Research into this concept would begin in mid-2012 should the project be selected for support by the Center.

Patent Disclosures

Four patent disclosures were filed with the Georgia Institute of Technology's Office of Technology and Licensing over the course of the reporting period (these are in addition to the seven filed in 2010). Their specific titles and reference numbers are shown below.

1. "Hydraulic Hose Lined with Syntactic Foam," Invention Disclosure to the GT Office of Technology Licensing, February, 2011. Nick Earnhart*, Co-Inventor. GTRC 5567.

2. "Tuned Syntactic Foam," Invention Disclosure to the GT Office of Technology Licensing, February, 2011. Nick Earnhart*, Co-Inventor. GTRC 5568

3. "Microtextured Hose Lining," Invention Disclosure to the GT Office of Technology Licensing, February, 2011. Nick Earnhart*, Co-Inventor. GTRC 5569

4. "Water Hammer Arrester," Invention Disclosure to the GT Office of Technology Licensing, February, 2011. Nick Earnhart*, Co-Inventor. GTRC 5672

C. Member company benefits

This project is yielding very positive results that are strongly rooted in practical application and the development of new technology. There are fully functional prototypes for an in-line silencer, Helmholtz resonator, tuning coil, and Quincke tube that have demonstrated performance characteristics. For the Helmholtz resonator, there is a significant improvement in compactness over existing technologies. In addition, should a sponsor company be convinced of the merits of the work, a portfolio of intellectual property is available.

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Project 3D.1 Leakage Reduction in Fluid Power Systems

Research Team

Project Leader:	Richard F. Salant
Graduate Students:	Yuli Huang
Industrial Partners:	Trelleborg Sealing Solutions, Freudenberg, Bosch-Rexroth, John Deere, Caterpillar, Concentric AB (formerly Haldex), R. T. Dygert

1. Statement of Project Goals

The general goal of this project is the development of realistic numerical models of the seals and seal systems used in fluid power systems, which would be capable of predicting the key seal performance characteristics, especially seal leakage and friction, and serve as design tools. A further aim is to develop a fundamental understanding of the physics of sealing through the model development.

2. Project Role in Support of Strategic Plan

The project attacks the effectiveness barrier by providing tools and physical understanding that will allow the development of seals that will eliminate or substantially reduce leakage from fluid power components such as actuators, valves and pumps. It constitutes fundamental research, which will have long term benefits.

3. Project Description

A. Description and explanation of research approach

The fluid power industry has recognized that the reduction or elimination of leakage of hydraulic fluid from fluid power systems is a fundamental prerequisite for the expanded use of fluid power. Leaking rod seals are the most significant sources of environmental pollution in fluid power systems. There is also a need to reduce seal friction to both reduce energy dissipation and eliminate control problems. At the present time, these seals are developed through empirical means, using trial and error techniques, since the fundamental physics of seal operation has been poorly understood.

Rod seals are reciprocating seals. Past research on such seals is described in a recent review paper [1]. Serious studies date back to at least 1964, but these have not had a significant impact on the practical aspects of seal design since they ignore both the roughness of the seal surface and mixed lubrication in the seal-rod interface.

The present author and his students had made a start in developing a more realistic model of rod seal operation [2-4], under a project funded by the National Fluid Power Association, Cooperative Network for Research. The present project, in the CCEFP, builds on that work. At the same time, several other researchers have been making advances in this area [5-9].

The models developed in this project include analyses of the fluid mechanics, contact mechanics, thermal processes (in some cases) and deformation mechanics, and an iterative computational procedure. Inputs to the models include the operating conditions, material properties, macro-geometry, and micro-geometry of the sealing surfaces.

Model development involves analyzing the fundamental physics of the various processes, setting up numerical analyses and computational strategies, constructing appropriate algorithms and writing code. Model validation makes use of experimental results obtained from industrial collaborators. As required, simulations of seals suitable for the test bed are performed and, based on the results of the simulations, design recommendations are made for the test bed seals.

B. Achievements

To date, both a steady-state and a transient rod seal model that take account of seal roughness and mixed lubrication have been constructed. These models treat the seal as elastic. The steady-state model has been used to simulate the performance of single lip, double lip, tandem U-cup seals and a seal with a sawtooth micropattern on the sealing surface. The steady-state model has been used to aid in the selection of a rod seal for the orthotics test bed. Steady-state model predictions compared well with test measurements at two industrial partners, Eaton Hydraulics and Trelleborg Sealing Solutions.

The transient model has been used to simulate the performance of a single lip U-cup seal. Simulations have been generated for a time-varying rod speed with constant sealed pressure case, and a time-varying rod speed and time-varying sealed pressure case.

The results of the above simulations have revealed much about the basic physics of rod seal operation. They show that these seals operate with mixed lubrication, and for a given set of operating conditions and seal design, there is a critical seal surface roughness below which there will be zero net leakage per cycle, and above which the seal will leak. They also show that for a given stroke length, net leakage decreases with rod speed and above a critical rod speed there will be zero net leakage. Comparison of simulations of non-leaking and leaking seals show that the following characteristics are conducive to zero or reduced net leakage: a thinner lubricating film, a larger film thickness during instroke than during outstroke, cavitation in the sealing zone during outstroke, reduced or no cavitation during instroke.

In addition to the above elastic models, a viscoelastic transient seal model has been developed. When viscoelastic effects are taken into account, the behavior of the seal at any instant of time depends not only on current conditions, but also on the entire past history of the seal. This model makes use of the Generalized Maxwell Model constitutive relation with a five term Prony Series. It takes account of the viscoelasticity in both the contact mechanics analysis and the deformation analysis. The viscoelastic model has been used to produce a number of simulations of an injection molding application and a short stroke, high frequency actuator application.

To obtain the best values of the viscoelastic seal properties for input to the seal model, measurements were made on samples of seal material. An optical profilometer was used to determine the surface characteristics and the bulk viscoelastic characteristics were determined using a Dynamic Mechanical Analysis (DMA) device.

To explore the homogeneity (or non-homogeneity) of the seal surface, measurements on the surface were made using an atomic force microscope (AFM). The topography was determined using standard AFM procedures, while the viscoelastic properties were determined by using the AFM in the tapping mode. The results are extremely interesting: very large variations in the viscoelastic moduli occur on the micron and submicron scale. Maximum values of the relaxation modulus are found to be several times the value of the bulk value.

Progress during the current reporting period

During the CCEFP Year 6 reporting period, a seal model that includes the rod surface geometry has been developed. The seal models described above treat the seal surface as rough and the rod surface as perfectly smooth. This is because the rod surface is typically much smoother than the seal surface. However, it is well known from engineering experience that the rod surface geometry can affect the seal behavior. This new model includes three major components, as do the models described above, namely a fluid mechanics analysis, contact mechanics analysis and deformation analysis. During the instroke and outstroke the rod speed and sealed pressure are held constant.

Inclusion of the rod surface geometry affects all three analyses (fluid mechanics, contact mechanics, deformation). As surface features on the rod move past the seal, they generate film thickness fluctuations, leading to changes in the pressure field due to squeeze film effects. Thus, even though the rod speed and sealed pressure are held constant, the squeeze film term is included in the Reynolds equation. The surface features on the shaft are treated deterministically while the asperities on the seal surface are treated statistically using the flow factor approach of Patir and Cheng. The rod surface features indent the softer seal surface and affect the finite element analysis of the seal deformation. As the rod surface features move past the seal, the seal deformations change with time. As in the previous models, the Greenwood Williamson contact model is used to simulate the contact of asperities on the seal surface with the irregular rod surface.

Based on observations of chrome-plated plunge ground shafts, a shaft model consisting of an axial sinusoidal surface geometry was constructed and a series of simulations have been run for a base case. Results so far show that the chrome-plated plunge ground surface features have very little effect on the friction force, but can have a significant effect of the leakage. That effect is quite complex due to the fact that several competing physical processes occur simultaneously. Thus, the resistance to leakage can be either enhanced or impaired by the surface features, depending on the rod speed, seal roughness characteristics and seal design, as well as on the rod surface feature details. A series of parametric studies is presently underway to further study these effects. Plans are also being developed for validation testing with an industrial partner.

The research generated by this project thus far has been published in 8 archival journal papers [11-18] (1 additional submitted [19]), presented in 1 plenary and 1 keynote lecture [20], [21], 2 invited papers [22], [23], 22 additional conference presentations [10], [24-44] and 5 seminars [45-49].

Planned Progress and Milestones

During the next two years the major effort will be directed toward determining, through simulation, optimum engineered micro- patterned rod surfaces to reduce friction while maintaining zero net leakage.

The simulation work done on this project has revealed much of what it takes, through seal design, to prevent net leakage. However, this research has also shown that extremely large friction forces are exerted by the rod seal on the rod, in agreement with experimental measurements by a seal manufacturer (Trelleborg). For a 50 mm (1.97 inch) diameter rod, these forces are in the range of 1000-1500 N (225-337 lbf). For energy conservation and control purposes, there is therefore an obvious need to reduce this friction while still maintaining the sealing effectiveness.

Over the last several years there has been substantial tribological research on reducing friction by the application of micro-patterns on mating surfaces using laser texturing and photolithography. This has been applied to such machine elements as journal bearings, piston rings, mechanical seals and the shafts of rotary lip seals.

In the present project such engineered micro- patterns on the rod surface will be studied for the purpose of reducing rod seal friction, while maintaining seal effectiveness. To do this it is necessary to develop a simulation model that will be able to handle these surface patterns. This will be done by making use of components from the previous models developed under this project, and introducing new features. In particular, two distinctive characteristics of the micro- patterns must be taken into account, their two-dimensionality and their regularity.

To account for the two-dimensionality, a two-dimensional Reynolds equation solver will be constructed. This will involve, as in the past, using the finite volume discretization technique. The two-dimensional discretized equations will be solved with the ADI (alternating direction, implicit) technique on a solution space spanning the seal width, but extending only over a circumferential segment. Periodic boundary conditions can then be applied, allowing the use of the TDMA (tri-diagonal matrix algorithm) and cyclic TDMA algorithms.

As in some of the previous models, an online finite element code will be used for the deformation computations. Due to the two-dimensionality of the surface features, a three-dimensional finite element computation would be required for an exact solution. However, such an approach would require unacceptably high computation times so an approximate approach will be used. The fluid pressures computed over the circumferential segment will be averaged at each axial location, with the average fluid pressure being applied around the entire inner circumference of the seal. A similar procedure will be used with the contact pressures, computed with the Greenwood-Williamson contact model.

Once the general model is developed, specific rod surface geometries will be constructed and simulated running against a step seal and a U-Cup seal. The simulations will predict leakage and friction, as well as the detailed behavior in the sealing zone, as in the past. The particular geometries to be investigated will be chosen during the course of the study. Consultation and collaboration with Project 1D: Micro - Texturing for Low Friction Fluid Power Systems will occur during this and later stages of the project.

C. Member benefits

All of the publications and computer programs will be available to Center members.

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Project 3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems

Research Team

Project Leader: Scott Bair, School of Mechanical Engineering, Georgia Tech
Graduate Students: Adam Young
Industrial Partners: Eaton, Shell, Lubrizol

1. Statement of Project Goals

The goal of the project is to develop the tools that may be used by engineers to design more compact, reliable and energy efficient fluid power components by improving the film thickness and reducing mechanical loss in the full-films occurring between non-conforming rolling/sliding machine elements. A fundamental rheological foundation for the field of elastohydrodynamic lubrication (EHL) has been lacking since the inception. For example:

a. The proper definition has not been found for a parameter (a pressure-viscosity coefficient) to quantify the piezoviscous strength of any Newtonian liquid, regardless of the nature of the piezoviscous function, so that Newtonian film thickness may be predicted.

b. The properties of a liquid that must necessarily be included in a film thickness calculation when the Newtonian prediction is inaccurate have not been specified.

c. The properties of a liquid that must necessarily be included in a full-film friction calculation have not been specified.

This project is providing the rheological foundation to solve these important problems.

2. Project Role in Support of Strategic Plan

Compactness

More compact components must necessarily have smaller radius of curvature of the contacting elements. A clear strategy for making more compact components is also to increase the operating pressure. The resulting increase in contact pressure and decrease in radius of curvature of the sliding/rolling elements will result in diminished film thickness. The reduced film must impact the reliability.

An example can be made of the conversion from organic based fluids to water/glycol solutions. This usually results in having to reduce the operating pressure to retain the fatigue life of the concentrated contacts. Water/glycol produces a substantially thinner film than do organic based fluids (by an order-of-magnitude) [1]; however, present EHL theory is completely incapable of predicting the film reduction as there is currently no means to simulate the rheology of linear piezoviscous liquids. We have solved this problem in the last year and experimentally validated the results.

The ability to predict film thickness of any liquid from properties that can be measured and associated with the chemistry of the liquid will enable the formulation of fluids for improved durability at smaller scales.

Efficiency

Surprisingly, there has been little progress within EHL over the last forty years in explaining the mechanism of mechanical dissipation in full EHL films. In very recent related work [2] using the temperature/pressure correlation devised by this project, the first experimentally validated EHL friction calculation was performed which included thermal-softening and shear-thinning. Fragility has been shown to be the principal property controlling friction. In particular, the results of this project may be used to rank the mechanical energy loss of contacts lubricated by fragile hydraulic oils. A visiting Fulbright Scholar, Wassim Habchi, will be performing simulations to find the relationships between friction and the dimensionless groups such as the Nahme number and Weissenburg number.

3. Project Description

A. Description and explanation of research approach

A significant opportunity to investigate the elastohydrodynamic lubrication (EHL) problem using experimental film measurements, high pressure rheological measurements and numerical analysis (quantitative elastohydrodynamics) has recently appeared as a result of this project. In an exciting departure from previous methods, new film behavior regarding the effect of scale and load has been predicted from EHL simulation using measured rheological properties and the predictions have subsequently been experimentally validated [3]. Both film thickness and friction may now be predicted [4], at least for light loads, from primary properties rather than from fictitious properties adjusted to fit analysis to measurements of film thickness or friction. Film thickness may now be calculated from the properties of mixtures [5]. Thermal EHL calculations using measured rheology have revealed the importance of the high-pressure thermal properties of lubricants in calculations which have been experimentally validated [2].

An unfortunate aspect of EHL research over the last several decades has been the use of adjusted viscosity to validate hypotheses. Rather than test the predictions of theory by comparison of predictions with experiment using calculations based upon the measurable viscosity, in most cases, viscosity has been adjusted to ensure a successful outcome. As a result, many of the outstanding questions remain unanswered.

The present time is propitious for the EHL field to embrace a quantitative description of the temperature and pressure dependence of viscosity since there has been, over the last decade, an interest by the physics community in the pressure evolution of the dynamic properties of the supercooled liquids such as lubricants [6]. Fragility, a property strongly affecting EHL friction [7] and transient EHL film response [8] is now being intensely studied [6]. Fragile liquids experience greater changes in their properties (are more non-Arrhenius) as the glass transition is approached by cooling or compression than do strong liquids [9].

A description of the temperature and pressure dependence of viscosity is also necessary for the calculation of the relaxation times which determine the onset of shear-thinning response and the onset of time-dependent behavior in both shear and compression. For example, the shear-dependent viscosity of liquids is often described by the single-Newtonian Carreau law [10]:

$$\eta = \mu\left[1+\left(\lambda\dot{\gamma}\right)^2\right]^{\frac{(n-1)}{2}}$$

where n is the power-law exponent which in the limit of high shear rate is:

$$n = 1 + \partial \ln \eta \big/ \partial \ln \dot{\gamma}$$

The generalized viscosity, η, departs from the low-shear Newtonian viscosity, μ, when the product of shear rate $\dot{\gamma}$ and relaxation time, λ, approaches unity. The commonly quoted form [11] of the Einstein-Debye relation for the rotational relaxation time of a molecule in terms of the universal gas constant, R_g, is:

$$\lambda = \frac{\mu M}{\rho R_g T}$$

Now, the molecular weight, M, is constant and the product of mass density and temperature, ρT, varies only slowly with temperature and pressure as compared with the viscosity. Therefore, for practical measurements and EHL calculations, it is sufficient to set λ proportional to μ. This simple rule also provides an alternative method of measurement of low-shear viscosity. Any measurement of relaxation time under conditions which overlap with a viscosity measurement will provide the constant of proportionality which will allow extrapolation of the viscosity data to the conditions of the relaxation time measurement [12].

An essential part of this program involves collaboration with partners around the world. A list of collaborators which have been instrumental to the progress made to date follows.

1. Ashlie Martini, Purdue University, simulation
2. Ivan Krupka, Brno University, Czech Republic, film thickness measurement
3. Riccardo Casilini, George Mason University, measurements of relaxation time
4. Mike Roland, Naval Research Laboratory, rheology
5. Michael Khonsari, Louisiana State University, simulation
6. Punit Kumar, National Institute of Technology, India, simulation
7. Philippe Vernge, INSA Lyon, France, film thickness and traction measurement
8. Kees Venner, Univ. of Twente, Netherlands, film thickness measurement and simulation
9. Paul Michael, MSOE, lubricant formulation
10. Arno Laesecke, NIST Boulder, viscosity correlations
11. Wassim Habchi, Lebanese American University, simulations
12. Hubert Schwarze, Technische Universität Clausthal, high-frequency viscosity measurements under pressure

B. Achievements

<u>Publications</u>

The achievements may best be summarized looking at the resulting publications. Twenty-one papers have resulted from the four years of work; seven have been written, submitted or published within the last year alone. They are listed at the end of this report and referenced in the following section.

<u>Progress During the Reporting Period</u>

Truly substantial progress, which is transforming the field of EHL, has been realized during the reporting period.

We have extended our work on the effect of scale [P2] on generalized Newtonian EHL film thickness to include the effect of load (pressure) [P8]. Earlier in this program, we showed through analysis using realistic shear dependent viscosity that the classical Newtonian theory understates the dependence of film thickness on scale [P2]. We later experimentally validated this effect by measuring film thickness for various size steel balls against glass discs [P7]. For this year further analysis indicted that a similar effect was important to contact pressure and experimental measurements using a WC ball against a sapphire disc validated the theory [P8]. We found that the film thickness is reduced due to the shear stress dependence of viscosity for any process which increases the pressure gradient within the inlet zone.

These investigations lead to the observation of measurable molecular degradation in an operating EHL contact [P16]. In each case, for shear thinning liquids, experimental film thickness was more sensitive to load and scale than the rheology would suggest [P7, P8]. Although these were ostensibly pure rolling contacts, the most obvious explanation was molecular degradation from the shear applied to the liquid. To test this hypothesis, time-dependent film thickness measurements [P16] between a steel ball and a glass disc were made with the most shear dependent liquid we have studied, a gear oil. The film thinned rapidly after the first revolution of the ball and reached a steady thickness after about ten revolutions. To investigate the effect of stress history on the shear dependence of viscosity, flow curves were generated with a new pressurized Couette viscometer. Viscosity was measured as a function of increasing shear stress to 1.2 MPa and, afterward, as a function of decreasing shear stress [P16]. The exposure of the liquid to high stress permanently decreased the viscosity measured at low stress, an indication of molecular scission.

By examining the measured and predicted film thicknesses for very low viscosity liquids, ordinary liquids at very high temperature and water-based solutions, we have developed the first film thickness formula for linear piezoviscous liquids [P13]. The new formula predicts that the speed sensitivity will be reduced at high temperatures for many low-viscosity liquids. The formula was then experimentally validated [P13].

We developed a framework for transient modeling of sliding EHL including thermal effects [P11]. The volume anomaly which occurs as the glass-to-liquid boundary is crossed as the liquid is decompressed was included in the calculation to explain anharmonic variation in film thickness from harmonic variation in entrainment velocity. We concluded that these anomalies cannot be explained by solutions of the Reynolds equation which is only valid when the product of shear stress and local pressure-viscosity coefficient is less than one [P11].

We have applied the Ashurst-Hoover viscosity scaling that was developed earlier in the program [P4] to other materials including dimethyl pentane and a volatile refrigerant [P15]. The Stickel analysis technique was useful in identifying a second regime of viscosity scaling different from that of ordinary hydraulic oils which are fragile glass-formers having more complex molecules. Building on this success we found a new normalization for volume in the scaling parameter using the molecular (Van der Waals) volume. Stickel plots using the newly normalized scaling parameter [P17] reveal a characteristic form which appears to describe the complete range of viscosity dependence on temperature and pressure for compressed liquids. The master curve can be represented by a combination of two exponential power law terms. These may be seen as expressions of different molecular interaction mechanisms similar to the two free-volume models of Batschinski-Hildebrand and Doolittle, respectively. The new correlation promises to yield more reasonable extrapolations to extreme conditions of temperature and pressure than free-volume models and it removes the singularity that has prevented wide acceptance of free-volume models in numerical simulations.

In three papers [P4, P6, P10] we have set out a rheological framework for realistic numerical simulations of film and friction behavior in lubricated concentrated contacts. In associated work, see [2], a full EHL simulation of sliding contacts with significant dissipation clearly shows the profound effect of the pressure dependence of the liquid thermal conductivity on friction. This simulation was thoroughly validated experimentally. The relationship between thermal conductivity of a liquid and full-film friction has not been reported previously.

<u>Planned Progress and Milestones</u>

New opportunities for advancing the field of EHL have been appearing from each discovery. These “targets of opportunity” will be examined as they arise. For example:

1. It seems that the speed dependence of the film thickness depends on the form of the piezoviscous function.
2. Sliding friction in full films can be strongly dependent upon the thermal properties of the liquid. The characterization of the pressure and temperature dependence of thermal conductivity will be a priority.
3. There is presently no single standard definition of “alpha” which characterizes the piezoviscous strength for film-forming for all liquids.
4. A new opportunity has presented to validate an alternative approach to characterizing the shear-dependence of viscosity of lubricating liquids. The Cox-Merz rule states that dependence of viscosity on angular frequency in a periodic shear measurement is the same as the dependence of viscosity on shear rate in steady shear measurement. Hubert Schwarze of Technische Universität Clausthal will provide measurements at high variable frequency using a pressurized torsionally vibrating crystal viscometer for comparison with our measurements in steady shear. If the Cox-Merz rule is validated, we will have a new technique which will extend the viscosity measurement capability to cover nearly the full range of conditions experienced in tribological contacts.

C. Member company benefits

Elastohydrodynamic lubrication (EHL) calculations using the real pressure and real shear dependence of viscosity have begun to reveal previously unsuspected features of the friction and film generating mechanism of liquids. It will soon be possible the answer the question “what properties describe the best lubricant for this application?”

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Test Bed 1: Heavy Mobile Equipment – Excavator

Research Team

Project Leader:	Prof. Monika Ivantysynova, Purdue University, School of Mechanical Engineering, Dept. of Agricultural & Biological Engineering
Other Faculty:	Prof. Andrew Alleyne, UIUC Prof. Wayne Book, Georgia Tech Prof. Paul Michael, MSOE Prof. Kim Stelson, University of Minnesota
Test bed manager/staff:	Anthony Franklin, Edat Kaya
Graduate Students:	Josh Zimmerman, Rohit Hippalgaonkar and Enrique Busquets
Undergraduate Student:	Cheng Lu
Industrial Partners:	Bobcat, Caterpillar, Parker Hannifin, Moog, Husco, Sauer Danfoss

1. Statement of Test Bed Goals

Prior to February 2012

Since the beginning, the goal of this test bed has been to study new system concepts based on throttle-less actuator technology and to demonstrate fuel savings and improved performance and compactness using this technology for the large sector of construction, agricultural and forestry machinery. Also the test bed has served to study and demonstrate effective control strategies for complex multi actuator systems and robot like machine functions, including new human/machine interfaces such as those which provide haptic feedback.

In the past and in conjunction with project 1A.2, dramatic improvements on fuel economy have been studied and demonstrated on the test bed. Also, through project 1A.2, a study for the feasibility for engine downsizing utilizing hydraulic hybrid architectures proved that a significant reduction in engine size is possible while equaling or exceeding the performance capability of the standard version of the machine.

After February 2012

The primary question to be answered for the future is what are the technological barriers, solutions and potential for displacement controlled actuation and hydraulic hybrid technologies to be successful in drastically improving fuel consumption in multi-actuator mobile machines?

Key task definition and functional requirements are:

- Reduce engine size by 50% compared to a standard excavator
- Meet current Tier emission standards
- Maintain standard machine performance

2. Test Bed Role in Support of Strategic Plan

Test Bed 1 (TB1) supports the Center first goal to achieve a drastic improvement in efficiency of existing fluid power applications and to reduce petroleum consumption and pollution. The test bed will be used to demonstrate fuel savings by more efficient fluid power actuator technology and effective machine power management, especially for large and high power equipment. The demonstrated new actuator technology will open new applications in both large scale heavy duty machinery and robots and in human scaled applications like surgery robots or other portable devices where efficient and compact actuator technology is necessary.

3. Test Bed Description

A. Description and explanation of research approach

Test Bed 1, the excavator, was selected to primarily demonstrate potential energy savings, which could be achieved for multi-actuator mobile machines through innovative system designs and advanced control strategies. However, the system is also very suitable for demonstrating the capabilities and performance of individual components developed by projects across CCEFP. Thus, while the focus of the test bed research is to improve the energy efficiency and performance of multi-actuator mobile hydraulic machines, the scope of the test bed also includes demonstrations of individual components and evaluations of their effect on system performance.

The core of the test bed will be based upon the theoretical results from project 1A.2 although technologies developed within the scope of several projects throughout the CCEFP will be integrated onto the test bed for demonstration. All contributing project leaders have been contacted and agreed to the milestone and deliverables timeline listed in the previous section. The contributions are as follows:

- Project 1A2 (Prof. Ivantysynova, Purdue)
    - Controls for optimal power management of multi-actuator DC hydraulic system
    - Controls for energy based trajectory optimization
    - Design and installation of hybrid hydraulic system and downsizing of excavator engine
    - Reduction of hydraulic cooling power due to improved system efficiency
    - Design and installation of smart pump with integrated electronic pump controls
- Project 1B1 (Prof. Ivantysynova, Purdue)
    - Development of next generation of highly efficient and smart variable displacement pumps
- Project 1E2 (Prof. Lumkes, Purdue)
    - Development of virtual variable displacement pump for the excavator low pressure hydraulic system using high speed on-off valves
- Project 1E3 (Prof. Lumkes, Purdue)
    - Development of a high efficiency, high bandwidth, actively controlled variable displacement pump/motor
- Project 1G1 (Prof. Michael, Milwaukee School of Engineering)
    - Testing of energy efficient hydraulic fluids
- Project 3A1 (Prof. Book, Georgia Tech)
    - Tele-operation of the test bed using haptic controls and the Phantom controller
- Project 3D3 (Prof. Klamecki, University of Minnesota)
    - Improved seal design based on adaptive materials

B. Achievements

<u>Achievements prior to the reporting period</u>

- Four variable displacement pumps were installed on TB1 (compact excavator) along with associated sensors and electronic control hardware. All 8 functions (swing, boom, stick, bucket, track drives, boom offset, and blade) are now displacement controlled.
- Control laws for pump displacement, actuator position and actuator velocity were designed and implemented on TB1.
- The DC hydraulic system is operational and was demonstrated by video at the CCEFP annual meeting on October 7, 2009 and in person to a delegation from Caterpillar on November 4, 2009.
- Performance measurements made on the test bed indicated 50% energy savings compared to original LS valve-controlled hydraulic system for soil digging duty cycle.
- Measurement and simulation results have determined that at least 50% of the cooling power requirement in the system could be reduced
- Productivity and fuel test for Test bed 1 with DC hydraulics was conducted in cooperation with Caterpillar, Inc.; Test bed 1 consumed 40% less fuel on average than the standard machine while moving the same amount of dirt and productivity was increased by 16.6%, which lead to a fuel efficiency (tons/kg) improvement of 69%
- The proposed optimal power management algorithm from project 1A.2 was evaluated and fuel efficiency results indicated a 56.4% for a cycle similar to a pipe laying or other realistic tasks for an excavator.
- Through project 1A.2, a feasibility study predicted that a parallel hybrid system could be limited to half of the maximum engine power, suggesting that the engine size could be reduced without sacrificing the productivity of the machine for the truck loading cycle

<u>Achievements during the reporting period</u>

Transition to Hybrid DC excavator system

A new hybrid technology combining the advantages of secondary control (a series hybrid solution) in parallel with DC actuators has been designed for TB1 (see Figure 1). A provisional patent was filed and the full patent application process is underway. A static sizing methodology for the energy storage system, consisting of the pump size (V_1), the motor size (V_2), and the accumulator size (V_0). Equations were derived to size each of these parameters as a function of the minimum operating pressure of the accumulator. This sizing assumes a given energy requirement for the accumulator, a given power requirement for the pump and a given torque requirement for the motor and the resulting sizing for each of these parameters is shown in Figure 2 as a function of the minimum operating pressure of the accumulator. The multi-body dynamic simulation model developed for the test bed was used to simulate the hybrid system [22]. These simulations predict the engine power can be reduced by as much as 50% without loss of productivity for a truck loading cycle and reducing the fuel consumption from the non-hybrid by 20% (52% savings from LS).

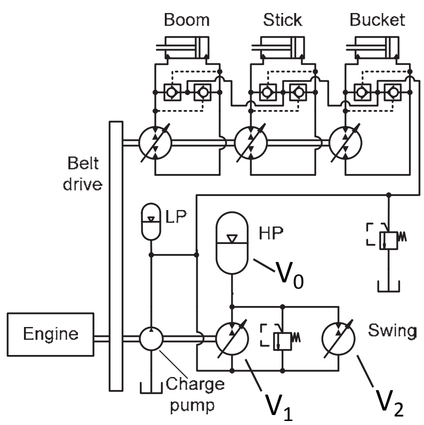

Figure 1: Series-Parallel Hybrid DC Excavator System

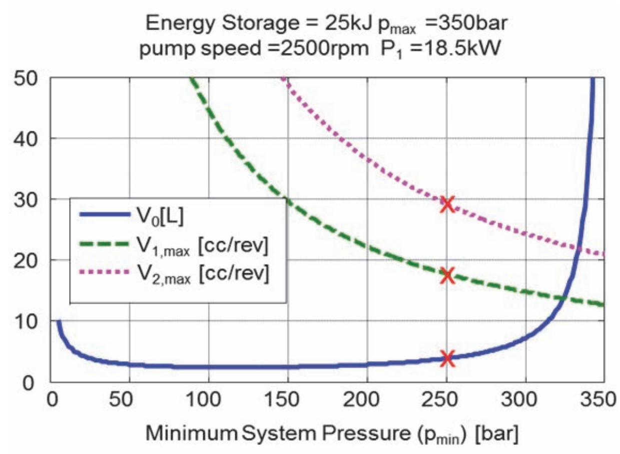

Figure 2: Static Sizing Map

For implementation on TB1 the existing swing motor must be replaced with a variable displacement motor for secondary control. In secondary control, a variable displacement motor is directly connected to a high pressure supply and the motor displacement is regulated to control its torque output. Currently, pump (V_1), which will provide the high pressure for secondary control, is 18 cc/rev. The sizing map (Figure 2) shows that this corresponds to 30 cc/rev for V_2 and a 5 L accumulator for V_0. Unfortunately, the 30 cc unit with the required controls for secondary control was not available, so a 45 cc/rev unit was requested. Simulations have shown that this would not have a significant impact on system performance.

Figure 3: Sauer H1B Series 45 cc Pump

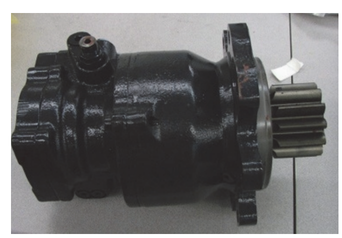

Figure 4: Bobcat Gearbox

The parts required for this transition have been sized and selected, and CCEFP members Sauer-Danfoss and Bobcat have agreed to donate them. The current fixed displacement radial piston swing motor will be replaced by a variable displacement, over-centre and bi-directional axial piston pump/motor. The Sauer H1-B Series 45 cc/rev pump (Figure 3) was selected. Bobcat also donated a gear-box from their latest series of compact excavators, the M-series that allows higher operating speeds for the swing unit required for secondary control (Figure 4).

Cooling Power Reduction

An extensive study along with measurements was performed for the determination of an accurate machine cooling power requirement. The thermal hydraulic behavior of the machine was simulated and measurements were gathered using TB1. Two different cycles were simulated, the first one with 100% cooling capacity installed in the machine and a second one with no cooling capacity. Both cycles were performed under the same conditions. Due to precautionary measures the second cycle is shorter to ensure machine integrity. The results from the study are shown in Figure 5.

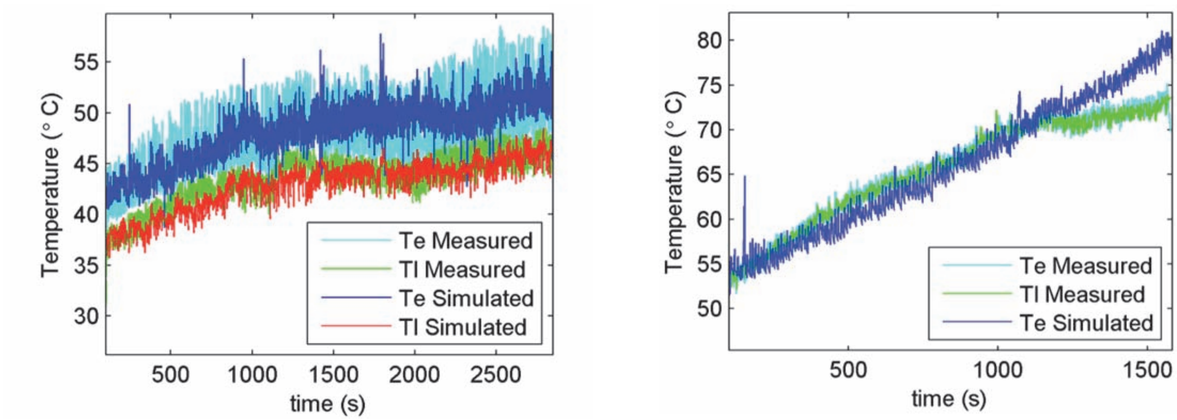

Figure 5: Cooler measured and simulated temperatures. (Left) Full cooling capacity (Right) No cooling capacity

Since the cycle which has no cooling capacity is too short to accurately determine where the temperature stabilizes, the measurement data from both cycles was replicated multiple times to form a 15,000 s cycle. The simulation of such cycle allows for the determination of an accurate steady state temperature and finally of an accurate cooling power requirement. Figure 6 shows the results for such simulation.

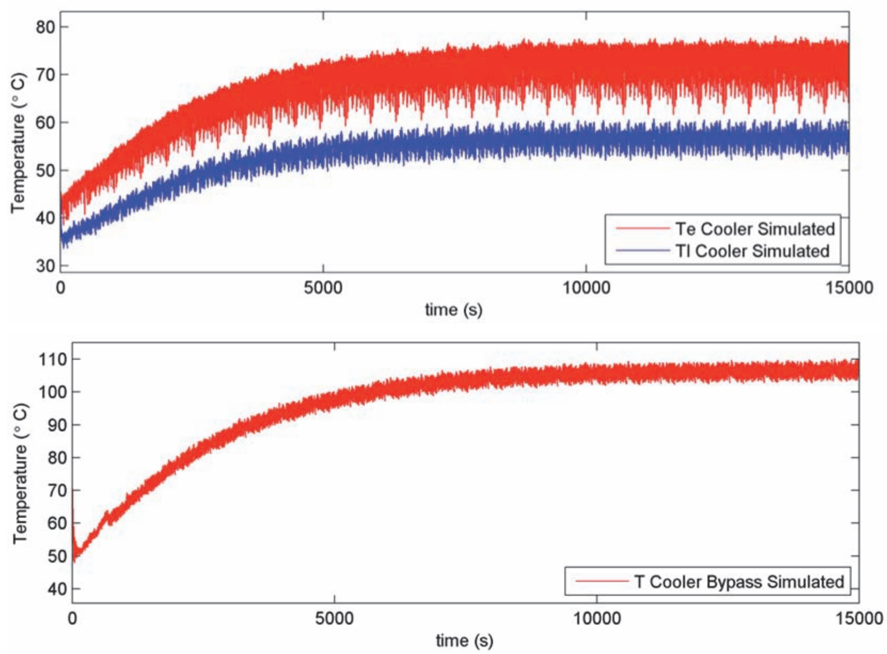

Figure 6: Simulated cooler temperatures for 15,000 s cycles (Top)Full cooling capacity (Bottom) No cooling capacity

Based on these results it has been determined that at least 50% of the current machines' cooling capacity can be removed while maintaining allowable working temperatures for hydraulic multi actuator machines.

National Instruments Central Control and Data Acquisition

Up to the present, TB1 has been controlled utilizing xPC-target, a real time controller developed by MathWorks. At the time of implementation, this system was the state of the art technology and offered many advantages when compared to alternative controllers; however, new systems such as the National Instruments technologies offer improved reliability, functionality, and many advantages in terms of real-time data acquisition and control. The implementation of such system has been started and it is expected to be completed by March 2012.

Preliminary Fault Detection
A preliminary fault detection system with the following goals was implemented in TB1 as part of the summer undergraduate research program. The system allows for the following fault detections:

- Faults in sensors and actuators (relying on both DAQ / control software and hardware)
- Faults for ground (relying on hardware only).
- Display fault to operator so that the operator can react promptly.

Georgia Tech Collaboration
Georgia Tech's Phantom interface resulting from project 3A.1 was successfully tested on TB1 in August, 2011. This interface allowed for tele-operation of the excavator.

Demonstration of Fine Actuator Control
TB1 was tuned and demonstrated for fine actuator control at a Bobcat facility. Several expert operators, systems and test engineers, and marketing personnel tested the excavator to their satisfaction on April 22, 2011.

<u>Planned Achievements following the reporting period</u>

- Conduct on-vehicle experiments
  - Deliverables:
    - Installation of hybrid hydraulics and smaller engine (04/01/2012)
    - Measurements of fuel and performance of hybrid system (06/01/2012)
    - Implementation of optimal controls onto test-bed (04/01/2013)
    - Measurements of fuel and performance of hybrid test-bed (04/01/2013)
    - Demonstration of pump-switching technology on test-bed (01/06/2014)
    - Incorporation of system prognostics schemes (01/06/2014)
- Demonstration of technologies from associated projects
  - Deliverables:
    - Integration of high speed valves from project 1E.2 to create a virtual variable displacement pump for low pressure system and measurements or resulting energy savings. (2012)
    - Comparison of energy consumption of the test bed using standard hydraulic oil and energy efficient fluids developed in project 1G.1. (2012)
    - Integration of next generation of efficient pumps for control of a single actuator (2013)
    - Demonstration of adaptive material for seals from project 3D3. (2013)
    - Installation of next generation smart pump and demonstration of control of a single actuator. (2013)
    - Demonstration and energy measurements for digital pump control of a single actuator using a prototype high efficiency, high bandwidth, actively controlled variable displacement pump/motor (from project 1E.3). (2013-2014)

C. Member company benefits

The results of the work on TB1 are directly transferable to industry and have already offered benefits to member companies. Some of these benefits include:

- Test Bed 1 provides a usable displacement controlled actuator prototype that can be evaluated and tested by industry members. This saves them much time and money compared to if they were to build prototypes themselves in order evaluate the potential of displacement controlled actuation hydraulic systems.
- The results of this test bed have shown that up to 40% fuel savings can be achieved which would clearly be a benefit to OEM companies within the Center.
- The improved efficiencies and potential for reduced engine power made possible by the technologies being developed in this project will help OEMs meet upcoming emission regulations under the US EPA Tier IV nonroad diesel engine emissions standards currently being implemented.

D. Publications pertaining to TB1

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Test Bed 3: Hydraulic Hybrid Passenger Vehicle

Research Team

Project Leader: Prof. Perry Y. Li, Mechanical Engineering, University of Minnesota
Other Faculty: Prof. Thomas R. Chase, Mechanical Engineering, University of Minnesota
Graduate Students: Kai-Loon Cheong, Jonathan Meyer, Zhekang Du, and Henry Kohring
Undergraduate Students: David Rose, Andrew Harm
Industrial Partners: Bosch-Rexroth, Eaton, Parker, Sauer-Danfoss, and others

1. Statement of Test Bed Goals

The overall goal of Test Bed 3 (TB3) is to realize hydraulic hybrid power trains for the passenger vehicle segment which demonstrate both drastic improvements in fuel economy and good performance. As a test bed project, it also drives and integrates associated projects by identifying the technological barriers to achieving that goal. The design specifications for the vehicle include: (i) fuel economy of 70 mpg under the federal drive cycles; (ii) an acceleration rate of 0-60 mph in 8 seconds; (iii) the ability to climb a continuous road elevation of 8%; (iv) emissions levels that meet California standards; and (v) size, weight, noise, vibration and harshness comparable to similar passenger vehicles on the market. Resulting power trains must demonstrate advantages over electric hybrids to be competitive.

2. Test Bed Role in Support of Strategic Plan

Test Bed 3 directly supports goal 2: improving the efficiency of transportation. Efficiency is achieved by utilizing fluid power to create novel hybrid power trains for passenger vehicles. The power trains integrate high efficiency components and hydraulic fluids (Thrust 1), compact energy storage (Thrust 2) and methodologies for achieving quiet operation (Thrust 3) from related CCEFP projects.

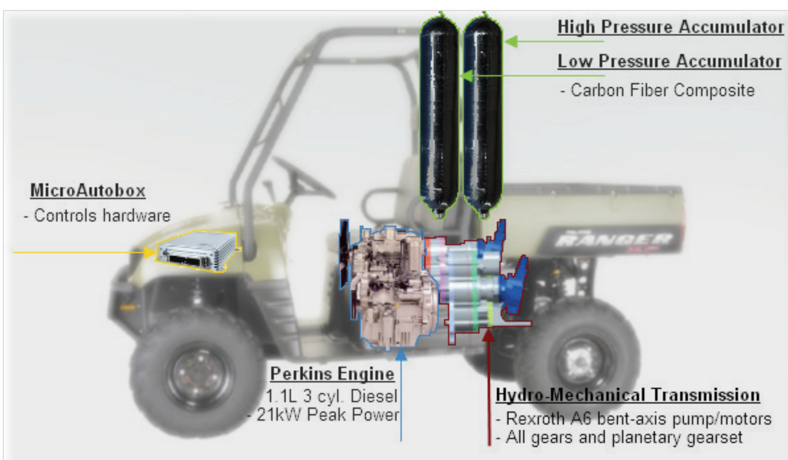

Figure 1: Overview of Test Bed 3 HHPV Generation 1

3. Project Description

A. Description and explanation of research approach

The high power density of hydraulics makes it an attractive technology for hybrid vehicles since they should be able to provide both high mileage and high performance. A few hydraulic hybrid vehicles have been developed for heavy, frequent stop-and-go applications such as garbage or delivery trucks. However, hydraulic hybrids have not yet reached the much larger passenger vehicle market. In order to succeed in this market, hydraulic hybrid drive trains must overcome limitations in component efficiency, energy storage density, and noise. These barriers represent worthwhile challenges that stretch the envelopes of existing fluid power technologies.

Electric hybrids provide the closest competition to hydraulic hybrids. While hydraulic hybrids cannot match the energy density provided by electric batteries, they have superior power density. This is

particularly valuable for regenerating braking energy. Furthermore, hydraulic hybrids eliminate the need for batteries, and thereby eliminate the cost, life and environmental concerns associated with them.
Three possible families of architectures for hybrid drive trains are series, parallel and power split. A series drive transmits all power from the engine to the wheel with hydraulic pumps and motors. This architecture enables running the engine at its most efficient combination of torque and speed; however, it cannot take advantage of the high efficiency of purely mechanical power transmission through a shaft. A parallel architecture augments the engine with a pump/motor. It transmits power to the wheels through the efficient mechanical shaft, but it has less ability to keep the engine at its best operating point. TB3 focuses on power split architectures which are not as well studied as other hydraulic hybrid architectures. Power-splits combine the positive aspects of the series and parallel drive train.

This test bed is currently developing two hydraulic hybrid passenger vehicles, each of which offers unique research benefits. The "Generation 1" (Gen 1) vehicle (Figure 1) was built in-house using the platform of a utility vehicle (a Polaris "Ranger"). The vehicle has been outfitted with a modular power train. This enables experimenting with different pump, motor and energy storage technologies, including those developed in complementary CCEFP projects. However, this vehicle cannot be driven at speeds higher than about 25 MPH due to concerns about vehicle stability.

The "Generation 2" (Gen 2) vehicle is being developed in partnership with Folsom Technologies International (FTI). It is built on the platform of a F150 pickup truck, which has refined vehicle dynamics capable of highway speeds. Its powertrain uses a custom-built continuously variable power split hydromechanical transmission (HMT) developed by FTI which will be complemented with hydraulic accumulators to enable hybrid operation. The powertrain is built as a compact, integrated, self-contained package. However, the integrated package prevents changing the hydraulic pump/motors or instrumenting them individually. Also, the transmission is not optimally sized for hybrid operation and presents some control restrictions when operated in hybrid modes. Therefore, the Gen 1 vehicle is being continued despite the pending availability of the roadworthy Gen 2 vehicle.

B. Achievements

Energy Management Strategy

An energy management strategy that can be applied to the control of either vehicle has been developed [8]. The strategy is based on the three level hierarchical control approach that was developed in previous years [5]. Specifically, [5] describes a Lagrange multiplier approach, which is a computationally efficient method for solving the optimal control problem of energy management for hydraulic hybrid vehicles. It has been shown to be effective for use in power train design optimization [2, 10]. However, this method is limited by two restrictions: (1) the accumulator is assumed to remain at a constant pressure, which is equivalent to assuming that it is infinitely large, and (2) the drive cycle must be known beforehand.

The new strategy, explained in detail in reference [8], overcomes the first restriction. It relates the power loss from using the accumulator to power lost through the drive train for a specific drive cycle. The Lagrange multiplier can be interpreted as the normalized equivalent loss associated with charging and discharging the accumulator. Two alternative implementations of the new strategy are possible. In the first, the Lagrange multiplier is applied to a short time window to continuously optimize operation of the drive train. In the second, the Lagrange multiplier is made a function of the state of charge of the accumulator. The first approach is more computationally intensive in real time, but the second must be optimized in advance before it can be applied in real time. Both alternatives are able to maintain the state of charge of the accumulator within its physical limits with only a 3-5% penalty on fuel economy compared dynamic programming, which is the best, but most computationally expensive, optimization method.

Future work will consider estimating the drive cycle based on statistics to alleviate the need for deterministic drive cycle information.

Achievements and Plans for the Generation 1 Vehicle

Drive Train Redesign: The original Generation 1 vehicle drive train, which was capable of independent wheel torque control, suffered from several limitations that restricted its usefulness. The vehicle's frame would flex enough during driving that chains in the system would sometimes skip teeth. In addition, the planetary gear trains, which combine power from hydraulic pump/motors with engine power at the rear wheels, were undersized, so they were not capable of carrying the full wheel torque specification.

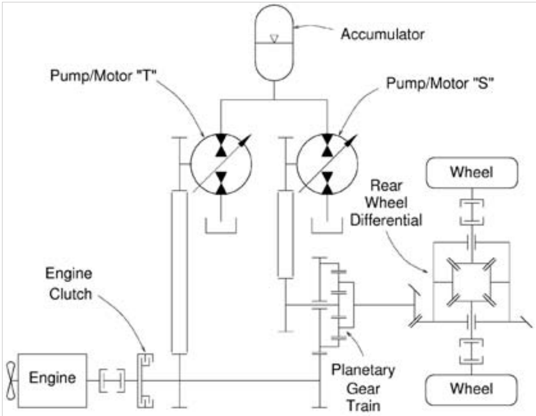

Figure 2: Schematic representation of redesigned Generation 1 HHPV powertrain

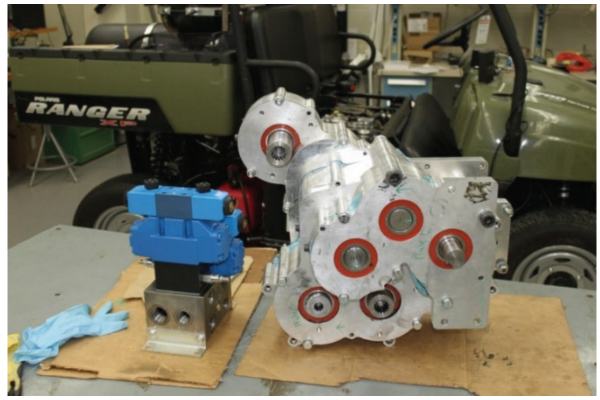

Figure 3: Assembled transmission and valve block

The drivetrain was completely redesigned in 2010. Figure 2 shows schematic of the revised system. The problems experienced in the original drivetrain have been eliminated by using only gears. The drivetrain has been simplified by replacing dual rear wheel "speeder" pump/motors and planetary gear trains with a single "speeder" pump/motor and a stock automotive rear wheel differential. The original axial piston type pump/motors have been replaced with a set of 28cc high efficiency bent axis piston units. Gear ratios and pump/motor sizes have been chosen to optimize fuel economy under EPA driving cycles and to satisfy the acceleration specification. The original high pressure accumulator had developed a leak, so it has been replaced with a new 52 liter carbon fiber composite accumulator.

The transmission assembly was completed in August 2011 (Figure 3) and it was installed in the vehicle in November 2011. Vehicle plumbing was done in collaboration with the Fluid Power Group at Hennepin Technical College (completed February 2012). The vehicle should be ready for testing in Spring 2012.

In parallel with the installation of the transmission, the controls firmware has been upgraded from MATLAB xPC Target to a popular automotive industrial standard system, MicroAutobox, from dSpace. The upgrade will improve robustness and computational power of the controller.

Hydrostatic Dynamometer System: An in-house hydrostatic dynamometer was designed in 2011. The main purpose of building the dynamometer is to provide rapid experimental validation of the hybrid powertrain's performance. The target of this system is to be able to conduct a dynamometer test on a mid-size vehicle through EPA's Urban Dynamometer Driving Schedule and Highway Schedule. The new dynamometer eliminates the need for a test track (neither the Gen 1 nor the Gen 2 vehicles can be driven on public streets) or third-party dynamometer access costs. It allows year-round access and is also more repeatable than outdoor testing, thereby alleviating weather-related delays. It is expected to significantly accelerate the design and tuning of the vehicle controller.

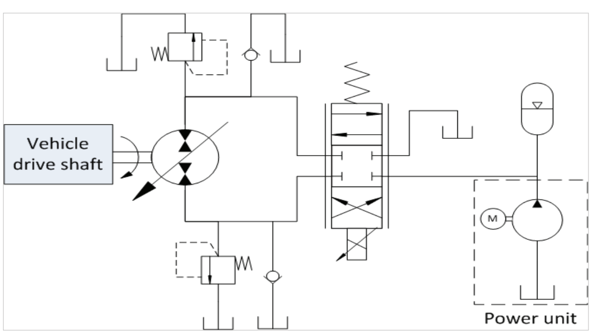

Figure 4: Hydrostatic Dynamometer System Schematic

A hydrostatic dynamometer is chosen for this application mainly due to its capability of both absorbing and motoring. Other advantages include lower cost than an electrical dynamometer and high bandwidth due to its low inertia. The dynamometer is not intended to achieve industrial standard accuracy, but it is targeted to be repeatable.

The dynamometer is shown schematically in Figure 4. The assembly of the dynamometer system is complete. It will first undergo constant load testing to ensure proper hardware operation. Then, computer control will be added to both the hybrid vehicle and the dynamometer. Computer control will enable a 'virtual driver' to drive the test vehicle through any desired speed trajectory with the dynamometer exerting the required load to produce the specified speeds.

Pump/Motor Performance Characterization: Performance maps for the bent axis pump/motors used in the rebuilt transmission of the Gen 1 vehicle were generated by gathering 2000 data points under a variety of operating conditions using a test stand built previously [6]. These maps are necessary to design controllers to optimize vehicle efficiency. Results show significant deviation from manufacturer's data.

Future Plans for the Generation 1 Vehicle: Plans for the Gen 1 vehicle include: testing the redesigned transmission in continuously variable transmission (CVT) mode, integrating the Project 1A.1 high level control strategies, testing the efficiency of advanced hydraulic fluids, determining the efficiency of a virtually variable displacement pump/motor created in Project 1E.1, and testing two novel accumulators. These plans are described in order below.

Initially, the Gen 1 transmission will be operated in a degenerate CVT mode rather than as a full hydraulic hybrid. These experiments have two purposes. First, operation as a CVT serves to prove the effectiveness of the low level control strategy. Second, the fuel economy obtained from operation as a CVT provides a benchmark for comparing improved energy management strategies.

Hybrid operation will be tested next with the implementation of various energy management strategies. Both the modified Lagrange multiplier strategy and Project 1A.1's rule-based control strategy will be implemented. The more complex Stochastic Dynamic Programming (SPD) and Model Predictive Control (MPC) algorithms developed in Project 1A.1 will be implemented and tested in Summer 2012.

A new project which utilizes the Gen I vehicle as a test bed for Project 1G.1 is planned. A synthetic biodegradable ester will be utilized as the hydraulic fluid, which is expected to exhibit higher efficiency at low speeds [11]. The new oil will be compared with a shear stable high viscosity index hydraulic fluid that serves as the baseline oil for the vehicle. The new vehicle dynamometer will be utilized for these tests.

Two new accumulator designs will be tested during the 2012-2013 period. Discussions are underay for testing an efficient accumulator developed by an outside corporation that operates at near isothermal conditions. Also, a prototype of the strain energy accumulator being developed by Project 2C.2 is expected to be ready for testing next year. The strain energy accumulator will have the advantage of constant pressure operation, thereby improving the energy density of the hydraulic powertrain. The modular architecture of the redesigned transmission enables the pump/motors to be changed out.

The bent axis pump/motor used as pump/motor "S" will be replaced with a pulse width modulated fixed displacement pump/motor designed in Project 1E.1 during summer 2013. Simulations have been performed to optimize the gear ratios for the pulse width modulated pump/motor [9]. The actual efficiency using the new pump/motor will be experimentally determined and compared to the baseline efficiency.

<u>Achievements and Plans for the Generation 2 Vehicle</u>
Effort on the Generation 2 vehicle in 2011 has focused on returning the FTI transmission to service, and creating a test plan for generating the efficiency map of the transmission. Each of these efforts is described below. Continuing plans for 2012 are described at the end.

Returning FTI Transmission to Service: Ford has donated an F150 truck for the project. The FTI transmission, hybridized with hydraulic accumulators, will replace the original transmission of the truck. FTI transmission will characterize the efficiency of the transmissions before it is sent to UMN.

Problems with the controls on the FTI dynamometer in early 2010 resulted in the transmission being driven at high speed in reverse. Since no lubricant is supplied in this configuration, extensive damage occurred to both mechanical and hydraulic components in the transmission. While the transmission has now been repaired, residual problems have arisen repeatedly, causing several delays.

Efficiency Map Test Results: The dynamometer tests have produced some results (see Figure 5). The input speed of the transmission is set to 1000 rpm, the transmission ratio is set to a specified value, and then the output load is varied. The results show an improvement in efficiency by using a shear-stable high viscosity index (VI) hydraulic fluid. Standard Automatic Transmission Fluid (ATF) with 5 cSt viscosity is used as a baseline for this test (blue lines in Fig. 5). The high VI hydraulic fluid (15 cSt), provided by Evonik Rohmax (Magenta lines in Fig. 5), reduces volumetric losses within the hydraulic units [11]. The improvement is especially significant at higher transmission ratios as shown in Fig. 5(a). Performance of the transmission is similar with both fluids at overdrive transmission ratios (Fig. 5(b)). These results are consistent with those of Project 1G.1 [12]. The highest efficiency achieved was 92%. A full range of dynamometer tests are essential for fuel economy prediction and the design an optimal controller.

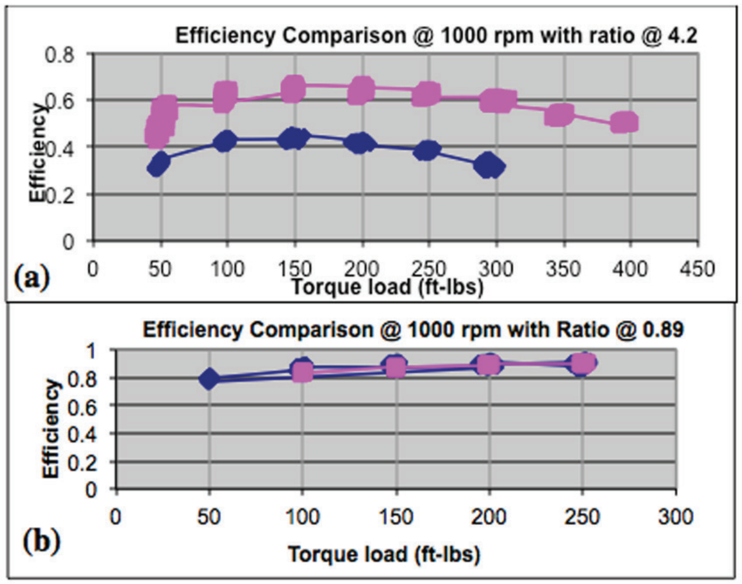

Figure 5: Dynamometer efficiency test results with different fluid comparison (Blue: Standard ATF, Magenta: Rohmax Hydraulic Fluid)

Future Plans for the Generation 2 Vehicle: A new mechanical problem in the FTI transmission is currently being repaired. Following that, the dynamometer tests described above will be completed. The transmission and accumulators will then be installed in the truck. A basic controller will be developed to make the truck operational at FTI. The truck is expected to be delivered to the University of Minnesota in Summer 2012. Development of the full controller can then begin. Much of the controller development that has been completed for the Generation 1 vehicle will be adaptable to the Generation 2 vehicle.

Milestones and Deliverables

- Hydro-static Dynamometer System operational (2/12)
- Test drive of Generation 1 vehicle completed (3/12)
- Efficiency evaluated in CVT mode using Energy Management Strategies (4/12)
- Project 1A.1 integrated by implementing Stochastic Dynamic Programming (SDP) and Model Predictive Control (MPC) (7/12)
- Efficiency of alternative hydraulic oils compared (12/12)
- Performance of alternative hydraulic accumulators compared (3/13)
- Project 1E.1 pump/motor installed as Pump/Motor “S” in Generation 1 vehicle (8/13)
- Project 2C.2 Strain energy hydraulic storage integrated on Gen 1 vehicle (6/14)
- Transmission efficiency characterized with Folsom dynamometer facility (6/12)
- Generation 2 vehicle operational (8/12)
- Controller demonstrated in Generation 2 vehicle (12/12)
- EPA cycle fuel economy evaluation (3/13)
- Initiation of Generation 3 transmission design on mid-size sedan vehicle (1/14)

C. Member company benefits

Practical hydraulic hybrid passenger vehicles would create a new and lucrative market for hydraulic products. Also, development of the HHPV enables members to gain experience in a non-traditional potential market segment which requires very high efficiency at relatively low power.

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Test Bed 4: Compact Rescue Robot

Research Team

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Other Faculty:	Prof. Michael Goldfarb, Mechanical Engineering, Vanderbilt University Prof. Eric Barth, Mechanical Engineering, Vanderbilt University James Huggins, Research Engineer, Mechanical Engineering, Georgia Institute of Technology
Graduate Students:	Hannes Daepp, Rahul Chipalkatty
Undergraduate Students:	Michael Valente, Michael Baker
Industrial Partners:	Bimba, Festo

1. Statement of Project Goals

The goal of this test bed is to demonstrate a compact rescue robot, an example of portable, untethered human scale fluid power applications. Current rescue robots are electric. They can navigate and observe, but do not have the needed force or power to perform rescue operations. Our goal is to develop a mobile fluid-power robot that can operate for a reasonable length of time (2 hours minimum), navigate in difficult terrain (urban disaster site), produce a required force (500 lbs of lift) with precision control and resulting dexterity (sufficient to apply medical test and treatment devices) and transport a specified weight (250 lbs.).

2. Project Role in Support of Strategic Plan

The Compact Rescue Robot occupies the power range from 100W to 1KW in the Center's efforts to apply to the full power range of applications. This range is poorly addressed by fluid power today due to barriers, including a lack of compact power supplies, lack of miniature components and difficulty in tele-operation and control.

3. Project Description

A. Description and explanation of research approach

The existing applications at the human scale are simple one degree-of-freedom devices and generally dependent on large external power supplies. Examples are log splitters and the "jaws of life" for extracting victims of accidents. While the technology is very successful and indicates the potential of fluid power, their applications are limited. Expansion to more degrees of freedom will require untethered power, miniaturized components and remote or autonomous operation. Addressing these issues in the context of fluid power requires an imaginative leap into devices with this collection of requirements. Rescue in disaster scenarios is the leap we have taken. Advances will be relevant to scenarios in the military, construction, agriculture, personal service and assistance to the handicapped and aged. The state of the art in rescue robots has been reviewed by NIST in its periodic examination published in the Rescue Robotics Handbook.[1] All entries are electrically powered, although a few extremely heavy ones have hydraulic manipulators attached. Some have been exercised on a few disaster sites, but have not been capable of an actual rescue. The military (DARPA) is pursuing rescue on the battlefield with a battlefield extraction assist robot (BEAR [2]) and a quadriped field transportation robot (Big Dog [3]), both employing hydraulics. Neither would meet the specifications for Test Bed 4 (TB4).

TB4, residing at the top of the three plane chart, will demand inputs from several projects to be successful. Possible compact power supplies are a free piston engine compressor or pump, or a hot gas vane motor. Safe and intuitive tele-operation will be accomplished through multi-modal haptic user interfaces. The current incarnation of TB4 uses pneumatics, and the free piston engine-compressor is the current project that will be able to provide power in a suitable package.

B. Achievements

In the past years, TB4 has advanced most through the development of two separate platforms. At Vanderbilt, a four-legged crawler actuated by custom miniature high-pressure valves coupled with a Bimba cylinder and linear damper, has been designed and constructed (Figure 1). The robot is controlled via CANbus communication to local microcontrollers at the three joints on each leg. In the past years, the Vanderbilt hardware has been pre-programmed with several low-level gaits for motion across relatively predictable surfaces, including a crawl, a walk, and a trot. The Vanderbilt technology has been intended for use with hardware designed at Georgia Tech: An operator workstation that uses two Sensable Phantom™ haptic joysticks together with an A/V headset to provide feedback to the operator (Figure 2). The workstation maps the two joysticks to the four legs of the robot, granting the operator intuitive control of gait and manipulation motions. Georgia Tech has also developed a two-legged platform for manipulation testing and interim functionality. These platforms are interfaced using xPC Target real-time software.

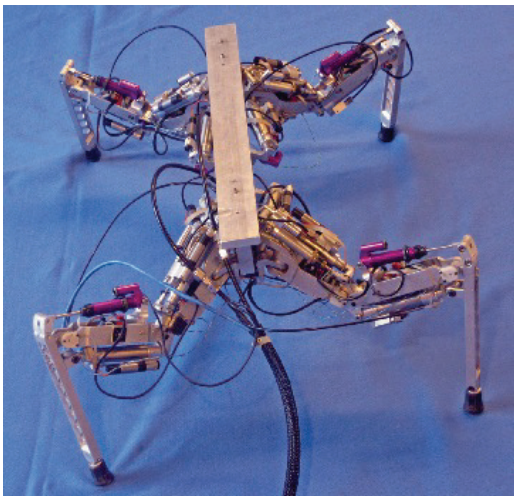

Figure 1: The four legged robot at Vanderbilt.

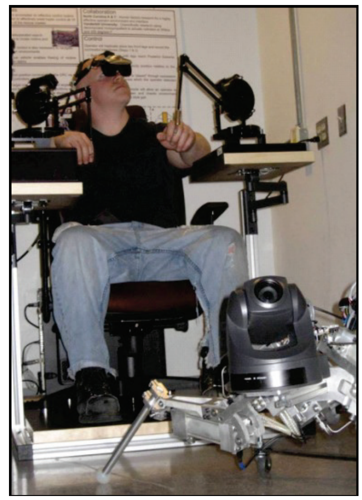

Figure 2: Operator workstation and surrogate robot at Georgia Tech.

<u>Quantifiable Performance Advantages</u>: A study, undertaken at Vanderbilt, used the mass and performance of the TB4 hardware in combination with properties of Center-developed power sources to point out the substantial improvements in energy efficiency that TB4 can bring to mobile human-scale platforms capable of significant manipulation. These studies, shown in Table 1, demonstrate that using fluid-power can greatly reduced the mass of the system, especially as longer run-times are expected. This reduction in weight in turn allows the system to carry larger loads and last for longer periods of time on less energy, thereby validating many of the efforts of TB4 and associate CCEFP projects.

System	**Run Time (hrs)**	**Mass (kg)**	**Extra Weight (relative to lightest version)**
Electric	3	21	10.9
IC Engine Hydraulic	3	23.1	13.0
HGVP Hydraulic	3	17.7	7.6
Free Piston Compressor	3	10.1	0
Electric	10	36.5	24.0
IC Engine Hydraulic	10	25.9	13.4
HGVP Hydraulic	10	25.2	12.7
Free Piston Compressor	10	12.5	0

Table 1: Quantitative Analysis of Rescue Robot Mass for Fluid Power and Electric (Battery) Energy Sources

Hardware Advances: The Vanderbilt robot has been completed, revised for functionality, documented, and brought to Georgia Tech. Because it had originally been developed in a non-real time environment, changes were needed to ensure that the hardware functioned with the operator interface created at Georgia Tech. An undergraduate researcher, Michael Baker, successfully converted several programs developed by Keith Wait at Vanderbilt from non-real time Simulink to xPC Target compatible Simulink. He has thus far converted several of the key components needed for control of the motions, and is in the process of applying these to the pre-programmed gait software that had been developed at Vanderbilt.

Georgia Tech has also improved the two-legged testbed, which is used as simulation verification and as a platform for actuator control improvements. Whereas the four-legged testbed couples a damper with a cylinder to make control of the position control joints simpler on a mechanical level, the two-legged testbed employs pressure sensors and Bimba™ cylinders with position feedback. This allows testing of alternate control strategies, such as passive control. In the last year, substantial improvements have been made to this platform. Control was achieved via the operator workstation, using commands from the haptic joysticks to direct motion of the legs. Electronics were reconfigured for a cleaner, more effective, and robust design. The previous custom cylinders were replaced with Bimba hardware, as noted above, actuated by Festo proportional directional valves. An undergraduate researcher, Michael Valente, redesigned the legs to accommodate the different, more compact cylinders and increase leg motion. The revised design was used in an extensive study for the MS thesis of Hannes Daepp, which explored the modeling of pneumatic systems of this type.

In the future, the Georgia Tech revised design will be completed and implemented with the new cylinders and improved range of motion. This will be used to test control techniques targeted at precise movement of large loads by pneumatically actuated manipulators. Venkat Durbha, a University of Minnesota PhD student advised by Prof. Perry Li, is exploring improved controllers following a passivity based design approach using this version of the test bed.

The Vanderbilt hardware will be completely integrated into the Georgia Tech platform, allowing usage of both the low-level, pre-programmed gaits and the semi-autonomous operator-guided gaits to control the robot. Control techniques similar to the ones used on the two-legged Georgia Tech testbed will be implemented here, too. The robot will also be further equipped with A/V feedback using a pan-and-tilt camera that moves together with operator motions of an associated headset, previously developed at Georgia Tech on the interim test bed. Alternative vision displays have been considered by Hisashi Mizumoto, a visiting graduate student from Kyoto University. This display provides a trailing view of the robot as if the operator were actually following behind the rescue robot. Such a display has been shown to be superior in giving the operator a better understanding of the robot's situation in the environment. It places a computer generated drawing of the robot with current limb angles and orientation in an image taken from the robot a few steps earlier. Technical difficulties with the robot made a complete demonstration of the technique impossible, but the concept applied to legged robots was presented.[4]

Testing Environment: While the low-level gaits used on the four-legged crawler have been tested in several outdoor environments, a necessary component to proving the versatility of the designed hardware is the usage of standardized "challenging" terrains. Using the NIST [1] environments as a guide, a modular terrain block was created that can be configured to illustrate several difficult scenarios. This terrain will be used as a way of verifying the capabilities of the robot and simulation.

Advances in Simulation: Another key component of TB4 is the hardware simulation. The simulation was created in 2008/09, and uses an open source robotics library, courtesy of Seoul National University, known as SrLib. This library lets the user select from a variety of joints and links to create kinematic representations of the desired hardware. These are then placed in a simulated dynamic environment, where joints can be controlled either by actuated forces (representative of the actual hardware), or desired positions (representative of the ideal circumstance). This serves several key functions: First, it enables the testing of higher level control and operator interface features that would otherwise not be possible without a complete and functional robot, control scheme, and environment. Similarly, it allows design of the operator interface in parallel with robot design, which can be tested within the safe and efficient bounds of the simulation.

A third feature of simulation is the result MS thesis work by Hannes Daepp providing a better understanding of joint dynamics and allows simulated testing of new control techniques. This is made possible by coupling the dynamic simulation of the robot with a low-level model of an actuator, consisting of the valve, cylinder, and associated controller. This model, which has been discussed in two papers [4, 5] published/accepted for publication this year, has been designed in Simulink and uses a simple proportional valve model, internal cylinder dynamics, and a friction model to generate a force output. The model has been verified within Simulink to show near equivalent position and pressure behavior as physical systems, using a simple test setup as a measurable comparison. These models have also been implemented together with the simulation, where they have demonstrated similar behavior and drawn conclusions on the effect of naturally occurring time delays in multi-platform simulations on the behavior of pneumatic models.[5]

The dynamic actuator models were then applied to the joints and improved upon to ensure equivalence not only in single-platform simulations, but also when combining multiple software tools for a comprehensive dynamic simulation.[6] The model developed is being used as a basis for advanced controls approaches, starting with establish pneumatic control techniques such as sliding mode control and LQR-derived control. The simulation itself will continue to be used as a guide for interface design and operator control strategies.

<u>Operator Interface and Robot Control</u>: The final key component of the TB4 platform is the operator interface. This interface uses two Phantom haptic joysticks to control the legs of the robot, using a strategy known as the Follow-the-Leader gait to map the user to the robot for gait motions. This strategy allows the user to place the front legs, while to computer decides where to place the rear ones based on knowledge of variables such as stability, safe footholds, and desired direction.[7] Several changes have been made in this interface in the past year. Haptic guidance has been enabled, granting the user a better sense of telepresence through feedback from the joysticks. The interface has also been redefined on a software level, using several modes of operation and internal state machines to provide clarity and ease of use to both the operator and the designer. Several new gaits were added, including haptically guided ones developed at Georgia Tech and the pre-programmed low level gaits provided by Vanderbilt.

The operator interface has also benefited from a higher level controller developed at Georgia Tech that places a penalty on stability (with respect to balance, not actuator performance) of the robot and relates it back to the user in the form of haptic feedback. Thus, the user is guided to move in such a way that the stability of the robot is never compromised. This operator-in-the-loop controller results in more effective overall motion without impeding too heavily on the user’s level and sense of control.

Future plans for the operator interface are primarily focused on applying it to the four-legged crawler and ensuring complete functionality. This entails coupling higher level control approaches that related robot balance and user desired motion with lower level actuator motion control to ensure that the user is able to effectively guide the robot across difficult terrain, as well as move the legs to lift items when necessary.

The priority focus of TB4 in the coming months is integration with the Free Piston Engine Compressor (FPEC), Project 2B.1. In order to demonstrate the viability of this development, the robot must operate without power tethers, meaning the FPEC must ride on the robot. This guides modification of the robot in several ways. First, the entire operation must be made more reliable. Second, we must contend with the possibility that pressures will be lower than the 300 psi value originally conceived as provided by a monopropellant (H_2O_2) power source. We also may need to develop strategies for consuming a smaller volume of compressed gas. In order to stress the utility of a legged vehicle, a means of using two legs for manipulation is being developed. In order to free up the front legs for this purpose, outriggers are being fitted to the robot. When extended, the outriggers will hold up the front of the robot at a height suitable for the manipulation task at hand. Representative of these tasks are administering aid to a victim, positioning a pneumatic jack for lifting a fallen timber, or testing the stability of damaged structures.

Since originally conceived as a test bed for fluid powered devices, both pneumatic and hydraulic, of human scale, alternatives to the current rescue scenario are being considered. The opportunity to work with another Engineering Research Center, the Quality of Life Technology (QoLT) Center at Carnegie Mellon University and the University of Pittsburgh, recently emerged with an appropriate application. The need to transfer patients who are unable to move themselves is very pervasive. Movement from bed to chair, chair to toilet, and back again occurs many times a day for each patient. Multiple people are typically involved in each move and each time the patient and the care giver is prone to injury. The concept is for a device that can function as the member of a team which includes one or more human caregiver. In their studies to date, electrical drives have proven inadequate because of the low force density, where hydraulics excels. Initial contact has been made and a general strategy for cooperation between centers has been devised. The challenges of this application are within the scope of the CCEFP, including the need for quiet, leak free, safe operation in close proximity to people. Compactness is also a priority. In the coming round of funding it is anticipated that hydraulics at the human scale will be directed in this manner, to rescue individuals from the confines of a hospital bed.

TB4 has also supported several undergraduate researchers, as noted throughout the summary of achievements. Allison Byrum, contributed towards control and dynamic modeling of the two-legged testbed. REU Michael Baker and undergraduate researcher Michael Valente both worked on TB4, integrating the Vanderbilt model with the Georgia Tech system, constructing terrain obstacles, and designing and constructing a revised manipulator design for the two-legged platform working with the newly acquired Bimba cylinders.

Finally, work on TB4 has resulted in several additional papers [8, 9] on modeling, simulation, and interfaces of fluid-powered technologies, presented or accepted to be presented at conferences both within and outside the fluid power community.

C. Member company benefits

Festo, Bimba, and Enfield are the companies most closely related to TB4 in its present incarnation. Hydraulics component and fluid companies stand to gain from future advances. The end users and integrators for this power range of devices do not generally exist, but could include John Deere, Toro, Caterpillar and Bobcat.

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Test Bed 6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses)

Research Team

Project Leader:	Prof. Elizabeth Hsiao-Wecksler, MechSE, UIUC
Other Faculty:	Prof. Will Durfee, Mechanical Engineering, UMN Dr. Geza Kogler, Applied Physiology, Georgia Tech
Graduate Students:	David Li, UIUC; Emily Morris, UIUC; Kathy (Braun) Houle, UMN; Jicheng Xia, UMN
Undergraduate Students:	UIUC: Seth Gordon, Princeton (REU); UMN: Derick Monroy (REU), Kali Johnson, Anshul Gupta, Connor Mulcahy
Industrial Partner:	Parker Hannifin (Richard McDonnell)

1. Statement of Project Goals

The goal of this testbed is to drive the development of enabling fluid power technologies to:

(1) Miniaturize fluid power systems for use in novel, human-scale, untethered devices that operate in the 10 to 100 W range.

(2) Determine whether the energy/weight and power/weight advantages of fluid power continue to hold for very small systems operating in the low power range, with the added constraint that the system must be acceptable for use near the body.

Human assist devices developed in TB6 provide functional assistance while meeting these additional requirements: (1) operate in the 10 to 100 W target power range, (2) add less than 1 kg of weight to a given segment of the body, excluding the power supply, and be designed to minimize physical interference during use, and (3) provide assistance from 1 to 8 hours. The focus of this testbed is the development of novel ankle-foot-orthoses (AFOs) to assist gait. An AFO with its stringent packaging constraints was selected because the ankle joint undergoes cyclic motion with known dynamic profiles, and requires angle, torque, and power ranges that fit within the testbed goals.

2. Project Role in Support of Strategic Plan

This testbed facilitates the creation of miniature fluid power systems by pushing the practical limits of weight, power and duration for compact, untethered, wearable fluid power systems. This testbed benefits society by creating human-scaled fluid power devices to assist people with daily activities and is creating new market opportunities for fluid power, including opportunities in medical devices.

3. Test Bed Description

A. Description and explanation of research approach

Problem Statement: In the US alone, individuals who suffer from or have been affected by stroke (4.7M), polio (1M), multiple sclerosis (400K), cerebral palsy (100K) or acute trauma could benefit from a portable, powered, daily wear AFO [1]. For individuals with impaired ankle function, current solutions are passive braces that provide only motion control and joint stability. These designs often fail to restore normal ankle function because they lack the ability to actively modulate motion control during gait and cannot produce propulsion torque and power.

The ideal AFO should be adaptable to accommodate a variety of functional deficits created by injury or pathology, while simultaneously being compact and light weight to minimize energetic impact to the wearer. These requirements illustrate the great technological challenges facing the development of non-tethered, powered AFOs. The core challenges that must be met to realize such a device are: (A) a compact power source capable of day scale operation, (B) compact and efficient actuators and transmission lines capable of providing desired assistive force, (C) component integration for reduced size and weight, and (D) control schemes that accomplish functional tasks during gait and effectively manage the human machine interface (HMI). Therefore, the development of *light, compact, efficient, powered, un-tethered AFO systems* has the potential to yield significant advancements in orthotic control mechanisms and clinical treatment strategies.

State-of-the-Art: Passive AFO designs are successfully used as daily wear devices because of the simplicity, compactness, and durability of the designs, but lack adaptability due to limited functionality. To date, powered AFOs have not been commercialized and exist as research laboratory devices constructed from mostly off-the-shelf components [2, 3].The size and power requirements of these components have resulted in systems that require tethered power supplies, control electronics, or both [4, 5].

Research Approach: We are following a roadmap for developing portable fluid powered AFO devices with increasing complexity and performance requirements. In 2008, the design and construction of an energy-harvesting AFO that selectively restricted joint motion using a pneumatically-driven locking mechanism was completed [6]. The lessons learned during this design process were used to accelerate the design of a portable fluid powered AFO. Using a systems engineering approach, the fluid powered AFO system has been divided into four subsystems that align with our core system challenges: power supply, actuator/valving, structural shell, and control system (electronics, sensors, and HMI). The subsystems have target specifications that must be met to realize a fully functional device. The power supply must weigh < 500 g, produce at least 20 W of power, run continuously for ~ 1 hour, and be acceptable for use near the human body. The actuator and valving must weigh < 400g and provide a minimum of 10 Nm of assistive torque at a reasonable efficiency. The structural shell must weigh < 500 g, be wearable within a standard pair of slacks (fit inside a cylinder with 18 cm OD), and operate in direct contact with the body. The control system must control the deceleration of the foot at the start of stance, permit free ankle plantarflexion up to mid stance, generate a propulsive torque at terminal stance, and block plantarflexion during swing to prevent foot drop; all in a robust and user friendly manner. In 2008, University of Minnesota students were added to the testbed team to examine opportunities to increase propulsion torque and power through high pressure hydraulics. Over subsequent years, Illinois and Minnesota teams have been using the portable fluid powered AFO platform to explore lower pressure pneumatics and higher pressure hydraulics, respectively, as promising technology paths for tiny fluid power systems suitable for untethered human assist devices.

B. Achievements

Portable Pneumatic AFO (PPAFO) UIUC

In 2010, we constructed our first generation portable, powered, ankle-foot orthosis (PPAFO) using off-the-shelf commercially available components to demonstrate device feasibility (Figure 1). The Gen1.0 PPAFO is an improvement over state-of-the-art passive and active systems [4, 5] because it provides subject-specific motion control and torque assistance without tethered power supply or electronics. A U.S. patent covering the technology embodied by the PPAFO is being filed [7]. Description of the PPAFO system hardware, characterization of system performance, and preliminary results from both healthy and impaired walkers were formally detailed [8]. The Gen 1.0 PPAFO can generate up to 12 Nm at 115 psig and run continuously for about 40 min at 30 psig for both plantarflexor and dorsiflexor assistance, falling short of the more than 1 hour of use requirement. Preliminary component and operational efficiencies of the Gen1.0 PPAFO system were examined [9]. An overall system efficiency of 19% was calculated from the product of the two efficiencies (component: 50% and operational: 39%).

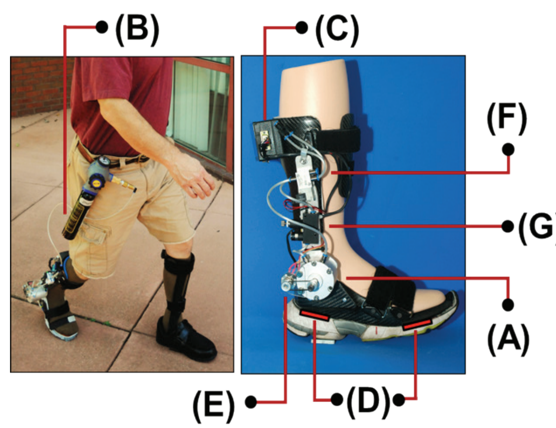

Figure 1: Gen1.0 portable powered ankle foot orthosis (PPAFO) shown assisting an impaired walker (Left). The rotary actuator (A) is powered using a compressed CO_2 bottle (B) worn by the subject on the waist. Onboard electronics (C), force sensors (D), and an angle sensor (E) are used to control the solenoid valves (F). A second pressure regulator (G) is used to modulate the magnitude of the dorsiflexor assistance.

In 2011, in a continued effort to improve the overall efficiency of the PPAFO, we investigated the thermal impact of the gas intake and possible means to save fuel by thermal regulation. These efforts were started by a summer REU student and continued in our collaboration with a CCEFP E&O sponsored yearlong capstone senior design team in Mechanical Engineering at Bradley University in Peoria, Illinois.

Due to the thermal cooling nature of liquid CO_2, gas temperature and output pressure decrease over time, which result in reduced thermal efficiency of the system. We hypothesized that gas intake at a higher temperature can decrease fuel consumption and increase run duration. The summer REU study determined that utilizing longer tubing submerged in room temperature water resulted in fuel savings up to 7%. The capstone team has studied the thermal impact on the CO_2 bottle during continuous use in two extreme cases (isothermal and isentropic). They have determined that 17% of the CO_2 in the bottle is wasted by being converted to dry ice in an isentropic scenario. Preliminary results suggest that sufficient heat exchange to maintain the bottle at room temperature will increase fuel savings. Solutions to improve the overall system efficiency will continue to be investigated in 2012, e.g., warming gas intake, heat exchanger on the bottle, recycling compressed exhaust gas, and harvesting of human energy during gait.

During the beginning of 2011, we realized that the compact integrated rotary actuator developed by MSOE in 2010 would not be a viable design. Therefore, in efforts to continue to driving a technology pull for a compact rotary pneumatic actuator, we have pursued three avenues. (1) MSOE has been tasked to improve their design – they are exploring improving the original design and also have proposed a new design based on bellow technology. (2) The UIUC TB6 team has been collaborating with CCEFP industry partner Parker Hannifin to utilize their expertise in pneumatic rotary actuators to design a custom product. (3) The Bradley University capstone design team is also exploring the development of a rotary actuator that incorporates a gear system. In 2012, we expect to see prototypes from each of these efforts and will be incorporated into a new (Gen 1.1) PPAFO prototype.

One of the challenges in making the PPAFO a portable gait assistance device is its ability to provide assistance accordingly at various scenarios (level ground walking, stairs ascending/descending). In 2011, we began work in gait mode recognition. There are two critical aspects of this problem: first, the original sensor array on the PPAFO has limited sensing ability (only heel and toe contact forces and ankle joint angle), which do not contain enough information to reliably detect gait mode. Second, the gait mode has to be recognized at the earliest possible time to prevent potential misfiring and loss of balance risk to the wearer. To address these limitations, we used a 6DOF inertial measurement unit (IMU). Preliminary results successfully estimate the 3D motion of the PPAFO, and recognize different gait modes at the very beginning of the mode change (Figure.2). Future work includes proper actuation scheme implementation to assist functional gait and use of IMU data to track the foot during seating therapy.

Figure 2: Stair ascending gait mode recognition. Real-time 3D PPAFO position was tracked using a 6DOF IMU at the toe.

We have targeted the PPAFO to be a portable device, which can operate outside of the laboratory or clinic for at-home assistance or therapy. During 2011, we have refined potential applications for the PPAFO. Along with CCEFP faculty and students at NCAT on Project 3A3, we are pursuing the development of a computerized clinician user interface that can be used to track the patient's medical history, therapy progression, and ultimately allow for recording and monitoring of the PPAFO performance while on the patient and also clinician programming of the PPAFO attributes. Additionally, we now seek to investigate the efficacy of the PPAFO as an integrated and portable rehabilitation robot in a seated ankle rehabilitation therapy for acute post-stroke patients. Recent studies using a powered, but tethered, AFO have been found to successfully improve ankle function and gait performance in post-stroke patients (Roy 2011). NCAT is also assisting with the development of an interactive game (using a serious gaming approach) to be used by the patient while using the PPAFO as a joy stick to navigate the game.

We continue to work with several CCEFP projects, which are contributing to the testbed to improve subsystem performance given target specifications. Center technologies are being used to address subsystem limitations, including the miniature HCCI air compressor power supply (Project 2B2), an integrated shell with thermal management abatement (Project 2D), and the pneumatic MEMS proportional valves to improve compactness (Project 2F).

Hydraulic AFO (HAFO) activity at Minnesota:
In 2009, we identified high pressure hydraulics as a promising technology path for tiny fluid power systems suitable for applications such as the untethered AFO. In 2010, theoretical analysis of tiny hydraulic systems was conducted to understand their limits [15]. Additionally, a compact fluid power EHA system was assembled with LiPoly battery, Maxxon motor, Oildyne cartridge pump and Bimba hydraulic cylinder, to demonstrate the capabilities and limits of using off-the-shelf components.

During 2011, theoretical analysis of tiny hydraulic systems was continued to identify the design guidelines.

- Efficiency models for the piston and vane pump were built and verified, which enabled us to compare these two types of pumps in a complete system. The analysis showed that a piston pump gives a lighter AFO weight due to its higher efficiency. So we decided to use a piston pump as the pumping component of the hydraulic AFO system.
- Further analysis showed that the power unit of the hydraulic AFO has to be separated from the actuator unit to achieve a better performance than the equivalent electromechanical system. This suggests an AFO architecture that is similar to a miniaturized hydraulic excavator.

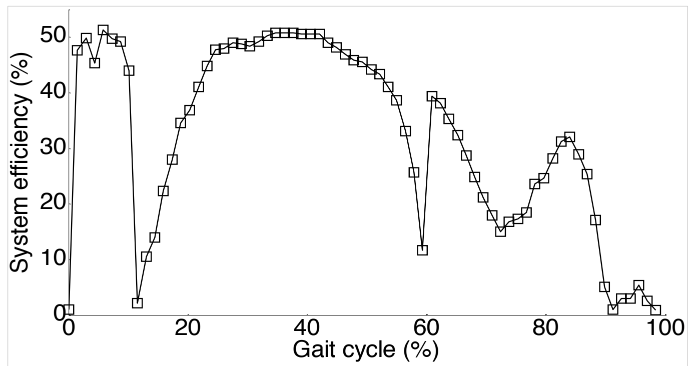

Figure 3: Hydraulic AFO system efficiency

- The design of a complete hydraulic AFO system that was targeted to recover the full ankle joint function is underway. Analysis results showed that a gearhead was mandatory to minimize the weight of the system. The efficiency of the system, which is determined by the efficiency of two hydraulic cylinders, two hydraulic hoses, a hydraulic pump, a planetary gearhead, a brushless electric motor and a LiPo battery, was modeled, as shown in Figure 3.

Publications
During 2011, work associated with Test bed 6 has resulted in 6 peer-reviewed publications in scholarly journals, 8 conference proceedings, and 1 trade journal article.

Plans, Milestones and Deliverables for Next Year
PPAFO:

- (Spring 2012) Gait mode recognition testing for different scenarios (level ground, ramp, stairs ascending/ descending); PPAFO pneumatic system component efficiency analysis and design guidelines; Subject testing for energy recycling scheme
- (Summer 2012) Construction of Gen 1.1 PPAFO with enhanced shell, wireless microcontroller, OTS proportional valves; Demonstration of HCCI engine prototype and thermal management structure,

  clinician user interface, and MSOE, Bradley, and Parker rotary actuators on PPAFO; Explore pressure & air flow control for torque & rotational velocity control
- (Winter 2012) Investigate iterative learning control of the PPAFO actuation
- (Spring 2013) Demonstration of MEMS proportional valves on PPAFO; Preliminary integration of rehabilitation application interface with serious gaming

HAFO:

- (Spring 2012) Full system efficiency analysis of ver2 HAFO, for dynamic load application; Finish customizing piston pump (modified from Oildyne pump) and cylinders

- (Summer 2013) Fully functional and integrated ver2 HAFO; Design a control strategy for ver2 HAFO

Plans, Milestones and Deliverables for Next Five Years

Over the next five years of this testbed, we will future develop the current technologies and explore new ones to continue driving new technology needs.

Continued work:

- Pneumatics: Push development of compact proportional valves, actuators, power sources; energy harvesting through recycling and human power harvesting.
- Hydraulics: Push development of compact fluid power EHA system; Improve actuation speed
- Clinical applications of portable powered AFO: computerized clinician user interface; seated ankle therapy for post-stroke rehabilitation

New areas:

- Develop comprehensive and accurate mathematical model of complete pneumatic AFO system. Use model to create pneumatic AFO devices that optimize efficiency with the goal of increasing run-time and decreasing weight.
- Create new knowledge on a high pressure pneumatic AFO device where "high pressure" means around 500 psi. First assess this technology with comprehensive mathematical models, then validate the models by designing, constructing and evaluating physical devices.
- Continue to research tiny hydraulic devices operating at about 2,000 psi. Critical needs include (1) validated, comprehensive mathematical models that can be used to predict behavior of hardware, (2) concepts for generating pressurized fluid from either battery or hydrocarbon fuel stored energy sources, (3) comprehensive assessment of safety when high pressure tiny hydraulic devices are used in close proximity to humans.

C. Member company benefits

New technologies that miniaturize current components such as power sources, actuators, and valves will be developed. This could spawn new markets for miniature fluid power systems. During 2011, we have been in discussion with a CCEFP industry partner regarding licensing the PPAFO technology.

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Education and Outreach Program of the Center for Compact and Efficient Fluid Power

Education and Outreach Core Project Portfolio	University Education	K12 Education	Industry Education
Thrust A: Public Outreach **Bringing the message of fluid power to the general public**			
A.1 Interactive Exhibits Fluid Power	x	x	x
A.3 Multimedia Educational Materials	x	x	x
Thrust B: Pre-College Education **Bringing fluid power education to K-12 students, with a focus on middle and high school**			
B.1 Research Experiences for Teachers (RET)		x	
B.2 Project Lead The Way		x	
B.3 Hands-on Fluid Power Workshops	x	x	x
B.4 gidaa STEM Programs		x	
B.5 BRIDGE Program	x	x	
Thrust C: College Education **Bringing fluid power education to undergraduate and graduate students**			
C.1 Research Experiences for Undergraduates (REU)	x		
C.2 Fluid Power OpenCourseWare	x		x
C.3 Fluid Power Projects in Capstone Design Courses	x		x
C.4 Fluid Power in Engineering Courses	x		
C.5 giiwed'anang North Star Alliance	x		
C.6 Fluid Power Simulator	x	x	x
C.7 Fluid Power Basic Training (on hold)	x		
C.8 Student Leadership Council (SLC)	x	x	x
C.9 Undergraduate Research Diversity Supplement (URDS)	x		x
C.10 Graduate Research Diversity Supplement (GRDS)	x		x
C.11 Innovative Engineers	x	x	x

Thrust D: Industry **Making connections between CCEFP and industry**			
D.1 Fluid Power Scholars/Interns	x		x
D.2 Industry Student Networking	x		x
D.3 Advanced Fluid Power Engineering Workshops (on hold)	x		x
D.5 CCEFP Webcasts Series	x		x
D.6 Publications	x	x	x
Thrust E: Evaluation **Measuring CCEFP program effectiveness**	x	x	x

Education and Outreach Affiliated Projects *Projects < 1 Year in Funding*	**University Education**	**K12 Education**	**Industry Education**
Zephyr Wind Energy Teacher Training by KidWind *Alyssa Burger, CCEFP*		x	
Hand Powered Water Pumps for Developing Countries: International Service Learning to Cameroon, Africa *John Lumkes, Purdue University*		x	

Proposed Education and Outreach Projects	**University Education**	**K12 Education**	**Industry Education**
High School Research Opportunity Program (HSROP) *Alyssa Burger, CCEFP*		x	
Hydraulic Fluid Power for Fuel-Efficient School Buses *Michael Leamy, Georgia Institute of Technology*	x	x	x
Fluid Power Educational Smart-App for Mobile Devices *John Lumkes, Purdue University*	x	x	x

Introduction

This document summarizes the Education and Outreach (EO) projects that are active in the Engineering Research Center for Compact and Efficient Fluid Power (CCEFP).

The mission of the Education and Outreach Program of the NSF Center for Compact and Efficient Fluid Power (CCEFP) is to develop research inspired, industry practice directed fluid power education for pre-college, university and practitioner students; to integrate research findings into education; to broaden the general public's awareness of fluid power; and through active recruiting and retention, to increase the diversity of students and practitioners in fluid power research and industry.

The vision of the Education and Outreach Program is a general public that is aware of the importance of fluid power and the impact of fluid power on their lives; students of all ages who are motivated to understand fluid power and who can create new knowledge and innovate; industry that capitalizes on new knowledge to lead the world in fluid power innovation; and participants in all aspects of fluid power who reflect the gender, racial and ethnic composition of this country.

The strategy of the Education and Outreach Program is to develop and deliver high quality projects that wherever possible capitalize on existing, broadly distributed education and outreach networks to maximize program impact; to develop projects that can be replicated and/or adapted by other educators and program leaders for new audiences; and to leverage and coordinate the accomplishments of individual Education and Outreach projects to facilitate the progress and successes of other Education and Outreach projects.

Organization: The EO program is divided into thrusts, each containing several projects. Some projects are focused on STEM education with examples drawn from fluid power when appropriate, while other projects are specific to fluid power technology and its application.

Diversity: The CCEFP is striving to change the face of fluid power by providing opportunities for a diverse population to become involved in fluid power--women, underrepresented minorities and those with disabilities. The CCEFP is committed to recruiting, engaging and retaining these diverse audiences in its programs: university faculty, undergraduate and graduate students; pre-college students and teachers; and students of all ages through its outreach activities. Some of these efforts are conducted through the offices and programs at each of its seven universities; others are realized through the work of the Center's affiliated organizations, including NSBE, LSAMP and the National GEM Consortium; still others are coordinated by the CCEFP staff.

Thrust A: Public Outreach

The purpose of this thrust is to bring the message of fluid power—its ubiquity and its potential—to the general public.

Project A.1 Interactive Exhibits on Fluid Power

The staff of the Science Museums of Minnesota (SMM) is creating, field-testing and displaying exhibits that demonstrate basic attributes of fluid power and highlight CCEFP research. These exhibits serve as models for dissemination to other science museums, student centers at technical universities, and/or lobbies at fluid power companies. Fluid Power exhibits currently on display at SMM include an axial piston pump, hydraulic hybrid car, hydraulic transmission, super-mileage car and a hydraulics lab. SMM has also developed a fluid power activity kit that volunteer staff use to introduce visitors to fluid power concepts.This project is now being extended in order to engage undergraduate engineering students, enrolled in Senior Capstone Design courses, in developing prototypes of interactive exhibits relevant to fluid power, working with industry mentors wherever possible. These prototypes will be further developed by SMM staff and eventually housed in industry and university sites around the country. [Project Leader: J Newlin, SMM]

Project A.3 Multimedia Educational Materials

The CCEFP continues to reach out to audiences outside academic communities through the production and dissemination of videos. *Discovering Fluid Power*, a 25-minute television documentary produced by Twin Cities Public Television and the CCEFP, is shown nationwide on public television channels and is available for viewing at www.ccefp.org. Plans are in place for its use by Project Lead The Way teachers as a part of PLTW's *Principles of Engineering* course for high school students. An additional video on wind power is under development. *Teaching Fluid Power*, a CCEFP-produced video for pre-college teachers, also appears at the CCEFP website and segments of videos relevant to the fluid power industry are posted on YouTube. [Project Leaders: Kim Stelson, UMN; Alyssa Burger, UMN]

Thrust B: Pre-College Education

The purpose of the education thrust is to bring fluid power education to K-12 student audiences, with a focus on middle and high school students.

Project B.1 Research Experiences for Teachers (RET)

As a part of the National Science Foundation's RET program aimed at improving science, technology, engineering and mathematics (STEM) education, the CCEFP's RET program enables teachers in pre-college schools to introduce fluid power to their students, drawing on their summer-long experiences in CCEFP research labs. Every summer the CCEFP hosts at least six RET teachers at CCEFP universities. A special CCEFP RET focus is recruiting teachers from high schools participating in the Project Lead The Way program. [Project Leader: Alyssa Burger, UMN]

Project B.2 Project Lead The Way (PLTW)

Project Lead The Way (PLTW) is a not-for-profit national program dedicated to developing STEM-relevant courses for middle and high students.The National Fluid Power Association (NFPA) and PLTW are affiliated organizations within the CCEFP and, together with the Center, form a three-way partnership for this project. Initially, NFPA funding enabled the inclusion of new fluid power content in several of PLTW's high school and middle school curriculum modules. Now, faculty from CCEFP and engineers from CCEFP member companies serve as subject matter experts for PLTW, reviewing curriculum relevant to fluid power and identifying opportunities where new content can be inserted. CCEFP faculty and students are working with PLTW to develop the hands-on fluid power lab activities to complement PLTW curricula as well as approaches to assist PLTW teachers in using these materials. In addition, PLTW teachers participate in the CCEFP RET program. The newest cooperative effort in this partnership is the development of a fluid power simulator (see project C6). [Project Leader: Will Durfee, UMN]

Project B.3 Hands-On Fluid Power Workshops

Fluid power is most easily understood by students of all ages when accompanied by hands-on experiments. This project develops hands-on workshops based on the apparatus and curricula developed in projects B.3a and B.3b, as well as incorporating other fluid power hands-on activities. The developed apparatus demonstrates principles of fluid power, and student and instructor guides are written for specific education levels. Targeted audiences for the workshops, all of whom can lead various student groups in these learning experiences, include CCEFP faculty and students, SMM staff, CCEFP industry member engineers and technical college and pre-college classroom teachers. [Project Leader: Alyssa Burger, UMN]

B.3a Hands-on Pneumatics Workshop: The goal of this project is to create curricular material and portable lab kits for use in hands-on workshops about pneumatics. The 43,000 high school students participating in FIRST Robotics make up one of the targeted audiences. The curriculum for the workshop will eventually include: (1) a basic hands-on tutorial, (2) an advanced workshop tailored to experienced FIRST Robotics teams, (3) web-based self-learning material, and (4) a module for PLTW teacher training workshops and for PLTW courses. Member companies are contributing by donating or offering discounts for kit parts. Materials have been field tested with FIRST Robotics teams in Atlanta and Minneapolis, with PLTW teachers, with RET teachers and with groups of high school students. Workshops and kits will be disseminated nationwide through engineers from CCEFP member companies and CCEFP faculty. [Project Leader: Will Durfee, UMN]

B.3b Portable Fluid Power Demonstrator and Curriculum: The goal of this project is to develop a demonstration kit and accompanying activity-based curriculum that teaches the basics of fluid power in a way that is complex enough to provide challenging learning experiences for teachers and students, yet simple enough to be economical, reliable and portable. The design and construction of the kit is finished and an accompanying curriculum is posted at the CCEFP website. The kit includes materials needed to assemble a complete working mini-excavator, using water hydraulics or pneumatics, which can be built and implemented in classrooms or hands-on displays. Fabrication instructions for the apparatus have been developed for dissemination throughout CCEFP and its member companies. [Project Leader: John Lumkes, Purdue]

Project B.4 gidaa STEM Programs

The CCEFP, NSF's National Center for Earth-Surface Dynamics and the Fond du Lac Tribal and Community College together organize a number of activities under the name of gidakiimanaaniwigamig (Our Earth Lodge, in Anishinaabe) for K-12 students, with a particular goal of interesting and retaining Native American students in STEM subjects. [Project Leaders: Alyssa Burger, UMN]

B.4a gidaa K-12 STEM Camp: The consortium offers camps for students in 3rd through 10th grade. Offered as a day-camp, once per month, the camps provide students with a mix of lab science and field science experiences. Program highlights include an introduction to the scientific method and a focus on Native American Indian culture. [Project Leaders: Holly Pellerin, Fond du Lac]

B.4b gidaa odaangiina anaangoog (Shooting for the Stars) Robotics Program: Under the gidaa STEM Program umbrella, staff and teachers have introduced K-12 robotics day and after-school curricula using Lego Wedo-Webots, NXT Kits, Vex Kits and Textrix kits and software. In order to extend this program to new audiences, a robotics teacher training program has being added in 2011, involving six additional teachers in the gidaa impact area. [Project Leaders: Cameron Lindner, SouthRidge School, Alyssa Burger, UMN]

Project B.5 BRIDGE Project
BRIDGE (Building Resources and Innovative Designs for Global Energy) is a project spearheaded by the National Society of Black Engineers (NSBE), the Innovative Engineers (IE), and the American Indians in Science and Engineering Society (AISES) student groups at the University of Minnesota. Since 2006 the BRIDGE Project has impacted students and communities across the state of Minnesota and around the world. Participants create designs for renewable energy systems from scrap, waste, or found materials. They use these designs as an easily understandable foundation for outreach for at-risk students in inner-city schools and on Native American Reservations. The project brings engineering concepts and methods to life for at-risk students. The BRIDGE Project uses these designs to implement renewable energy systems in remote communities. This work is done in collaborations with groups in developing nations. [Project Leaders: Paul Imbertson, UMN]

Thrust C: College Education
The purpose of the education thrust is to bring fluid power education to undergraduate and graduate engineering student audiences. The vision of the college education program is that all undergraduate mechanical engineering students in this country be exposed to fluid power in their required curriculum.

Project C.1 Research Experiences for Undergraduates (REU)
The objective of National Science Foundation's REU program is to encourage top undergraduate students nationwide to continue their studies as graduate students in STEM fields. This interest is kindled by providing selected students with a summer experience in a university research lab. The CCEFP supports this initiative by hosting at least 14 REU students each year, a minimum of two per university site. The Center's REU program includes an orientation to and instruction in fluid power technology, its applications and the research activities of the CCEFP, followed by work in the Center's research labs. The CCEFP actively recruits women, students with disabilities and underrepresented minority students for its REU program. [Project Leader: Alyssa Burger, UMN]

Project C.2 Fluid Power OpenCourseWare
The purpose of the Fluid Power OpenCourseWare (FPOCW) project is to create, digitally publish, disseminate and use high quality college level teaching materials in fluid power. The material can be used in fluid power elective courses, but more importantly can be inserted into core engineering courses taken by all students. Materials exist in the lecture notes, problem sets and lab exercises of CCEFP faculty, as well as faculty outside the center. A small number of engineering undergraduate students nationwide will take fluid power elective courses, but all students in mechanical and related engineering ABET accredited degree programs take required courses in fluid mechanics, thermodynamics, system dynamics and machine elements. These courses cover topics that form the core of fluid power yet currently do not contain fluid power applications. One special project is the creation of college-level mini-books on various aspects of fluid power. The initial mini-book on fluid power system dynamics targets the introductory course on system dynamics taken by every undergraduate mechanical engineering student in the United States. Typically, the course text has a chapter on fluid system dynamics, but that chapter does a poor job of covering the system dynamics of modern fluid power. Future mini-books will target the introductory fluid mechanics course and the introductory thermodynamics course, with the latter introducing pneumatics from a thermodynamics viewpoint. The FPOCW project has the potential of exposing every undergraduate mechanical engineering student in the United States and around the world to fluid power. [Project Leader: Will Durfee, UMN]

Project C.3 Fluid Power Projects in Capstone Design Courses
All ABET accredited undergraduate engineering degree programs have a capstone design experience where fourth-year students work in teams for one or two semesters on a practical design project. The objective of this project is to work with fluid power companies to sponsor and actively engage with students in capstone design projects with fluid power content. This is a collaborative project with the Science Museum of Minnesota and the National Fluid Power Association, both affiliate organizations of the CCEFP. [Project Leader: Will Durfee, UMN, Jim Van De Ven, UMN]

Project C.4 Fluid Power in Engineering Courses

The goal of this project is to develop new, semester-length undergraduate and graduate courses in fluid power, and to include substantial content on fluid power in existing undergraduate and graduate courses. [Project Leader: Jim Van De Ven, UMN]

Project C.5 giiwed'anang North Star Alliance

In conjunction with the University of Minnesota (UMN) National Center for Earth-surface Dynamics, the Office of Diversity and Outreach in the UMN College of Science and Engineering, and the North Star LSAMP Alliance, the CCEFP coordinates, sponsors and hosts all activities of the giiwed'anang North Star Alliance. Goals of the Alliance include: 1) engaging students in STEM-related activities, 2) interesting students in pursuing their education at two-year and/or four-year schools and universities, 3) developing a regional student cohort network. The network involves students in Minnesota, Wisconsin, North Dakota and South Dakota. The project also strives to grow and nurture the student and professional regional chapters of the American Indian Science and Engineering Society (AISES). [Project Leader: Alyssa Burger, UMN]

Project C.6 Fluid Power Simulator

For undergraduate mechanical, aerospace and agriculture engineering students, high-school students in a PLTW program and professionals new to fluid power, the CCEFP fluid power simulator (FPS) will be a medium-fidelity, essential-capability, easy-to-use, freeware simulator of fluid power systems. Unlike existing commercial simulators, the CCEFP FPS will be targeted towards the education market, but will maintain technical rigor. [Project Leaders: Chris Paredis, Georgia Tech and Will Durfee, UMN]

Project C.7 Hydraulics Basic Training (on hold)

Work cooperatively with CCEFP industry members and member universities to develop a basic hydraulics training curriculum that can be easily disseminated to CCEFP engineering graduate students and incoming faculty members. Development of a complementary pneumatics curriculum is also planned. [Project Leader: Brad Bohlmann, UMN]

Project C.8 Student Leadership Council (SLC)

The Student Leadership Council is an independent board of the CCEFP. (It is listed here since its budget is included under the Education and Outreach program umbrella.) .The SLC's current and proposed activities support the education and outreach program of the Center and impact all students within the CCEFP. An SLC officer is a member of the Center's Executive Committee and participates in the meetings of the Industrial Advisory Board. The SLC is managing a travel and project grant program used to support student travel between CCEFP institutions and to companies engaged in the fluid power industry. The travel grant program will foster greater communication between the research institutions as well as between students and industry partners. In addition, SLC members are responsible for the Center's webcast program, and provide recommendations and guidance for other Center programs including the annual student retreat and various networking opportunities with industry [Project Leaders: Alyssa Burger, UMN; SLC officers]

Project C.9 Undergraduate Research Diversity Supplement (URDS)

The Center's Education and Outreach program is committed to proving opportunities to broaden the participation of underrepresented students in undergraduate engineering programs through this Undergraduate Research Diversity Supplement to current CCEFP research projects. [Project Leaders: Alyssa Burger, Kim Stelson, UMN]

Project C.10 Graduate Research Diversity Supplement (GRDS)

The Center's Education and Outreach program is committed to broadening the participation of underrepresented students in engineering programs through channels including the NSF Graduate Research Diversity Supplement (GRDS) to current CCEFP research projects. This effort is complemented by the CCEFP's own Undergraduate Research Diversity Supplement (URDS). (See E&O Project C.9.) Ideally, the CCEFP's URDS would positively influence a student to enter graduate school within the Center where a faculty advisor, in turn, would apply for the NSF GRDS award. [Project Leaders: Alyssa Burger, Kim Stelson, UMN]

Project C.11 Innovative Engineers (IE)

The Innovative Engineers (IE) student group was formed in 2010 by engineering students at the University of Minnesota who were inspired to actively pursue renewable energy solutions for people in remote and developing areas. IE fills a need at the university by providing a space where engineering students can take part in active pedagogy, learning and honing their engineering skills by working on real projects. The CCEFP and the Eolos Wind Research Consortium have partnered with the Innovative Engineers Student Group to promote student engagement and to bring an awareness of fluid power to the student engineering community by sponsoring projects with fluid power components. [Project Leaders: Paul Imbertson, UMN]

Thrust D: Industry

The purpose of the industry thrust is to build bridges of communication and knowledge transfer between engineering faculty and their students and the corporate stakeholders of the fluid power industry—manufacturers, suppliers, distributors, and their customers.

Project D.1 Fluid Power Scholars/Interns

Internship programs bring opportunities for engineering students to gain practical experience working in the fluid power industry while providing host companies with access to a diverse pool of talented engineering students. Working with industry, the CCEFP created the the Fluid Power Scholars/Intern program and launched it in the summer of 2010. Sixteen Fluid Power Scholars/Interns have been named to date through the cooperative efforts of faculty, industry, and CCEFP staff. Fluid Power Scholars/Interns receive a scholarship to an intensive three+-day instructional program in fluid power, taught at the Milwaukee School of Engineering's Fluid Power Institute, and then join a corporate supporter of the CCEFP for a paid summer internship. The Scholars/Interns Program is open to undergraduates who have successfully completed at least two years in an accredited engineering program in the United States. [Project Leader: Alyssa Burger, CCEFP]

Project D.2 Industry Student Networking

The goal of this project is to provide CCEFP students with opportunities to network within the fluid power industry in a variety of ways. In doing so, there are multiple benefits to students and companies: all students will better understand the fluid power industry and the applications of fluid power technology; companies will be able to meet, interact, learn about Center research, and discuss potential employment opportunities with students, benefiting from the fresh insights and perspectives that students bring to these these exchanges; students' efforts to find internships and later job opportunities in the fluid power industry will be facilitated. Channels utilized in this project include company tours, poster sessions, and resume exchanges as well as additional opportunities that extend the Center's outreach to more students and companies. [Project Leader: Alyssa Burger, CCEFP, Student Leadership Council]

Project D.3 Advanced Fluid Power Engineering Workshops *(on hold)*

The objective of this project is to facilitate knowledge transfer between CCEFP faculty and the Center's industry supporters (with a special focus on engineers in design and manufacturing positions) as well as other faculty and their students. These workshops enable individual faculty members in the Center to share their expertise in advanced topics relevant to fluid power, relating it to current and potential research activities. The first workshops were held in conjunction with a key industry trade show in March 2011. Future workshops will be held via webcasts and in conjunction with meetings generating strong industry and university attendance. [Project Leader: Dewey Tinderholm, CCEFP Industrial Liaison Officer, UMN]

Project D.5 CCEFP Webcast Series

The CCEFP hosts bi-weekly webcasts, each with two to three presenters describing either research projects or discussing Center-wide programs such as education an outreach projects, strategic planning initiatives, special topics, or project evaluation. The webcasts are open to all CCEFP students and faculty and to all CCEFP member companies. The webcasts are an important means for Center-wide communication and knowledge transfer. [Project Leader: Alyssa Burger, CCEFP, Student Leadership Council]

Project D.6 Publications

Publications included here include press releases and articles detailing results of research and education/outreach projects. Targeted publications for the publications include those intended for industry-specific audiences, as well as the engineer and educator communities. [Project Leader: Kim Stelson, UMN]

D.6a Press Releases and Articles: The Center works with the editorial staffs of these publications, providing material of general interest based on the Center's research, education and outreach activities. (Formerly Project A.3b, which focused on industry, this project has been broadened to include journals of professional organizations.)

D6.b Academic Journal Special Issues: Subject-specific, issue-length coverage of research topics central to CCEFP.

Thrust E: Evaluation

The purpose of the evaluation thrust is to provide comprehensive and rigorous evaluation of the CCEFP education and outreach projects and programs.

Administration of the Education and Outreach Program

The E&O Program is lead and coordinated by Education Program Director Paul Imbertson and Education Outreach Director Alyssa Burger. The Directors report to CCEFP Director Kim Stelson. Additionally, Principal Investigators of specific projects contribute to program direction and implementation.

The Education and Outreach Network (EON), comprised of one representative from each of the seven universities., facilitates communication among the CCEFP sites and is a core working group for a number of E&O initiatives.

Responsibility for fluid power education and outreach rests with every CCEFP participant. Each research and test bed project in the Center has an E&O component. The E&O activities of individual research projects are reported in the project update reports.

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Project A.1: Interactive Exhibits

Project Team

Project Leader: J. Newlin, Director of Physical Sciences, Engineering & Math, Science Museum of Minnesota

Other Personnel: Science Museum of Minnesota Team:
Forrest Price, Master Prototyper
Peder Thomson, Master Prototyper
Cliff Athorn, Head of Exhibit Production
Chris Burda, Senior Exhibit Developer

1. Project Goals and Description

The purpose of this project is to educate the public about fluid power and the CCEFP through creating and displaying exhibits that convey the basic message of fluid power as well as exhibits that highlight CCEFP research. Prototypes and exhibits developed and field-tested at the Science Museum of Minnesota, an organization affiliated with the CCEFP, will serve as models for dissemination to other science museums around the world.

2. Project Role in Support the EO Program Strategy

SMM will support CCEFP by developing products for public exhibition that will reach Minnesota museum audiences and that can be replicated and/or adapted by other educators and program leaders for new audiences. These products will introduce public audiences to the concepts behind fluid power and the possibilities for future industrial and social applications of fluid power.

3. Achievements

SMM has pursued three approaches to date: working with senior undergraduate mechanical engineering classes to develop exhibit prototypes as capstone design projects, working with a team of high school students on a supermileage car, and building display prototypes in SMM's exhibit shop.

Capstone Projects

In 2007, 2008, and 2011, small teams of University of Minnesota seniors developed exhibits as part of their capstone design courses. The first (2007) was an exhibit about a hydraulic scheme for regenerative braking in vehicles. The second (2007) was a an exhibit that introduced two basic principles of fluid mechanics - the use of fluids to transmit force and the development of mechanical advantage through coupling cylinders of different diameters. The third (2008) was a comparison of the use of pulse-width modulation for control of electrical lighting circuits with its use for controlling fluid power applications. The fourth (2008) was a prototype of a water-based fluid power experiment lab for use by museum visitors. The fifth (2011) was an exhibit that demonstrates the power of hydraulics to assist human effort and shows a model of a hydraulic-powered ankle orthosis. The first of these exhibits has been on display at the museum since 2007 (Figure 1). Another inspired the hydraulics lab exhibit (see description below) on display since 2010 and now being improved by museum staff. Plans for this coming year include rebuilding the hydraulic assist exhibit so it can be placed on the museum floor.

High School Project

In 2008, an SMM prototyper (Price) worked an advisor to a team of students from Eden Prairie High School who developed a hydraulic hybrid Supermileage Car. The team ran the car, powered by a 1 cylinder gasoline engine controlled to pump fluid into an accumulator at its most efficient speed and torque, in a supermileage contest and achieved a mileage of 170 miles per gallon. Since the contest did not include stops and restarts, the hydraulic regenerative braking system did not come into play. Students improved the car after the contest and then worked with SMM staff to prepare it for display (Figure 2). It has been on the exhibit floor since 2008.

Museum Projects
SMM prototypers have produced two finished exhibits that are now on display on the museum floor. One of these is a hydraulic variable torque transmission with accumulator-based energy storage (Figure 3). The second is a working cut-away variable-displacement axial piston pump arranged to pump tall streams of clear hydraulic fluid (Figure 5). These exhibits have been on display since 2008.

SMM has also completed a Hydraulics Lab (Figure 4) that allows museum visitors to set up their own fluid power demonstrations and experiments. This bench consists of a large shallow work surface mounted on legs at table height. Visitors use clear water tubes with quick-connect fittings to build fluid power circuits that include pumps and reservoirs; check valves and spool valves; flow indicators; raised tanks and pressurized accumulators; and actuators of various kinds.

There has been an expanding group of Fluid Power exhibits on display at the Science Museum of Minnesota since 2008. They now include Axial Piston Pump, Hydraulic Hybrid Car, Hydraulic Transmission, Supermileage Car, and the Hydraulics Lab. In late fall, 2010 SMM reinstalled these exhibits, placing the Hydraulics lab inside a low-walled "corral" and including a table with a set of four new exhibits that define simple hydraulic circuits:

- At Hydraulic Crane, visitors employ a pair of different sized pistons connected by a clear hydraulic line to lift a weight on a movable arm – either quickly with much effort or slowly with much less effort.
- At Hydraulic Circuit, visitors pump water out of a reservoir, through a check valve, into and out of a piston pump, through a second check valve, and back into the reservoir.
- At Accumulator, visitors use a piston pump to force water from a reservoir through a spool valve into an accumulator. By changing the spool valve position, they allow the pressurized water to flow through a flow meter back into the reservoir.
- At Double Acting Cylinder, visitors pump water from a reservoir through a four-port spool valve into a double acting cylinder, forcing it to move a piston that rings a bell. By changing the spool valve, they pump the piston back again.

SMM has refurbished and installed an exhibit that uses a very low friction pneumatic bearing to support a large Double-weight Pendulum. This consists of a granite spherical cap supported by air flowing into a spherically-ground concave base. A rod extends vertically from the center of the cap on which visitors may adjust a weight to change the vibration frequency of this double weight pendulum.

SMM has also developed a Fluid Power Activity Kit that museum volunteers use to introduce visitors to concepts in fluid power. Visitors experiment with a long-tube water level, syringe systems filled with air and water, a hydraulic jack, an "airzooka" that sends a puff of air ten feet, and a set of air-powered cylinders and valves that toss and catch tennis balls. This activity is presented regularly at the Experiment Gallery Activity Station.

Exhibit Brochure
SMM prepared an illustrated proposal of four exhibits that could be replicated for other museums, for CCEFP partner university student centers, or for the lobbies of major fluid power companies. These exhibits include Axial Piston Pump, Hydraulic Transmission, Hydraulic Hybrid Car, and Hydraulics Lab. Replication of single exhibits is fairly expensive with a range of $35,000 to $60,000 each. Producing multiple copies could significantly reduce the cost of single exhibits.

In late August 2010, SMM joined Eric Lanke of the National Fluid Power Association in a presentation and discussion of potential fluid power exhibits at Milwaukee's Discovery World science center. These exhibits could be supported by NFPA companies and at least partially built by NFPA volunteers.

SMM worked with CCEFP E&O staff to develop a proposal for a capstone design competition that would involve mechanical and electrical engineering students from all CCEFP partner universities.

4. Plans, Milestones and Deliverables

Spring of 2012. SMM is working with a team of 6 senior mechanical engineering students to develop an exhibit that demonstrtes compressed air storage of wind power. The students will build a small wind turbine that operates an air compressor that pumps air from the atmosphere into a constant pressure accumulator. Air stored in the accumulator is then used to turn an air motor connected to a pancake coil generator. An ancillary display links this system to an open accumulator wind power energy storage project now being researched by CCEFP engineers.

SMM prototypers are reengineering parts of the Hydraulic Lab and building a new hydraulic-powered carousel to add interest and challenges for visitors.

Summer 2012 – Spring 2013. SMM will improve its Hydraulic Lab design and installation to increase visitor satisfaction and learning. SMM will work with E&O staff on a project to involve CCEFP senior engineering students in building fluid power exhibits for their own student centers and local science centers. SMM will plan a capstone design project for a new fluid power exhibit that introduces museum visitors to current CCEFP research.

Future Years. SMM will continue adding to its collection of exhibits about engineering with fluid power both through developing exhibits in its shops and through working with Capstone Design teams. SMM will work with CCEFP and NFPA staff to develop a practicable plan to distribute core exhibits on fluid power to science centers associated with CCEFP partners, to participating university student centers, and beyond.

Figure 1: Exhibit of a hydraulic scheme for regenerative braking in vehicles.

Figure 2: The Eden Prairie High School hydraulic hybrid Supermileage Car.

Figure 3: Hydraulic variable torque transmission with accumulator-based energy storage.

Figure 4: The Hydraulics Lab allows museum visitors to set up their own fluid power demonstrations and experiments.

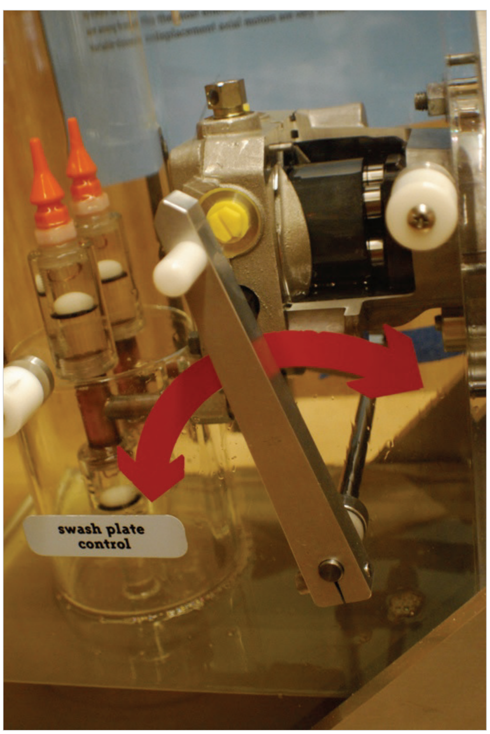


Figure 5: Functional cut-away variable-displacement axial piston pump.

Project A.3: Multimedia Educational Materials

Project Team

Project Leader: Kim Stelson, CCEFP Director

Other Personnel: Alyssa Burger, CCEFP Education Outreach Director

Industrial partners: Eric Lanke, National Fluid Power Association
Tom Trow, Twin Cities Public Television
Eolos Wind Research Consortium
John Lumkes, Purdue University

1. Project Goals

The CCEFP continues to reach out to audiences outside academic communities through the production and dissemination of videos. As evident by the frequency with which it has been shown over the past few years on public television outlets nationwide, the Center's *Discovering Fluid Power* has been successful in this outreach effort. In the same vein, at least one additional video is planned, and segments of CCEFP work appear on YouTube. Additionally, a three-part video, *Teaching with Fluid Power*, produced by the CCEFP, is available at the Center website.

2. How Project Supports the EO Program Strategy

The CCEFP's Education and Outreach Program supports the transfer of knowledge among the Center's many constituents. Here, using video as the communication medium, pre-college teachers, students and teachers as well as the general public are the focus for knowledge transfer.

- General public, teachers and students: *Discovering Fluid Power,* a 25-minute documentary video, offers a basic introduction to fluid power technology and features footage, with accompanying narratives, which highlight the many applications of hydraulics and pneumatics. The production and distribution of *Discovering Fluid Power* is an excellent example of another CCEFP strategy—seeking out strong partners to help and support the Center's education and outreach program. Produced in collaboration with the National Fluid Power Association (NFPA is an affiliate organization of the CCEFP) and Twin Cities Public Television (TPT), *Discovering Fluid Power* is a companion to NFPA's video, *Fluid Power: A Force for Change,* which focuses on careers in fluid power. Much of the application footage in both videos was contributed by the Center's industry supporters and by fluid power trade associations around the world. Students and faculty of the CCEFP as well as industry representatives provide the narratives for both videos. *Discovering Fluid Power* and *Fluid Power: A Force for Change* are appropriate for upper elementary, middle and high school students as well as for adult audiences.
- Pre-college teachers: *Teaching with Fluid Power* is a three-part video developed to help classroom teachers devise lessons and hands-on activities that will help students better understand fluid power technology. While particularly well-suited for use in Project Lead The Way classrooms, the content of this video can be easily used by all teachers of middle- to high school age students.

3. Achievements

- Since its full release in 2008, *Discovering Fluid Power* has been broadcast nationwide. Airings in Los Angeles, Milwaukee, Madison, Denver, Minneapolis/St. Paul, and Kent (Ohio) are confirmed. It is also repeatedly viewed through a PBS network (six stations) in Minnesota. It is likely that the video also has been aired on other stations; however, it is difficult to keep this information complete and current. While no new promotional efforts have been launched in 2011, the following summary of promotions and successes, as reported in our 2009 Annual Report, continues to be current:
  - The video is broadcast through the Research Channel--on broadcast rotation in many communities as well as on-demand.

- NFPA is continuing its efforts to market the two videos: to additional public television stations nationwide, to its sister trade associations worldwide, and to its network of technical college and university members. Several of these schools have volunteered that *Discovering Fluid Power* offers a useful and entertaining introduction to hydraulics and pneumatics.
  - TPT is a partner in promoting the video, too, through its magazine (85,000 readers) and e-blasts (45,000 viewers).
  - The Internet provides an important distribution channel beyond e-blasts. *Discovering Fluid Power* can be viewed at no cost at the Center's website (www.ccefp.org), at Project Lead The Way's Virtual Academy (an online resource site for PLTW teachers), and at www.nfpa.org. Excerpts are available on YouTube.
  - CCEFP as well as NFPA staffs have mailed copies worldwide to schools, universities, businesses and individuals. The Center's university and industry networks also have access to the video and report using it in classes and for student on-campus visits as well as for employee orientations.
  - Copies are being included with the hands-on workshops discussed at B.3.
- *Teaching with Fluid Power* is available, at no charge, to the public at the CCEFP website. It is also a resource for Project Lead The Way.

4. Plans, Milestones and Deliverables

- *Discovering Fluid Power*: The producers at Twin Cities Public Television, along with industry and Center reviewers, took special care to insure a long "shelf life" for this video. With that said, the video will soon be five years old hence active promotions have tapered off. While the video will continue to be available to many audiences through the above channels, active efforts will focus on getting as many copies as possible into classrooms. In doing so, the CCEFP will capitalize on links to industry and educational websites; promote the video as a learning tool to middle school, high school, technical college and university educators; and engage the Center's universities and other partners in using their networks to promote and distribute the video.
- **Proposed: *Discovering Wind Power***: The CCEFP and the Minnesota Channel of Twin Cities Public Television (TPT) will collaborate to create a video documentary that will communicate ongoing research in wind energy to public audiences. The program, for both broadcast on public television stations and for extensive distribution via the internet and DVDs, will explain the science and technology behind the efforts to capture and use wind energy, and bring viewers to the edge of the latest discoveries and ideas involving wind power. *Discovering Wind Power* will build on the impressive success that a similar CCEFP produced program, Discovering Fluid Power, had among both public audiences and in classrooms. The 30-minute program will be produced by Minnesota Channel Productions of Twin Cities Public Television, and will be broadcast at least five times per year by way of all six PBS stations in Minnesota. The management team, including scientists and engineers from the CCEFP, STEM and evaluation experts at the U of M, members of the EOLOS Wind Energy Research Consortium at the U of M, and staff from the Science Museum of Minnesota will contribute content suggestions, direction and focus for the production, scientific oversight, and the identification of appropriate individuals to be interviewed. Photographs, video and film clips from other sources will be collected by CCEFP for making this an even richer production. TPT staff will be responsible for all aspects of the television program itself, from its high-definition production through its broadcast and online distribution. Ultimately, CCEFP will own the copyright, and will be able to use the program beyond its broadcast for any purpose that CCEFP staff may consider appropriate, including distribution of DVDs to communities for public discussions, providing copies on request to educators for

classroom purposes, creating additional sites for web streaming, or even broadcasting the program on PBS stations in other cities.

- **Proposed: Fluid Power Education App** for smart-phones and tablets: The CCEFP is proposing the development of a mobile “App” for smart-phones and tablets. The fluid power based app will use physics based models to complete a game. For example, users could be giving a set system pressure and modify the cylinder areas, stroke lengths, valve sizes, etc., to launch a projectile or smash objects. Component costs would scale by performance (size, speed, etc.), so when a maximum cost is imposed, or reflected in the score, users can decide what “design” tradeoffs provide the best performance. Selecting “question mark” icons while choosing components would pop-up a small “tutorial” on how that component functions, some basic equations, etc. Once a certain score is reached, additional components (pump, accumulator, etc.) can be purchased. Educational Impact: The target audience is 6-12 grades, although the App could be downloaded by all ages. Depending on the underlying physics models it could be distributed through pre-engineering programs in high schools, and/or used to supplement PLTW curriculum. At the basic level the game should be fun to play, with the motivation for “learning fluid power” embedded in the ability to score more points. The impact is hard to access in a general sense, since only the number of downloads is known, not how the App is utilized. In a school setting it would be possible, and beneficial, to develop a pre- post-use skills survey to assess the knowledge gained, and the perception of the game.

6. Member Company Benefits

- The videos are a promotional as well as an educational tool for the fluid power industry and for the Center. The cooperative efforts between industry, NFPA and the CCEFP in preparing both videos combine to tell their own success story. Now, industry leaders as well as everyone in the Center have every reason to continue to cooperate in distributing both videos to as many audiences as possible.
- The fluid power industry benefits as more teachers and students learn about fluid power. By using video as a communication tool, the CCEFP is able to reach many audiences in many locations.

Project B.1: Research Experiences for Teachers (RET)

Project Team

Project Leader:	Alyssa Burger, Education Outreach Director, CCEFP
Other Personnel:	CCEFP faculty advisors

1. Project Goals

The CCEFP's RET program enables teachers in pre-college schools to introduce fluid power to their students, drawing on their experiences in CCEFP research labs. In this six-week summer program, teachers learn first-hand about fluid power basics and are engaged in research through their work in the Center's university network. With these experiences as a foundation, teachers develop research-inspired curriculum modules to bring back to their classroom. Special efforts are made to recruit Project Lead The Way (PLTW) teachers to this program in geographic locations where the Center's RET program is hosted and where PLTW has a presence.

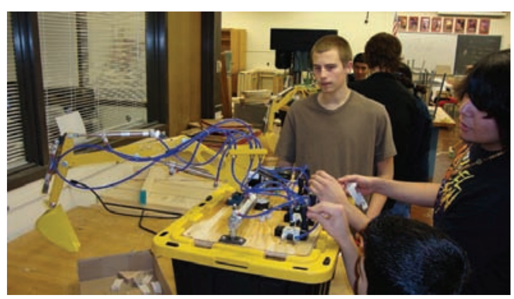
2. How Project Supports the EO Program Strategy

The RET program is an example of the CCEFP's strategy to maximize program impact: one teacher reaches many students; many teachers reach many classrooms. And, in sharing the curriculum modules they develop, RET teachers support another key CCEFP strategy—development of projects that can be replicated and/or adapted by other educators for new audiences. The work of RETs can be used by a host of teachers who have not participated in the RET program.

3. Achievements

- Six teachers participated as RETs in summer 2011, the fifth year of the CCEFP RET program: two at the University of Minnesota, two at Vanderbilt and two at Purdue University.
- The CCEFP requires that all RET participants submit their classroom curriculum to the TeachEngineering.com website which is a repository of evaluated and reviewed curriculum modules. The CCEFP is the only ERC to have RET curriculum modules successfully accepted to the site. The three curriculum modules that have been accepted are named below; six more are under review.
    - Hybrid Vehicle Design Challenge - Joel Daniels, Vanderbilt, CCEFP RET 2009
    - Fun with Air-Powered Pneumatics - Jacob Givand, Jeffrey and Melissa Schreifels, University of Minnesota, CCEFP RET 2009
    - Fluid Power Basics - Brian Bettag, Purdue, CCEFP RET 2009

  The CCEFP encourages each RET to beta test the curriculum modules s/he has developed in the school year following the RET experience, modifying as necessary, and then submitting it as a final module at the end of the academic year. TeachEngineering.com then helps to review, edit and craft the curriculum for a well-rounded module. The modules are indicative of state standards as well.
- A 2011 RET team at Purdue University continued to work on the Fluid Power Demonstrator Kit and Curriculum under the guidance of Professor John Lumkes. (See EO Project B.2 of this report for additional details.) Professor John Lumkes, along with two teachers and a number of high school students, will visit Bangang in Cameroon, Africa in May 2012. Students will assist local villagers with the task of retrieving fresh water by using fluid power technology and equipment.



    - **Summary:** Students learn about the basic fundamental concepts of human power pumping, which include defining key terms, history of pumps, and appropriate technology.
    - **Engineering Connection:** Engineers have developed many pumps over the years to be used depending on the availability of supplies and location of water supply.

Understanding how the basics of water pumping work; will allow continued improvement on the quality of life when engineers and technologists investigate how to use this technology to become more efficient, sustainable and cost effective.

- **Learning Objectives:** After this lesson, students should be able to: Identify different types of hand pumps; Identify and explain basic components and functions of a working pump; Differentiate between different kinds of pumps for certain tasks; Create and test a new pump.
- **Africa Trip:** Professor Lumkes and the RETs will be taking a group of senior students from McCutheon high school to the village of Bangang in Cameroon, Africa, May 2012. Students will assist local villagers with the task of retrieving fresh water by using fluid power technology and equipment.

- A 2011 RET / Faculty team at the University of Minnesota worked on enhancing fluid power-relevant content in Project Lead The Way's *Principles of Engineering Course*, helping teachers to present this content to their students in newly effective ways. At this writing, results of that work are confidential (to protect the PLTW curriculum) but note that the enhancements will be used in PLTW teacher training across the country.

- A 2011 RET leveraged the work of the Innovative Engineers student organization at the University of Minnesota to build a hands-on 10W wind turbine which can be used as a create-design-build demonstration inside the classroom as well as a basis for a wind energy/power curriculum module. This experience was exponentially beneficial as the teacher's home school district recently installed a 10kW for building use as well as a FabLab for educational purposes. Additionally, this RET also participated in the Zephyr Wind Power Teacher Training funded by Xcel Energy and the CCEFP. Further description can be found in E&O Project C.10 Innovative Engineers and the BRIDGE Project and Associated Project: Zephyr Wind Power Teacher Training.

- Other relevant work: In addition to their summer research experiences, the CCEFP encourages cross-collaboration with other activities within the Center such as outreach activities, workshops and piloting curricula. RETs are encouraged to remain a part of the Center by bringing their classrooms to campus for a tour, or other such opportunities. Several of these RET projects are connected to other E&O Projects. Also, further work has been invested in an on-line repository of teaching and learning materials at the CCEFP.org website. Materials can be found: *www.ccefp.org -> Get Involved -> Educators -> Teaching and Learning Materials*. Such materials include:
    - TeachEngineering.com fluid power curriculum by CCEFP RETs
    - Teaching Fluid Power video tutorials by Professor William Durfee, UMN
    - Fluid Power Demonstrator Kit and Curriculum by Professor John Lumkes, Purdue
    - Pneumatics Demonstrator Kit (Ball and Cup) and Curriculum by Professor Will Durfee, UMN
    - Fluid Power Hands-on Tools designed by the Science Museum of Minnesota Youth Science Team
    - Supply sources for fluid power teaching and learning materials

- Past CCEFP RET Programs:

- **2010**: Six teachers participated in summer 2010, the fourth year of the CCEFP RET program: two at the University of Minnesota, two at Vanderbilt and two at Purdue University.
  - Three of the six were Project Lead The Way (PLTW) teachers. PLTW assists by recruiting PLTW teachers for the CCEFP RET program.
  - The CCEFP held its Annual Meeting in June 2010 at Purdue University in West Lafeyette, IN . All RET teachers attended the meeting which included an program orientation led by Prof. Stacy Klein-Gardner from Vanderbilt University.
- **2009**: Twelve teachers participated in summer 2009, the third year of the CCEFP RET program: five at the University of Minnesota, two at Vanderbilt, two at North Carolina A&T, and two at Milwaukee School of Engineering.
  - The three teachers from the University of Minnesota from the 2008 program returned for a second summer and leveraged their previous experience in mentoring the new participants as well as getting a head start on their project.
  - Seven of the 2009 RETs attended the Vanderbilt RET Boot Camp in Nashville. This helped cross-collaboration among the teachers, as well as renewed some previous acquaintances as several teachers had participated in PLTW teacher trainings in the past.
- **2008**: Eight teachers participated in the RET summer 2008 program; three at the University of Minnesota, two at Vanderbilt, one at Georgia Tech, and two at MSOE.
  - At three of the four schools, pairs (one trio) of teachers were hired together in order help all maximize their learning experiences.
  - The 2008 program was the first to bridge with another NSF program by fostering cross-collaboration with the NSF RET VaNTH Site at Vanderbilt University. A total of ten of the 2008 and 2009 teachers have attended the three-day RET orientation there hosted by Dr. Stacy Klein Gardner. In addition to providing a good introduction to the RET program, the event enabled teachers at different CCEFP sites to make connections and begin networking. During the RET "boot camp," participants learned to translate research into a curriculum module and also learned strategies to connect current content with new content. Not only are lesson plans designed around state education standards, but Dr. Klein Gardner also encourages curriculum writing surrounding The Legacy Cycle. Teachers were required to modify their curricula to meet the standards of the NSF-sponsored TeachEngineering.com, an on-line repository of tools for K-12 teachers.

4. Plans, Milestones and Deliverables

- In 2012, the CCEFP commits to hosting between six-eight teachers within its university network. Though the CCEFP will not pursue an NSF RET Site Award for 2012, the Center will host a strong and effective RET program and through each year of the Center's existence.
- While there are effective programmatic resources in place at the UMN, Vanderbilt and Purdue, sites of previous RET placements, the CCEFP may rotate RET sites in 2012 and utilize other mentoring sources across the Center's seven institutions.
- The Center will promote the newly developed fluid power curriculum modules at its website, on TeachEngineering.com, on YouTube and TeacherTube, as well as on other appropriate channels.
- The CCEFP will continue to enable access to this curricula through its OpenCourseWare project (see C.2).
- The Center will continue to leverage the Project Lead The Way (PLTW) teacher network for recruiting.
- The model of multi-year RET participation proved to be successful at UMN in years 2008-2011. The CCEFP will encourage this model wherever possible and will engage the RETs throughout the year in the implementation of their curricula.
- A challenge is to remain connected to the teacher once the summer session is over as well as remaining in contact in the years following the RET experience. The CCEFP aims to encourage

faculty advisors to communicate regularly with the teacher participants and inquire as to the status of the curriculum implementation and development.

5. Member Company Benefits

Following their RET experiences, teachers can bring their experiences in university research as well as their expanded understanding of fluid power concepts to their classrooms. New curricula stemming from these experiences should inspire and motivate a next generation of leaders in the engineering, corporate and/or academic arena.

Project B.2: Project Lead The Way (PLTW)

Project Team

Project Leader:	Linda Western, Education Co-Director, CCEFP
Other Personnel:	Will Durfee, Education Co-Director; Alyssa Burger, Outreach Director; John Lumkes, Purdue University; Kim Stelson, CCEFP Director
Industry Partners:	Volunteers from the membership of the National Fluid Power Association's Education Committee

1. Project Goals
Project Lead The Way (PLTW) is a not-for-profit national program dedicated to developing STEM-relevant courses for middle and high school students. An affiliate organization of the CCEFP, PLTW is a strong and growing partner in the Center's outreach efforts to help teenage students and their teachers better understand fluid power technology, its applications, and the research that is shaping the industry's future.

2. How Project Supports the EO Program Strategy
Seeking out partnerships with highly regarded and broadly distributed education and outreach networks in order to maximize program impact is central to CCEFP strategy. The Center's affiliation with PLTW does just that. The PLTW network currently involves 350,000 students in all 50 states. More than a half million students reportedly have taken at least one PLTW class.* As another of its core strategies, the CCEFP seeks to leverage and coordinate the accomplishments of individual Education and Outreach projects in facilitating the progress and successes of other E & O projects. Implementation of this strategy is very evident here as other E & O projects (e.g., A.3 and B.3) interface with the PLTW initiative.

3. Achievements

- PLTW teachers nationwide continue to use the fluid power curriculum embedded in the Principles of Engineering course.
- PLTW teachers participated in the CCEFP RET program.
- PLTW teachers use the "How to Teach with Fluid Power" video created by CCEFP faculty and staff.
- In March, 2011, Professor Will Durfee (UMN) and RET participant and PLTW teacher Bix Baker delivered a workshop on teaching with fluid power to the Minnesota PLTW Statewide Conference. The workshop featured the pneumatics and hydraulics learning kits developed by CCEFP.
- In Summer 2011, RET participant and PLTW teacher Bix Baker and Professor Will Durfee (UMN) developed the draft of a new Principles of Engineering module on fluid power informed by the experiences PLTW teachers had in working with the fluid power material.
- CCEFP and PLTW agreed that CCEFP will develop a fluid power simulation application that would be used in PLTW courses. PLTW curriculum development staff worked with CCEFP faculty to define the requirements for the simulation. See EO Project C.6.

4. Plans

- Recruit PLTW teachers for the 2012 CCEFP RET program.
- Continue work on revising the Principles of Engineering fluid power module
- Revise the pneumatics workshop kit to meet PLTW teacher needs, based on feedback from PLTW teachers.
- Continue work on fluid power simulation application.

5. Milestones and Deliverables:
Every teacher of Project Lead The Way's *Principles of Engineering*, *Gateway to Technology* and *Computer Integrated Manufacturing* has received fluid power material from CCEFP and will use it in their course delivery before the end of Year 7.

CCEFP faculty will continue to serve as a resource and as reviewers as PLTW moves toward a new course revision schedule.

6. Member Benefits
All industry members of the CCEFP join other stakeholders in the fluid power industry in their concern about the adequacy of current pre-college science, technology, engineering-related and mathematics (STEM) education. The cooperative efforts of the CCEFP with PLTW (often involving NFPA, too) respond to this concern given PLTW's goal of increasing the number, quality and diversity of a new generation of engineers. PLTW's evolving curricula engages students in hands-on experiences, applying STEM-relevant concepts to solving real-life problems.

* Note that not all PLTW students and teachers engage in the units, lessons and projects with fluid power content developed through this project.

Project B.3: Hands-on Fluid Power Outreach

Project Team

Project Leader: Alyssa A. Burger, Education Outreach Director

Other Personnel: Will Durfee, University of Minnesota
John Lumkes, Purdue
CCEFP Faculty
CCEFP Student Leadership Council
CCEFP Graduate Students

Industry Partners: Donaldson
Bimba Manufacturing Company

1. Project Goals

Through this project portable demonstratioin kits and curricular materials have been developed for use in hands-on workshops about hydraulics and pneumatics. These workshops benefit many audiences: high school students (including those participating in FIRST Robotics and in Project Lead The Way Courses); RETs and other teachers interested in learning about and teaching fluid power; fluid power manufacturers and distributors; and participants in outreach activities sponsored by museums, technical colleges and universities. All the materials and kits developed under this project's umbrella are designed for use in reaching key CCEFP goals: developing research-inspired, industry practice-directed awareness of and education about fluid power for pre-college, university and practitioner students as well as for the general public.

2. How Project Supports the EO Program Strategy

This project supports EO Program Strategy in several ways. Our work with strong partners (as examples, PLTW, industry donors, and FIRST) optimizes both distribution and use. The ease with which these projects can be replicated maximizes opportunities for use by many workshop leaders in many settings--another EO strategic priority. And, reflecting yet another priority of EO strategy, this project supports other EO projects: B.1, RET program, B.2 - Project Lead The Way, and B.4 - gidaa STEM Programs.

3. Achievements

- In a single reporting year, over 35 unique fluid power outreach events have occured across the CCEFP. Outreach events include laboratory and demonstraton tours, fluid power activities and engineering workshops, special groups presentations (Boy Scouts and 4-H), family fun fairs, math and science fairs, campus engineering week celebrations, etc. Thousands are exposed to fluid power through these outreach events including K-8, high school, community college, undergraduate and graduate students, community and public audiences. (2011)
- Four targeted curriculum modules are being developed for the pneumatics kit (B.3a): 1) a basic hands-on tutorial, 2) an advanced workshop tailored to experienced FIRST Robotics teams, 3) web-based self-learning material, and 4) use by Project Lead The Way in its Gateway Academy program and other of its curricular activities.
- Directions for and curriculum accompanying the water hydraulics project Project B.3b, Portable Water Hydraulics Demonstrator and Curriculum, are posted at the CCEFP website and are available for free download.
- Industry support of pneumatics kit components: received grants of $15,000 from Donaldson (2009) and $3,000 from Bimba Manufacturing Company (2010)
- Hired a part-time undergraduate engineering student from the giiwed'anang Northstar Alliance to assemble the pneumatics kits (2010).

- Several Purdue graduate students as well as a Purdue RET (summer 2010) have participating in the fabrication of the Hydraulic Demonstrator and the development of its accompanying curriculum.
- All participants of the CCEFP Student Retreat were able to build and assemble both the Hydraulic Demonstrator and a Pneumatic Kit, Chicago, 2009.

Pneumatics Kit

Portable Fluid Power Demonstrator

4. Plans

- External evaluators will begin to formally study this project to assess the impact of the outreach. With that input as well as with what is learned during ongoing experiences with teachers and students, the CCEFP will continue to refine and evaluate accompanying curricular materials.
- With company support, the Center will expand its efforts to assemble and distribute kits through its industry and academic networks.
- The CCEFP will set a workshop schedule in place across all seven participating universities led, in part, by the Student Leadership Council and other student volunteers as well as outreach outfits across the CCEFP.
- PLTW will include the pneumatics workshop in its Gateway Academy, a STEM-focused summer camp program for middle school students. The Society of Manufacturing Engineers is a program co-sponsor. .
- All 54 FIRST teams in the 2009 Minnesota Regional were surveyed in order to better understand attitudes towards pneumatics. Twenty one teams used pneumatics (39%) and 33 did not. The reasons for not using pneumatics included “Past teams used electric—so that’s what we did,” “Not familiar with pneumatics,” and “Not enough time to learn.” The reasons for using pneumatics included “Pneumo: simple, compact” and “Pneumatics is pricey but small.” In Spring 2010, FIRST teams in the Milwaukee, Atlanta, West Lafayette and Minneapolis areas will be queried with a similar survey. Survey replies affirm the opportunities for expanding learning experiences in pneumatics and will guide further development of appropriate instructional approaches.

5. Milestones and Deliverables

- At least two K-12 workshops per semester will be organized and led by faculty/students at each of the Center's seven universities in 2012.
- The Student Leadership Council is leading an effort to support fluid power outreach events by providing funding to students to organize and initiate additional activities.

6. Member Company Benefits
These workshops contribute to an increased awareness of fluid power by a growing number of pre-college students.

Fluid Power Outreach Events in Year 6

01.07.2012	Wind Power Outreach and Implementation in Nicaragua
01.13.2012	Wind Power Outreach Event
01.14.2012	KidWind Wind Power Outreach Event
01.26.2011	Marcy Open Science Night
02.01.2012	NCAT College of Engineering Symposium
02.17.2012	Women in Engineering
02.29.2012	Capstone Senior Design Project (Bradley University in Peoria, IL)
03.11.2011	Fluid Power Exhibit
03.11.2011	Miniature Hydraulic Excavator Exhibit
04.07.2011	Fluid Power Elementary School Demonstration
04.11.2011	Women in Engineering Program
06.08.2011	4H Science Workshops
06.15.2011	Demonstration for Emma McSawley, 4th grade Student
06.15.2011	Demonstration for Paul Stevens
06.21.2011	4H Youth Round-Up Career Exploration Day
07.11.2011	STEP (Seminar for Top Engineering Prospects)
07.11.2011	Experience Purdue
07.13.2011	Exploring Careers in Engineering and Physical Science
07.26.2011	Hoosier Ag Science Academy (HASA) Summer Institute
07.27.2011	Project Discussions w/ Boeing Engineer
10.06.2011	North Star STEM Alliance Kick-Off
10.14.2011	Zephyr Wind Power Teacher Training Workshop with KidWind
10.29.2011	Fluid Power Hands-On Outreach
11.09.2012	Wind Power Outreach Event
11.10.2011	American Indian Science and Engineering Society
11.11.2011	Fluid Power Hands-On Outreach
11.12.2011	First Lego League (Robotics)
11.12.2011	Fluid Power Outreach Event
11.15.2011	Vanderbilt Engineering Explorers - High School Students
11.16.2011	Technology Enrichment for FIRST Robotics
11.18.2011	Intro to Engineering and Fluid Power
11.19.2011	Hydraulic Pet Racer Outreach Event
11.19.2011	Fluid Power Outreach Event
12.15.2011	Demonstration for Andrew Brown

Project B.3a: Hands-On Pneumatics Workshops

Project team:

Project Leader: Prof. Will Durfee, University of Minnesota, Education Co-Director, CCEFP
Other personnel:

1. Project Goals
The goal of this project is to create curricular material and portable lab kits for use in hands-on workshops about pneumatics. The target audiences for workshops include high school students participating in FIRST Robotics, CCEFP RET teachers and their students, teachers and students engaged in the fluid power curriculum embedded in Project Lead The Way (PLTW) pre-engineering courses, and CCEFP pre-college outreach workshops. The curriculum for the workshop will eventually include: (1) a basic hands-on tutorial, (2) an advanced workshop tailored to experienced FIRST Robotics teams, (3) web-based self-learning material, and (4) a module for PLTW teacher training workshops and for PLTW courses.

2. How Project Supports the EO Program Strategy
Pneumatics is easy to understand, easy to work with, and relatively inexpensive to demonstrate through hands-on activities. Workshops based on pneumatics serve to broaden an awareness of fluid power among pre-college students and their teachers. The strategy for the CCEFP EO program is to leverage existing networks. The kits are used to train FIRST Robotics teams in pneumatics and there are currently approximately 1,500 FIRST teams involving over 30,000 students. Workshop contents could be used in the PLTW program, another large network connected to CCEFP. The workshops are also used by CCEFP RET teachers, who in turn reach their students. Reaching only a fraction of this motivated audience serves to bring fluid power to the target audience.

3. Achievements

- Additional kits were constructed and distributed to CCEFP sites and CCEFP RET teachers .
- Dozens of FIRST Robotics students participated in the pneumatics workshops sponsored by the University of Minnesota at the FIRST Splash event in December, 11 and the workshops sponsored by Georgia Tech in Fall 2011. Additional workshops were conducted through the UMN College of Science and Engineering's Office for Diversity and Outreach in 2011.
- The kit was featured at a PLTW regional conference (see Project EO B2 report.

4. Plans

- Revise the kit, based on feedback from PLTW teachers, so that it is more suitable for the typical PLTW classroom.
- Develop a version of the workshop for professionals with a target market of employees in engineering, marketing and sales at fluid power companies who are new to fluid power. The workshop would be intended for company in-service training. .

5. Milestones and Deliverables

- Maintain the number of workshops
- Increase the number of kit distributed
- Curriculum and instructors guide 2.0
- Revised kit based on PLTW feedback

6. Member Company Benefits
Increased awareness of fluid power by a growing number of pre-college students.

Project B3.b: Portable Fluid Power Demonstrator and Curriculum

Project Team

Project Leader: Professor, John Lumkes, Purdue University

Other Personnel: Kyle Merrill, Purdue University
Jordan Garrity, Purdue University
Gary Werner, McCutcheon High School

Industrial Partner: Clippard Instrument Laboratory, Inc., Vex Robotics

1. Project Goals and Description

The Portable Fluid Power Demonstrator (PFPD) was developed for K-12 classrooms, with an initial focus on middle and high schools. The kits can enhance current and enable new activities for organizations that include PLTW, FIRST Robotics, science museums, children's museums, and for activities within the CCEFP. The PFPD is being used to promote awareness and/or increase interest of fluid power education in high school grades 8-12. Through the addition of microcontrollers the PFPD can be used to teach robotics and mechatronics.

2. Project Role in Support the EO Program Strategy

This project directly supports the CCEFP mission to "develop research inspired, industry practice directed education for pre-college, university and practitioner students; to integrate research findings into education; to educate the general public; and through active recruiting and retention, to increase the diversity of students and practitioners in the fluid power research and industry". Project B.3.b specifically targets the fifth component of the ERC's vision for education, to "increase public and K-12 student awareness of the importance of fluid power, and the excitement and possibilities that new technologies of the Center will bring".

3. Achievements

Undergraduate level students from Purdue were recruited for independent study classes to help design the PFPD kit and curriculum. REU students have also participated in the design phase.

For approximately $800 USD a complete working micro-excavator using water hydraulics or pneumatics can be built and implemented in classrooms or hands-on displays. The kit includes a case, water pump, necessary power supplies, hardware (nuts, bolts, etc.), cylinders, valves, tubing, fittings, and excavator arm. It is possible to completely build the demonstrator using only common shop tools (wrenches, screwdrivers, hacksaw, and drill). This design was revised and a construction manual was published on the CCEFP website along with an accompanying curriculum guide.

In early 2010, a new, electronically controlled PFPD was designed and about a dozen generation III, electrically controlled PFPDs were constructed at Purdue and utilized in various K-12 outreach programs, museums, high schools, conferences, and distributed to CCEFP member universities.

Summary of PFPD outreach activities to date

Between February 2011 and January 2012, Purdue offered six pre-college outreach programs. There were 161 participants, of whom 77 were female, 84 were female, and 78 were from under-represented ethnic groups.

In total, Purdue has offered over 26 programs, reaching over 790 students with over 50% of the participants being female and/or from under-represented groups.

Since the project inception there have been multiple undergraduate students involved in the design, construction, and delivery (outreach programs), along with REU and RET participation in the summer and high school involvement on a variety of levels. The kits have been use a various high schools, state fairs, outreach events, tours, and workshops..

4. **Plans, Milestones and Deliverables?**
The near term goals for the project include the distribution of the assembly manual for the PPBL (manual and electronic controls, various end effector options), a continued strengthening of the relationships with local high schools that have used or expressed interest in using the kits, and continuing the development of a new outreach tools.

The underlying concepts of the PFPD can be applied to various expansion platforms for different applications with the design of add on kits (for example, instead of an excavator, an airplane flight control system).

5. **Member Company Benefits**
This project will directly benefit member companies involved in fluid power by providing a methodology and demonstration kits to capture the imagination of future engineers, their future workforce. All reports and publications will be available to Center members

Project B.4: *gidaa* STEM Programs

Project Team

Project Leader: Alyssa A. Burger, Education Outreach Director, CCEFP

Other Personnel: Holly Pellerin, *gidaa* Coordinator
Diana Dalbotten, National Center for Earth-surface Dynamics (NCED)
Lowana Greensky, Director of American Indian Education in St. Louis County Schools

1. Project Goals

The Center for Compact and Efficient Fluid Power, together with the National Center for Earth-surface Dynamics (NCED) and the Fond du Lac Tribal and Community College (FDLTCC), organize Native American Education Immersion Programs in the Cloquet, Minnesota region, which is also home to the Fond du Lac Indian Reservation. Camps for K-12 Native students, originally known as *gidakiimanaaniwigamig* (Our Earth Lodge, in Anishinaabe), have been held on a regular seasonal basis since 2003. Since then the "*gidaa*" program has taken on a life of its own to include other educational outreach programs that bridge several federally funded organizations.

gidakiimanaaniwigamig is committed to engaging Native American students as they work towards their high school graduation and prepare for post-secondary education in the areas of Science, Engineering, Technology and Math (STEM). CCEFP and NCED have sponsored this ongoing program through professional and financial support of seasonal camps, science fairs, and robotics day and after-school programs. *gidaa* is also committed to training teachers using strategies that help them integrate STEM into their classrooms across curricula. Progressive models such as eSTREAM, standards outlined in the Atlas of Science Literacy (AAAS), and organizations like the American Indian Science and Engineering Society (AISES) continue to educate and provide enrichment.

The relationship between the University of Minnesota (including CCEFP as well as other centers and programs in the University) and *gidaa* continues to grow and develop as new areas of study and opportunities become available. Students attending *gidaa* come from many Minnesota communities including Crookston, Carlton, Cass Lake, Cloquet, Duluth, Fond du Lac Reservation, Greenway, Leech Lake Reservation, Minneapolis, Saginaw, Tower, Walker and Wrenshall.

The projects and activities known as ***gidaa* STEM Program** include:

- *gidaa* STEM Camps (CCEFP Project B.4a)
- *gidaa* odaangiina anaangoog (Shooting for the Stars) Robotics Program (CCEFP Project B.4b)
- giiwed'anang North Star Alliance (CCEFP Project C.5)
- Robotics Undergraduate and Pre-Engineering Curriculum (FDLTCC and MN NASA Space Grant Consortium)
- Annual local, regional and national science fairs (NCED, CCEFP, *gidaa*)
- *gidaa* manoomin (Wild Rice) Project (NCED, LaCore, Geology - UMN)

2. How Project Supports the EO Program Strategy

Essential elements of the CCEFP strategic plan include promoting diversity in science, technology, engineering, and math (STEM) fields and preparing Native American youths for STEM careers. The EO program also seeks out strong partners with whom to work in assuring success. All of the initiatives under the *gidaa* "umbrella" represent implementations of these strategies.

3. Achievements

The *gidaa* STEM program is the "umbrella" of Native American educational/outreach activities in northern Minnesota, with a network that spans several cities and counties in the region. It is a well established program, with a solid core group of teachers, curricula aligned with national standards, and regular visits by research scientists from the University of Minnesota and other institutions all in place. The most critical challenges moving forward include: 1) establishing programs at the undergraduate level at the University of Minnesota and FDLTCC and surrounding regions that will meet the needs of Native American students as they graduate from high-school and transition into the next phases of their education, 2) maintaining and extending the partnerships with other institutions that enrich the program, 3) continuing to incorporate national and state standards in new curricula. These challenges will be met by utilizing the *gidaa* Circle of Learning which promotes good communication between all partners and participants in the program, mediating between the (at times) contradictory goals and visions of stakeholders and helping them instead to seek out the shared goals that will drive the program's strategic plan.

gidaa continues to expand with new programs and cultivate the partnerships that have allowed the project to establish a complete pipeline from kindergarten to college and beyond. Its network of teachers, leaders, staff and students continues to grow, too.

- *gidaa* is in its third year of the odaangiina anaangoog (Shooting for the Stars) Robotics Program. The *gidaa* feeder schools such as South Ridge School (formerly Albrook School) currently host the robotics activities. This program includes day and after-school robotics courses, CCEFP Project B.4a.
- In 2009, *gidaa* was awarded an NSF Opportunities for Expanding Diversity in the Geosciences grant titled "The manoomin (wild rice) project" which provides $1.5M over 5 years. This funding will support the *gidaa* program as well as an associated research project that involves evaluating the past, present and future effects of the environment on the wild rice lakes on the Fond du Lac Tribal Reservation in Cloquet, MN.
- A former *gidaa* participant received a special invitation in the Fall of 2010 to visit the President of the United States. She and other bright young scientists from across the nation gathered in Washington D.C. to share their science, engineering, or mathematics research with President Obama during the White House Science Fair. The student was recommended to attend the fair and present her research to the President by the American Indian Science and Engineering Society (AISES). Through CCEFP and NCED sponsorship, she had attended the AISES national science fair over the past four years and each year was one of the top Grand Awards winners at the event.
- The CCEFP supports these initiatives, working most directly with *gidaa* STEM Camps, *gidaa* Robotics Program, and the giiwed'anang North Star Alliance.

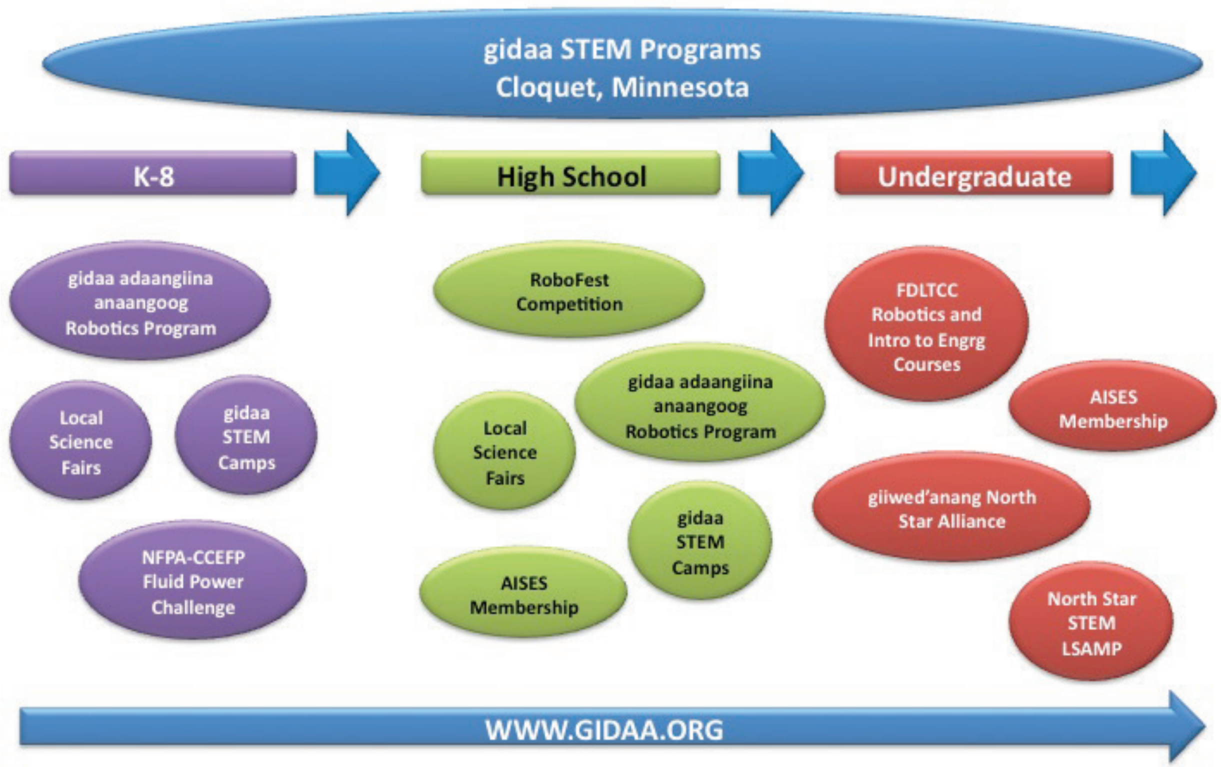
4. Plans

Through cooperative efforts between the Fond du Lac Tribal and Community College (FDLTCC), the University of Minnesota's College of Science and Engineering, the National Center for Earth-surface Dynamics (NCED) and the Center for Compact and Efficient Fluid Power, plans are in place to continue to support these efforts. The leadership of the *gidaa* program will continue to apply for funding in order to duplicate *gidaa* in geographic locations where there is a critical mass of Native American communities. The manoomin Project is a good example of the type of funding *gidaa* is seeking. Whenever possible, the two (or more) *gidaa* programs can bridge events and activities to create a stronger network of Native American students learning about STEM. Program Directors will continue to submit for support for a second *gidaa* site in the Bemidji, MN area. Currently, all evaluation and assessment is carried out by the National Center for Earth-surface Dynamics.

5. Milestones and Deliverables

- 200 students per year participating in program camps and related programs.
- Greater interest among these students in science, technology, engineering and mathematics.
- A majority of *gidaa* participants choosing to attend college, with a significant number majoring in science, math, engineering or technology.

6. Member Company Benefits
Several students from the *gidaa* program have begun taking classes at the FDLTCC as part of the Minnesota Post-secondary Education Option, which allows students to take college courses without charge while still in high school. These students will begin transferring to 4-year programs. We also have introduced the CCEFP to students who are current undergraduates at FDLTCC. These students will be encouraged to job-shadow at local corporations as part of the North Star STEM LSAMP Alliance. We expect this program will help in matching students with the Center's member companies for internships as they begin transferring into 4-year programs.



Project B.4a: gidaa STEM Camp

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director, CCEFP
Other Personnel:	Holly Pellerin, Camp Coordinator Diana Dalbotten, National Center for Earth-surface Dynamics Lowana Greensky, Director of American Indian Education in St. Louis County Schools

1. Statement of Project Goals

The Center for Compact and Efficient Fluid Power, together with the National Center for Earth-surface Dynamics (NCED) and the Fond du Lac Tribal and Community College (FDLTCC), organizes camps known as *gidakiimanaaniwigamig* (Our Earth Lodge, in Anishinaabe), for students in grades 3 through 10. Offered monthly throughout the year, these camps provide students with a mix of lab and field science experiences selected to coincide with current science education standards as well as culturally relevant study. Program elements include both an introduction to the scientific method and a focus on Native American culture. This program illustrates the CCEFP's commitment to increasing the diversity of students and practitioners in STEM-related fields.

2. How Project Supports the EO Program Strategy

Essential to the CCEFP's strategic plan is its work with strong partners in order to assure program success. As partners, NCED and FDLTCC are key in helping to organize and deliver program content.

3. Achievements

- 2012
  - Enrollment continues to grow. Over 400 students have attended a gidaa activity, including the robotics program at the local K12 school. Over 65% of these students have repeat attendance. 40 students participate in gidaa camps per year.
  - There are two graduating seniors in 2011, one planning on attending FDLTCC and the other attending Penn State with a full academic scholarship. Nine other gidaa students are continuing on as college students, two are Master's candidates and one has just been accepted into a graduate program.
  - Several gidaa teachers participated in the CCEFP co-sponsored Zephyr Wind Power Teacher Training at Mahtomedi Area Community Center in October 2011.
  - gidaa continues to provide lessons to students focusing on green energy of the future. Two fluid powered activities have been covered with students exploring the mechanics of wind power being used to run water pumps. Teachers leading these activities are also those who are responsible for the gidaa Robotics E&O Project B.4b.
  - The gidaa program and K-12 camps continue to work on the *manoomin* project – The Investigation of Past, Present, and Future Conditions of Wild Rice on the Fond du Lac Reservation.
- 2011
  - In 2011, more than 360 students have participated in gidaa. Over 60% of these participants have attended more than one camp.
  - 10 out of 12 gidaa high school graduates are attending college and 5 other high school students are attending Fond du Lac Tribal Community College where they are enrolled in PSEO courses.
  - The gidaa STEM programs continuously update its website: **www.gidaa.org**.
  - There was a great CCEFP and gidaa focus in 2011 on learning about the fluid power involve in today's new forms of green energy. Hands on lessons were provide to

students to gain understanding of how fluid power drives the wind turbines of today. CCEFP provided state of the art *Kid Wind* kits as a learning platform for the students. Instructors facilitated 2 different 2 hour long wind turbine sessions to 30 students over 2011.

- In 2011 CCEFP and gidaa focused on providing students with the understanding of hydraulic power in drive systems. Instructors used the most up to date technical lessons and supplies from *Teacher Geek* (hydraulic racers) as the main learning platform. Instructors facilitated 3 different 2 hour long hydraulic racer sessions to 30 students in 2011.

- 2010
  - In 2010, eight weekend camps and 2 week-long camps including a week at the University of Minnesota and a extended trip to Montana for an experience at the Salish Kootenai Tribal College. A fluid power activity is demonstrated in each camp, tied to the camp's theme.
  - In 2010, the CCEFP supported two high school students to attend the NAISEF Science Fair in Albuquerque, NM.

- 2009
  - In 2009, ten camps and/or associated activities have been held in connection with gidaa. In addition to seven gidaa camps, associated activities include the National American Indian Science and Engineering Fair in March 2009, FIRST Robotics Competition in April 2009 and Valleyfair Physics Fun Day in July 2009.
  - In the fall of 2009, following the manoomin Project (NSF Opportunities for Enhancing Diversity in the Geosciences) award, gidaa initiated monthly weekend camps that begin with a community Friday Forum. (Note: The manoomin project provides partial funding and partial programming for gidaa programs like this one.The grant also funds evaluations of the past, present and future effects of the environment on the wild rice lakes on the Fond du Lac Tribal Reservation in Cloquet, MN. High school and undergraduate students are involved in these research efforts.) Two high school gidaa students presented their science fair posters at the AISES National Conference in Portland, Oregon, October 2009. One student received the Best Poster Award for a high school student.
  - In 2009, 27 students presented posters or science fair projects at the NAISEF Science Fair in Minneapolis, Minnesota. Students brought home over 30 medals and awards, including a NASA award, two Women in Science and Engineering awards and two Grand Awards.

Winter 2010 gidaa STEM Camp.

Other Relevant Work

- Partners in the gidakiimanaaniwigamig program are working in conjunction with the University of Minnesota-led North Star Louis Stokes Alliance for Minority Participation to create a Minnesota state alliance of American Indian Science and Engineering Society student chapters (CCEFP Project C.5 giiwed'anang North Star Alliance). The North Star STEM LSAMP Alliance is an NSF-funded alliance of Minnesota colleges and universities, promoting diversity in STEM fields.
- The gidaa STEM Programs also include the gidaa Robotics Program (CCEFP Project B.4b). The coordinators of the gidaa STEM Programs are key facilitators in promoting the high school and undergraduate level robotics as well as introduction to engineering courses at Albrook School in Saginaw, Minnesota, and the Fond du Lac Tribal and Community College in Cloquet, Minnesota.
- CCEFP and NCED sponsored the the Minnesota-based TRIBES-E (Teaching Relevant-Inquiry-Based Environmental Science and Engineering) Teacher Enrichment Program, headquartered in the Bemidji, Minnesota area. See CCEFP Affiliated Projects.

4. Plans

- Continue to engage Native American students in gidaa camps and related programs, encourage their graduation from high school and support their interests in post high school studies, including those in STEM related fields. Plans are in place to continue support of these efforts through the ongoing cooperation of the Fond du Lac Tribal and Community College (FDLTCC), the University of Minnesota's Institute of Technology, the National Center for Earth-surface Dynamics (NCED) and the Center for Compact and Efficient Fluid Power. But there are challenges. (For example, NCED is in year 8 of its NSF funding.) However, as noted above, with new funding from an OEDG grant (the manoomin project), support will be available for the next five years
- The program coordinators have determined that the gidaa STEM program participants enjoy the weekend-stay camps. Consequently in upcoming years there will be a combination of both day-camps and weekend-stay camps. gidaa will have residential camps during the winter months and day camps for the remainder of the year. A year-round schedule is very important. It is crucial for the student participants to be regularly mentored by gidaa staff and teachers. It is also crucial that they are in and among their peers who have the same interests in science, technology, engineering and mathematics.

5. Milestones and Deliverables

- Increase the number of K12 Native American students in gidaa programs.
- Participants return year after year.
- Participants graduate high school and enter college.
- Additional funding sources to support growing program.

6. Member Company Benefits

This program is closely aligned with industry's hope for and support of efforts that prepare for a talented and diverse pool of leaders in academia and in our future workforce.

Project B.4b: gidaa odaangiina anaangoog (Shooting for the Stars) Robotics Program

Project Team

Project Leader: Alyssa A. Burger, Education Outreach Director, CCEFP

Other Personnel: Cameron Lindner, Robotics Program teacher
TJ Ray, Robotics Program teacher
Richard Rhoades, Robotics Program teacher
Lowana Greensky, St. Louis County American Indian Ed Program Director
Holly Pellerin, gidaa Coordinator

1. Project Goals

The goal of the gidaa odaangiina anaangoog Robotics Program is to to interest and prepare Native American youths for STEM careers. This effort is closely aligned with the Center's goal of developing research inspired, industry relevant education for students of all ages. As the successful FIRST Robotics program attests, robotics is an effective channel for introducing children to basic principles of engineering and related disciplines. Under the gidaa STEM Program umbrella, staff and teachers have drawn on lessons learned through FIRST and introduced K-12 robotics day and after-school curricula using Lego Wedo-Webots, NXT Kits, Vex Kits and Textrix kits and software.

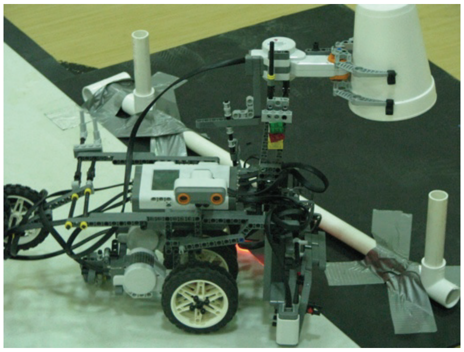
2. How Project Supports the EO Program Strategy

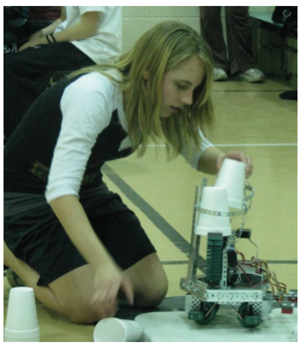
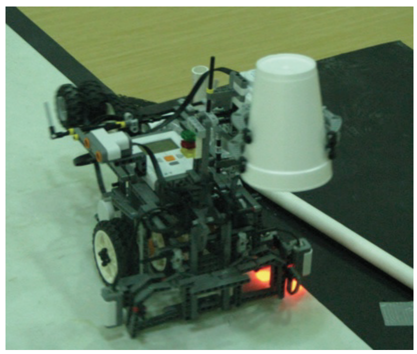
An essential part of the CCEFP strategic plan is to promote diversity in science, technology, engineering, and math (STEM) fields. The Shooting for the Stars Robotics Program enables Native American students in and around Cloquet, Minnesota to use concrete learning experiences with robotics to better understand physics concepts; develop mathematical thinking, problem solving, and programming skills; and participate in team-building through hands-on construction engineering. Ideally, graduates of gidaa and the gidaa odaangiina anaangoog Robotics Program will continue their education either at a community college or a four-year university, joining the giiwed'anang North Star Alliance (Project C.5) there as active undergraduate members. This program currently engages students at the elementary, middle and high school levels. A college-level robotics course at Fond du Lac Tribal and Community College is in its third year.

3. Accomplishments

- **2011**: AlBrook is now closed and the new school, South Ridge, is open in Culver MN. South Ridge was built with the intentions of providing a perfect environment for robotics to be taught. South Ridge is able to now offer its students a year long robotics course, along with a three month intensive after school program that meets two nights a week.
    - This year long course, offered to 10-12 graders, allows students to explore the world of robotics through VEX Robotic systems and NXT Robotic systems. Students learn different types of programming languages including "Graphic Based" and "C".
    - Students will use the problem solving and programming to complete a series of tasks and challenges.
    - The after school program, offered to 7-12 graders, allows students to build a robot to compete in the RoboFest challenge, while the 2-6 grade after-school program uses Wedo-Webots to introduce robotic/programming concepts.
    - South Ridge School will now be hosting its third annual RoboFest. It is currently the only site in the state of Minnesota to allow students to qualify for the international competition, which is held at Lawrence Technical College in Southfield Michigan.
    - Last year CCEFP helped to send the first ever Minnesota and AlBrook team to the international competition.

- South Ridge is also offering teacher training to other technology educators in the area who are showing interest in starting their own robotics programs with gidaa odaangiina anaangoog (Shooting for the Stars) Robotics Program support.
- Over 60 students students, 65% of them from underrepresented groups and over 40% of them female, have participated in the robotics program.




- **2010**: Teachers at the Albrook School in Saginaw, MN, are leading the effort to implement the robotics activity both in the day-time and after-school programs. Following a start-up year, the following activities continue:
  - Fall Semester in school course: 30 students working on robotics, setting the stage and gaining interest in particpating in the 2nd Annual Robofest Competition (to be held March 2011).
  - Spring semester in school program: 30 students working on engineering. Examples of projects: 2 litter water rockets, and fluid power mouse trap racers.
  - The Albrook School is in transition as it is less than one year away from its new building where a lab area has been reserved for an engineering / robotics classroom with sufficient space for computers, equipment and storage just for this purpose and program.
  - Afterschool: 20+ students participate in learning about robotics in preparation for the Robofest Competition, March 2011. Students will receive a robotic challenge in which they compete against other robots in a local competition with other teams across Northern Minnesota. This will be the second year of Robofest. Both the Albrook School, gidaa, and the CCEFP sponsor this event.
  - Albrook is the model for a successful robotics program. The Center will continue to support these activities in all interested schools in this district.
  - Through robotics, gidaa has expanded its recruitment of more technology teachers from the area, some of whom have become experts in the robotics curriculum. gidaa program students are graduating. Through robotics, gidaa is reaching out to students who would

not otherwise have had exposure to robotics and the larger lessons it teaches. The enrollment demonstrates the interest.

  - Some robotic activity exists at the Ojibwe School on the Fond du Lac Indian Reservation near Cloquet and Saginaw, MN school district, however, changes in personnel has limited the impact and resources in this current year. A new teacher, interested in robotics has recently been hired. The same is true for the Cloquet Middle and High School.
  - Albrook School will host the RoboFest Competition for up to 6 other local school districts. Undergraduate students of the Robotics course at Fond du Lac Tribal and Community College will serve as judges.

- 2009
  - Following the 2009 FIRST Robotics season, gidaa program directors determined that FIRST was not the appropriate medium to introduce robotics to the community. Instead, they decided to leverage available resources to build a sustainable day and after-school robotics curriculum in the region, including competition in the Lawrence Technological University's Robofest (www.robofest.net).
  - The Albrook School (gidaa K12 partner) is the only Minnesota site host of Robofest (March 2010). gidaa plans to pioneer the Robofest program in Minnesota. This locally-hosted competition will allow greater number of students to participate.
  - The CCEFP helped to support over 100 students in grades 3 - 12 in various robotics day and after school programs at the Albrook School, Ojibwe School and Cloquet Middle and High Schools including a college-level Robotics course at Fond du Lac Tribal and Community College.
  - FIRST Robotics Competition -- 2009: 27th place.
- 2008:
  - The Center supported the first Minnesota Native American FIRST Robotics Team *anishinaageb ogichidaag*, Team Number 2510. This team has received two $10,000 grants from the University of Minnesota Foundation to join the competition.
  - FIRST Robotics Competition -- 2008: 14th place.
  - In 2008 and 2009, two teachers attended the Carnegie Mellon Robo Academy.
  - In 2008, another teacher attended Art & Code conference.

4. Plans

The CCEFP will continue to foster the growth of the academic and educational programs that have been initiated through gidaa. While most of the curriculum development and implementation will happen at the local level, the Center plays a key role in providing the subject matter expertise, resources and encouragement needed to help these students succeed in school and in STEM.

- The CCEFP will continue to identify sources of additional funding and support to expand this program, support more schools and teachers.
- The Robotics Program will continue to identify potential collaborators in the local area to have a network of robotics teachers and to utilize the RoboFest competition to generate additional interest.
- The program will recruit new and interested teachers in teaching robotics activities in the Cloquet and Saginaw and Fond du Lac Indian Reservation geographic area.
- gidaa will affect change in STEM curriculum across the local school districts. For example, in the fall of 2010, the first Robotics Course was offered as an elective at the Albrook School, grades 9-12. Albrook School will serve as an engineering feeder school to a pre-engineering program at Fond du Lac Tribal Community College.

- As teachers learn, the Ojibwe school will expand its STEM-relevant curriculum and course development. Although there will be limitations, teachers anticipate the participation will increase in day class enrollment, which will, in turn, generate college level interest.
- Expanding Lawrence Technological University's Robofest Competition across Minnesota. Efforts will include working with CCEFP teacher networks: RETs and teachers from the TRIBES teacher-enrichment program in Bemidji, Minnesota.
- gidaa will consider loaning Robotics materials to youth in the Bemidji, Minnesota area, under the guidance of the TRIBES teachers.
- Relationships with other tribal colleges will continue to grow.

Related Projects
This project is closely aligned with several of the Center's initiatives, in cooperation with the Fond du Lac Indian Reservation and the local area schools in Cloquet, Minnesota, that focus on fostering and mentoring the K-14 students of the reservation as well as in creating programs to help bridge transitions from middle school to high school to college. This all illustrates a very important recipe in making these programs successful: repetition, relationships, trust, a support structure within the community and ongoing support from dedicated partners: the Center for Compact and Efficient Fluid Power, the National Center for Earth-surface Dynamics, the North Star STEM LSAMP Alliance, the University of Minnesota and the Fond du Lac Tribal and Community College.

5. Milestones and Deliverables

- Increase number of participants and expand the robotics activity to other local K12 institutions
- Continue current support and seek additional funding for the program
- Promote the RoboFest to other local K12 institutions, including those in the TRIBES-E teacher network in Bemidji, MN
- Increase the number of teachers participating in robotics activities
- Demonstrate the effectiveness by identifying students who continue in the robotics program, and who decide to pursue STEM after high school graduation.

6. Member Company Benefits
This program is closely aligned with industry's hope for and support of efforts that prepare for a talented and diverse pool of leaders in academia and in our future workforce.

Project B.5: Building Resources and Innovative Designs for Global Energy (BRIDGE) Program

Project Team

Project Leader: Paul Imbertson, CCEFP Education Director

Other Personnel: Alyssa Burger, CCEFP Education Outreach Director
Francisco Gonzales, Director, INATEC (The National Technical Institute of Nicaragua)
Victorino Centeno, Executive Director, AVODEC (Association of Volunteers for the Development of Communities)

1. Project Goals and Description

BRIDGE (Building Resources and Innovative Designs for Global Energy) is a project spearheaded by the National Society of Black Engineers (NSBE), the Innovative Engineers (IE), and the American Indians in Science and Engineering Society (AISES) student groups at the University of Minnesota.

Since 2006 the BRIDGE Project has impacted students and communities across the state of Minnesota and around the world. Participants create designs for renewable energy systems from scrap, waste, or found materials. They use these designs as an easily understandable foundation for outreach for at-risk students in inner-city schools and on Native American Reservations. The project brings engineering concepts and methods to life for at-risk students. The BRIDGE Project uses these designs to implement renewable energy systems in remote communities. This work is done in collaborations with groups in developing nations.

The BRIDGE Project employs a holistic approach to learning, using authentic pedagogy and community service to engage students in work that highlights the world-changing potential of engineering and puts students on the front lines of engineering in action. Everyone involved, from the university students, to the minority high school students, to the BRIDGE partners in economically depressed Nicaragua, takes equal ownership in the project which, while educational, is ultimately a collaboration of people helping each other to reach a meaningful goal.

The BRIDGE Project started in 2006 as a class project overseen by Michael Davis, a student from Southern Alabama University, who was participating in a Research Experience for Undergraduates (REU) program at the University of Minnesota. Mr. Davis led a group of incoming minority and female engineering students through the process of designing and building a wind turbine from scratch.

As instructive and interesting as this activity was, the students soon realized the broader value of their work and determined that their work should be brought out of the classroom. The University of Minnesota chapter of NSBE took the project under its wing and work began to define the scope of the project. The project took shape over a span of several months.

The project has expanded and currently the BRIDGE Project works with

- Four partners in Nicaragua: AVODEC (Association of Volunteers for the Development of Communities), INATEC (The National Technical Institute of Nicaragua), UNI (National Engineering University of Nicaragua), and the community of La Hermita
- Two high schools in Minnesota: North Community High School in North Minneapolis, and the Circle of Life School on the White Earth Indian Reservation
- Three student groups at the University of Minnesota: National Society of Black Engineers (NSBE), Innovative Engineers (IE) and the American Indian Science and Engineering Society (AISES)

Design work in the BRIDGE Project is an example of service learning. Students engaged in service learning develop solutions to real community problems. Their efforts are not purely academic, but their learning outcomes can be more complete and their understanding can be deeper than they might have obtained through purely academic exercises.

Outreach efforts are based on meaningful learning. Students are brought in as active partners in solving renewable energy problems for remote communities. The high school students are full partners in the BRIDGE mission with the expectation that they will positively impact people and communities far removed from their own experiences, giving them a link to people and communities outside of their neighborhoods.

The CCEFP has partnered with the BRIDGE Project to promote student engagement and to bring an awareness of fluid power to these students.

***2.* Project Role in Support the EO Program Strategy**

In 2011 the CCEFP staff saw opportunities of partnering with BRIDGE, a program of social and educational relevance for so many audiences. In establishing this partnership, the Center is implementing one of its core strategies--identifying and then working with strong partners. Note that up until 2011, the work of BRIDGE did not directly relate to fluid power. That is changing (see the section Plans, Milestones and Deliverables).

3. Achievements

Its relationship with the CCEFP is new this year, but BRIDGE has an impressive list of accomplishments, which is particularly noteworthy given that it is almost entirely student driven. It is these accomplishments that prompted the CCEFP to join in a new partnership.

- The project has developed usable designs to use in implementing wind energy systems in remote communities. A 1kW wind turbine was installed in the community of La Hermita, Nicaragua.
- BRIDGE has sought out ways to engage at-risk high school students by hosting events at North Community High School for several years and by sponsoring visits for these students to university laboratories. (For example, in Spring 2011, BRIDGE brought 210 high school students to the UMN campus to visit 19 separate research labs. This required the efforts of 80 university student volunteers.) BRIDGE also worked with students at the Circle of Life High School (COL) on the White Earth Indian Reservation in Northern Minnesota in week long summer enrichment programs in 2009 and 2011. BRIDGE is currently working with the COL students, helping them to build a wind turbine for their school.
- In total, BRIDGE members have made nine trips to rural Nicaragua to build long-term relationships.
- BRIDGE members participate in the University on the Prairie program. This workshop program brings the university to students in farming communities in outstate Minnesota exposing students to opportunities in science and engineering by providing hands-on projects related to energy.

4. Plans, Milestones and Deliverables?

Given that the BRIDGE project is in its sixth year, great progress has been made but there is always room for growth and the project has concrete goals for the future. The project has been almost entirely student driven to this point. While plans are for the project to remain student driven, the support, encouragement, and expertise of the CCEFP will help to move the project forward in a much more efficient and effective way.

- The design team continues to put effort towards the development of new and more efficient designs that can be incorporated in the high school science curriculum and can be implemented in remote villages around the world.
- The project expects to test the hybrid hydraulic/electric wind turbine being developed by students in the Innovative Engineers group in association with the CCEFP.
- Several additional communities have been identified for as candidate sites for wind turbine implementations. The BRIDGE project will encourage and enable the local technical school in Jinotega, Nicaragua to take the lead on these installations and will actively involve inner-city and reservation high school students in in this work.
- In part because one of the key teachers at North Community High School was assigned to other schools over the last two years, the BRIDGE project has not had an ongoing presence

at the school in that time. Plans are underway to revive the programmatic work at North High.
- The project expects to enable direct collaboration between students at the Circle of Life School on the White Earth Indian Reservation, North Community High School in North Minneapolis, and INATEC (The National Technical Institute of Nicaragua).
- The BRIDGE project will continue to host university visits for at-risk youth.

5. **Member Company Benefits**

All of industry, and certainly the CCEFP's member companies, appreciate programs that are socially and educationally relevant. BRIDGE is such a program, building STEM skills among pre-college and university students; contributing to the quality of life within communities in need; and, given its new partnership with the CCEFP, including elements that build an awareness of fluid power, an understanding of its technological base, and new avenues for its application.

BRIDGE member working a student at North Community High School in inner-city Minneapolis

Student built wind turbine at INATEC in Nicaragua.

Project C.1: Research Experiences for Undergraduates (REU)

Project Team

Project Leader:	Alyssa A Burger, Education Outreach Director, CCEFP
Other Personnel:	CCEFP faculty advisors CCEFP graduate student mentors

1. Project Goals
The REU program is aligned with several CCEFP goals: developing research inspired, industry practice directed education; facilitating knowledge transfer; integrating research findings into education; and increasing the diversity of students and practitioners in fluid power research and industry. Through its REU program, undergraduate engineering students from schools nationwide participate in cutting edge research under the mentorship of Center faculty. The program also provides professional development activities for these students.

2. How Project Supports the EO Program Strategy
REU students learn through the expertise of faculty mentors--an example of knowledge transfer. After completing their summer-long programs, REU engineering students are more likely to enroll in a graduate engineering program, often at the REU-hosting school. Further, the Center's efforts to recruit REUs from a diverse student population improve the likelihood of increased diversity among the students, faculty and industry professionals in fluid power.

3. Achievements

- 2011: Eighteen REU students participated in summer 2011, the fifth year of the program: two at the University of Minnesota, two at the University of Illinois, six at Purdue, two at MSOE, two at North Carolina A&T, two at Georgia Tech and two at Vanderbilt University. None of these REU students had previous CCEFP REU experience. Nine of the 18 were recruited from outside the CCEFP's core institutions.
  - For the first time in program history, the CCEFP hosted an REU Fluid Power Bootcamp. The bootcamp was held at the University of Minnesota and all students participated with the exception of those at Purdue. Led by CCEFP graduate students, the Bootcamp provided teaching and learning experiences for all involved as well as networking opportunities for the 12 REUs in attendance.
  - The REU program launched a blog in which all REU students posted weekly updates about their research activities.
  - 2011 REU demographics:

Number of Students	18
Male	11
Female	7
Percentage of students from underrepresented groups 1) racial minority 2) gender minority 3) disability	1) 27% 2) 38% 3) 1%

Number of Students enrolled / demographics

- Four 2010 Summer REU Students attended the CCEFP Annual Meeting and NSF Site Visit held at the International Fluid Power Expo in Las Vegas, March 2011. All four participated in the CCEFP Poster Session and one student spoke on behalf of all REUs during the Education & Outreach presentation at the Center's Annual Meeting..
- The CCEFP has launched a research supplement program for faculty who wish to extend an REU opportunity to an underrepresented student during the academic year. The CCEFP funded two students in 2011, and we expect this program to grow significantly.

- The Center expanded its recruiting database from over 400 schools to 700 schools, with multiple contacts at each school, paying particular attention to minority-serving institutions.

CCEFP 2011 REU Participants at the first Fluid Power Bootcamp at the University of Minnesota.

- 2010: Twenty-three REU students participated in summer 2010, the fourth year of the program: five at the University of Minnesota, three at the University of Illinois, seven at Purdue, two at MSOE, one at North Carolina A&T, three at Georgia Tech and two at Vanderbilt University. None of these REU students had previous CCEFP REU experience. Twelve of the 23 were recruited from outside the CCEFP's core institutions. Several REU students from CCEFP schools participated in the research projects of other universities within the Center network.
    - The CCEFP held its Annual Meeting in June 2010 at Purdue University in West Lafeyette, Indiana and all REU students attended. Events included an REU orientation that enabled the REUs across the seven Center institutions to meet each other. This was the first time the Center was able to bring all REU students together in person.
    - At the end of the summer, 11 REU students attended the CCEFP Student Retreat, held at the University of Minnesota. At the retreat, REUs presented their summer research projects to faculty and graduate students and went on tours of two CCEFP industry members, MTS and Eaton Corporation, both in Eden Prairie, MN.
    - Additional poster presentations were made on REUs' respective campuses.
- Twenty-four REU students participated in summer 2009, the third year of the CCEFP REU program: five at the University of Minnesota, three at the University of Illinois, six at Purdue, two at MSOE, three at North Carolina A&T, two at Georgia Tech and three at Vanderbilt University. One REU student returned from a previous CCEFP REU experience; the others had no prior CCEFP experience. Only eight of the twenty-four were recruited from within the CCEFP's core institutions.

4. Plans, Milestones and Deliverables

- The CCEFP's first NSF REU Site Proposal was given high recommendations for funding, but ultimately, was not issued the reward. The CCEFP resubmitted a new REU Site Proposal in August 2011 and awaits word..
- If the Center does not receive this funding, we will continue to host between 14 and 20 REU students each summer--two or three students at each university in the CCEFP network. (Some sites will host additional students due to leveraged funding from other sources.)
- The CCEFP will host its 2012 Fluid Power Bootcamp at Purdue Unversity.
- As in 2011, the 2012 REU program will include a research blog, launched and contributed to by the students involved.
- At least three webcasts will be held for REUs through the summer in order to facilitate knowledge transfer.
- The Center will continue to work with other campus-based REU programs to create a strong network of students at the local level, and also will host activities on-line that foster collaboration

and a sense of a greater community outside the walls of the hosting institution. Consequently, students will realize that the program of which they are a part extends into the other six CCEFP universities and that the overall REU program is nationwide in scope.

- Social networking sites will continue to be used in establishing personal connections among the Center's REU participants.
- The Center has initiated a membership relationship specific to an ERC with the National GEM Consortium. Through this effort, the CCEFP expects to broaden its recruiting network in identifying underrepresented students in engineering.
- Additionally, using its network and database of contacts, the CCEFP will strive to recruit and retain racially underrepresented students as well as women, those with disabilities and recent war veterans.
- The Center will continue to encourage education focused research topics.
- The Center will hold an REU Advisor orientation webcast prior to the start of the 2012 program.

5. Member Company Benefits

Member companies can participate in REU projects through project mentorship. Here, member companies get a first look at a bright, diverse pool of students trained in fluid power who may become future intern or permanent employees. More generally, the REU program contributes to the building of an informed and motivated student group—future leaders for industry and academia.

Project C.2: Fluid Power OpenCourseWare

Project Team

Project Leader:	Prof. Will Durfee, University of Minnesota, CCEFP
Other personnel:	Prof. Jim Van de Ven, University of Minnesota
	Prof. Paul Michaels, Milwaukee School of Engineering
	Prof. Zongxuan Sun, University of Minnesota
	Prof. Eric Barth, Vanderbilt University
	Prof. Andrea Vacca, Purdue University

1. Project Goals
The purpose of the Fluid Power OpenCourseWare (FPOCW) project is to create, digitally publish, disseminate and use high quality college level teaching materials in fluid power. The material can be used in fluid power elective courses, but more importantly can be inserted into core engineering courses taken by all students. Materials exist in the lecture notes, problem sets and lab exercises of CCEFP faculty, as well as faculty outside the center. A small number of engineering undergraduate students nationwide will take fluid power elective courses, but all students in mechanical and related engineering ABET accredited degree programs take required courses in fluid mechanics, thermodynamics, system dynamics and machine elements. These courses cover topics that form the core of fluid power yet currently do not contain fluid power applications. The FPOCW materials can also be used as training materials for BS level engineers at fluid power companies.

Opencourseware is a concept that is gaining traction (www.ocwconsortium.org), and recently popularized by MIT (ocw.mit.edu). We are doing the same for fluid power education. Education materials that are part of the FPOCW collection are under a Creative Commons intellectual property license which essentially allows unlimited use, with attribution for non-commercial purposes. This includes use at companies so long as the FPOCW education materials are not sold for profit.

2. How Project Supports the EO Program Strategy
New departments or four-year majors in fluid power are unlikely. Insertion of fluid power into standard engineering courses is not only achievable but also the most direct route towards increasing the number of engineering students trained in the basics of fluid power.

3. Achievements

- Fluid Power in Fluid Mechanics project under the direction of Prof. Andrea Vacca, Purdue University, launched as a sub-project. Report from this project is appended.
- Lectures from ME 4232, Fluid Power Control Laboratory, spring semester 2012, taught by Prof. Jim Van de Ven, are being captured on video for adding to the FPOCW site.

4. Plans
Gather additional college-level fluid power training material from CCEFP faculty and disseminate by posting to the site. Continue work on mini-books: (1) modeling and system dynamics of pneumatics, (2) n fluid power in fluid mechanics, (3) hydraulic fluids.

5. Member Company Benefits
Member companies can use the FPOCW repository for internal training, or sales forces can use to educate customers. Member companies also benefit as more engineering students receive training in fluid power.

Project C.2 Appendix: Fluid Power in Fluid Mechanics

Project Team

Project Leader:	Andrea Vacca (Assistant Professor, ABE/ME, Purdue University)
Other Personnel:	Davide Cristofori (PhD, ABE – Purdue University), Massimo Dall'Asta (MS, University of Parma, Italy), Andrew O' Bannon (CCEFP SURF student, summer 2010), Kewen Han, Purdue University

1. Project Goals

The goal of this project is to develop a model to infuse the fluid power discipline into traditional mechanical engineering curriculum through the creation of educational material specifically targeted to introduce fluid power concepts in the introductory classes on fluid mechanics. The project aims to establish an intriguing methodology to provide challenging learning to teachers and students, and it is based on the development of:

- a mini-book titled "Fluid Power in Fluid Mechanics" containing examples aimed to accompany the students in the learning of the main features of hydraulic systems during their completion of the required fluid mechanics introductory class. The examples support the description of basic physical laws of fluid mechanics allowing the comprehension of basic fluid power concepts at the same time.
- demonstration high pressure water hydraulic test rig and the accompanying documentation suitable to present both basic and advanced concepts of fluid mechanics, measurement systems and fluid power.

The two products will widen the educational sources developed or currently under development by the CCEFP, avoiding any overlap of contents.

2. How Project Supports the EO Program Strategy

The project supports the CCEFP education strategic plan, in particular the mission "to develop research inspired, industry practice, directed education for pre-college, university and practitioner student; to integrate research findings into education; to educate the general public; and through active recruiting and retention, to increase the diversity of student and practitioners in the fluid power research and industry". The project specifically addresses college education, providing a model to expand the fluid power discipline to larger undergraduate and graduate engineering student audiences.

3. Achievements

Fluid power to teach fluid mechanics was piloted in Fall 2011 in ME309, the required fluid mechanics course taken by all mechanical engineering majors at Purdue. The number of students taking ME309 was 219. Fluid power lecture notes were developed (57 pages) as were a collection of meaningful fluid power examples suitable for describing basic concepts of fluid mechanics. Two 50-minute lectures were devoted to fluid power. Additional fluid power examples were scattered throughout the course. The following table lists the fluid power examples introduced during the course.

Fluid Mechanics basic concepts touched by the examples	Component / system described in the examples
- bulk compressibility modulus for liquids; - vapor and gas cavitation; - hydrostatic forces on plane submerged surfaces; - conservation of mass; - first law of thermodynamics; - momentum equation; - Bernoulli equation; - unsteady differential continuity equation; - dimensional analysis; - laminar and turbulent flow; - flow in pipes and ducts; - calculation of friction losses; - flow measurement; - hydraulic power; - machines to extracting/doing work (power) from/on a fluid; - calculation of the operating point in fluid systems;	- Hydraulic accumulators - Positive displacement machines (pumps, motors) - Flow control valves - Pressure control valves - Hydrostatic transmission

A hydraulics test stand for demonstrations and lab experiences was developed at the Maha Fluid Power Research Center. Tap water at 140 bar (2,000 psi) is used for the fluid. Tap water complicated the design but was used to demonstrate recent advances in water hydraulics and was used to meet lab safety and environment regulations. The test stand ws installed in the mechanical engineering fluid mechanics teaching lab at Purde and tested in ME309. All 219 engineering students successfully operated the test stand and documented their work through lab reports.

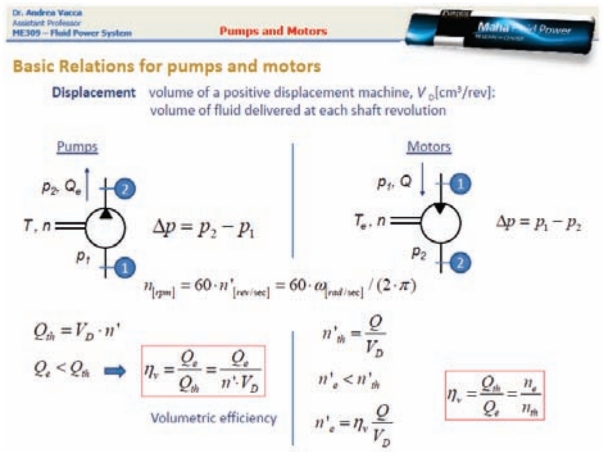
The great excitement among the students caused by the lab experience was measured by their lab grades but also by the unexpected elevated number of requests from students for continuing activities related to fluid power after the end of Fall 2011. In Spring 2012, five junior students are continuing their fluid power studies through ME497 research projects. Ine group is pursuing a project to design a human powered green vehicle based on a hydrostatic transmission and this vehicle will represent Purdue at the Parker Chainless Vehicle Challenge in April 2012 at Irvine, CA. Another group is involved in a project aimed to increase the performance of external gear machines at Maha. Several students wanted a research experiences through SURF program or internships at fluid power companies. This interest in fluid power among undergraduates was never measured before at Purdue Mechanical Engineering and should directly impact on the graduate fluid power program already existing at Purdue, by bringing a higher number of Purdue ME graduates joining the Master or PhD fluid power programs.

4. Plans

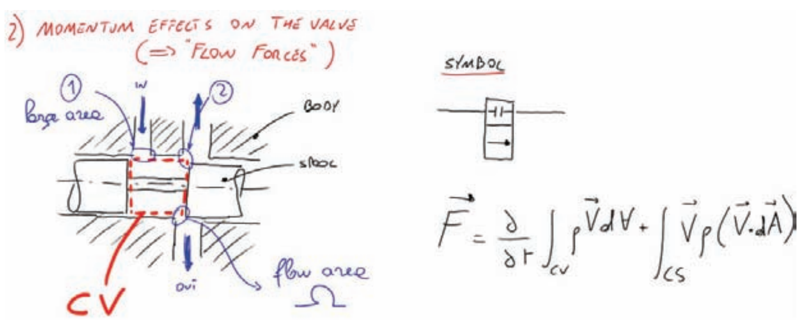
1. Continue to teach fluid power in ME309.
2. Write the “Fluid Power in Fluid Mechanics” mini-book based on course lecture notes and example problems.

5. Member Company Benefits

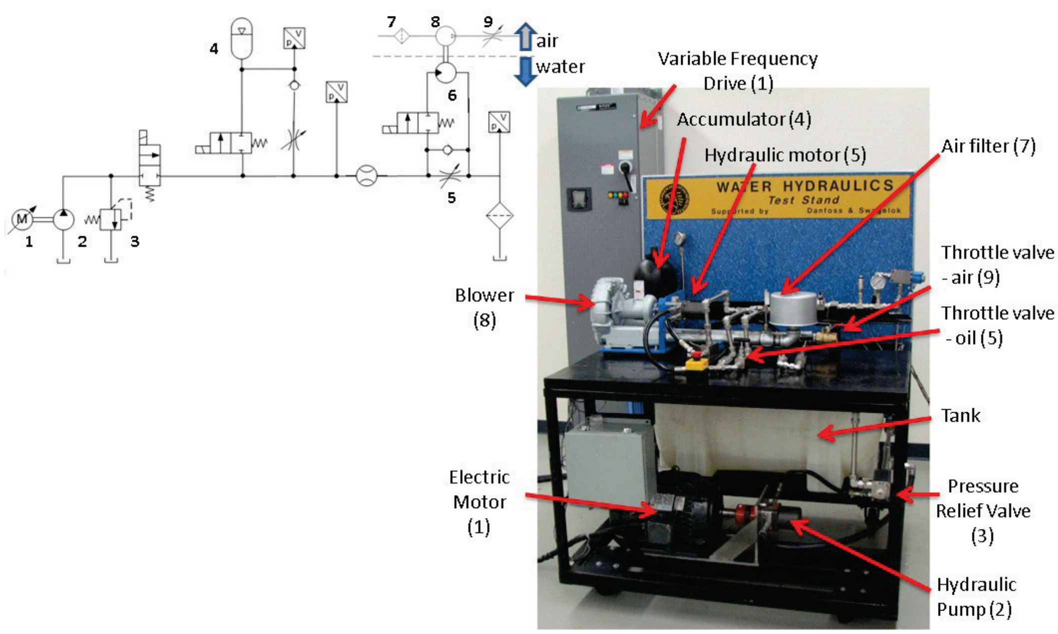
The Fluid Power in Fluid Mechanics mini-book will be available to member companies. Its content can be used for internal training or to educate costumers. Another benefit is that companies will see increased numbers of engineering students educated in fluid power.



One of the 57 page document on Fluid Power basics prepared by Dr. Vacca for class lectures. The document was used during ME309 - Fall 2011 and accessible to students through Purdue Blackboard Vista



Example of application of the basic control volume formulation of momentum equation for the analysis of flow control valves. Snapshot of the instructor's handwriting projected during one ME309 lecture (Fall 2011)



The water hydraulic test stand realized at Maha and installed at the Fluid Mechanics lab of Purdue ME

Project C.3: Fluid Power Projects in Capstone Design Courses

Project Team

Project Leader: Jim Van de Ven, University of Minnesota
Other personnel: All CCEFP faculty
Industry partners: NFPA member companies sponsoring projects

1. Project Goals
The objective of this project is to work with fluid power companies to sponsor and actively engage with students in capstone design projects with fluid power content. This is a collaborative project with the National Fluid Power Association (NFPA).

2. How Project Supports the EO Program Strategy
Engagement in these projects provides undergraduate engineering design students with a hands-on experience in fluid power design and development, reinforcing communications with CCEFP and NFPA member companies. These cooperative efforts are directly in line with the CCEFP's goal of fostering knowledge transfer between industry and universities.

3. Achievements
With the assistance of CCEFP, NFPA took substantial steps to promote capstone design projects to its member companies http://www.nfpa.com/education/capstone_design_project.asp . NFPA board members committed to each sponsoring a capstone project. Board member companies were matched to nearby ABET engineering programs. A process was developed where CCEFP faculty would facilitate matching NFPA companies with an interest in sponsoring a project to the appropriate engineering program. Results from this NFPA + CCEFP effort should be apparent in the coming year.

The CCEFP Education and Outreach program also provided a small grant to Elizabeth Hsiao-Wecksler at UIUC to host a joint fluid power capstone project with a local university. The grant provided funds for transportation and supplies for students of Bradley University.

A compilation of recent fluid power capstone projects at Center schools is shown in Figure 1.

University	Year	Sponsor	Project Title
UIUC	Fall 2011	CCEFP	Capstone Senior Design Project with Bradley University, Peoria, IL. Project was to improve torque output of a pneumatic rotary pancake actuator by using a plastic sun gear train. (Elizabeth Hsiao-Wecksler)
UMN	Fall 2011	CCEFP	Parker Hannifin Chainless Challenge Senior Design Project. (Brad Bohlmann)
UMN	Fall 2011	CCEFP	Open Accumulator Display (Perry Li)
UMN	Spring 2012	CCEFP	Hydraulic Fuel Pump Drive (Brad Bohlmann)
MSOE	Spring 2010	CCEFP	An Investigation of the Tribological Conditions and Lubrication Mechanisms Within a Hydraulic Geroler Motor
MSOE	Spring 2010	CCEFP	Fluid Power Actuator for use in Active Ankle Foot Orthotics

PU	Spring 2010	CCEFP	Skid Loader Boom Extension
UMN	Fall 2010	Tennant	Tile Marking Mechanism
UMN	Spring 2011	Eaton	Hydromechanical transmission
UMN	Spring 2011	Science Museum of Minnesota	Fluid Power Ankle Orthosis Exhibit
GT	Spring 2011	CCEFP	An Educational Simulation Tool for Hydraulic Systems

Figure 1: Recent fluid power capstone projects

4. Plans

New fluid power capstone design projects every year. Continue to work with NFPA on the process of connecting CCEFP member companies to their local college or university to sponsor a capstone design project. The CCEFP will also provide small grants for supplies and travel to faculty who offer to lead or advise capstone design projects.

5. Member Company Benefits

Capstone projects are a way to connect the Center to the engineering program at a local university. Advising a project results in a close relation with the student team and provides an opportunity for industry members to observe students in a job-like situation before selecting the best for job offers. It also provides a way to get bright minds on an engineering problem of interest to the company.

Project C.4: Fluid Power Courses

Project Team

Project Leader: Jim Van de Ven, University of Minnesota

Other personnel: Will Durfee, University of Minnesota
All CCEFP faculty

1. Statement of Project Goals

Develop new, semester-length undergraduate and graduate courses in fluid power, and include substantial content on fluid power in existing undergraduate and graduate courses. The expectation is that most CCEFP faculty will find a way to insert fluid power curriculum into their courses.

2. How Project Supports the EO Program Strategy

Developing new courses or making substantial modification to courses in CCEFP universities will help to create a cadre of highly skilled students who will become future fluid power industry professionals and future engineering faculty. Advanced graduate courses with content based on CCEFP research provide a means for knowledge transfer of research results. New courses require significant faculty effort and must be consistent with teaching loads and departments' policies for new course adoption, which are outside the control of the Center.

3. Achievements

- ABE 460: Sensors and Process Control taught by Professor John Lumkes at Purdue University utilizes the CCEFP educational activities developed by an REU student during the 2011 Summer. New 2011.
- ME309: Fluid Mechanics taught by Professor Andrea Vacca at Purdue University. The traditional introductory class on Fluid Mechanics at Purdue has been modified according to the project "Fluid Power in Fluid Mechanics" supported by CCEFP and NFPA. Two lectures were completely dedicated to fluid power. Moreover, a new lab experience on fluid power has been introduced. The lab experience is based on a high-pressure water hydraulic test rig developed by Dr. Vacca's team at Maha Fluid Power lab. (More information, see project EO Project C.2). New: 2011.
- ME 4803 / ISyE 4803: Model-Based Systems Engineering taught by Professor Christiaan Paredis and Leon McGinnis at Georgia Institute of Technology. Model-Based Systems Engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. New: 2011.
- ME 8287: Passivity & Control of Interactive Mechanical and Fluid Power Systems is a new graduate course at UMN, created and taught by Professor Li. New: 2011.
- ME 460: Industrial Control Systems – Lab taught by CCEFP Graduate Student Tim Deppen, University of Illinois, Urbana-Champaign. Lab portion of a Frequency Domain controls class. Currently offered, ongoing course using ERC related content. New: 2011.
- ME 8287: Design and Control of Automotive Powertrain taught by Professor Sun at the University of Minnesota. Significant content on hydromechanical systems and modeling and control of hydraulic hybrid vehicles CCEFP. New: 2011.
- ME 4012: Motion Control taught by Professor Wayne Book of Georgia Institute of Technology. Existing courses modified to include CCEFP research. New: 2011.
- ME 4232: Fluid Power Control Laboratory taught by Professors Li, Stelson and Van de Ven, includes CCEFP research and guest lectures by engineers from CCEFP member companies. New faculty instructor 2012.

- INEN 371 Human Factors Engineering, INEN 665 Human Machine Systems, INEN 735 Human-Computer Interface taught by Professor Eui Park of North Carolina A&T State University. These are courses at NCAT modified to include CCEFP research.
- ME 597 /ABE 591 Design and Modeling of Fluid Power Systems taught by Professor Ivantysynova at Purdue University. Graduate course, which has substantial content from CCEFP research.
- ME 697/ABE 691 Hydraulic Power Trains and Hybrid Systems taught by Professor Ivantysynova at Purdue University. Graduate course, which has substantial content from CCEFP research.
- ME 3015: System Dynamics and Control, taught by Professor Ueda at Georgia Institute of Technology, used a pneumatic pressure control system as a class project.
- ME 234 System Dynamics taught by Professor Webster at Vanderbilt University includes CCEFP research results and guest lectures by CCEFP graduate student researchers.
- UIUC undergraduate course in system dynamics will include fluid power material based on mini-book on fluid power system dynamics. Taught by Professor Hsiao-Wecksler.

4. Plans

- Continue to encourage the incorporation of fluid power content into existing courses and to develop new lecture and lab courses in fluid power. The Fluid Power OpenCourseWare project (Project C.2) makes it easier for instructors to include college-level fluid power material in their courses.
- Encourage competition of ongoing projects to develop mini-books.
    - Andrea Vacca, Purdue – Fluid Mechanics module
    - Paul Michael, MSOE – Hydraulic Fluids
    - Will Durfee and Zongxuan Sun, UMN – Fluid Power System Dynamics – revision
- Develop problem sets associated with the mini-books to ease course integration.
    - Possibly utilize the SLC for assistance in developing problems & solutions.
- Utilize multiple modes to increase digital repository content.
    - Video capture existing fluid power related courses and course modules.
    - Capture presentations by industry experts aimed at collegiate audience.
    - Capture advanced topic presentations by faculty aimed at academic researchers and industry members.
- Have CCEFP faculty who are teaching core undergraduate classes to write and present papers in the education sections of technical conferences on infusing fluid power modules into existing mechanical engineering classes (system dynamics, fluid mechanics, and thermodynamics).
    - Encourage participation by providing travel support to authors.
    - Publicize presentation among technical conference colleagues to increase exposure.
- Increase awareness of digital repository among industry members through distribution of a brochure at meetings.
- Encourage CCEFP member schools to include fluid power in list of ABET outcome objectives for related core mechanical engineering courses (system dynamics, fluid mechanics, and thermodynamics).

5. Member Company Benefits

Graduate and undergraduate students who are learning fluid power through their courses. These educated students become the new employees of the companies.

Project C.5: giiwed'anang North Star Alliance

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	Diana Dalbotten, National Center for Earth-surface Dynamics Simone Gbolo, North Star STEM LSAMP Anne Hornickle, North Star STEM LSAMP
Participating Colleges / Universities / Community or Tribal Colleges	*Minnesota Institutions:* University of Minnesota, University of Minnesota-Duluth, University of Minnesota-Morris, Fond du Lac Tribal and Community College, Saint Cloud State University, Leech Lake Tribal College, Bemidji State University, Minneapolis Community Technical College, Century College *Outside Minnesota:* Lac Courte Oreilles Ojibwe Community College (WI), Salish Kootinah Tribal College (MO), University of North Dakota (ND), Michigan Tech (MI)

1. Project Goals

The American Indians in Science and Engineering Society (AISES) and The Advancement of Chicano/Latino and Native Americans in Science (SACNAS) are national organizations with a shared goal: to increase the number of Native American college students in STEM fields. In conjunction with the UMN National Center for Earth Dynamics (NCED), the UMN Institute of Technology Office of Diversity and Outreach, and the North Star (LSAMP) STEM Alliance, the CCEFP is coordinating, sponsoring and hosting all activities of the giiwed'anang North Star Alliance. Goals of the Alliance include: 1) engaging students in STEM-related activities, 2) encouraging students to pursue their education in STEM-related fields at two-year and/or four-year schools and universities, 3) developing a Minnesota student cohort network, 4) increasing the number of AISES and SACNAS chapters.

This alliance aims to form a partnership between the AISES and newly formed SACNAS chapters in Minnesota and to provide tools and resources to assist the students that participate in Minnesota's student chapters. The goals of the giiwed'anang North Star Alliance include forming relationships between Minnesota AISES and SACNAS chapters; providing educational opportunities, academic guidance and opening research doors to Native American students; and bridging the gap between high school, pre- and post-secondary education and industry in STEM fields. By networking with Minnesota corporations and educational institutions, this alliance fosters both fund-raising capabilities and professional support which should lead to an increase in the number of professional student chapters in Minnesota. In turn, the increased number and activities of these chapters should should encourage a larger representation of American Indians in STEM fields and disciplines.

Figure 1: giiwed'anang North Star AISES Alliance Logo

2. How Project Supports the EO Program Strategy
This program is designed to build interest in and prepare under-represented students for STEM careers, a key goal of the CCEFP's Education and Outreach program. Our work with strong and committed partners in reaching this goal illustrates a basic E&O strategy.

3. Achievements

- **2011**
  - The giiwed'anang Northstar STEM Alliance has expanded its number of students from 35 to over 60 Native American undergraduate students participating in at least one giiwed'anang Northstar STEM activity during this current reporting year.
  - The giiwed'anang Alliance was represented on the organizing committee for the National AISES Conference in Minneapolis, Minnesota, November 2011.
  - The University of Minnesota AISES chapter has expanded from six members to over 15. CCEFP Education Outreach Director, Alyssa Burger, serves as the AISES Chapter advisor at UMN.
  - The giiwed'anang Alliance continues to receive financial support from the University of Minnesota Northstar STEM (NSF LSAMP) Program.
  - The giiwed'anang Alliance sponsored 22 students to attend the Region V AISES regional meeting in Souix Falls, SD, in April 2011.
  - The giiwed'anang Alliance sponsored 10 students to attend the National AISES Conference in November 2011.
  - The giiwed'anang Alliance co-sponsored two rocket teams that participated in the All-Nations Launch. One from Fond du Lac Tribal and Community College and the other from the University of Minnesota. Teams earned both first and second place. Co-sponsor was the Minnesota NASA Space Grant Consortium.
  - The giiwed'anang Alliance has helped to launch the Minnesota Region Professional AISES Chapter which is now over 60 members strong and includes Native people in industry, up from 30 just one year ago. The Professional chapter is now eager to begin working with students.
  - The giiwed'anang Alliance is now being accepted as a model for other sub-regions to consider.
  - The giiwed'anang Alliance has successfully established relationships with undergraduate and graduate students in AISES chapters across the states of Minnesota, Wisconsin and North Dakota. Building relationships, mentoring and a support structure is entirely what this Alliance is designed to do.
- **2010**
  - The Alliance has helped to initiate an AISES Chapter with St. Cloud State University (SCSU).
  - The Alliance received funding from the Minnesota NASA Space Grant to sponsor a UMN Rocket Competition Team to participate in the All-Nations Launch, a rocket competition for students in AISES.
  - The Alliance extended its partnerships to actively include the University of Minnesota - Morris which has a very strong AISES Chapter.
  - The Alliance visited and attended AISES Meetings of over 6 partner institutions in the Fall of 2010.
  - The Alliance hosted a Native Skywatchers event and dinner at SCSU in November 2010, with 18 faculty and students in attendance (Figure 2).
  - The Alliance co-sponsored a dinner at the AISES National Meeting in Albuquerque, NM, November 2010 for over 40 students associated with the Alliance. Other sponsors include the Northstar STEM (LSAMP) Alliance and the US Nuclear Regulatory Commission, as a former Alliance student now is an employee with USNRC and was serving as an exhibitor at the conference.
  - The Alliance helped to launch the revitalization of the AISES Professional Chapter in the state of Minnesota, which now has over 30 professional members who will serve as mentors to students in the giiwed'anang Alliance.

    - The Alliance supported 9 undergraduate students to attend the Regional AISES Meeting in Fargo, North Dakota, March 2010.

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- **2009**
    - The Alliance worked with St. Cloud State University and Leech Lake Tribal College on initiating AISES student chapters at those schools.
    - The Alliance grew from eight participants at the first retreat to nearly 45 students across Minnesota as well as in North Dakota and Wisconsin. (While this project is still focused in Minnesota, some students subsequently transferred to schools outstate).
    - In the third year of this program, the CCEFP hired an Alliance undergraduate student to work on building the pneumatic kits, part of CCEFP Education Project B.3a.
    - The giiwed'anang Northstar Alliance assumed responsibility for the re-initiation of the Professional AISES Chapter in Minnesota. The Professional Chapter held three meetings since its revitalization in late 2009.
    - Alyssa A. Burger presented on "How to Start a State-wide Alliance" at the National AISES Conference in Portland, Oregon, in November 2009.
    - Since the inception of the giiwed'anang North Star Alliance, the program has received permanent and partial funding for this program from the North Star STEM LSAMP Alliance headquartered at the University of Minnesota as one of its official undergraduate programs.
    - The Alliance held seven giiwed'anang retreats where students gathered, networked, and shared academic and career goals, set the agenda and purpose for the Alliance and worked to build a greater network of undergraduate Native American students in STEM across Minnesota.
    - The Alliance supported 12 undergraduate students to attend the AISES National Conference in Portland, Oregon in November 2009.
    - The Alliance co-sponsored and co-hosted the Regional AISES Meeting in Minneapolis, MN in April 2009.
    - The Alliance members served as judges at the National American Indian Science and Engineering Fair (NAISEF) hosted at the Science Museum of Minnesota in March of 2009.
- **2008**
    - The Alliance supported 12 giiwed'anang students to attend the AISES National Conference in Anaheim, California in November 2008.
    - The Alliance supported 13 students to attend the Regional AISES Meeting in Rapids City, South Dakota in April 2008.
    - In the first and second year of this program (2008 and 2009), June Sayers from St. Cloud State University was hired as an REU student at the National Center for Earth-surface Dynamics at the University of Minnesota. The giiwed'anang Alliance also contributed to the creation of an AISES Chapter at the Cloquet Middle School in Cloquet, Minnesota as well as St. Cloud State University in St. Cloud, Minnesota.
    - While still in its infancy, the Alliance continued to gain exposure and create partnerships across the state of Minnesota, with a solid base of students in four core schools and a significant network of contacts across the Native American community.

- Other relevant work: This project is closely aligned with several of the Center's initiatives with the Fond du Lac Indian Reservation, a tribal and community college and the local area schools in Cloquet, Minnesota that foster and mentor the K-14 students of the reservation as well as create programs to bridge middle school to high school to college. The high school students who participate in the gidaa Robotics Program (CCEFP Education Project B.4b) will serve as mentors to the gidaa STEM Camps and the gidaa Robotics day and after-school programs as well as the Robofest teams. Ideally, our graduates of gidaa and gidaa Robotics will continue their education either at a community college or a four-year University and subsequently join the giiwed'anang North Star AISES Alliance and be active undergraduate members of this organization. As noted above, this progressive involvement is illustrative of a very important recipe in making these programs successful: repetition, relationships, trust and a support structure within the community as well as with the Center for Compact and Efficient Fluid Power, the National Center for Earth-surface Dynamics, the North Star STEM LSAMP Alliance, the University of Minnesota and the Fond du Lac Tribal and Community College.

4. Plans, Milestones and Deliverables

- In 2012, the CCEFP will invite its evaluation team to include this Alliance as part of the evaluation portfolio.
- Every effort will be made to:
    - Increase the number of participants and institutions in the North Star Alliance.
    - Find additional funding for the Alliance and expand its program options.
    - Expand the Alliance network at the community and industry levels.
    - Increase the number of AISES Chapters in Minnesota.
    - Promote the Alliance framework to other states.
    - Increase the number of students participating in research experiences or internships.
- The North Star STEM LSAMP Alliance will continue to serve as the partial funding source for this program, enabling the Alliance to host three retreats per year and sponsor and/or support student travel to professional conferences, leadership meetings, or academic events. The CCEFP would like to identify additional sources of funding for this Alliance. The CCEFP will consider approaching the AISES Professional Chapter.
- The Alliance will provide information for educational opportunities such as research experiences for undergraduates, industry internships, mentorships, outreach opportunities, etc.
- The Co-Directors of the Alliance will continue to be sources of support and mentorship as giiwed'anang students work towards their undergraduate degrees in STEM.
- The Alliance intends on ensuring that all participating students graduate from their respective schools. In turn, this success will increase the number of students in AISES Chapters in Minnesota as well as increase the number of chapters. We expect to see an increase in transfers from 2-year to 4-year institutions and see the number of students participating in the North Star STEM LSAMP increase to include a greater number of Native American students. By creating a strong network of Native undergraduate students, the Alliance will promote Native education in Minnesota by providing a tool that enables students to complete their education and earn their undergraduate degrees. The Alliance will promote graduate school for participants' respective degrees.

5. Member Company Benefits

Several students from the giiwed'anang program have begun taking classes at the FDLTCC as part of the Minnesota Post-secondary Education Option, which allows students to take college courses without charge while still in high school. These students will begin transferring to 4-year programs. We also have introduced our Center to students who are current undergraduates at FDLTCC. These students will be encouraged to job-shadow at local corporations as part of the North Star STEM LSAMP Alliance. We expect this program will help us match students to our member companies for internships as they begin transferring into 4-year programs. This Alliance will continue to foster STEM education and in turn that will be a direct benefit to society as a whole.

Project C.6: Fluid Power Simulator

Project team:

Project Leader: Prof. Will Durfee, University of Minnesota, CCEFP
Other personnel: Prof. Chris Paredis, Georgia Tech, CCEFP

1. Project Goals

For undergraduate mechanical, aerospace and agriculture engineering students, high-school students in a PLTW program and professionals new to fluid power, the CCEFP fluid power simulator (FPS) will be a medium-fidelity, essential-capability, easy-to-use, freeware simulator of fluid power systems. Unlike existing commercial simulators, the CCEFP FPS will be targeted towards the education market, but will maintain technical rigor.

2. How Project Supports the EO Program Strategy

Not all students have access to fluid power hardware through teaching labs or to professional-grade fluid power simulation applications. Exposing more undergraduate and pre-college students to fluid power engineering can be achieved by providing a high quality simulation package that can be used by anyone without charge. Because PLTW has a particular interest in a simulation package for use by PLTW schools that cannot purchase fluid power hardware, the strategy of educating pre-college students in fluid power by embedding fluid power into PLTW courses will be aided by provided a high quality fluid power simulation package to PLTW

3. Achievements

- Simulator requirements were determined.
- A decision was made to build the CCEFP simulator as a front end to the existing Hopsan simulator.
- A rough prototype simulation package was completed by students at Georgia Tech under the direction of Prof. Paredis.

4. Plans

- Continue development with the goal of a first release during Y7.

5. Milestones and Deliverables

- First release of simulator by May 2013.

6. Member Company Benefits

Increased awareness of fluid power. Increased knowledge of fluid power by PLTW students.

Project C.8: Student Leadership Council

Project Team

Project Leader:	Alyssa Burger, University of Minnesota
Other Personnel:	SLC Officers SLC University Representatives Student Members of the CCEFP

1. Project Goals and Description

The primary role of the CCEFP's Student Leadership Council is to serve as one of five advisory boards to the CCEFP. The SLC also functions as a service organization, a social club, and a student government entity for all students at the CCEFP. The SLC promotes inter-university and industrial collaboration directly with CCEFP students through a travel grant program, provides students with funding opportunities to conduct outreach programs at their local universities through a project grant program, organizes and produces the Center's bi-weekly webcast and is also responsible for planning the annual student retreat.

Each university nominates one graduate student representative to serve on the student leadership council. The SLC members elect four individuals to serve in officer roles: President, Vice President, Secretary, and Treasurer. The officers may be university representatives, but it is not required. The SLC serves as a liaison between the student body and the senior CCEFP leadership voicing concerns and relaying important information between these two groups.

2. Project Role in Support the EO Program Strategy

The SLC serves a vital role in meeting the EO program's goal of providing fluid power education and awareness for pre-college, university, and practitioner students. At the university level, the SLC strives to make the education and research resources of each member university accessible to all CCEFP students through the creation of student directed travel grant program. For pre-college students, the SLC supports programs to have current CCEFP students teach basic fluid power concepts to future engineers and students. Due to the age proximity between pre-college students and current CCEFP researchers, it stands to reason that some of the most effective methods of connecting to younger individuals could come through the student body of the CCEFP. Presently the SLC sponsors project grants which allow individuals at member universities to pursue projects that allow them to connect better with and educate the youth of their communities.

3. Achievements

This past year was particularly exciting for the SLC. Previously, the structure and funding of the SLC somewhat limited the real impact that was possible and student interest was consequently affected. However, this year a significant, positive change was made in both funding and the SLC's overall impact on the CCEFP student body. The two most prominent changes this year were the creation of SLC sponsored Travel and Project grants.

<u>Travel Grants</u>

The SLC Travel Grant Program aims to provide funds for students to travel to another project or industry location, making collaboration more accessible. Three times a year the SLC solicits travel proposals, with a call addressed to all CCEFP students. Students submit written grant proposals and the SLC discusses and votes on which travel grants to approve and which to deny. The maximum grant for any trip is $1,000, and preference is generally given to collaboration between projects over collaboration with industry.

This program has proven to be very popular among students and faculty. During year 6 the SLC held two calls for proposals. In the first call for proposals, the SLC received 4 grant applications and for the second call, just two months later, the number of applications doubled. Eleven project grants have been funded, comprising either past or future travel involving all but one of the CCEFP member universities; future travel is also planned to one non-CCEFP university and three member companies. Below are two testimonials from CCEFP students who utilized the travel grant programs:

- "Jicheng Xia, Lei Tian, and I went to UIUC in the middle of January. Jicheng and I wanted to discuss our current design decisions for the next version of the hydraulic AFO. We learned how Liz Hsiao-Wecksler's group does gait analysis and uses biomechanics to understand how the gait is affected by their device. As we develop our device we are starting to model the system in SimHydraulics. A previous student in their lab has done this for the pneumatic AFO so we talked about how to use the simulation and models. It was good to have conversation about our design parameters and theirs. Their device has been through a few more generations so we talked about how it has evolved and why they chose their initial requirements. We also went to lunch and dinner with a few students, and spent time getting to know them better. Overall I believe the trip was very useful, I was better able to understand their work and its impact on my research. I also believe it fostered a closer relationship between the two research groups which will benefit these projects in the future." – Kathy Houle
- "I traveled to UIUC together with two others who are associated with CCEFP Test Bed 6, to visit Prof. Hsiao-Wecksler and her group. It was a good time as we examined their AFO prototype and control electronics, and discussed about collaboration among projects. Compared to our monthly web conferences for TB6 related projects, this visit was more first-hand and easier to communicate. I definitely believe it will make future web conferences easier to understand topics and ideas having now actually seen them." – Lei Tian

In addition to providing an outstanding collaborative opportunity for CCEFP graduate students, it also is a good experience for members of the SLC who must review and vote on a variety of differing proposals.

Project Grants
The SLC project grant program is intended to fund outreach or social activities in which primarily CCEFP students will be involved. This may include activities such as building hydraulic demonstration kits, travel to an elementary school to teach about fluid power, or pizza for biweekly webcast presentations. Projects may be one-time or recurring, but should be presented in a single proposal as long as recurrence occurs in the same fiscal year. Proposals are limited to $500 per request.

During the reporting period of this report, three project grant proposals were submitted to the SLC; however, voting and grant awards have not yet occurred. It is expected that the first round of project grants will be awarded early in March 2012. With the introduction of these new grant programs just this year, initial emphasis was placed on promotion the travel grant program. Now that the travel program seems to be well established, advertisement focus is being shifted to the project grant program. This advertisement seems to be effective given the recent submission of three proposals, and hopefully this program will be similarly well established by next year.

New Student Guide & Orientation Webcast
The high turnover of graduate students constantly poses problems in an organization that is comprised of, and dedicated to serve, the CCEFP graduate student community. Frequently, many new CCEFP students don't understand the organization of the higher CCEFP administration, much less the existence of the SLC, until after their first annual conference. This was an unfortunate truth in past years simply due to the lack of a proper program to educate new members.

That changed this year thanks to the effort of the SLC with the creation of the "New Student Guide." This guide book is a 33 page document that gives a well-balanced introduction to the CCEFP. The guide lists member companies, short project and test bed descriptions, outlines the CCEFP administrative / advisory boards and their respective membership. It outlines some of the yearly requirements of students, provides an overview of the resources section of the CCEFP website, and is even complete with photos and descriptions of the center's primary administration. The new student guide was printed and distributed to every new CCEFP student at the beginning of the Fall 2011 semester. Additionally, a CCEFP website was dedicated to introduce new students (and remind current ones) of the many points mentioned in the guide and provided a nice forum of dialog and discussion for the new students.

<u>CCEFP Bi-Weekly Webcasts</u>

The Center estimates between 45 - 60 participants per webcast on a regular basis. Participants include industry, faculty, staff and students. Note that we realize that the Center's seven universities as well as industry often arrange for a conference call and meeting space for multiple listeners. In addition to including an audio feedback component, the Center has greatly improved its efficiency and effectiveness with the CCEFP webcasts. The SLC's vice president hosts each webcast, creating seamless transitions between each presenter.

Presentations are not just project-specific information; they also include information on how each project is aligned with the Center's strategic plan. For research, presentations describe how work is demonstrated on the Center's test beds, how current research aligns with what has been done previously as well as how it is breaking new ground, etc. These inclusions have added important new dimensions to the webcasts and have provided another avenue where students, faculty and Center leadership can continue to strategize on the direction of the research projects across the Center. Additionally, webcasts now include more special topics, education outreach presentations and "State of the CCEFP" discussions presented by Center Leadership.

<u>SLC Social Activities and Student Retreat</u>

In addition to providing all of the previously mentioned resources, the SLC also aims, in part, to foster a positive social atmosphere between its student members. Given the physical separation of much of the student body, time spent together at conferences and meetings is particularly important to forming bonds that will enable greater overall moral and collaboration.

The 2011 CCEFP annual meeting was held in conjunction with IFPE (an international exposition and technical conference dedicated to the integration of fluid power with other technologies for power transmission and motion control applications) and CONEXPO-CON/AGG, a world-wide event for the construction industries, in Las Vegas, NV. This was an excellently organized event as it provided students attending the annual meeting with the opportunity to visit the vast number of commercial booths at both shows. As part of this event, the SLC sponsored activities involving the students attending including the Freemont Street Zipline (Fig. 1).

Figure 1: A photograph of the Freemont Street Zipline, a social activity promoted by the SLC in 2011.

The 2011 CCEFP student retreat was held in Schaumburg, IL in conjunction with the 2011 NFPA Industry and Economic Outlook Conference. It was during this retreat that the travel and project grants were first announced to the general CCEFP student body. Additionally, other business meetings such as an SLC meeting, CCEFP Industry team, and Industry-Student connection meetings took place. The retreat portion of the event formally concluded with a faculty/student dinner. On the following day, many of the students in attendance at the retreat stayed to attend the IEOC conference and present their work at an industry focused poster show. The day after the IEOC conference, a former CCEFP graduate student organized a tour of the company where he is now employed for current Center students. Through tours such as this, the graduate students of the CCEFP continue to see the real-world application of their work.

SLC SWOT Analysis

Every year the SLC conducts a Strengths, Weaknesses, Opportunities, and Threats analysis of the student body to identify what efforts are working and identify what areas need continued improvement. An online survey of CCEFP student members was conducted this past year to gauge how students felt the Center has changed since the last SWOT analysis. The results of this survey and the SLC analysis can be found in the SLC SWOT analysis in section *4.5.1 Systems Vision and Value Added of the Center*, sub-section *4.5.1.1 Systems Vision*.

Figure 2: CCEFP 2011 Student Retreat Attendees.

4. Plans, Milestones and Deliverables

The deliverables of the SLC efforts this past year have been clear. Through the hard efforts of many of its members, an orientation guide was created, travel and project grants were incepted, and bi-weekly webcasts continue to educate CCEFP student members and external companies of recent research developments. Additionally, the SLC sponsors and promotes social events to encourage the development of strong relationships between fellow researchers at SLC student retreats and any other event where many CCEFP students are present.

Plans for the future continue to promote and expand the travel and project grant programs, enabling CCEFP students to continue collaboration with their colleges at other institutions. Additionally, although the SLC tends to sponsor a corporate tour once or twice a year, few graduate student summer internships have occurred with member companies. Naturally, some of this might be due to the unique schedules of graduate students; however, it is something the SLC wishes to promote in the future. The SLC is investigating the best ways to aid students in obtaining internships with member companies and hopes to have an initial program in place for the next year.

5. Member Company Benefits

- SLC funded travel grants enable CCEFP students to travel to industrial locations for training or further education.
- The SLC organizes industrial tours at locations near-by to conference locations were numerous students will already be in attendance.
- The SLC is looking to promote and foster internships between CCEFP graduate students and member companies in the next year.
- The SLC hosted Webcast continues to be the primary means by which industry members can receive continuous updates on CCEFP research projects and Testbeds.
- Student retreats offer significant networking opportunities for companies wishing to get to know students or hire them.

Project C.9: Undergraduate Research Diversity Supplement (URDS)

Project Team

Project Leader:	Alyssa Burger, Education Outreach Director, CCEFP
Other Personnel:	Paul Imbertson, Education Director Kim Stelson, Center Director CCEFP Faculty Advisors

1. Project Goals

The CCEFP is committed to promoting the increased participation of diverse undergraduate students in engineering. The short and long-term goals of this supplement program are:

- to provide CCEFP faculty with the means to involve additional undergraduate students on CCEFP research projects,
- to identify an underrepresented student who might not otherwise consider a research opportunity in CCEFP laboratories,
- to encourage students to consider graduate study or an employment position in the fluid power industry by fostering a learning and career advancement environment,
- to further provide exposure to fluid power technology to a diverse audience, and
- to answer the country's need for greater retention of underrepresented students in engineering.

2. How Project Supports the EO Program Strategy

The Center's Education and Outreach program is committed to proving opportunities to broaden the participation of underrepresented students in undergraduate engineering programs through this Undergraduate Research Diversity Supplement to current CCEFP research projects.

3. Achievements

This program was launched in Year 6 of the CCEFP and the response has been favorable. To date, two supplemental requests have been granted:

- A Caucasian Female Undergraduate supported on CCEFP Testbed 6.
    - Advisor: Professor Elizabeth Hsiao-Wecksler. University of Illinois, Urbana-Champaign
    - Project description: Under Testbed 6, researchers have developed an untethered powered AFO system, which is called the portable-powered ankle-foot orthosis (PPAFO). This system uses pneumatic power from compressed CO_2 to drive a rotary actuator that provides bi-directional assistive torque at the ankle joint: dorsiflexor assistance (toes up) and plantarflexor assistance (toes down).
- An African-American Female Undergraduate supported on CCEFP Testbed 6 affiliated project: Ankle-Foot Orthosis.
    - Advisor: Professor Zongliang Jiang, North Carolina A&T State University
    - Project description: The construction and implementation of a database system is essential to the success of the AFO user interface. The long-term goal of the AFO user interface project is to establish an effective and user-friendly interface for the clinicians to interact with the AFO enabling them to examine a patient's rehab progress and prescribe a new assistance plan or therapy regimen. This proposed database manages patient data (e..g., medical history, past therapy sessions and results) which are crucial pieces of information in the decision-making processes of clinicians during their interaction with the AFO for maximized effectiveness in rehabilitation or daily assistance. How such data is organized and accessed by the clinicians is fundamental to the effectiveness of the entire AFO user interface

- The CCEFP E&O program has an application and proposal process for this URDS which includes the following:
    - **Candidates:**

    - Candidates must be a currently enrolled undergraduate student, in good standing, at CCEFP institution
    - A candidates must be a student of underrepresented status in engineering or other related discipline. This includes students who are women, African American, Native American or Native Alaskan, Pacific Islander, Hispanic or Latino/a, a person with disabilities, or a recent war veteran of the armed services
    - Candidates must be United States citizens, nationals, or permanent residents of the United States.
- **Supplement request requirements:**
    - **A proposed research project**. A maximum of 2 pages.
    - **Undergraduate student mentoring plan**. Include a brief description of mentoring activities that will be provided for the proposed candidate. This could include a timeline and set of deliverables, career counseling and networking, professional development, presentation opportunities, seminar/conferences or workshops, etc.
    - **Previous CCEFP experience**. Include a brief description of previous CCEFP experience, if applicable. Eligibility requirements of this supplement require that awardees are not current student employees of the CCEFP.
    - **Student statement of purpose**. The candidate indicates interest in undergraduate research including academic and career goals.
    - **Student resume.**
    - **Budget and justification**. Submit a budget that is fully burdened, inclusive of 25% indirect on participant support costs. Maximum request is $2,000.
- **Award Information:** Awards will be granted based on proposal merit. The Education Outreach Director, in consultation with Center Director, will make decisions on the supplement awards. Anticipated funding for this supplement is $11,250 under the CCEFP Education and Outreach Program. The estimated number of supplements to be awarded will be four to six. The end date of the supplemental award is May 31, 2012.

4. Plans, Milestones and Deliverables

- As usual, a start-up program requires time to gain footing. To date, and as noted above, two awards have been granted to undergraduate underrepresented students in engineering.
- The CCEFP E&O program will continue to support this program as long as the research program can sustain it. The CCEFP understands that hands-on research experiences, with the guidance of a mentor, are key to promoting graduate school to underrepresented students in engineering. The CCEFP has the resources, tools and leadership to make significant impacts in fluid power education.
- The CCEFP will continue to support up to six undergraduate students per year beginning in year 7. At least half of the URDS awardees will be women and at least half will represent racial or ethnic minorities.
- The CCEFP will inquire into additional and external funding to support this program -- sponsored funding and/or industrial support.
- The E&O program will require advisors to issue a mentoring plan for each student and invite awardees to present at one of the following events: CCEFP Annual Meeting, CCEFP Site Visit, or CCEFP IAB Summit or CCEFP Research Webcast.
- When appropriate, the CCEFP will encourage awardees to apply to the National GEM Consortium, which is a national program committed to promoting graduate student study for racially or ethnically underrepresented students in engineering. The GEM Consortium has a fellowship program, which is supported by its industry members. The GEM Consortium and the ERC membership are key to the CCEFP Diversity strategy.
- Lastly, the E&O program will begin to include the URDS program as part of its evaluation portfolio, following the REU pre and post-survey model.

5. Member Company Benefits

The URDS program contributes to the building of an informed and motivated student group—future leaders for industry and academia.

Project C.10: NSF Graduate Research Diversity Supplement

Project Team

Project Leader:	Alyssa Burger, Education Outreach Director, CCEFP
Other Personnel:	Kim Stelson, Center Director, CCEFP Paul Imbertson, Education Director, CCEFP CCEFP Faculty advisors

1. Project Goals

The CCEFP is committed to promoting the increased participation of diverse graduate students in engineering. The short and long-term goals of this supplement program are:

- to provide CCEFP faculty with the means to involve additional graduate students on CCEFP research projects,
- to identify a graduate student who might not otherwise consider a research opportunity in CCEFP laboratories,
- to encourage students to consider graduate study or an employment position in the fluid power industry by fostering a learning and career advancement environment,
- to further provide exposure to fluid power technology to a diverse audience, and
- to answer the country's need of greater retention of underrepresented students in engineering.

2. How Project Supports the EO Program Strategy

The Center's Education and Outreach program is committed to broadening the participation of underrepresented students in engineering programs through channels including the NSF Graduate Research Diversity Supplement (GRDS) to current CCEFP research projects. This effort is complemented by the CCEFP's own Undergraduate Research Diversity Supplement (URDS). (See E&O Project C.9.) Ideally, the CCEFP's URDS would positively influence a student to enter graduate school within the Center where a faculty advisor, in turn, would apply for the NSF GRDS award.

3. Achievements

The CCEFP has applied for and been awarded three years of funding under this supplement and has supported three female graduate students. The CCEFP has applied for a fourth year of funding which would support yet an additional female graduate student in engineering.

Proposed: 2012 - 2013: **Ms. Charreau Bell**, Vanderbilt, 1st Year of Proposed Funding
Ms. Morgan Boes, UIUC, 2nd year of Proposed Funding

<u>GRDS Proposal: Description of Proposed Scope of Work</u>

The supplement will be used to fund two female GRDS awardees, Charreau S. Bell and Morgan K. Boes. The supplement will be a key element in recruiting Charreau Bell, a perspective African-American Ph.D. student in the Department of Mechanical Engineering at Vanderbilt University (VU) beginning in August 2012. Her research mentor will be Professor Pietro Valdastri, a new faculty member in the CCEFP and the Department of Mechanical Engineering at Vanderbilt University, whose limited startup funds, alone, would not allow Charreau's recruitment. The supplement will also be used for a GRDS renewal project for another female student, Morgan Boes who started as a PhD student in the Department of Bioengineering at the University of Illinois, Urbana-Champaign (UIUC) in January 2012, the start-date of her current GRDS support. Morgan's mentor will be Professor Elizabeth Hsiao-Wecksler (UIUC) on CCEFP Test Bed 6, Human Assist Devices. The GRDS funds have allowed Morgan to move to an engineering-based project for her PhD dissertation. Both women's long-term career goals are to obtain positions in major research universities. Morgan is part of the Medical Scholars MD/PhD Program at UIUC. Her career goal is to be a physician-researcher at a research university with a medical school. Charreau's goal is to obtain a tenured faculty position in a major research university.

Funded: 2011 - 2012: **Ms. Katherine (Braun) Houle**, UMN, 2nd & Final Year of Funding
Ms. Emily Morris, UIUC, 3rd and Final Year of Funding
Ms. Morgan Boes, UIUC, 1st Year of Funding

Outcomes:

- **Morgan Boes** is working on Test Bed 6 (Human Assist Devices: Fluid Power Ankle-Foot Orthosis (AFO)). TB6 is one of four test beds in the CCEFP. Of the four, it is the smallest size scale and is intended to answer the question of whether the energy-to-weight and power-to-weight advantages of fluid power continue to hold for tiny, mobile fluid power systems in the 10 to 100 W range. Test Bed 6 also serves to drive the development of enabling fluid power technologies that are powerful, compact and lightweight and has the practical objective of creating new portable, wearable fluid power assist devices. Test Bed 6 is a joint project between the University of Illinois (UIUC) and the University of Minnesota (UMN) with UIUC integrating the technology and conducting biomechanical testing on low-pressure pneumatic systems and UMN looking at advanced technologies with high-pressure electro-hydraulic solutions.
- **Kathy (Braun) Houle** continues to work at the CCEFP on Test Bed 6. She is part of the UMN team working on a hydraulic version of the powered AFO. Kathy used her expertise in musculoskeletal mechanics to translate biomechanical requirements into engineering designs. She conducted detailed assessments of the torque, velocity and power produced by the ankle during normal walking and translated these into appropriate design requirements for the hydraulic components in the AFO. This was a non-trivial task as informed trade-offs must be made to accommodate realistic hydraulic configurations. She also directed the test plan to evaluate performance of the first version of the hydraulic AFO, which includes comparing performance to computer simulations. In addition, Kathy has taken on leadership roles including presenting the TB6 project for CCEFP project reviews and mentoring a summer REU student.
- **Emily Morris** decided to complete her master's degree and thesis at the end of August 2011. She returned to industry working for Caterpillar in Peoria, IL, a CCEFP Industry member. Caterpillar served as her employer prior to starting her graduate studies. During the spring and summer of 2011, she worked on projects to improve the efficiency of the PPAFO inTB6. She performed computational analyses to assess inefficiencies due to pressure loss. The work was presented at the 2011 International Fluid Power Expo and a journal paper is in preparation. During the summer, she worked with a CCEFP REU to experimentally explore use of thermal regulation of the CO_2 power source bottle or supply line to the rotary actuator to improve system efficiency.Morgan Boes will continue these activities by incorporating Emily's design modifications into the next generation PPAFO. Emily continues to work with the CCEFP and TB6 as an advisor for a Mechanical Engineering senior design team at Bradley University in Peoria, which has a CCEFP Education & Outreach grant for AY11-12 to develop a pancake pneumatic rotary actuator using a novel design. During Emily's master's program, she authored eight abstracts/papers for scholarly or professional conferences (four as first author), and presented at two national technical conferences and multiple UIUC campus and CCEFP events and meetings. Two journal papers are also in preparation from her work.

Funded 2010 - 2011: **Ms. Katherine Braun**, UMN, 1st Year of Funding
Ms. Emily Morris, UIUC, 2nd Year of Funding

Outcomes**:**

- **Katherine Braun** started her graduate studies at UMN and in the CCEFP in August 2010, working on a team of UMN graduate and undergraduate students focused on Test Bed 6, Human Assist Devices: Fluid Powered Ankle-Foot Orthosis (AFO), to further develop and test tiny fluid power technology. To better understand hydraulic power and its application to the AFO, Katherine started by doing background research and literature searches in the field. She also tested and modified a large-scale hydraulic AFO built by a previous UMN undergraduate design group. This design was built with currently available components and it was heavy and bulky. The system was analyzed to find its ideal operating conditions and to prove its efficacy at providing sufficient torque to assist human gait. These findings are being used to understand how to build tiny hydraulic components better suited to wearable applications. Katherine worked closely with Jicheng Xia, another UMN PhD student, who was developing a tiny hydraulic vane pump that can be used to lift a person. This pump will be combined with the hydraulic AFO prototype to reduce its weight and size. Katherine strengthened her understanding of machine/product design, hydraulic power, the biomechanics of gait, and controls by taking several courses including *New Product Design and Business Development, Analog and Digital Control, Human Factors and Work Analysis,* and *Materials in Design*. Shemaintained a 3.77/4.0 grade point average. To better understand gait pathologies, Katherine performed analyses on hydraulic systems and gait mechanics, and presented this work in conjunction with Jicheng Xia's work on tiny hydraulics at the CCEFP Annual Meeting in March 2011 and at the Design of Medical Devices Conference in April 2011.
- In the interest of developing a dynamic gait model for use in the analysis of the ankle foot orthosis (AFO), **Emily Morris** used a freely available open source, movement simulation software called OpenSim. OpenSim was developed by the Simbios National Center for Biomedical Computing at Stanford University. Emily attended the OpenSim Developer's Jamboree in July and gained useful insight into the workings of the software, which added functionality to the model. Emily also mentored an undergraduate student who was using OpenSim to analyze human movement. Emily also performed a detailed analysis of the current AFO system components. In a pneumatic system, inefficiencies occur at areas of pressure loss. These inefficiencies result in a decrease of potential work, and thus need to be either eliminated or reduced. Her analysis combined both theoretical and experimental methods. As a result of this analysis, Emily was able to not only identify the major contributors to the system pressure losses, but she was also able to improve the system efficiency by 20%, simply by changing the flow path routing. Emily presented her work to the remainder of the Test Bed, and it was used as a benchmark for future prototypes. Her work was also presented at the 2011 International Fluid Power Expo. Emily has also continued to strengthen her understanding of human movement, gait pathologies, and biomechanics. Over the past several months, Emily aided with the experiments of two impaired subjects wearing the AFO, and analyzed the resulting motion data. She also assisted with experiments on healthy adults wearing the AFO to perturb gait. Emily analyzed the motion data and sent her results to her collaborators at Georgia Tech. Emily also presented her analysis on pathological gait at the American Society of Biomechanics in August.

Funded 2009 - 2010 **Ms. Emily Morris**, UIUC, 1st Year of Funding

Outcomes:

- **Emily Morris**: The supplement was used to fund a newly admitted female student, **Emily Morris**, in the MS/PhD program in the Department of Mechanical Science and Engineering at the University of Illinois at Urbana-Champaign. Emily enrolled in the graduate program beginning in August 2009 and worked on research supporting Test Bed 6 of the CCEFP (Human Assist

Devices). Her research mentors are Professor Elizabeth Hsiao-Wecksler in the Department of Mechanical Science and Engineering at the University of Illinois and Professor Zongliang Jiang in the Department of Industrial & Systems Engineering at North Carolina A&T State University (NCAT). Emily Morris brings a unique educational and industrial experience background that is ideally suited to the Test Bed 6 team. She has a BS in Mechanical Engineering with a concentration in bioengineering and a minor in biology. During her undergraduate studies, she was involved in a number of projects that utilized her knowledge of design, biological sciences, and fluid mechanics. Since graduating, she has been working as an engineer for Caterpillar, Inc. During a 12 month rotation in their Hydraulics Division, Emily gained experience in component testing, manufacturing, and computational simulation.

4. Plans, Milestones and Deliverables

- The CCEFP E&O and Research program will continue to support this program as long as the research opportunities within the Center can sustain it.
- The CCEFP will continue to request NSF supplemental support for up to two graduate students per year during CCEFP years 7, 8 and 9.
- At least half of the GRDS awardees will be women; at least half of the GRDS awardees will represent racial or ethnic minorities.
- The supplement will require advisors to issue a mentoring plan for each student and invite awardees to present at one of the following events: CCEFP Annual Meeting, CCEFP Site Visit, or CCEFP IAB Summit or CCEFP Research Webcast.
- The program will be evaluated and assessed in Years 7 and beyond.
- Efforts will be made to encourage GRDS awardees to achieve their PhDs through the CCEFP.

5. Member Company Benefits

Member companies can participate in graduate research projects as mentors. Here, member companies get a first look at a bright, diverse pool of students trained in fluid power who may become future intern or permanent employees. More generally, the GRDS program contributes to the building of an informed and motivated student group—future leaders for industry and academia.

Project C.11: Innovative Engineers (IE) Program

Project Team

Project Leader: Paul Imbertson, CCEFP Education Director

Other Personnel: Alyssa Burger, CCEFP Outreach Director
Student Members of the Innovative Engineers (IE) Student Organization

1. Project Goals and Description

The Innovative Engineers (IE) student group was formed in 2010 by engineering students at the University of Minnesota who were inspired to actively pursue renewable energy solutions for people in remote and developing areas. Since their inception, they have grown from about 15 original members to well over 70. IE fills a need at the university by providing a space where engineering students can take part in active pedagogy, learning and honing their engineering skills by working on real projects.

The CCEFP has partnered with the Innovative Engineers Student Group to promote student engagement and to bring an awareness of fluid power to the student engineering community by sponsoring projects with fluid power components.

2. Project Role in Support the EO Program Strategy

A core mission of CCEFP Education and Outreach program is to educate university students and to bring awareness of the CCEFP and fluid power to those engineering students. Partnering with the Innovative Engineers student group gives the CCEFP a unique opportunity to address that mission by becoming an integral partner in a large and active group of engineering students. The CCEFP will provide project and organizational support to IE.

3. Achievements

Since its formation in 2010, the Innovative Engineers has been very busy as can be seen from articles that have been written about them in the press.

- "Innovative Engineers Power Third World", Minnesota Daily, March 2010
- "U Engineers Aid Nicaraguan Village", Minnesota Daily, November 2010
- "Building turbines and relationships", College of Science and Engineering", April 2011
- "Promueven energia eolica en Jinotega (Promoting Energy in Jinotega)", Laprensa, May 2011
- "Wind-Wind Situation", University of Minnesota Foundation, Summer 2011
- "Winds of Change", Inventing Tomorrow, a publication for alumni of the College of Science and Engineering, Winter 2011

Much of the work of IE is documented in these publications, and includes:

- The group built and installed a wind turbine in the community of La Hermita in Nicaragua for the BRIDGE Project. The CCEFP supported the final installation efforts.
- IE worked with middle school students through a program with the Science Museum of Minnesota to build a wind turbine over a series of Saturday work sessions.

- In 2010 IE formed an international branch of IE at the Universidad Ibero Americana in Mexico City.
- Work was started on the design and development of a hybrid electric/hydraulic wind turbine. This work is directly supported by the CCEFP.

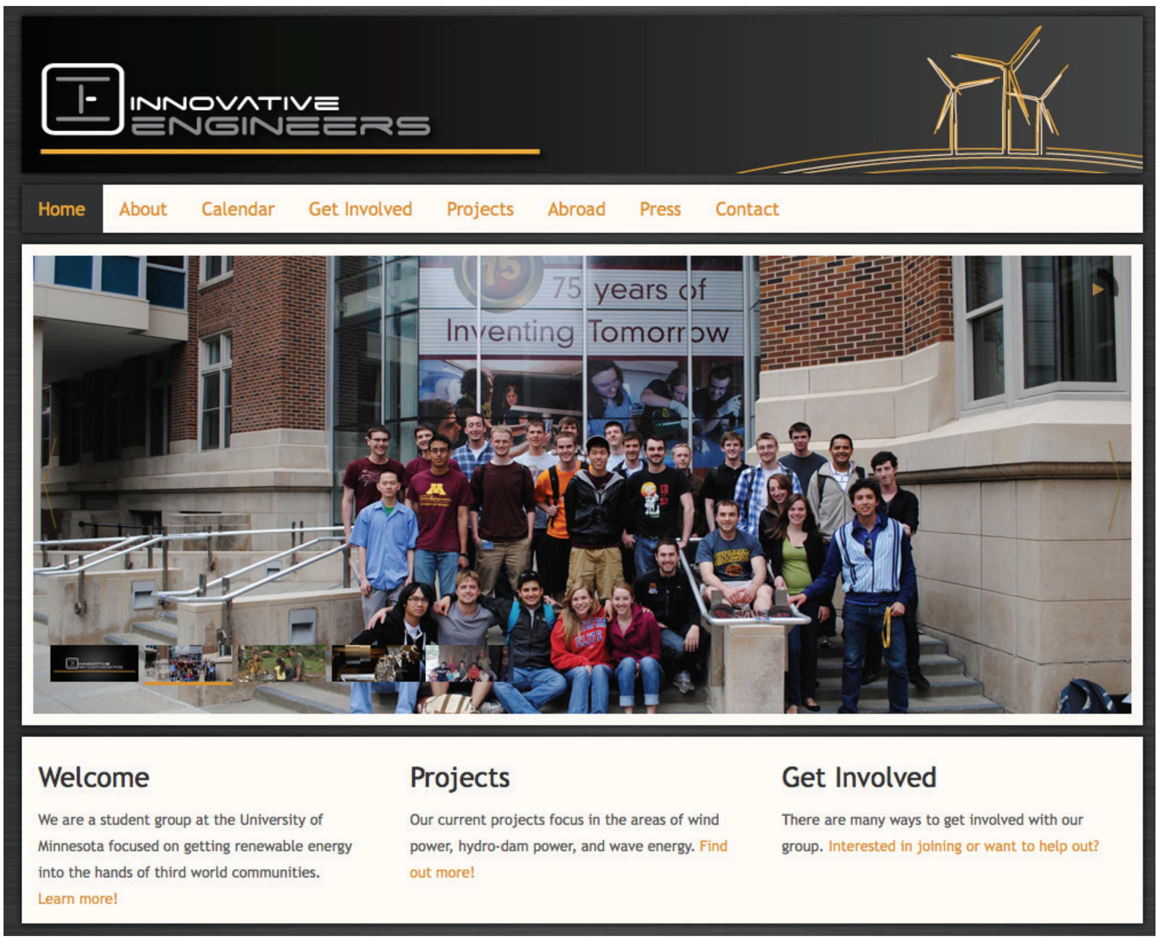
4. Plans, Milestones and Deliverables?

Innovative Engineers is positioned for growth and more efficient project development with the partnership with the CCEFP. Future plans include:

- Hydraulic brick press
- Expansion to other CCEFP partner institutions
- Partner with SAFL and EOLOS

5. Member Company Benefits

Benefits to member companies includes access to students and projects. Further, member companies may benefit from the public visibility that can come from an association with IE.



Project D.1: Fluid Power Scholars/Interns Program

Project Team:

Project Leader: Alyssa Burger, CCEFP Education Outreach Director

Other Personnel: Linda Western, Education/Industry Program Coordinator

Industry Partners: Members of the CCEFP Industrial Advisory Board; volunteer sponsors/mentors from the ranks of the Center's industry supporters

1. Project Goals

The Fluid Power Scholars program benefits participating students and the companies that sponsor them. Student participants gain hands-on experience in fluid power technology as they work as summer employees in a "real world" work environment. Sponsoring companies benefit as the students they mentor contribute to workforce productivity, often bringing new perspectives to their tasks based on what they have learned in the classroom. An internship program also provides companies with opportunities to determine whether their scholar/intern might work well as an employee following graduation. Recognizing these benefits, the CCEFP has made a good model even better by adding an intensive orientation to fluid power at the outset of the internship experience in order to enable scholar/interns to make more immediate and effective contributions to their host companies.

2. How Project Supports the EO Program Strategy

Cultivation of cooperative efforts, informed by and of benefit to the academic and corporate world of fluid power, is key to CCEFP education and outreach program strategy. The Fluid Power Scholars/Interns Program rests on partnerships between industry, the Center, and engineering students nationwide. The program also facilitates knowledge transfer between Center constituents--from the classroom to the shop floor.

3. Achievements

Establishing an effective internship program--one that draws top engineering students to work in the fluid power industry--was a priority of the CCEFP even at its proposal stage. The appeal of the program rests on the promise of shared benefits. As interns, students learn about hydraulics and pneumatics through hands-on experiences while companies with whom they work (possible future employers?) learn about them. Though the benefits to everyone were clearly apparent, developing a successful internship program through the CCEFP proved to be very difficult. For some companies, Center intervention wasn't necessary; they already had established internship programs. For others, the Center's help was welcomed, but within this group there were (still are) a myriad of differences: facility location, start times and internship duration, preferences for where interns should be in their programs (undergraduates or graduate students, students from Center schools or elsewhere), etc. With the benefit of all these lessons learned, the following steps were taken in order to create an appealing and workable plan:

- 2008: Center staff together with a task force of industry members explored why the Center's intern program had stumbled, and looked for ways to create something better—a program that would appeal to many companies regardless of where they stood on internships, one that would draw on assets unique to the Center. The Fluid Power Scholars/Interns Program is the product of this group's design. In order to make this program stand out to students and companies alike, participants on the planning team agreed that it should be unique, drawing on resources that set the Center apart. They determined that up to ten Fluid Power Scholars would be named in early spring, each matched through a competitive application process with a corporate supporter of the CCEFP who agreed to be a program sponsor. Sponsors would provide a paid internship and also cover the costs (travel, room and board) that their scholar would incur in attending a three-day intensive orientation to fluid power taught by faculty at the Milwaukee School of Engineering's Fluid Power Institute. The CCEFP would cover costs of instruction. Company internships would begin following the orientation.

- 2009: The worldwide economic downturn profoundly affected the fluid power industry and the Fluid Power Scholar/Intern program was placed on hold.

- 2010 program launch and execution:
    - Beginning in October, every supporting company of the CCEFP learned about the 2010 Fluid Power Scholars/Interns program through an ambitious communications campaign led by CCEFP staff. Multiple channels—in print, e-mail, telephone, and website—were employed in this campaign. The campaign was successful. Seven companies offered to support eight scholars in the summer of 2010: Caterpillar, Deltrol Fluid Products, John Deere, Enfield Technologies, Parker Hannifin Corporation, Sun Hydraulics, and Tennant Corporation. Their internship positions were posted at the Fluid Power Scholars section of the Center website.
    - Student recruitment: An equally ambitious student recruitment effort, organized by CCEFP staff, resulted in over 40 student applications. Students representing universities within and outside of the Center applied through an on-line process at the Center website. (Note that the Scholars/Interns Program is open to undergraduate students who have successfully completed at least two years in an accredited engineering program anywhere in the United States.)
    - Matching process: All sponsoring companies had access to a secured section of the CCEFP website where student applications were posted. Company personnel studied these applications and selected their top choices for the internships they had posted. While they informed CCEFP staff of these choices, companies were solely responsible for contacting students to set up and conduct telephone interviews and to subsequently make internship offers. 2010 scholars/interns represented Carnegie Mellon (1), Illinois Institute of Technology (1), Montana State University (2), University of Michigan (1), University of Minnesota (2), and University of South Florida (1). (The "myriad of differences" in company choices, noted above, was manifested in the selection process. In only one instance did companies name the same student as their top choice.)
    - Fluid power orientation at the Milwaukee School of Engineering: Internal evaluations by MSOE and evaluations led by the Center for Applied Research for Education Improvement (CAREI) indicated high student satisfaction with this element of the Scholar/Intern Program. In fact, several of the students recommended that it be lengthened from three days to perhaps as long as a week.
    - End-of-program evaluations: All corporate sponsors of the 2010 fluid power scholars/interns indicated their satisfaction with the program and indicated their willingness to participate in 2011. With one exception, students also indicated their strong satisfaction.

- 2011 program
    - The set up of the 2010 program was so workable by all accounts, that the same promotion, recruitment and selection procedures were followed again in this, the program's second year.

    - Scholar/Intern positions: Seven companies offered to support eight scholars in the summer of 2011: Caterpillar, Deltrol Fluid Products, John Deere, Case New Holland (2), Parker Hannifin Corporation, Sun Hydraulics, and HUSCO International. Their internship positions were posted at the Fluid Power Scholars section of the Center website.
    - Student recruitment: The CCEFP received applications from 60 students at __ universities. Students representing universities within and outside of the Center applied through an on-line process at the Center website. (Note that the Scholars/Interns Program is open to undergraduate students who have successfully

completed at least two years in an accredited engineering program anywhere in the United States.)

- Matching process: All sponsoring companies had access to a secured section of the CCEFP website where student applications were posted. Company personnel studied these applications and selected their top choices for the internships they had posted. While they informed CCEFP staff of these choices, companies were solely responsible for contacting students to set up and conduct telephone interviews and to subsequently make internship offers. 2011 scholars/interns represented Case Western Reserve (1), University of Florida (1), Purdue (1), Clarkson (1), University of Minnesota (2), and University of Missouri-Columbia (2). (The "myriad of differences" in company choices, noted above, was manifested in the selection process. None of the companies named the same student as their top choice.)

2011 Fluid Power Scholars

- Ongoing evaluations: Following an evaluation model established and conducted by the Center for Applied Research and Educational Improvement (CAREI) in 2010 as well as reference to CAREI's relevant background work in 2008 and 2009, CCEFP staff evaluated the 2011 program through surveys and telephone interviews with student scholar/interns and their corporate sponsors.

Fluid Power Scholars	**2010**	**2011**
Number of Students	8	8
Males	6	8
Female	2	
% of students from underrepresented groups		
1) racial minority	13%	0%
2) gender minority	25%	0%
3) disability	0%	0%

Achievements:

- The number of applicants to the 2011 program, when compared with the 2010 program, increased by 50%--from 40 to 60.
- Several of the CCEFP's scholar/interns in 2010 and 2011 have been/will be hired by their corporate mentors. At this writing, the CCEFP is aware of the following hires from among 16 scholars/interns: Sun Hydraulics (2), Enfield Technologies (1), Caterpillar (2), John Deere (1), HUSCO International (1).
- All company sponsors have expressed their satisfaction with the program. Of the nine corporate sponsors in 2010 and 2011, six are sponsors for the 2012 program. The other three elected not to participate in 2012 for reasons other than any dissatisfaction with the program.
- The orientation to fluid power offered to scholars/interns at the outset of the program by faculty at the Milwaukee School of Engineering's Fluid Power Institute has been highly reviewed by scholars/interns and their corporate sponsors.
- Recruitment efforts continue to generate interest in the program among students within and outside of the CCEFP university network.

4. Plans, Milestones and Deliverables

- As of this writing, company and student recruitment for the 2012 Fluid Power Scholars/Interns Program has concluded and students are being interviewed by the 2012 corporate sponsors: CAT, Deere, CNH (2), Parker Hannifin, Sun Hydraulics, HUSCO International (all repeating program participants) and Eaton Corp. (a new corporate sponsor).
- The orientation to fluid power offered by MSOE to scholars/interns will be lengthened by a day in 2012. This follows from recommendations by students and industry.
- Given student and corporate interest, the Fluid Power Scholars/Interns program will continue beyond 2012, potentially with added scholar/intern opportunities in 2013 and thereafter. In order to sustain this growth, all sponsoring companies will be encouraged to help in the recruitment effort by sharing their program success stories with non-participating companies.
- The CCEFP's website page that provides links to internships within the fluid power industry outside of the Scholars Program will continue to be maintained. Though complementary to Center goals, these internship programs are independent of the Scholars/Interns Program. See http://www.ccefp.org/get-involved/internships.
- A thorough evaluation of the Scholars/Interns Program will be conducted at the launch and at the end of summer 2012 with the help of Quality Evaluation Designs. New data, along with comparisons with the old, will help to shape the Fluid Power Scholars/Interns Program going forward.

5. Member Benefits

- Internships provide companies with opportunities to directly participate in educating and training a next generation of engineers.
- Fluid power interns provide an excellent way to locate motivated, short-term engineering help.
- Long term, internships are viewed by many in industry as an invaluable tool for identifying talented candidates for future full-time employment. And the program has proven to do just that; sponsoring companies have established a track record of hiring fluid power scholars. Of the 15 students who completed the Fluid Power Scholars program, seven have been hired by CCEFP member companies. Four more have taken positions with companies that are important in one way or another to the fluid power industry. Three of the scholars have continued their studies, and one has established his own business.

Project D.2: Industry Student Networking

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	Student Leadership Council CCEFP Graduate Students Industrial Advisory Board
Industrial Partner:	All CCEFP Industry Members

1. Project Goals and Description

The goal of this project is to provide CCEFP students with opportunities to network with industry representatives through a variety of channels. In doing so, there are multiple benefits: all students will better understand the fluid power industry's needs and its markets; interested students will be able to find internships and later job opportunities upon graduating; companies will be able to meet, interact, and discuss potential employment opportunities with students. Channels utilized in this project include company tours, poster sessions, and resume exchanges as well as additional opportunities that extend the Center's outreach to more students and companies.

2. Project Role in Support the EO Program Strategy

This program aligns well with the goals, mission, and strategy of the CCEFP by engaging students in the fluid power industry, often offering them opportunities to stay in this industry so they can have an impact in fluid power research and applications. This project also provides industry with mechanisms to contact and interact with students (possibly perspective employees) who have become familiar with fluid power through the Center's work.

3. Achievements

- Since 2006, the CCEFP has held an annual meeting at each of the following locations: the University of Minnesota, MSOE, Georgia Tech, North Carolina A&T, Purdue, and in conjunction with IFPE (see below). Representatives of the Center's industry members attended each of these meetings.
- In March 2011, the CCEFP co-located its Annual Meeting and NSF Site Visit with the International Fluid Power Expo (IFPE) and CONEXPO-CON/AGG, a trade show for the construction and aggregates industries (markets for fluid power) at the Las Vegas exposition center. The combined shows are among the largest expos in the world. IFPE is held every three years, and many companies in the fluid power industry, particularly hydraulics, attend either as exhibitors or attendees. The CCEFP had three booths at this expo staffed by Center personnel, including students, who talked to representatives of CCEFP member companies as well as those representing non-member companies in the fluid power industry and its customer base.
- A poster session has been held at each of the CCEFP's Annual Meetings. These events allow students to enhance their presentation and professional skills as they describe their research to industry members, while industry members can stay informed of research being done in the Center. A poster competition was added at the 2011 NSF Site Visit and Annual Meeting. Industry members served as judges, awarding prizes to presenters of the top three posters.
- Each year a student retreat is held for all CCEFP students. These have been held at member institutions, as well as in conjunction with the National Fluid Power Association's (NFPA) 2009 and 2011 Industry and Economic Outlook Conference. Retreats provide students with the opportunity to expand their networking connections as they present their research to company representatives, some of whom are not members of the CCEFP but work in fluid power.

- At the CCEFP Annual Meeting in 2011, a resume exchange session was held between Center students and representatives of its member companies. Each company had its own designated table, and students could rotate around the tables to speak to as many representatives as they wished. The representatives gave a brief background and introduction to their company, along with providing details about the projects they are currently pursuing. Students were encouraged to bring their resumes to share with companies representatives to discuss internship and job opportunities. This event provided students the opportunity to talk with industry representatives one-on-one in a more personal setting.
- Various company tours have been organized for CCEFP students. During the 2010 student retreat held at the University of Minnesota, company tours of Eaton and MTS were planned and highly attended by the students. After the student retreat in 2011, a group of students organized a tour of Bucyrus (now Caterpillar) and HUSCO International. Individual universities within the CCEFP network also plan their own tours of local companies, (e.g., Precision Associates, Sauer-Danfoss, and Toro). Tours are an effective means for generating student interest as they see first-hand how a company works.
- The Fluid Power Scholars program was initiated in 2008 and first implemented in 2010. IAB members worked with Center staff to design and make this program a success. The goal is to introduce and interest undergraduate engineering students to the possibility of working in the fluid power industry. This is a highly selective program for undergraduates nationwide. Prior to beginning an internship in a member company, each scholar attends an intensive Fluid Power Bootcamp program at MSOE. To date, seven of the 15 Fluid Power Scholars have been hired full-time by their host companies. For more information, please refer to EO Project D.1.
- Industry members have provided their knowledge and expertise to senior design capstone projects. Project examples include a hydraulic pedicab, a chainless bicycle powered by hydraulics, and numerous demonstrations, on display at the Science Museum of Minnesota.

4. Plans, Milestones and Deliverables

- Future student retreats will be held at CCEFP member companies. In summer 2012, the CCEFP student retreat will be held at Sauer-Danfoss in Ames, IA. Holding retreats at company facilities will provide more students the chance to interact with practicing engineers and will facilitate opportunities for knowledge transfer.
- Given positive feedback from both the students and the industry members, future poster sessions at CCEFP Annual Meetings will continue to include a competition, with industry representatives as judges. This guarantees that some representatives from industry will be visiting each poster, while providing students with additional incentive to put together a good poster and presentation.
- Based on positive feedback from students following the "elevator speech" competition held at the National Science Foundation's Engineering Research Center Annual Conference (December 2011), the CCEFP will incorporate this competition into future CCEFP Annual Meetings. As with the poster competition, judges will come from industry. In a preliminary round, speeches will be submitted by students via video before the meeting and judged by industry members. The top contenders from this round will advance to a final round, where they will give their 90 second elevator pitch--live--to a panel of judges from industry. The top winners will receive prizes.
- Resume exchange/roundtable discussions will continue at future CCEFP Annual Meetings. Industry information kiosks are being proposed for the 2012 Annual Meeting at UIUC. Industry members will be invited to host a small booth with literature, small displays and multimedia about their companies. Students will have a chance to visit the booths and see which companies are of particular interest. A resume exchange session will follow, where industry representatives will sit one-on-one with students to meet, conduct something of an informal interview, and explore

mentoring and research project sponsorship opportunities. This event provides students with a more private atmosphere to talk with company representatives, one-on-one.

- A new online system is being developed to facilitate students and industry communication--a "one-stop shop" for CCEFP students and its industry members to find each other through posted resumes and job opportunities in the fluid power industry. Students will be able to post their resumes on a secure website, and industry will be able to search through the website for candidates to interview. Likewise, industry will be able to post job openings and internship opportunities; in turn, interested students will be able to search this site and initiate contacts. This forum could be incorporated into the new Project Center site launched by the CCEFP in January 2012. Feedback from students and industry will be collected to determine the best way to proceed with implementation of this system.
- Industry sponsorships will be encouraged as a way of getting middle and high school students interested in fluid power. In 2009 the CCEFP successfully hosted the Fluid Power Challenge for 8th grade students, a competition in which students had to design a device to accomplish a task using fluid power. Competition judges included representatives from local industries who invited students to ask them questions about their careers. Future ideas include industry sponsorship of fluid power kits, which could be donated to local schools and used in the classroom, along with sponsorship of replications of fluid power displays currently at the Science Museum of Minnesota.
- An education committee of industry representatives will be formed to brainstorm and develop new activities within this project. The goal is to have 3-5 representatives from industry work with Center staff to help devise additional strategies for networking. Committee members would also become "points of contact" for students who are looking for a career in fluid power or assistance on a project, but are not sure of where to begin.
- The Student Leadership Council is exploring the challenges student face when trying to enter into internships in Industry. The SLC will identify ways to encourage students to take advantage of industry internships during their graduate study.

5. Member Company Benefits

This project, with its current and planned programs and activities, enables CCEFP member companies to interact on many levels with engineering students, some of whom will join their work forces, others of whom will work within the fluid power industry's customer base; and still others who will find their way to the classroom where they will teach a next generation of engineers, instilling in them a knowledge of and interest in fluid power.

Annual Meeting Student-Industry Resume Session

Annual Meeting Poster Show and Competition

Project D.5: CCEFP Webcasts

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	SLC President and Vice President CCEFP graduate students CCEFP staff Invited speakers outside the CCEFP network
Industrial Partners:	All CCEFP Industry Members

1. Project Goals and Description

The goal of the webcast series is to maintain a consistent means of technology transfer throughout the Center—students, faculty and industry supporters. On a regular basis, the CCEFP hosts a webcast featuring two presentations, each discussing either research projects or other Center-wide programs (e.g., special topics, strategic planning, education and outreach, project evaluation, etc.). These webcasts are open to all CCEFP students and faculty and to all CCEFP member companies. The webcasts are presentation based, with audio and visual capabilities. The audience is welcome to interact with the presenters during the question and answer session following each presentation. Each webcast is recorded and archived for retrieval and is posted and available on a members-only secured section of the Center's web site.

2. Project Role in Support the EO Program Strategy

This program aligns well with the mission, vision, and strategy of the CCEFP by creating widespread awareness of its research and education projects as well as the Center's administrative and evaluative work. Since many of the webcast presentations are made by Center students, participation in this project fosters professional development as they "learn by doing" how best to communicate—describing their work and also responding to and benefiting from the input of faculty, their peers and industry.

3. Achievements

- The Center estimates between 45 - 60 participants join the webcast on a regular basis, up from an average of 35 - 45 in previous years. Participants include industry, faculty, staff, and students.
- Webcasts now include more special topics, education outreach presentations, and "State of the CCEFP" discussions presented by Center Leadership.
- The Center has greatly increased the efficiency and effectiveness of the webcasts. In addition to including an audio feedback component, the Student Leadership Council emcees each webcast, making for seamless transitions between presenters.
- The Student Leadership Council began a new student orientation program in Fall 2011. One aspect of this is an internal webcast mandatory for new Center students working on funded projects and associated projects and highly encouraged for current CCEFP students. A CCEFP staff person gave a 30 minute presentation on an overview of the Center, while a representative from the SLC gave an introduction to the students' role in the Center. The goal is to make students aware that they are part of a large organization, and how their project fits in with the goals and mission of the CCEFP.
- The webcasts continued to feature Special Topics which include invited talks from Industry as well as from experts on matters such as intellectual property, patents, ethics, etc.
- Presentations are not just project-specific information; they also include information on how each project is aligned with the Center's strategic plan. For research, presentations describe how work is demonstrated on the Center's test beds, how current research aligns with what has been done previously as well as how it is breaking new ground, etc. These inclusions have added important

new dimensions to the webcasts and have provided another avenue where students, faculty and Center leadership can continue to strategize on the direction of the research projects across the Center.

- The Center evaluated the options for software and costs associated with the webcasts and selected Adobe Presentation software in which the University of Minnesota has a site license to use. There was a steep learning curve in using this software, and while the initial stages of the webcasts were cumbersome, the curve has now leveled off and the presentations run smoothly. In an effort to satisfy the need for real-time question and answer feedback, the Center opted to incorporate a conference call service in collaboration with the web presentation software. This has greatly improved the level of compatibility between the Center's seven institutions and the many industry representatives participating in the webcasts.
- The Center initiated the webcasts in June 2007 with a bi-weekly schedule of presentations given by the graduate students working on their respective projects. Based on the success of these webcasts, the Center introduced weekly webcasts during the fall of 2008. In early 2009, the Student Leadership Council conducted a survey among identified webcast participants, collecting information regarding preferences for the frequency of the webcasts, the quality, the technology and any additional recommendations. Survey results were very helpful in planning for future webcast series. While the Center clearly has enough information to share on a weekly basis, the Center received internal, external and advisory board recommendations to return to a bi-weekly schedule.

4. Plans, Milestones and Deliverables

- The webcasts will continue to include an internal webcast once or twice a year mandatory for new students and encouraged for current students. A portion will feature an overview of the new Project Center website so students will know how to add themselves and their academic and project affiliations to make it easier to track their involvement with the CCEFP.
- With the introduction of the Student Leadership Council's travel grant program, presentations will include collaborations and results from awarded proposals. As the Center matures, more projects will be incorporated into testbeds and industrial applications, and this will provide an opportunity for all members of the CCEFP to see these collaborations.
- With the success of the Fluid Power Scholars program and the initiation of the Student Leadership Council's graduate student internship program, presentations will include participants from these programs. Students would give a description of the project they worked on and results from the project. This could encourage other students to apply and/or promote these programs to other students, along with providing industry with examples of projects and generating ideas for projects of their own for these programs.
- As technology advances, the Center will continue to evaluate the effectiveness of the tools and software available for webcasts and will explore options for improvement. Costs will be a factor, too. Because the webcasts have become so popular, the Center finds it necessary to create a budget line for this program. As the number of participants increase, so does the cost to host the audio component of the webcast.
- Every effort will be made to expand participation among all audiences. The Center will continue to gather input from current and potential participants as we seek out ways to enhance this key Center project.
- The CCEFP will continue to host the webcasts which are a proven success, popular within the Center network and among its industrial members. They will continue to be recorded and archived on a secure portion of the website so they are accessible to all members. As the Center matures, so will the research and education outreach projects, and the webcasts will reflect the impact of these initiatives. The CCEFP will continue to survey faculty, students, and industry members to measure the value and effectiveness of the presentations, as well as gather suggestions for future presentations.
- The CCEFP will continue to monitor whether the webcasts should move from a bi-weekly schedule to a weekly schedule. As stated previously, an earlier survey indicated a bi-weekly

schedule is preferred. However, with the variety of topics that can now be included, one idea is to continue the research presentations for a general audience every two weeks, while on off weeks topics internal to the CCEFP could be presented (education outreach updates, professional skills development, internal Center topics, etc.).

5. Member Company Benefits

All Center participants—faculty, students, industry, and staff—have opportunities to get first-hand updates on research, education, and management level activities from project leaders. Webcasts also foster a sense of "community" throughout the Center network as all constituents regularly have opportunities to hear and learn from each other.

Project D.6: Publications

Project Team

Project Leaders:	Kim Stelson, Center Director, UMN
Other Personnel:	All CCEFP Researchers and Staff
Industry Partners:	Any industry representative contacted by a publication's staff for inclusion in a given article.

1. Project Goals

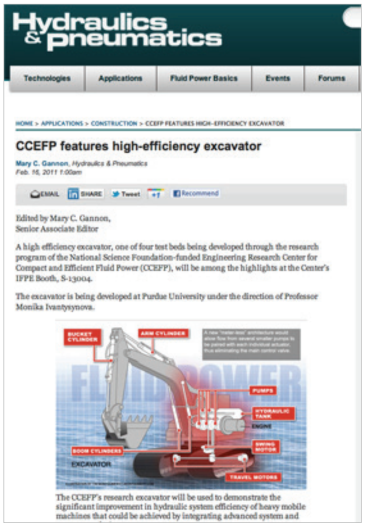
The CCEFP is committed to encouraging and enabling knowledge transfer. The Center's interactions with the trade press and academic journals create powerful channels for facilitating this invaluable informational exchange. Press releases and articles about the CCEFP's research and education programs appearing in a broad spectrum of on-line and in-print publications as well as in videos inform engineering researchers and educators in academia along with engineers working in industry.

2. How Project Supports the EO Program Strategy

In order to maximize its impact among diverse audiences, the CCEFP seeks to partner with broadly recognized and distributed networks. Publications that can be categorized under the trade press umbrella, specifically those whose readers have an interest in some aspect of fluid power, form a far-reaching network. The circulation base of individual titles in this publication category ranges from 25,000 to 200,000 readers. Whether taken individually or collectively, when articles about the CCEFP are carried in these publications, the Center is extending its reach, connecting with engineers and technicians in the fluid power industry and the many industries it serves. Similarly, publications read within the engineering and engineering education community provide a forum for the exchange of information and ideas relevant not only to Center research, but also to its efforts in promoting STEM- and fluid power-relevant education

3. Achievements:

- In the five and one-half years since its launch, fourteen trade press publications (on-line and in-print) have covered news of the Center: *Consulting-Specifying Engineer*, *Design News, Design World, Diesel Progress, Engineering News (South Africa), Equipment World, Fluid Power Journal, Hydraulics and Pneumatics, Lubes-n-Greases, Machine Design, Mobile Hydraulic Tips, OEM Off-Highway, Pneumatic Tips, Today's Medical Developments*). Though it is impossible to know how many have actually read these articles, it is safe to say that hundreds of thousands have had the opportunity to learn about the Center's work (Figure 1). Now, these articles are available--either in pdf format or as links--under the News Desk tab at www.ccefp.org.


Hydraulics & pneumatics

Technologies | Applications | Fluid Power Basics | Events | Forums

HOME > APPLICATIONS > CONSTRUCTION > CCEFP FEATURES HIGH-EFFICIENCY EXCAVATOR

CCEFP features high-efficiency excavator

Mary C. Gannon, Hydraulics & Pneumatics
Feb. 16, 2011 1:00am

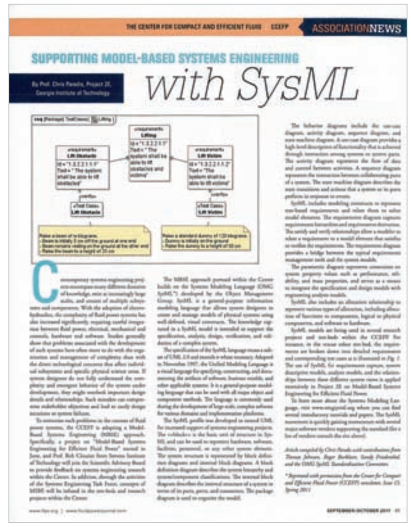
EMAIL | SHARE | Tweet | +1 | Recommend

Edited by Mary C. Gannon,
Senior Associate Editor

A high efficiency excavator, one of four test beds being developed through the research program of the National Science Foundation-funded Engineering Research Center for Compact and Efficient Fluid Power (CCEFP), will be among the highlights at the Center's IFPE Booth, S-13004.

The excavator is being developed at Purdue University under the direction of Professor Monika Ivantysynova.

The CCEFP's research excavator will be used to demonstrate the significant improvement in hydraulic system efficiency of heavy mobile machines that could be achieved by integrating advanced system and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SUPPORTING MODEL-BASED SYSTEMS ENGINEERING with SysML

By Prof. Chris Paredis, Project 2E, Georgia Institute of Technology

Figure 1: Examples of fluid power articles.

- Five of the above publications began covering the CCEFP in this reporting year.
- In this reporting year alone, twenty-five new articles carrying CCEFP news and related videos have appeared in trade press publications and/or on-line. This compares with ten articles/videos appearing in 2010.
- The CCEFP maintains a database of publications and associations that fit well under the "trade" umbrella. Its press releases are sent to the 70+ names in the database. These contacts represent approximately 60 unique publications or trade organizations.
- Publications of trade associations also reach key audiences. For example, the National Fluid Power Association features ongoing features about the work of the CCEFP in *The Reporter,* its monthly on-line publication. *The Reporter* has a readership of over 2,000 manufacturers, suppliers and distributors in the fluid power industry.
- The CCEFP continues to use the editorial guidelines it has developed and shared within its own network as well as with editors of the trade press on subjects that include lead-time, exclusivity, confidentiality, authorship and reviewing/editing rights. The guidelines have proven to be very helpful, answering inevitable questions from all sides early on in the writing/editing process.

4. Plans, Milestones and Deliverables

- Knowing how effectively the trade press can be in reaching the fluid power industry as well as its customers, the CCEFP is carrying on an ambitious press release campaign. Releases on CCEFP research as well as education and outreach projects are prepared every 1-2 months with the help of the PIs leading the selected projects. These releases are distributed to contacts in the Center's trade press database. (It is important to note that publications in the trade press complement but in no way duplicate publication in technical journals where articles about the Center's research also appear.)
- The CCEFP intends to increase the number of Center-related articles appearing in the trade press during the next reporting year, an ambitious goal considering that 25 new articles and/or videos appeared in the current reporting period. (Note that nearly 60 articles about the Center have been published in the trade press since June 2006.)
- In addition to developing articles based on CCEFP-generated press releases, a growing number of articles about the Center are now initiated by editors who call for information about the work

underway. The CCEFP plans to cultivate this enthusiasm, encouraging an increasing number of editors (and publications) to initiate contacts with the Center.

- In addition to increasing the number of articles, the CCEFP intends to add at least five more publications to its list of trade press publications currently covering the Center. Five new publications were added in 2011; one new publication was added in 2010.
- CCEFP faculty have now set their sights on developing special issues/articles in journals such as *Mechanical Engineering (*journal of the American Society of Mechanical Engineers), *ASEE Prism,* etc.

5. Member Company Benefits

Articles about the Center's work inform readers about the potential for fluid power. This information is a powerful tool, not only for the CCEFP's corporate members, but also for the entire industry in reaching its marketplace. In short, news about the Center appearing in the trade press is helpful to all parties.

Project E.1: External Evaluation of Education and Outreach Program

Project Team

Project Leader:	Proposed: Quality Evaluation Designs
Other Personnel:	Gary Lichtenstein, Principal, Quality Evaluation Designs Maggie Miller, Quality Evaluation Designs Paul Imbertson, Education Director, CCEFP Alyssa Burger, Education Outreach Director, CCEFP

1. Project Goals

Quality Evaluation Designs (QED) is the new, contracted external evaluator of CCEFP Education and Outreach projects. (QED replaces CAREI, the Center's initial extenal evaluator.) Evaluation activities include assessment of the overall E&O program goals as well as of individual projects. Each year QED will undertake evaluation activities of selected CCEFP programs.

The goals of the external evaluation are, first and formatively, to provide critical information about progress toward achieving overall program goals as well as the development, functioning, and efficacy of specific Education and Outreach projects. Second and summatively, QED's goal is to provide CCEFP with information about the achievement of the overall program goals and the effects, outcomes, and impact of specific Education and Outreach projects. QED plans to ensure that its well-targeted evaluation can result in identifying and sustaining programs which have proven to be efficient and effective

2. How Project Supports the EO Program Strategy

Partnership with QED is an application of a key EO strategy--identifying and working with a strong partner in order to maximize results.Specifically, QED's external evaluation will support CCEFP efforts by providing formative evaluation data and findings that allow the Education and Outreach leadership to revise projects and redeploy resources as they are warranted in order to make mid-course corrections. Further, summative evaluation data and findings will lead to judgments about the achievement of the overall program goals.

3. Achievements

While identifying a problem may not typically be considered an achievement, it has proven to be a worthwhile experience for the CCEFP over the past year. After much deliberation, consideration and the weighing of pros and cons, the Education and Outreach faculty and staff determined that it was best to end the CCEFP's contract with the Center for Applied Research and Educational Improvement (CAREI), the Center's first external evaluator; the contract was terminated in August 2011, three months into Year 6. The Center discovered, over time, given its dynamic menu, the E&O program and its attendant activities required a more committed evaluator, one that would be considered more of an "intellectual partner." Through CAREI, instruments were developed and assessments of some value were provided, but the E&O Program required more than tools. The program needed an external view of the overall scope of the E&O Program--its effectiveness and sustainability. The Center believes the staff of QED will successfully serve in this role. Work begins with QED on June 1, 2012, though dialog with its staff has already begun.

QED conducts education research and evaluation nationwide. In its new role with the CCEFP, QED will adhere to the policies of the Center (e.g., following and complying with IRB protocol) as it assumes a role as a branch of the organization.

4. Plans and Deliverables

- Scope of the project work with QED will begin with a visit to CCEFP Headquarters in April 2012. Contracted work will begin on June 1, 2012.
- Anticipated pre- and post- surveys of the REU, RET and Fluid Power Scholars programs will begin in June 2012; QED will establish its own protocol for these projects.

- Other aspects of the evaluation and assessment will be determined based on the scope of the project and recommendations by QED.
- QED will be guests at the May 2012 NSF Site Visit at the University of Minnesota.
- The results of QED's work will be presented in the Center's next Annual Report.

5. Member Company Benefits

QED's evaluation efforts with CCEFP indirectly benefit member companies and the entire industry as CCEFP works to increase the numbers and diversity of new engineers in fluid power. The main point of all the evaluation efforts is to assist CCEFP to work smarter and achieve program goals.

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Associated Project Abstracts: Research

Thrust 1 – Efficiency

Advanced Energy Saving Hydraulic System Architecture for a Wheel Loader
Project Leader: Monika Ivantysynova
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Advances in External Gear Machines Modeling
Project Leader: Andrea Vacca
Sponsors: Casappa S.p.A.

Abstract: This project is aimed to develop new modeling techniques for external gear pumps and motors. Particular focus is on the sealing gaps within the machine, in particular the lateral gap, between gears and lateral bushes. This gap strongly affects losses and reliability of the unit.

Design of low noise emission internal gear machines
Project Leader: Andrea Vacca
Sponsors: **confidential**

Abstract: This project is aimed to identify proper modeling techniques and design methodology for a new generation of quieter and efficient machines

Design of positive displacement machines for SCR automotive applications
Project Leader: Andrea Vacca
Sponsors: MGI Coutier, France

Abstract: In this project new solution for plastic gear pumps for SCR (Selective Catalytic Reduction) applications are investigates. The goal of the research is to identify proper modeling techniques to simulate the actual operation of the pumps and formulate new design criteria for optimal efficiency and durability.

Design, Simulation and Control of Hydraulic System Topographies with Integrated Energy Recovery
Project Leader: John Lumkes
Sponsors: National Fluid Power Association

Abstract: This project designed, modeled, simulated and tested a hydraulic system topography utilizing an intermediate pressure rail and a network of 2/2 proportional valves. The system is configurable via software to operate in multiple modes to maximize system efficiency and improve reliability. The valve network enables the system to operate with characteristics of multi-level load-sensing, displacement control, independent metering, energy recovery, and energy storage (with an optional accumulator). The modes can often co-exist and several new hybrid modes are possible. The TIER system (Topography with Integrated Energy Recovery) can re-route power in the event of component failure, allowing for future development of diagnostic and prognostic algorithms. The system described here was built and tested at Purdue University using twenty-six proportional 2/2 valves to operate a small backhoe arm (four actuators: swing, boom, stick, bucket). Two variable displacement swash-plate units, driven by an electric motor, were used to power the valve block and backhoe arm. The pump/motors can be operated as two pumps, two motors, or split as a pump and motor depending on the load requirements on the system. Experimental results demonstrate the feasibility of multiple operating modes and reduced energy consumption.

Efficiency Measurement on special axial piston pump
Project Leader: Monika Ivantysynova
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

<u>EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage</u>
Project Leader: Perry Li
Sponsors: National Science Foundation (NSF)

Abstract: "The goal of this project is to develop an efficient, powerful and cost effective localized energy storage concept for off-shore wind power using high pressure compressed air. The system is to be capable of storing several hours worth of wind energy. Research involves heat transfer improvement, efficient machine element, and system optimization and control."

<u>Fluid Efficiency</u>
Project Leader: Paul Michael
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

<u>Hydrostatic Transmission for Wind Power Generation</u>
Project Leader: Kim Stelson
Sponsors: Bosch Rexroth Corporation, Eaton Corporation, Racine Federated Inc. (formerly Hedland Flow Meters), Sauer-Danfoss, University of MN; IonE and IREE

Abstract: This project is focused on determining the effect of replacing the mechanical drivetrain in a wind turbine with a hydrostatic transmission (HST). The gearbox in a conventional wind turbine drivetrain is one of its highest reliability concerns. The use of an HST eliminates the need for the gearbox. The major research questions being asked in this project were (1) Can wind turbine reliability be improved by using an hydrostatic transmission (HST)? (2) Is it possible to improve wind turbine system efficiency through the use of a continuously variable HST? (3) Can an HST-based wind turbine provide lower life cycle cost of ownership than current state of the art systems?

<u>Mechanical Implementation of Waved Surface and Waved Piston Technologies</u>
Project Leader: Monika Ivantysynova
Sponsors: Purdue Research Park Trask Funds

Abstract: Unavailable due to confidentiality of project.

<u>Modeling and Analysis of Swash Plate Type Axial Piston Pump (Interface)</u>
Project Leader: Monika Ivantysynova
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

<u>Optimization Environment for the Architecting of Micro-grids in Ultra Low Energy Communities</u>
Project Leader: Christiaan Paredis
Sponsors: United Technologies Research Center

Abstract: The objective of this project is to develop a methodology and a software tool that support a master planner in charge of managing the energy systems on a military base. The method and tools enable the generation, optimization and selection of the best holistic energy system architecture that meets the demands of ultra low energy Army installations. Architectural concepts selected using this framework will have the lowest possible energy utilization and carbon emission, minimal fixed and operating cost, reduced physical footprint and energy autonomy. In the project, the Systems Modeling Language (SysML) will be used to define system architecture alternatives and to transform such architectural descriptions into analysis models in the TRNSYS simulation tool. The project is funded by the US Army Corps of Engineers, Construction Engineering Research Laboratory.

<u>PCA Mule- System Implementation and Testing</u>
Project Leader: Monika Ivantysynova
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Performance Prediction and System Control through Coupled Multi-domain Models: A Comparison Study
Project Leader: Monika Ivantysynova
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Pump Dynamic Model Development
Project Leader: Monika Ivantysynova
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Reliable Lightweight Transmission of Off-shore Utility Scale Wind Turbines
Project Leader: Kim Stelson
Sponsors: Eaton Corporation

Abstract: "The US Department of Energy (DOE) has goal of 20% of US energy from wind by 2030. In order to achieve this goal, off-shore wind sites will need to be developed. This requires the development of wind turbines that are 2-3+ times higher in output than current land sited wind turbines. One of the major reliability concerns in current utility scale wind turbines is the failure of the mechanical gearbox. This problem will be exacerbated as wind turbines grow in size and output. Increased reliability is especially important in off-shore wind turbines given their size and the logistical challenges associated with maintenance and repair. Even beyond the reliability challenges of ever larger gearboxes, the mass of the gearbox and its components and subsystems increase with higher power throughput, thus making construction, maintenance and repair more difficult. This project is focused on developing an advanced hydrostatic transmission (HST) drivetrain concept which considerably reduces the weight in the nacelle and replaces the gearbox with a much more reliable solution. The goal is to reduce the cost of energy (COE) and lower lifetime costs of a large off-shore wind turbine (6 MW=).

UMN's work on this DOE funded project was a continuation of the work initiated in the IREE funded project ""Hydrostatic Transmission for Wind Power Generation""."

Thrust 2 – Compactness

Functionally Graded Metallic Lattice Components for Advanced Propulsion Components
Project Leader: Vito Gervasi
Sponsors: DARPA Associated

Abstract: This DARPA funded project is aimed at producing advanced harsh environment components by leveraging additive manufacturing technologies and two-phase intertwined lattice structures to produce functionally graded materials. Applications include advanced non-eroding propulsion systems, armor, and some effort in the area of composite fluid power components.

Open Accumulator Compressed Air Storage Concept for Wind Power
Project Leader: Perry Li
Sponsors: University of MN; IonE and IREE

Abstract: The goal of this project is to determine appropriate methods to achieve adequate heat.

Precision Pneumatic MRI Compatible Robotic Surgery
Project Leader: Eric Barth
Sponsors: The Martin Company

Abstract: Conventional robotic actuation, such as electromagnetic motors, are incompatible with an MRI's imaging technology. This incompatibility currently makes intra-operative MRI guided robotic surgery and microsurgery unachievable. It is widely recognized in the engineering and scientific literature that pneumatic actuation is a viable solution for MRI compatible robotic surgery. Utilizing all plastic and other MRI compatible materials, pneumatically actuated robotic platforms have been demonstrated as presenting no image distortion. Through the utilization of air or other gas, pneumatic actuation presents no contamination issues. In addition, MRI compatible position and force sensing can be fully integrated through the use of fiber optics. The most significant barrier to the adoption of pneumatically actuated MRI compatible robotic platforms is their precision control. Pneumatic systems are highly nonlinear and require advanced control techniques. A viable pneumatic solution will require positioning precision better than 0.1 mm. Most results report a precision on the order of 1mm or worse. The best precision reported in the literature is 0.25 mm. The PI has experimentally achieved pneumatic positioning precision better than 0.05 mm through the use of adaptive nonlinear control techniques. Precision control of pneumatic systems will allow the realization of a pneumatic robotic platform capable of fully exploiting the image resolution of an MRI machine in real-time. This technology will enable stereotactic procedures such as biopsy, thermal ablations, brachytherapy, deep brain stimulation and other procedures to be performed in real-time while the patient is being imaged (intra-operative MRI guided surgery). Perhaps more importantly, this technology will enable new procedures that are currently impossible through any other means.

Single-Channel Hybrid FES Gait System

Project Leader: Will Durfee

Sponsors: National Institutes of Health (NIH)

Abstract: Thoracic-level spinal cord injuries (SCI) commonly result in the inability to control lower limbs. Individuals with SCI typically rely on a wheel-chair for mobility, which can lead to both physiological and psychological complications. Functional electrical stimulation (FES), the application of electrical current to activate motor nerves and induce muscle contraction can restore elementary gait in SCI subjects

Thrust 3: Effectiveness

Adaptive Control for Oscillation Damping

Project Leader: Andrea Vacca

Sponsors: CNH America, Inc.

Abstract: In this project new adaptive control strategies are developed to damp both actuators and cabin oscillations in offroad fluid power machines.

Analysis of transmission noise sources

Project Leader: Monika Ivantysynova

Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Development of an Experimental Pressurized Thin-film Couette Viscometer and Consultation

Project Leader: Scott Bair

Sponsors: Total Oil Company

Abstract: The shear-dependent viscosity of organic liquids at high pressures is of intense interest to the fields of hydrodynamic and elastohydrodynamic lubrication. Many lubricants, however, do not display shear-dependency until the applied shear stress is quite large-greater than 0.3 MPa. The Center for High Pressure Rheology at Georgia Tech has developed six different pressurized, thin-film Couette viscometers of increasing capability. These instruments are not routine viscometers; they are experimental devices for which mechanical and electrical failures may be unforeseen and may occur often. This project involves construction and assistance in the operation of a pressurized, thin-film Couette viscometer very similar to one in use in the Center for High Pressure Rheology at the George W. Woodruff School of Mechanical Engineering of Georgia Institute of Technology.

Evaluation of the High Pressure, High Shear Stress Capability at Georgia Tech

Project Leader: Scott Bair

Abstract: The Georgia Tech Center for High Pressure Rheology will characterize liquids, a base oil and some base oil plus viscosity modifier solutions to evaluate whether or not shear-thinning behavior can be demonstrated and if the techniques can differentiate the onset and extent of shear thinning. The eventual goal is to relate shear-thinning to polymer structure and concentration. The techniques to be employed are high-pressure, thin-film Couette viscometry and falling cylinder viscometry. These instruments provide the capability to measure viscosity across seven orders-of-magnitude, 1 to 10^7 Pa.

MRI-R2: Development of a Precise and High Speed Hydrostatic Dynamometer System for Research and Education in Automotive Propulsion Systems

Project Leader: Zongxuan Sun

Sponsors: National Science Foundation (NSF)

Abstract: This Major Research Instrumentation grant allows us to develop a state-of-the-art, precise and highly flexible instrument for testing and measuring the fuel efficiency, emissions and performance of automotive propulsion systems, especially the hybrid powertrain. The instrument employs a hydrostatic dynamometer to load or motor the engine/powertrain to experimentally mimic the hybrid architecture, vehicle load, and the hybrid power sources in coordination with an engine control system and a hardware-in-the-loop vehicle driveline emulator. The hydraulic components, transient fuel and emissions measurement instruments, and control hardware and software have been acquired and integrated into the system. Models of the hybrid powertrain and controllers for the hydrostatic dynamometer as well as the hybrid energy management have been designed and implemented. System integration and testing demonstrate the expected performance and functionality of the developed instrument.

Shaft Pumping by Laser Structured Shafts with Rotary Lip Seals

Project Leader: Richard Salant

Sponsors: University of Stuttgart/German Research Foundation

Abstract: "A simulation model to predict pumping by shafts with various surface finishes, in combination with a rotary lip seal, has been developed and validated by experiment. The model consists of a fluid mechanics analysis of the flow in the sealing zone coupled with a deformation analysis of the seal. The experimental validation consists of pumping measurements with shafts whose surface structures contain laser generated oblique grooves. Plots of pumping rate versus various parameters show good agreement between the model and experiment. Plots of torque vs. speed, as well, show good agreement between the model and experiment."

Understanding and Reducing the Adverse Effects of Biodynamic Feedthrough

Project Leader: Wayne Book

Sponsors: National Defense Science and Engineering Graduate Fellowship (NDSEG)

Abstract: This research investigates and seeks to mitigate the undesirable effects of biodynamic feedthrough in backhoe operation. Biodynamic feedthrough occurs when motion of the controlled machine excites motion of the human operator, which is fed back into the control input device. This unwanted input can cause significant performance degradation, which can include limit cycles or even instability. Backhoe user interface designers indicate that this is a problem in many conventional machines, and it has also proved to significantly degrade performance in the test bed used for this research. Dynamic models of this particular backhoe control system, including the biodynamic feedthrough, have been developed. Cab vibration control was selected as a means to mitigate the biodynamic feedthrough effect. Several variations of controllers were developed and tested in simulations, including both active and passive vibration compensation. Both use the working implement itself to reduce the cab motion, rather than adding additional hardware. In this case, the backhoe arm has dual functionality, to perform excavation operations and to cancel cab vibration. Both input shaping and active damping approaches proved to significantly reduce cab vibration both in simulation and in hardware, with minimal cylinder tracking performance degradation and without additional actuators. Extensive testing with human subjects and statistical analysis has confirmed the efficacy of this approach. The results show that both the input shaper and LOR with active vibration compensation can considerably reduce cab vibration. However, this correlates with more significant improvement in operator tracking performance with the LQR controller and active vibration compensation. The operator survey results give some clues about this difference.

Water-removing filters and relative humidity sensors
Project Leader: Paul Michael
Sponsors: **confidential**

Abstract: Investigation of water-removing filters and the use of relative humidity sensors to monitor their effectiveness.

Associated Project Abstracts: Education & Outreach

Through cooperation and collaboration, the CCEFP leverages its work with the following university and organizational programs and the funding each has received. These efforts follow from the CCEFP's strategy of seeking out strong partners in developing its educational and outreach programs.

Zephyr Wind Energy Teacher Training

Lead Personnel: Michael Arquin, KidWind Inc.
Sponsor: CCEFP and Xcel Energy Center, Mahtomedi School District, Mahtomedi Area Green Initiative (MAGI), Mahtomedi, Minnesota
Funding: $4,500 (CCEFP), $5,000 (Xcel Energy Center), $3,000 (Mahtomedi School District)

The Zephyr Wind Project Teacher Training seeks to build a brighter future for our communities and our world by empowering teachers to 1) advance students' knowledge of STEM concepts in a world that needs young people's creativity and problem-solving skills; and 2) to inspire the next generation to embrace and advance renewable energy technology as part of a healthy and sustainable energy infrastructure.

- Goal 1. Provide teachers with knowledge, skills and resources needed to effectively educate Early Childhood-Grade 12 students about wind energy.
- Goal 2. Educate students about the role innovation and application of STEM knowledge can play in building a more secure energy future through development of renewable energy technologies.
- Goal 3. Maximize the educational benefit of the Mahtomedi wind turbine.
- Goal 4. Provide opportunities for mutually beneficial collaboration between Mahtomedi teachers and teachers who serve Native American populations.
- Goal 5. Provide experiences to allow UMN-CCEFP and ZWP Teacher Training partners to compete for an NSF "Discovery Research K-12" grant (RFP anticipated Fall 2012) to scale up the program to a nationally applicable wind energy curriculum.

Hand Powered Water Pumps for Developing Countries

Lead Personnel: Gary Werner, John Lumkes, Isaac Zama, Vincent Kitio
McCutcheon High School/Purdue University
Sponsor: CCEFP, Purdue University, McCutcheon HS, African Centre for Renewable Energy and Sustainable Technologies (ACREST)
Funding: $11,000 in RET Support

This project was initiated during the summer 2011 CCEFP RET program. Gary Werner, a technology and pre-engineering teacher at McCutcheon HS, and John Lumkes, while discussing Purdue's involvement in international service learning and how to get students interested in fluid power, proposed combining real needs for pumping water in Africa with giving the students a real world fluid power design problem. During the summer the researchers contacted a Purdue partner NGO (ACREST) in Bangang, Africa and the project definition took shape. After the conclusion of the summer RET experience Gary incorporated the water pumping problem into his pre-engineering class. There are currently four high-school students planning a trip in May 2012, accompanied by Gary, to ACREST in Bangang, Africa to begin the implementation phase of their project, develop ideas for new projects, and get an early glimpse of engineering solutions to real problems.

North Star STEM LSAMP Alliance

Lead Personnel: Anne Hornickel, Program Director
Grant: LSAMP - Louis Stokes' Alliance for Minority Participation
LSAMP Funding: $293,025 / year
CCEFP Received: $5,000

Abstract: The Louis Stokes Alliance for Minority Participation (LSAMP) is an initiative funded by the National Science Foundation (NSF) which is intended to double the number of African-American, Hispanic/Latino, and Native American students receiving baccalaureate degrees in science, technology, engineering and math (STEM). In Minnesota, the LSAMP program is called the North Star STEM Alliance, a partnership of sixteen higher education institutions and two community partners, the Science Museum of Minnesota and Minnesota High Tech Association. The academic institutions represent the breadth of higher education institutions in Minnesota, and include both public and private colleges and universities, as well as technical colleges, and a tribal college. North Star STEM Alliance goals include: 1) doubling the number of underrepresented students receiving bachelor's degrees in science, technology, engineering, and mathematics among partner institutions; 2) developing an alliance of collegiate institutions and community organizations working toward increasing the likelihood of success of underrepresented students working toward their bachelor's degree.

CCEFP role: The CCEFP is the lead facilitator of the giiwed'anang Northstar Alliance which is sponsored in part by the North Star STEM Alliance. The giiwed'anang Alliance is considered an official undergraduate program under the North Star STEM LSAMP Alliance.

NSF ERC Recruiting Project
Lead Personnel: Alyssa Burger, CCEFP
Grant: NSF ERC Program
Funding: $5,000

Abstract: This project is in progress. Preliminary, plans are to build an ERC tradeshow booth for all Centers to share at recruiting events held in conjunction with national conferences such as AISES (American Indians in Science and Engineering Society), SACNAS (Devoted to Advancing Hispanics, Chicanos and Native Americans in Science), NSBE (National Society for Black Engineers), SHPE (Society for Hispanic Professional Engineers), SWE (Society of Women Engineers) etc. A verbal commitment from NSF has indicated a willingness to support the design and creation of such a such an apparatus.

CCEFP role: The Center will serve as the primary coordinator of this endeavor.

Universal Fluid Power Trainer
Lead Personnel: Medhat Khalil, Milwaukee School of Engineering
Sponsor: MSOE's Maha Fund
Funding: $ 366,000

Abstract: Universal Fluid Power Trainer will be the main training stands for the Professional Education Department at MSOE. After successful development of the prototype unit that was been funded by the CCEFP, MSOE invested $336,000 to develop three additional units to replace the existing and outdated fluid power training units. Presently, the three additional units are under fabrication. The four units of the Universal Trainer are expected to be in full operation. In tandem, Dr. Khalil is working to develop the new lab manual to make a smooth transition from the old to the new trainers.

CCEFP role: The Center provided the seed funding for this project in Years 2 and 3.

Purdue University - SURF REU Program
Sponsor: Purdue University
Funding: $16,000 in SURF REU Supplement (recurring)

Abstract: The SURF program provides students across all engineering, science and technology disciplines with an intensive research experience, allowing them to work closely with graduate students and professors in their respective schools. The interdisciplinary nature of the projects allows students to learn and work across other disciplines while still applying the concepts and skills from their own programs. This setting provides undergraduate students with an avenue to perform research in an academic environment while exploring future graduate study options.

CCEFP role: The Center hosts its own REU program at its seven participating universities. However at Purdue, the REU Program leverages the local REU efforts by receiving a 2:1 matching REU supplement award with the local program. In 2009, 2010 and 2011, the CCEFP hosted six REUs at Purdue; two were sponsored by SURF.

The Electrohydraulic Servovalve Coloring Book
Lead Personnel: Rosamond L. Dolid, MTS System Corporation
Sponsor: MTS System Corporation
Funding: Time of R. Dolid at no cost to the Center

Abstract: An electrohydraulic servovalve is a device that takes an electrical current and turns it into hydraulic flow which can then create linear, rotational, uni-directional or reciprocating mechanical motion. The purpose of the coloring book is to facilitate understanding of this complex device, which is not well understood even by those working in the fluid power industry. The inspiration to use coloring as a way of understanding complex ideas is drawn from *The Anatomy Coloring Book* (W. Kapit and L. Elson, third ed., 2002), long used by medical school students to deepen their understanding of how the human body works. Likewise, this book rests on the act of coloring as a means for better understanding just how a servovalve works. It is the first in a planned series of coloring books about fluid power components. College students and degreed engineers working in the fluid power industry are the targeted audiences for the series. Versions of this book have been used to train newly hired engineers at MTS Systems Corporation since 2007.

CCEFP role: Center faculty serve as subject matter experts, and university-level classes provide field testing sites. The book is currently used in course ME4232, Fluid Power Laboratory, at the University of Minnesota.

National Center for Earth-surface Dynamics (NCED)
Lead Personnel: Diana Dalbotten, Diversity Director, NCED
Grant: NSF Science and Technology Center, Diversity Programs
Funding: $250,000

Abstract: NCED is a partnership of research and educational institutions, government agencies, and industry that pursues its goal of predictive Earth-surface science by integrating physical, biological, and social sciences. NCED achieves research synthesis by focusing on a fundamental component of the Earth-surface system--channel networks and their surroundings--that recurs in varying but fundamentally related forms across a wide range of environments and scales. NCED collaborates with applied partners to identify knowledge gaps and develop tools to forecast landscape evolution and guide landscape management, restore river systems, find and develop subsurface resources, and promote environmental awareness. NCED shares the excitement of landscape science with a diverse community, exchanging perspectives through partnering, nurturing, and interacting in formal and informal education settings.

CCEFP role: The CCEFP serves as a partner to NCED in the gidaa STEM Programs and gidaa STEM Camps. The CCEFP shares in supporting all efforts of the gidaa STEM Programs, including science fairs, camps and robotics programs. NCED was recently awarded the manoomin (Wild Rice) Project from NSF (see below).

gidaa: The *manoomin* (Wild Rice) Project
Lead Personnel: Diana Dalbotten, Diversity Director, NCED
Sponsor: NCED, LacCore, Department of Geology at University of Minnesota, FDLTCC
Grant: NSF Opportunities for Enhancing Diversity in the Geosciences
Funding: Approximately $300,000 / year

Abstract: The *manoomin* project is designed to investigate the past, present, and future conditions of wild rice lakes on the Fond du Lac Band of Lake Superior Chippewa Reservation. Wild rice *(manoomin; Zizania palustris)* is at the center of Chippewa culture and identity. Some lakes on the Fond du Lac Reservation (FDL) are no longer hospitable to *Z. palustris.* However, the conditions necessary for its growth, its historical habitats, and the causes of recent changes are not well understood. The members of the Reservation are passionate about understanding historical conditions for wild rice growth, current challenges for restoring and enhancing its habitat, and ensuring future production. The answers to these questions will be sought as a collaborative effort between Fond du Lac Tribal Community College (FDLTCC), middle and high school student researchers, and the University of Minnesota (UMN) through the multiproxy analysis of multiple sediment cores from six lakes on the reservation, combined with geophysical profiling, remote sensing and visualization, and historical research. These efforts supplement FDL Resource Management Center's (FDLRMC) long-term modern lake sampling and monitoring program. We propose to build upon the successful science camps *gidakiimanaaniwigamig* (Our Earth Lodge, hereafter "*gidaa*"), for Fond du Lac middle- and high-school students that have been running as a collaboration between FDLTCC and UMN for the past five years. Students from grades 5-12 and undergraduates will participate in the proposed research through monthly meetings, internships, and pre-REU programs. We will support students in their significant transitions: middle to high school, high school to college, and tribal college to 4-year college. The college to graduate school transition will be supported through cooperation with the existing Purdue OEDG program.

CCEFP role: The CCEFP serves as a partner to NCED in the gidaa STEM Programs and gidaa STEM Camps and contributes to the support of all efforts of the gidaa STEM Programs including science fairs, camps and robotics programs. In addition to the research noted above, funds from the *manoomin* (Wild Rice) Project are nearly sufficient to fully support the gidaa STEM Camps. While this funding is key, it is important to note that the *manoomin* project is just one component of the overall gidaa STEM Program/Camp.

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Li, P; Loth, E; Simon, T; and Van de Ven, J; “Compressed Air Energy Storage for Offshore Wind Turbines,” 2011 International Fluid Power Exhibition (IFPE) (2011)

Merrill, K; Holland, M; and Lumkes, J; “Analysis of Digital Pump/Motor Operating Strategies,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 1.1 (2011)

Meyer, J; Stelson, K; “Developing an Energy Management Strategy for a Four-Mode Hybrid Passenger Vehicle,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 6.2 (2011)

Michael, P; Guevremont, JK; Devlin, M; and Ziemer, C; “Tribological Film Formation in Hydraulic Motors,” Proceedings of the STLE/ASME International Joint Tribology Conference, Paper IJTC2011-61029 (2011)

Pedchencko, A. V.; Barth, E. J.; "Finite Element Model-based Design of a Hyperelastic Strain Energy Hydraulic Accumulator"; Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 14.3 (2011)

Rice, A; Li, P; “Optimal Efficiency-Power Tradeoff for an Air Motor/Compressor with Volume Varying Heat Transfer Capability,” ASME DSCC 2011/Bath Symposium on PTMC, Arlington, VA, (2011)

Rose, J; and Ivantysynova, M; “A Study of Pump Control Systems for Smart Pumps,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; I11-27.1 (2011)

Schenk, A; Ivantysynova, M; “An Investigation of the Impact of Elastohydrodynamic Deformation on Power Loss in the Slipper Swashplate Interface,” Proceedings of 8th JFPS Int Symp on Fluid Power, Okinawa, Japan. (2011)

Schenk, A; Ivantysynova, M; “Design and Optimization of the Slipper-Swashplate Interface Using an Advanced Fluid-Structure-Interaction Model,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 4.2. (2011)

Schweiger, W., Schoefmann, W., and Vacca, A., "Gerotor Pumps for Automotive Drivetrain Applications: A Multi Domain Simulation Approach," SAE Int. J. of Passeng. Cars – Mech. Syst. 4(3):1358-1376, doi:10.4271/2011-01-2272 (2011).

Stelson, K; “Saving Energy by Advancing Fluid Power Technology,” Fluid Power Journal, March/April, 4 (2011)

Thul, B.; Dutta, R.; Stelson, K.; “Hydrostatic Transmission for Mid-Size Wind Power,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 40.2 (2011)

Tu, H; Rannow, M; Wang, M; Li, P; Chase, T; “High-speed 4 way rotary on/off valve for virtually variable displacement pump/motor applications,” ASME DSCC 2011/Bath Symposium on PTMC, Arlington, VA (2011)

Tu, H; Rannow, M; Wang, M; Li, P; and Chase, T; “The Advantages and Feasibility of Externally Actuating a High-speed Rotary On/Off Valve,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 20.3 (2011)

Vacca A; Dhar S; and Opperwall T; “A Coupled Lumped Parameter and CFD Approach for Modeling External Gear Machines,” Proceedings of The Twelfth Scandinavian International Conference on Fluid Power, May 18-20, Tampere, Finland (2011)

Vacca, A; and Guidetti, M; “Modelling and Experimental Validation of External Spur Gear Machines for Fluid Power Applications,” Elsevier Simulation Modelling Practice and Theory, 19 (2011)

Wang, F.; Randan, M.; and Stelson, K.; “Comparison between Hydraulic Hybrid and Electric Hybrid Passenger Vehicle using ADVISOR 2004,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 2.2 (2011)

Wang, M; Li, P; Tu, H; and Rannow, M; “Direct Displacement Control of Hydraulic Actuators Based on a Self-Spinning Rotary On/Off Valve,” 2011 International Fluid Power Exhibition (IFPE) (2011)

Wilfong,G; Holland, M; and Lumkes, J; “Design and Analysis of Pilot Operated High Speed On/Off Valves for Digital Pump/Motors,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 20.1 (2011)

Yong, Chao; Barth, Eric J.; "A Virtual-Cam Control Methodology for Free-Piston Engines", ASME DSCC 2011/Bath Symposium on PTMC, Arlington, VA; TuAT1.2 (2011)

Yong, C.; Willhite, J. A.; Barth, E. J; "A Virtual-Cam Control Methodology for a Novel Free-Liquid-Piston Engine Compressor"; Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 3.3 (2011)

Zecchi, M; and Ivantysynova, M; “A Novel Fluid Structure Interaction Model for the Cylinder Block/Valve Plate Interface of Axial Piston Machines,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; I11-9.2 (2011)

Zimmerman, J.; Busquets E.; and Ivantysynova, M.; “40% Fuel Savings by Displacement Control Leads to Lower Working Temperatures: A Simulation Study and Measurements,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 27.2 (2011)

Zimmerman, J; Hippalgaonkar, R; and Ivantysynova, M; “Optimal Control for the Series-Parallel Displacement Controlled Hydraulic Hybrid Excavator,” ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VA; TuBT1.4 (2011)

Thrust 2 – Compactness

Comber, D; Barth, E; “Precision Position Tracking of MR-Compatible Pneumatic Piston-Cylinder Using Sliding Mode Control,” Proceedings of the 4th Annual Dynamic Systems and Control Conference, Arlington, VA; TuAT1.1 (2011).

Cook, D; Vito, G; “High-Performance, Multi-Functional, Fluid-Power Components Using Engineered Materials,” 52nd National Conference on Fluid Power, Las Vegas, NV; 36.4 (2011)

Kerzhner, A; and Paredis, C; “A Formal Framework for Capturing Knowledge for Transforming Structural Models into Analysis Models,” Journal of Simulation, 5: 202-216 (2011)

Kerzhner, A; and Paredis, C; “Model-Based System Verification: A Formal Framework for Relating Analyses, Requirements and Tests,” Workshops and Symposia at MODELS 2010, Reports & Revised Selected Papers, Springer-Verlag, Berlin/Heidelberg, 6627:279-292 (2011)

Li, K; Sun, Z; “Modeling and Control of a Hydraulic Free Piston Engine with HCCI Combustion,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 21.1 (2011)

Li, K; Sun, Z; “Stability Analysis of a Hydraulic Free Piston Engine with HCCI Combustion,” Proceedings of the 4th Annual Dynamic Systems and Control Conference, Arlington, VA; WeAT2.4 (2011)

Min, B; Kerzhner, A; and Paredis, C; “Process Integration and Design Optimization for Model-Based Systems Engineering with SysML,” Proceedings of ASME IDETC/CIE; Aug 28; DETC2011-48453 (2011)

Moore, R; Paredis, C; and Romero, D; “A Rational Design Approach to Gaussian Process Modeling for Variable Fidelity Models,” Proc ASME IDETC/CIE, DETC2011-48227 (2011)

Turkseven, M; Ueda, J; “Design of an MRI Compatible Haptic Interface,” Proceedings of the 2011 IEEE International Conference on Intelligent Robots and Systems, San Francisco, CA; pp.2139 – 2144, 10.1109/IROS.2011.6095170 (2011)

Ueda, J; Turkseven, M; “Development of a Pneumatically Driven MRI-compatible Haptic Device,” Proceeding of the 29th Annual Conference of the Robotics Society of Japan, Tokyo, Japan (2011)

<u>Thrust 3 – Effectiveness</u>

Bair, S; and Laesecke, A; “High Pressure Viscosity Measurements of 1, 1, 1, 2-Tetrafluoroethan,” International Journal of Thermophysics, 32(5):925-941 (2011)

Bair, S; and Laesecke, A; “Normalized Ashurst-Hoover Scaling and a Comprehensive Viscosity Correlation for Compressed Liquids,” ASME J. Tribol (2011)
Casoli, P; Vacca, A; Anthony, A; and Berta, G; “Modellazione della Valvola di Controllo di un Sollevatore Agricolo,” Oleodinamica e Pneumatica, Tecniche Nuove, Milano, Italy (2012)

Cook, D; Newbauer, S; Pettis, S; Knier, B; Kumpaty, S; “Effective Thermal Conductivities of Unit-Lattice Structures for Multi-Functional Components,” Proceedings of the 22nd Annual International Solid Freeform Fabrication Symposium (2011)

Cristofori, D; and Vacca, A; “The Modeling of Electro-Hydraulic Proportional Valves,” ASME Journal of Dynamic Systems, Measurement and Control, 134 (2): 13 (2011)

Cunefare, K; Earnhart, N; and Marek K; “Novel, compact devices for reducing fluid-borne noise,” Proceedings of the SAE 2011 Noise and Vibration Conference and Exhibition (2011)

Cunefare, K; Earnhart, N; and Marek K; “Passive Noise Control in Fluid Power,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV (2011)

Cunefare, K; Earnhart, N; Marek K; Walsh, M; and Edirisinghe, R; “Noise control devices for fluid systems,” Noise-Con Proc. 129:877 (2011)

Earnhart, N; and Cunefare, K; “Cancelling noise at its source,” Hydraulics & Pneumatics (2011)

Elton, M; and Book, W; “An Excavator Simulator for Determining the Principles of Operator Efficiency for Hydraulic Multi-DOF Systems,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 18.3 (2011)

Elton, M; and Book, W; “Comparison of Human-Machine Interfaces Designed for Novices Teleoperating Multi-DOF Hydraulic Manipulators,” 20th IEEE International Symposium on Robot and Human Interactive Communication (2011)

Franklin, C.; Jiang, Z; and Jiang, X; “Learning Curve Analysis of a Haptic Controller,” The journal of Management and Engineering Integration, 4(1):63-70 (2011)

Hughes, K; Jiang, S; Jiang, Z; Park, E; and Mountjoy, D; “Assessment of Excavator Operator Performance Using an Integrated Human Performance Model,” The journal of Management and Engineering Integration, 4(1): 88-98 (2011)

Humphreys, H.; Book, W.; Huggins, J.; “Biodynamic Feedthrough Compensation and Experimental Results Using a Backhoe” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 22.3 (2011)

Humphreys, H.; Book, W.; Huggins, J.; “Compensation for Biodynamic Feedthrough in Backhoe Operation by Cab Vibration Control,” Proceedings of the IEEE International Conference on Robotics and Automation, Shanghai, China; (2011)

Michael, P; Blazel, B; Reuchel, R; Harville, X; “Hydraulic Fluid Compatibility and Filterability,”; Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 35.2, (2011)

Mizumoto, H; Daepp, H; Book, W; Matsuno, F; “Teleoperation system using past image records for legged robot,” 9th IEEE International Symposium on Safety, Security, and Rescue Robotics (2011)

Newbauer, S; Cook, D; and Pettis, D; “Multifunctional Components Using Engineered Lattice Structures as Materials,” Proceedings of the 2011 COMSOL Conference in Boston (2011)

Yang, B; and Salant, R; “EHL Simulation of O-ring and U-cup Hydraulic Seals,” Journal of Engineering Tribology, 225:603-610 (2011)

Testbeds and General

Cheong, K; Li, P; Chase. T; “Optimal Design of Power-Split Transmission for Hydraulic Hybrid Passenger Vehicles,” Proceedings of the 2011 American Control Conference, San Francisco, CA; pp. 3295 – 3300, (2011)

Cheong, K; Li, P; Sedler, S; Chase. T; “Comparison between input coupled and output coupled power-split configurations in hybrid vehicles,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 10.3 (2011)

Chipalkatty,R; Daepp, H; Egerstedt, M; Book, W; “Human-in-the-Loop: MPC for Shared Control of a Quadruped Rescue Robot,” IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2011)

Daepp, H; Book, W; “Modeling and Simulation of a Pneumatically-Actuated Rescue Robot,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 3.2 (2011)

Durfee, W.K; Kogler, G.; Morris, E.; Hsiao-Wecksler, E.; “Actuation Timing Strategies for a Portable Powered Ankle-Foot Orthosis,” Proceedings of the ASME Dynamic Systems and Control Conference (2011).

Li, D; Becker, A; Shorter, K; Bretl, T; and Hsiao-Wecksler, E; “Estimating System State During Human Walking with a Powered Ankle-Foot Orthosis,” IEEE/ASME Transactions on Mechatronics (2011).

Li, Y; Morris, E; Shorter, K; Hsiao-Wecksler, E; “Energy Efficiency Analysis of A Pneumatically-Powered Ankle-Foot Orthosis,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 3.1 (2011)

Mensing, F; Li, P; “Sizing and Optimal Operation of a Power Split Hydraulic Hybrid Drive Train,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 10.2 (2011)

Michael, P; Wanke, T; “Hydraulic Fluid and System Standards, Chapter 7,” Handbook of Hydraulic Fluid Technology, 2nd Edition, (2012)

Mishler, L; Garcia, J; Lumkes, J; “Engaging Pre-College Students in Engineering Using Hands-on Micro-Processor Controlled Portable Fluid Power Demonstrators,” ASABE Annual International Meeting, Louisville, KY; 1111500; (2011)

Shorter, K; Hsiao-Wecksler, E; Kogler, G; Loth, E; and Durfee, W; “A Portable Powered Ankle-Foot-Orthosis for rehabilitation,” Journal of Rehabilitation Research & Development (2011).

Shorter, K; Li, Y; Morris, E; Kogler, G; Hsiao-Wecksler, E; “Experimental Evaluation of a Portable Powered Ankle-Foot Orthosis,” 33rd Annual International IEEE EMBS Conference, Boston, MA; pp. 624 – 627; 10.1109/IEMBS.2011.6090138 (2011)

Kim A. Stelson
Center Director
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

Stanford University	Mechanical Engineering	B.S., 1974
Massachusetts Institute of Technology	Mechanical Engineering	S.M., 1977
Massachusetts Institute of Technology	Mechanical Engineering	Sc.D., 1982

Appointments

2006-present	Director, NSF Engineering Research Center for Compact and Efficient Fluid Power
1994-2006	Director, Design and Manufacturing Division, Department of Mechanical Engineering, Univ. of Minnesota
1994-present	Professor, Dept. of Mechanical Engineering, Univ. of Minnesota
2001-2002	Visiting Professor, Univ. of Bath, United Kingdom
1996	Visiting Associate Professor, Univ. of Auckland, New Zealand
1987-1994	Associate Professor, Dept. of Mechanical Engineering, Univ. of Minnesota
1992-1993	Visiting Senior Lecturer, Hong Kong Univ. of Science and Technology
1981-1987	Assistant Professor, Department of Mechanical Engineering, Univ. of Minnesota

Publications

Deppen, T. O., A. G. Alleyne, J. J. Meyer and K. A. Stelson, "Optimal Energy Use in a Light Weight Hydraulic Hybrid Passenger Vehicle," to be published in *Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control.*

Wang, Y., Z. X. Sun and K. A. Stelson, "Modeling, Control and Experimental Validation of a Transient Hydrostatic Dynamometer," *I.E.E.E. Transactions on Control Systems Technology,* Vol. 19, no. 6, Nov. 2011, pp. 1578-1586.

Deppen, T. O., A. G. Alleyne, K. A. Stelson and J. J. Meyer, "Model Predictive Control of an Electro-Hydraulic Powertrain with Energy Storage," *Proc. of the ASME Dynamic Systems and Control Conference*, Oct. 30-Nov. 2, 2011, Arlington, VA.

Stelson, K. A., "Center for Compact and Efficient Fluid Power (CCEFP), A National Science Foundation Engineering Research Center, United States," *Journal of the Japan Fluid Power Society,* Vol. 41, No. 1, Jan. 2010, pp. 60-63.

Stelson, K. A. and F. Wang, "A Simple Model of Piston-Cylinder Gap Efficiency in Positive-Displacement Hydraulic Pumps and Motors," Bath/ASME Symposium on Fluid Power & Motion Control (FPMC 2010), 15-17 September 2010, Bath, UK, pp. 417-429.

Synergistic Activities

Director, NSF ERC for Compact and Efficient Fluid Power, 2006-present

Director of Graduate Studies, M.S. in Manufacturing Systems, 1997-2001. A master's degree program for full-time employees in industry.

Director, STEPS Summer Camp for Girls, 2000-2002. A program for high school girls that motivates an interest in engineering by building and launching a rocket.

Associate Technical Editor, *ASME Journal of Manufacturing Science and Engineering*, 1995-2001; *SME Journal of Manufacturing Processes*, 1999-present; and *ASME Journal of Dynamic Systems, Measurement and Control,* 2003-present.

Editorial Board, *Transaction on Control, Automation and Systems Engineering,* 2000-present; and *IMechE Journal of Engineering Manufacture,* 2000-present. Scientific Committee, *Transactions of the North American Manufacturing Research Institute of SME,* 1999-present.

Collaborators & Other Affiliations

Graduate and Postdoctoral Advisors: Massachusetts Institute of Technology S.M. thesis advisor, Shawn Buckley; Massachusetts Institute of Technology Sc.D. thesis advisor, David Gossard.

Thesis Advisor and Postgraduate-Scholar Sponsor: A. Alleyne (Univ. of Illinois, Urbana-Champaign), T. Cui (Univ. of Minnesota), T. O. Deppen (University of Illinois, Urbana-Champaign), J. Dudney (St. Jude Medical), K. A. Edge (Univ. of Bath), R. Ertel, D. Fronimidis (Univ. of Bath); C. Groepper (MTS Systems), B. Hencey (Cornell), P. Y. Li (Univ. of Minnesota), S. C. Mantell (Univ. of Minnesota), J. J. Meyer (Univ. of Minnesota), A.R. Mileham (Univ. of Bath); S. Parthasarathy (Honeywell), R. Rajamani (Univ. of Minnesota), M. I. Ramdan (Univ. of Minnesota), T. W. Secord (Medtronic), M. A. Sokola (Univ. of Bath), Z. X. Sun (Univ. of Minnesota), B. R. Thul (Donaldson), F. Wang (Zhejiang U.), Y. Wang (Univ. of Minnesota), D. R. Youtt (BAE Aerospace), X. Yu (Univ. of N. Texas), H. Zhu (Baxter Medical).

Perry Y. Li
Center Deputy Director
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

Cambridge University	Electrical and Information Sciences	B.A. 1987
Boston University	Biomedical Engineering	M.S. 1990
University of California, Berkeley	Mechanical Engineering	Ph.D. 1995

Appointments

2008 – present	Professor of Mechanical Engineering University of Minnesota, Minneapolis MN
2006 – present	Co-deputy director, NSF ERC for Compact and Efficient Fluid Power, University of Minnesota, Minneapolis MN
2003 - 2008	Associate Professor of Mechanical Engineering University of Minnesota, Minneapolis, MN
1997 – 2003	Nelson Assistant Professor of Mechanical Engineering University of Minnesota, Minneapolis MN
1995 – 1997	Member of the Research Staff, Xerox Wilson Center for Research and Technology, Xerox Corporation, Webster, NY

Publications
1. P. Y. Li* and F. Mensing, "Optimization and Control of a Hydro-Mechanical Transmission based Hydraulic Hybrid Passenger Vehicle", Proceedings of the 7th International Fluid Power Conference, Aachen, Germany, March 2010.

2. J. Van de Ven and P. Y. Li, "Liquid Piston Gas Compression", Applied Energy, Vol. 86, Issue 10, pp. 2183-2191, October, 2009.

3. P. Y. Li, J. Van de Ven, and C. Sancken, "Open Accumulator Approach for Compact Energy Storage," ASME-IMECE, Seattle, WA, November 2007.

4. H. Tu, M. Rannow, M.Wang, J. Van de Ven, P.Y. Li and T.R. Chase, "High Speed Rotary PulseWidth Modulated On/Off Valve," ASME-IMECE, Seattle, WA, November 2007.

5. D.J. Lee and P.Y. Li, "Passive Bilateral Control & Tool Dynamics Rendering for Nonlinear Mechanical Teleoperators," IEEE Trans. on Robotics and Automation. Vol. 21, No. 5, pp. 936-951, Oct 2005.

Other Publications
1. Tone Reproduction Functions of a Xerographic Printing Process," IEEE Transactions on Control Systems Technology. Vol. 15, No. 2, pp. 349-357, 2007.

2. P.Y. Li and R.F. Ngwompo, "Power Scaling Bond Graph Approach to the Passification of Mechatronic Systems - With Application to Electrohydraulic Valves," ASME Journal of Dynamic Systems, Measurement and Control. Vol. 127, No. 4, pp. 633-641, December 2005.

3. Q.H. Yuan and P.Y. Li, "Robust Optimal Design of Unstable Valves," IEEE Transactions on Control Systems Technology. Vol. 15, No. 5, pp. 1065-1074, November, 2007.

4. S. Saimek and P.Y. Li, "Motion Planning and Control of a Swimming Machine," International Journal of Robotics Research. Vol. 23, No. 1, pp. 27-53, January 2004.

5. P.Y. Li and R. Horowitz, "Passive Velocity Field Control (PVFC). Part 1: Geometry and Robustness," IEEE Transactions on Automatic Control. Vol. 46, No. 9, pp. 1346-1359, September 2001.

Synergistic activities

- Director of the industry supported ”U. of Minnesota Fluid Power Control Education and Research Initiative”.

- Developed a new U/G course “Fluid Power Controls Laboratory” to integrate systems dynamics, modeling and control concepts, with practical aspects of fluid power and controls.

- P.I. for associated project on fluid power based surgical device design.

Collaborators
A. Erdman, T. Cui, T. Chase, T. Simon (U. of Minnesota); J. Van de Ven (WPI); E. Loth (U Virginia); S. Crane (Lightsail Energy)

Graduate advisors:
R. Horowitz (PhD, Berkeley), Z. Ladin (MS, Boston)

Thesis advisor to:
(all at U. of Minnesota)

Graduated PhDs:
S. Saimek (KMUTT, Thailand), D. J. Lee (U. of Tennessee), K. Krishnaswamy (Honey-well Labs), Q. Yuan (Eaton Innovation Center), Z. Liu (Corning), T. P. Sim (E-Ink).
Post-docs: J. Van de Ven (Worchester Polytechnic Institute)

Andrew Alleyne

University of Illinois at Urbana-Champaign

Professional Preparation

Ph.D.	Univ of California, Berkeley,	1994
M.S.	Univ of California, Berkeley	1992
B.S.E.	Princeton Univ.	1989

Research Areas

Control of Nonlinear Systems with Applications to Manufacturing, Thermal Systems, Vehicle Systems, Fluid Power.

Appointments

- NRC Research Associate, Wright Pat Air Force Base, 2011-2012
- F.I.R.S.T. Visiting Professor, ECEE Dept, CU Boulder, Jul 210-Aug. 2010.
- Associate Dean for Research, College of Engineering, Illinois, January 2009 – date
- Professor, Department of Mechanical Science and Engineering, UIUC, August 2004 – date
- Visiting Professor of Vehicle Mechatronics, Faculty of Design, Engineering and Production, Delft University of Technology, The Netherlands, January 2003 - July 2003
- Ralph M. and Catherine V. Fisher Professor of Engineering, UIUC, Aug 2002-date
- Associate Professor, Dept. of Mechanical & Industrial Engr, UIUC, Aug. 2000-date.
- Assistant Prof., Dept. of Mechanical & Industrial Engr, UIUC, Aug. 1994-Aug. 2000.

Selected Research Awards	Selected Teaching Awards
• NSF Faculty Early Career Development CAREER Award, 1996 • UIUC College of Engineering Xerox Award for Faculty Research, 2000. • Fulbright Fellowship (Netherlands) 2002-2003 • 2003 SAE Ralph R. Teetor Award • Ralph M. and Catherine V. Fisher Professorship, UIUC College of Engineering, 2002-date. • ASME Dynamic Systems and Control Division Outstanding Young Investigator Award, 2003. • Distinguished Lecturer, IEEE Control Systems Society, 2004 – 2007 • Fellow, ASME, 2005 • 2008 ASME Gustus L. Larson Memorial Award • 2011 NRC Research Award	• UIUC List of Teachers Ranked as Excellent by Their Students, 1995,2004,2006 • UIUC Engineering Council Award for Excellence in Advising, 1998,1999 • UIUC Engineering Accenture Award for Excellence in Advising, 2001, 2003 • UIUC College of Engineering Teaching Excellence Award, 2008 • UIUC Campus Award for Excellence in Undergraduate Teaching, 2008

5 Selected Relevant Publications

- Deppen, T., A. Alleyne, K. Stelson and J. Meyer, “Model Predictive Control Of An Electro-Hydraulic Powertrain With Energy Storage,” 2011 ASME Dynamic Systems and Control Conference, Arlington, VA, Oct 2011.
- Deppen, T., A. Alleyne, K. Stelson, and J. Meyer, "A Model Predictive Control Approach for a Parallel Hydraulic Hybrid Powertrain," 2011 American Controls Conference, San Francisco, CA, 2713 - 2718, June 2011.
- Meyer, J, K. Stelson, T. Deppen, and A. Alleyne, "Developing an Energy Management Strategy for a Four-Mode Hydraulic Hybrid Passenger Vehicle," 52nd IFPE National Conference on Fluid Power, Las Vegas, NV, March 22-26, 2011.
- Deppen, T., J. Meyer, A. Alleyne, and K. Stelson, "Predictive Energy Management for parallel Hydraulic Hybrid Vehicle," 2010 ASME Dynamic Systems and Control Conference, Boston, MA, October 2010.

- Deppen, T., A. Alleyne, K. Stelson, J. Meyer, "Optimal Energy Use in a Light Weight Hydraulic Hybrid Passenger Vehicle," accepted for ASME Journal of Dynamic Systems, Measurement and Control.

<u>Other Publications</u>

- Zhang, R., A. Alleyne, and E. Prasetiawan, "Modeling and H-2/H-infinity MIMO Control of an Earthmoving Vehicle Powertrain," ASME Journal of Dynamic Systems, Measurement, and Control, 124, 625-636, Dec. 2002.
- Zheng, D. and A. Alleyne, "Modeling and Control of an Electro-hydraulic Injection Molding Machine with Smoothed Fill-to-Pack Transition," ASME Journal of Manufacturing Science and Engineering, 125, 154-163, Feb. 2003.
- Zhang, R., A. G. Alleyne, and E. A. Prasetiawan, "Performance Limitations of a Class of Two-Stage Electro-Hydraulic Flow Valves," Int'l J. of Fluid Power, 3:1, 47-55, April 2002.
- Havlicsek, H. and A. Alleyne, "Nonlinear Control of an Electrohydraulic Injection Molding Machine via Iterative Adaptive Learning," IEEE/ASME Transactions on Mechatronics, 4:3, 312-323, 1999
- Zhang, Y. and A. Alleyne, "A Simple Novel Approach to Active Vibration Isolation with Electrohydraulic Actuation," ASME Journal of Dynamic Systems, Measurement, and Control, 125, 125-128, March 2003.

Selected Editorships	Synergistic Activities
• Associate Editor, ASME J. Dyn Sys Meas & Cntrl, 2000-03 • Editor, Vehicle System Dynamics, 2001-2008 • Associate Editor, IEEE Control Systems, 2003-2009 • Associate Editor, IEEE Trans on Control Syst Tech, 2010-date • Associate Editor, IFAC Control Engr Practice, 2010-date	• DARPA/DSO Defense Science Study Group, 2008-2010 • U.S. Air Force Scientific Advisory Board, 2009-2013 • Wash U, St. Louis, ME Board, 2009-date • Quanser Consulting, (Educational tools for controls) 2000-date

Collaborators within the past 48 Months:
Kim Stelson, Perry Li, Will Durfee (U. of Minnesota); Lucy Pao (Univ of Colorado); Placid Ferreira, John Rogers, Mark Shannon, Paul Kenis, Kent Choquette, Ilesami Adesida, Qin Zhang, Amy Wagoner Johnson, Elizabeth Hsiao-Wecksler, Eric Loth, Bill King, Jennifer Berhnard, William King (UIUC), Jakob Stoustrup (Aalborg), Maarten Steinbuch (TUEindhoven)

Invited Lectures (Last Five Years)
UCLA (2012), UC Irvine (2012), U Cincinnati (2012), Univ Florida (2011), Washington Univ, St. Louis (2010), U. Notre Dame (2010), Illinois Inst of Techn (2010), Northwestern University (2009), Johns Hopkins U, (2009), U. Arkansas (2008), Iowa St (2008), MIT (2008), U. Washington (2008), Aalborg University-Denmark (2007), TU Eindhoven (2007), Washington University in St. Louis (2007), RPI (2007), University of the West Indies (2007), Clemson University (2007).

Scott Bair
Regents' Researcher
The George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology

Professional Preparation

Georgia Institute of Technology	Mechanical Engineering	B.S.	1972
Georgia Institute of Technology	Mechanical Engineering	M.S.	1974
Georgia Institute of Technology	Mechanical Engineering	Ph.D.	1990

Academic/Professional Appointments

Regents' Researcher	Georgia Institute of Technology	2010-2012
Principal Research Engineer	Georgia Institute of Technology	1992-2010
Senior Research Engineer	Georgia Institute of Technology	1985-1992
Research Engineer	Georgia Institute of Technology	1974-1985

Publications

Publications Most Closely Related to Proposal

Bair, S., McCabe, C. and Cummings, P., "Comparison of NEMD with Experimental Measurements in the Non-Linear Shear Thinning Regime," Physical Review Letters, 88, 5, 8302, 2002.

Bair, S., "The High Pressure Rheology of Some Simple Model Hydrocarbons," Proc. I. Mech. E., 216, J, 2002, pp. 139-150.

Bair, S., McCabe, C. and Cummings, P., "Calculation of Viscous EHL Traction for Squalane using Molecular Simulation and Rheometry," Tribology Letters, 13, 4, pp. 251-254, 2002.

Bair, S., "Pressure-Viscosity Behavior of Lubricants to 1.4 GPa and Its Relation to EHD Traction," STLE Tribology Transactions, 43, 1, pp 91-99, 2000.

Bair, S. and Qureshi, F., "The Generalized Newtonian Fluid Model and Elastohydrodynamic Film Thickness," ASME, J. Tribology, 125, 1, pp. 70-75, 2003.

Other Significant Publications

Bair, S., "Normal Stress Difference in Liquid Lubricants Sheared Under High Pressure," Rheologica Acta, 35, 13, pp 13-23, 1996.

Bair, S., Qureshi, F., and Khonsari, M., "Adiabatic Shear Localization in a Liquid Lubricant Under Pressure," Trans. ASME, Journal of Tribology, 116, 4, 1994.

Bair, S. and Winer, W.O., "A New High-Pressure, High Shear Stress Viscometer and Results for Lubricants, "Tribology Transactions, 36, 4, pp. 721-725, 1993.

Bair, S., Qureshi, F., and Winer, W. O., "Observations of Shear Localization in Liquid Lubricants Under Pressure," Trans. ASME, Journal of Tribology, 115, 3, 1993.

Bair, S., Green, I., and Bhushan, B., "Measurements of Asperity Temperatures of a Read/Write Head Slider Bearing in Hard Magnetic Recording Disks," Trans. ASME Journal of Tribology, 113, No. 3, 1991.

Synergistic Activities

Awards

Co-Recipient of the 1983 Best Paper of the Year for the Tribology Division/ASME
Co-Recipient of the 1991 Best Paper of the Year for the Tribology Division/ASME
Jacob Wallenberg Foundation, 1996
Recipient of the 2000 Alfred Hunt Award from STLE for best paper
Fellow of ASME
Fellow of STLE
Co-Recipient of the 2006 Alan Berman Research Publication Award (with Roland and Casalini)
Recipient of the 2007 Alfred Hunt Award from STLE for best paper
Recipient of the 2009 Naval Research Laboratory Chemistry Division Alan Berman Research Publication Award (with Roland, Bogoslovov, Casalini, Ellis, Rzosca, Czuprynski, and Urban)
Recipient of the International Award for 2009, the highest honor given by the Society of Tribologists and Lubrication Engineers.

US Patents

4,349,130	Liquid Metering Pump
4,347,643	Power Assist Drive Upright Vacuum Cleaner and Power Assist Drive System
4,391,018	Vacuum Cleaner with Wheel and Nozzle Height Adjusting Mechanism [with Vermillion and Gromek]
4,998,228	Drinking Water Filter [with Eager]
5,562,692	Fluid Jet Surgical Cutting Tool
5,643,299	Hydrojet Apparatus for Retractive Surgery
5,735,815	Method of Using Fluid Jet Surgical Cutting Tool
5,853,384	Fluid jet Surgical Tool and Aspiration Device
5,865,790	Method and Apparatus for Thermal Phaco-emulsification by Fluid Throttling
6,126,668	Microkeratome
6,527,766	Instrument and Method for Phacoemulsification by Direct Thermal Irradiation

Collaborators And Other Affiliations

Collaborators Over The Last 48 Months:
Ashlie Martini, Purdue University, CCEFP
Ivan Krupka, Brno University, Czech Republic, Elastohydrodynamic film thickness measurements
Riccardo Casilini, George Mason University, Viscosity correlations
Mike Roland, Naval Research Laboratory, Viscosity correlations
Michael Khonsari, Louisiana State University, Elastohydrodynamic numerical simulations
Punit Kumar, National Institute of Technology Kurukshetra, Elastohydrodynamic numerical simulations
Paul Michael, MSOE, CCEFP
Kees Venner, U. of Twente, Netherlands, Elastohydrodynamic numerical simulations
Arno Laesecke, NIST Boulder, Viscosity correlations
Philippe Vergne, INSA de Lyon, Elastohydrodynamic numerical simulations
Wassim Habchi, Lebanese American University, simulations
Hubert Schwarze, Technische Universität Clausthal, high-frequency viscosity measurements under pressure

Eric J. Barth
Department of Mechanical Engineering
Vanderbilt University

Professional Preparation

University of California Berkeley	Engineering Physics	B.S., 1994
Georgia Institute of Technology	Mechanical Engineering	M.S., 1996
Georgia Institute of Technology	Mechanical Engineering	Ph.D., 2000
Vanderbilt University	Mechanical Engineering	Post Doc, 2002

Appointments

2010 – present	Associate Professor of Mechanical Engineering, Vanderbilt University
2002 – 2010	Assistant Professor of Mechanical Engineering, Vanderbilt University
2000 – 2002	Research Assistant Professor of Mechanical Engineering, Vanderbilt University

Publications

1. D. Comber, E. J. Barth. "Precision Position Tracking of MR-Compatible Pneumatic Piston-Cylinder Using Sliding Mode Control*". 2011 ASME Dynamic Systems and Control Conference & Bath/ASME Symposium on Fluid Power and Motion Control.* DSCC2011-5960, pp. 1-7, Oct 31-Nov 2, 2011, Arlington, VA.

2. Y. Zhu, E. J. Barth. "Accurate Sub-millimeter Servo-Pneumatic Tracking using Model Reference Adaptive Control (MRAC)". *International Journal of Fluid Power*, vol. 11, no. 2, pp. 43-55, 2010.

3. J. A. Riofrio and E. J. Barth. "Experimental Assessment of a Free Elastic-Piston Engine Compressor with Separated Combustion Chamber," *Bath/ASME Symposium on Fluid Power and Motion Control (FPMC 2008)*, pp. 233-244, September 10-12, 2008. Bath, U K. NOTE: Winner of the BEST PAPER AWARD for the entire Symposium.

4. Y. Zhu, E. J. Barth. "An Energetic Control Methodology for Exploiting the Passive Dynamics of Pneumatically Actuated Hopping". *ASME Journal of Dynamic Systems, Measurement and Control*, vol. 130, issue 4, pp.041004-1 – 041004-11, July 2008.

5. N. Gulati, E. J. Barth. "Dynamic Modeling of a Monopropellant-Based Chemofluidic Actuation System". *ASME Journal of Dynamic Systems, Measurement, and Control,* vol. 129, no. 4, pp.435-445, July 2007.

Other Publications

1. N. Gulati, E. J. Barth. "A Globally Stable, Load Independent Pressure Observer for the Servo Control of Pneumatic Actuators". *IEEE/ASME Transactions on Mechatronics*, vol. 14, issue 3, pp.295 – 306, DOI 10.1109/TMECH.2008.2009222, June 2009.

2. M. A. Adams, E. J. Barth. "Dynamic Modeling and Design of a Bulk-Loaded Liquid Monopropellant Powered Rifle". *ASME Journal of Dynamic Systems, Measurement and Control*, vol. 130, issue 6, pp.061001-1 – 061001-8, November 2008.

3. C. Yong, J. A. Riofrio and E. J. Barth. "Modeling and Control of a Free-Liquid-Piston Engine Compressor," *Bath/ASME Symposium on Fluid Power and Motion Control (FPMC 2008)*, pp. 245-257, Bath, U K, September 10-12, 2008.

4. Y. Zhu, E. J. Barth. "Passivity-based Impact and Force Control of a Pneumatic Actuator". *ASME Journal of Dynamic Systems, Measurement and Control*, vol. 130, issue 2, pp.024501-1 – 024501-7, March 2008.

5. M. Goldfarb, E. J. Barth, M. A. Gogola, J. A. Wehrmeyer. "Design and Energetic Characterization of a Liquid-Propellant-Powered Actuator for Self-Powered Robots". *IEEE/ASME Transactions on Mechatronics*, vol. 8, no. 2, pp. 254-262, June 2003.

Synergistic Activities

1. 2010-present: Chair of the ASME Fluid Power Systems and Technology (FPST) Division
2. Member of the ASME Dynamic Systems and Control Division (DSC) Conference Editorial Board (2009-2011)
3. ASME Fluid Power Systems and Technology Division (FPST): Executive Committee Member.
4. ASME Division of Dynamic Systems and Control (DSCD): Member of Mechatronics Technical Committee.
5. ASME Division of Dynamic Systems and Control (DSCD): Member of the Robotics Technical Committee.
6. Member of the National Fluid Power Association (NFPA) by invitation
7. Program Committee Member of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), October 9-14, 2006, Beijing, China.
8. Program Committee Member of the 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2005), July 24-28, 2005, Monterey, California, USA
9. Track Representative of Fluid Power Systems Technology Division (FPST) for IMECE 2005.
10. US Air Force Summer Faculty Fellow, AFRL, Wright-Patterson Air Force Base, 2005.

Collaborators & Other Affiliations

*Collaborators:*Andrew Alleyne, Ph.D., Department of Mechanical and Industrial Engineering, UIUC, Wayne Book, Ph.D., George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Michael Goldfarb, Ph.D., Department of Mechanical Engineering, Vanderbilt University, Monika Ivantysynova, Ph.D., Department of Mechanical Engineering, Purdue University, Suhada Jayasuriya, Ph.D., Department of Mechanical Engineering Texas A&M University, Perry Y. Li, Ph.D., Department of Mechanical Engineering, University of Minnesota, Nader Sadegh, Ph.D., George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Corey Schumacher, Ph.D, AFRL/VACA, Wright Patterson Air Force Base, Kim A. Stelson, Ph.D., Department of Mechanical Engineering, University of Minnesota, Alvin Strauss, Ph.D., Department of Mechanical Engineering, Vanderbilt University, Roger Quinn, Ph.D., Dept. of Mechanical and Aerospace Engineering, Case Western Reserve University

Advisors: Harry Bingham (deceased), Ph.D., Department of Physics, University of California Berkeley, Ye-Hwa Chen, Ph.D., School of Mechanical Engineering, Georgia Institute of Technology, Aldo Ferri, Ph.D., School of Mechanical Engineering, Georgia Institute of Technology, Michael Goldfarb, Ph. D., Department of Mechanical Engineering, Vanderbilt University, Bonnie Heck, Ph.D., School of Mechanical Engineering, Georgia Institute of Technology, Nader Sadegh, Ph. D., School of Mechanical Engineering, Georgia Institute of Technology, George Vachtsevanos, Ph.D., School of Electrical Engineering, Georgia Institute of Technology, David Nygren, Ph.D., Physics, Lawrence Berkeley National Laboratory

Thesis Advisor to: Chao Yong, Ph.D. (2011), Dept. of Mech. Engineering, Vanderbilt University, Alexander Pedchenko, M.S. (2011), Dept. of Mech. Engineering, Vanderbilt University, Andy Willhite, Ph.D. (2010), Dept. of Mech. Engineering, Vanderbilt University, Jose Riofrio, Ph.D. (2008), M.S. (2005), Dept. of Mech. Engineering, Vanderbilt University, Taib Tariq Mohamad, M.Engineering. (2007), Dept. of Mechanical Engineering, Vanderbilt University, Yong Zhu, Ph.D. (2006), Department of Mechanical Engineering, Vanderbilt University, Navneet Gulati, Ph.D. (2005), Department of Mechanical Engineering, Vanderbilt University, Mark Adams, M.S. (2004), Department of Mechanical Engineering, Vanderbilt University, *Current*: Mark Hofacker, Ph.D. Student, Dept. of Mechanical Engineering, Vanderbilt University, Alexander Pedchenko, Ph.D. Student, Dept. of Mechanical Engineering, Vanderbilt University, Dave Comber, M. S. Students, Dept. of Mechanical Engineering, Vanderbilt University, John Tucker, M. S. Students, Dept. of Mechanical Engineering, Vanderbilt University.

Wayne J. Book
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology

Professional Preparation

Massachusetts Institute of Technology	Mechanical Engineering	PhD.	1974
Massachusetts Institute of Technology	Mechanical Engineering	S.M.	1971
University of Texas, Austin	Mechanical Engineering	B.S.M.E.	1969

Appointments

2011 – present	Professor Emeritus
2001 – 2011	HUSCO/Ramirez Chair in Fluid Power and Motion Control, Georgia Tech
1986 - 2011	Professor, Georgia Institute of Technology
1980 - 1986	Associate Professor, Georgia Institute of Technology
1974 - 1980	Assistant Professor, Georgia Institute of Technology
1987 Summer	Faculty Fellowship, Oak Ridge National Laboratory
1981 – 1982	Visiting Scientist, The Robotics InstituteCarnegie-Mellon U.
1976 Summer	Research Fellow, NASA Johnson Space Center
1974 Summer	Research Associate, M.I.T. Dept. of Mechanical Engineering
1974 – present	Consultant, Numerous Companies

Publications

1. Munir, Saghir and Wayne Book, "Internet Based Teleoperation using Wave Variables with Prediction," *ASME/IEEE Transactions on Mechatronics*,v7 n2, June 2002, p 124-133.
2. Rhim, Sungsoo and Wayne J. Book, "Adaptive Time-delay Command Shaping Filter for Flexible manipulator Control," *IEEE/ASME Transactions on Mechatronics*, v9, n4, Dec. 2004, pp 619-626.
3. Gao, Dalong and Wayne J. Book, "Steerability for Planar Dissipative Passive Haptic Interfaces," in *IEEE/ASME Transactions on Mechatronics*, v11 n2, April 2006.
4. Ching, Ho and Wayne J. Book, "Internet-Based Bilateral Teleoperation Based on Wave Variable with Adaptive Predictor and Direct Drift Control," *ASME J. Dynamic Systems, Measurement and Control*, v128, n1, 8pp, March 2006.
5. Rhim, S., A. Hu, N. Sadegh, W.J. Book, "Combining a Multirate Repetitive Learning Controller with Command Shaping for Improved Flexible Manipulator Control," *ASME J. of Dynamic Systems, Measurement, and Control*, v123 n 3, September 2001, pp385-390.
6. Love, L.J. and W.J. Book, "Force Reflecting Teleoperation with Adaptive Impedance Control," *IEEE Transactions on Systems, Man, and Cybernetics Part B: Cybernetics*, v34, n1, pp.159-165, Feb. 2004.
7. George, Lynanne, and Wayne J. Book, "Inertial Vibration Damping Control of a Flexible Base Manipulator" *IEEE/ASME Transactions on Mechatronics*, v8 n2, June 2003, pp 268-271.
8. Krauss, Ryan and Wayne Book, "Transfer Matrix Modeling of a Hydraulically Actuated Flexible Robot," *International Journal of Fluid Power*, v8, n1, March 2007, pp 51-58.
9. Kontz, Matthew and Wayne Book, "Electronic Control of Pump Pressure for a Small Haptic Backhoe," *International Journal of Fluid Power,* v8, n2, pp 5-16, Aug. 2007.
10. Kontz, Matthew and Wayne Book, "Flow Control for Coordinated Motion and Haptic Feedback" *International Journal of Fluid Power* v8, n3, Nov. 2007.
11. Shenouda, Amir and Wayne Book, "Optimal Mode Switching for a Hydraulic Actuator Controlled with Four-Valve Independent Metering Configuration" *International Journal of Fluid Power,* v9, n1, pp 35-46, March 2008 .
12. Opdenbosch, Patrick, Nader Sadegh, Wayne Book, Todd Murray and Roger Yang, "Modeling an Electro-Hydraulic Poppet Valve" International Journal of Fluid Power. Vol 10, No. 1, pp 7-15 March, 2009.
13. Gao, Dalong and Wayne Book, "Steerability in Planar Dissipative Passive Robots," International Journal of Robotics Research, on line May 19, 2009 in print V29, n4, April 2010.
14. Enes, Aaron and W. Book "A Virtual Reality Operator Interface Station with Hydraulic Hardware-in-the-Loop Simulation for Prototyping Excavator Control Systems," 2009 IEEE/ASME

International Conference on Advanced Intelligent Mechatronics, Singapore, July 14-17, 2009, pp250-255.

15. Wang, Longke, Wayne Book and James Huggins, “A Control Approach with Applications to Variable Displacement Pumps,” 2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Singapore, July 14-17, 2009, pp1862-1867.
16. Humphreys, Heather, Wayne Book and James Huggins, “Modeling of Biodynamic Feedthrough in Backhoe Operation,” paper TuBT1.4, 2009 ASME Dynamic Systems and Control Conference, Hollywood, CA, October 12-14, 2009.
17. Ngoo, Cheng Shu and Wayne Book, “Digital Clay Force Observer Design and Shape Editing Concept,” paper TuCT7.2, 2009 ASME Dynamic Systems and Control Conference, Hollywood, CA, October 12-14, 2009.
18. Opdenbosch, Patrick, Nader Sadegh and Wayne Book “Auto-Calibration Based Control and its Application to a Kind of Electro-Hydraulic Poppet Valve,” *ASME J. Dynamic Systems, Measurement and Controls* published online, 29 September 2011 v133, n6.
19. Wang, Longke, Wayne Book and James Huggins, “A Hydraulic Circuit for Single-rod Cylinders,” *ASME J. Dynamic Systems, Measurement and Controls*, v134, n1, Jan. 2012, 11pp.
20. Wang, Longke Wayne Book and James Huggins, “Applying Singular Perturbation Theory to Hydraulic Pump Control”, *IEEE/ASME Transactions on Mechatronics* v17, n2, pp 251-259, April 2012.

Synergistic Activities

Editorial Activities: Senior Technical Editor, ASME Journal of Dynamic Systems, Measurement and Control, 1994-99; Associate Editor 1984-1987. Associate Editor, IEEE Transactions on Automatic Controls. Also International Journal of Fluid Power, 2004-present Management Committee, Joint ASME-IEEE Transactions on Mechatronics, 1995-2008. Chair for 1999.

Co-Founder of CAMotion, Inc. for commercialization of advanced motion control technology for automating manufacturing and material handling, 1997. Treasurer and consultant 1997 - present.

Conference Organization activities: General Chairman 1993 IEEE International Conference on Robotics and Automation, Atlanta, GA. General Chairman, 1988 ACC of the American Automatic Control Council. Service in various capacities in ASME, IEEE and the American Automatic Control Council.

Founding Director, Computer Integrated Manufacturing Systems (CIMS) Program, 1983-1987. The program won the 1986 University LEAD award for excellence in education in computer integrated manufacturing awarded by the Society of Manufacturing Engineers.

Steering and Advisory Committee service: Steering Committee, Oak Ridge National Laboratory, Center for Engineering Systems Advanced Research, 1983 - 1994. Advisory Committee, New York State Center for Advanced Technology .on Automation and Robotics, Rensselaer Polytechnic Institute, 1989 - 1993. Potomac Institute for Policy Studies NASA Computing And Communications Tech. Advisory Group, 2004.

Collaborators & Other Affiliations

Collaborators within the last 48 months (other than students listed):

Stephen Dickerson, Nader Sadegh, Christopher Paredis, Kenneth Cunefare, Richard Salant, all from the Georgia Institute of Technology. Kim Stelson and Perry Li (U. Minnesota); Michael Goldfarb (Vanderbilt U.); Monika Ivantysynova (Purdue U.); Andrew Alleyne (U. Illinois);

Ph.D. Students Supervised:

Noparat Punyapas, Viboon Sangveraphunsiri, Gordon Hastings, Thomas Alberts, Sabri Cetinkunt, Bau San Yuan, Jeh Won Lee, Dong Soo Kwon, Soo-Han Lee, J.J. Wang, Jae Lew, Jonathan Cameron, David Magee, Lonnie Love, John Hogan, Klaus Obergfell, Sungsoo Rhim, Saghir Munir, Lynnane George, Davin Swanson, Haihong Zhu, Lawrence Tognetti, Dalong Gao, Ho Ching, Amir Shenouda, Ryan Kraus, Benjamin Black, Patrick Op den Bosch, Longke Wang, Aaron Enes.

Ph.D. and M.S. Advisors:

Ph.D.: Daniel Whitney, Dept. of Mechanical Engineering, MIT.
M.S.: Russel Jones, Dept. of Civil Engineering, Massachusetts Institute of Technology

Research Visitors:
Prof. Dong Soo Kwon, KAIST, Korea

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Alyssa A. Burger
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

University of Minnesota	Kinesiology	B.S., 2003
University of Minnesota	Science Education	M.Ed., 2012

Appointments

2006 – present Education Outreach Director
Center for Compact and Efficient Fluid Power
University of Minnesota
Direct, develop and coordinate education and outreach programs

1998 – 2004 Executive Administrative Specialist
Department of Mechanical Engineering
University of Minnesota
Coordinate the administrative functions of a division

Synergistic Activities

- Advisor, University of Minnesota AISES Student Chapter and giiwed'anang Northstar AISES Alliance
- Advisor, CCEFP Student Leadership Council
- Lead Personnel, NSF OEDG Grant: Manoomin
- Lead Personnel, TRIBES-E, Teaching Relevant-Inquiry Based Environmental Science And Engineering Teacher Workshop
- Lead Personnel, Minnesota North Star Louis Stokes Alliance for Minority Participation

Collaborators

Gillian Roehrig, STEM Education Center Director
Tamara Moore, STEL Education Center Co-Director
Diana Dalbotten, Diversity Director, National Center for Earth-surface Dynamics
Holly Pellerin, gidaa Coordinator, NCED and CCEFP
Lowana Greensky, Indian Education Director, St. Louis County Schools

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Thomas R. Chase
Professor, Mechanical Engineering
University of Minnesota

Professional Preparation

Rochester Institute of Technology	Mechanical Eng	B.S., 1977
Rochester Institute of Technology	Mechanical Eng	M.S., 1983
University of Minnesota	Mechanical Eng	Ph.D., 1984

Academic/Professional appointments

2003-present:	Professor of Mechanical Engineering, University of Minnesota
1991-2003:	Associate Professor of Mechanical Engineering, Univ of Minnesota
1985-1991:	Assistant Professor of Mechanical Engineering, Univ of Minnesota
1983-1985:	Assistant Professor of Mechanical Engineering, Univ of Rhode Island

Publications

Publications Most Closely Related to Proposal:

1. Tu, H. C., Rannow, M. B., Wang, M., Li, P. Y., and Chase, T. R., "Design, Modeling and Validation of a High-Speed Rotary PWM On/Off Hydraulic Valve", submitted to *ASME Journal of Dynamic Systems, Measurement, and Control*, submitted December 2009, in revision.
2. Tu, H., Rannow, M., Wang, M., Li, P., Chase, T., and Cheong, K.L., 2011. "High-Speed 4-way Rotary On/Off Valve for Virtually Variable Displacement Pump/Motor Applications", *Proceedings of the ASME 2011 Dynamic Systems and Control Conference*, Arlington, VA.
3. Cheong, K. L., Li, P.Y., Sedler, S., and Chase, T.R., 2011. "Comparison Between Input Coupled and Output Coupled Power-Split Configurations in Hybrid Vehicles", *Proceedings of the 52nd National Conference on Fluid Power*, Paper No. NCFP_I11-10.2.
4. Fikru, Nebiyu and Chase, Thomas R., 2011. "A Review of MEMS Based Pneumatic Valves", *Proceedings of the 52nd National Conference on Fluid Power*, Paper No. NCFP_I11-11.2.
5. Tu, H. C., Rannow, M. B., Wang, M., Li, P. Y., and Chase, T. R., 2011. "The Advantages and Feasibility of Externally Actuating a High Speed Rotary On/Off Valve", *Proceedings of the 52nd National Conference on Fluid Power*, Paper No. NCFP_I11-20.3.

Other Significant Publications

1. Michael, D. G., et al. (including T. R. Chase), 2008, "The Magnetized Steel and Scintillator Calorimeter of the MINOS Experiment", *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Vol. 596, No. 2, pp. 190-228.
2. Michael, D. G., et al. (including T. R. Chase), 2006, "Observation of Muon Neutrino Disappearance with the MINOS Detectors in the NuMI Neutrino Beam", *Physical Review Letters*, Vol. 97, No 19, article #191801.
3. Adamson, P., et al. (including T. R. Chase), 2006, "First Observations of Separated Atmospheric ν_μ and ν_μ events in the MINOS Detector", *Physical Review D (Particles and Fields)*, Vol. 73, No. 7, article #072002.
4. Chase, Thomas R., 2006, "A Note on the Waldron Construction for Transmission Angle Rectification", *ASME Journal of Mechanical Design*, Vol. 128, No. 2, pp. 509-512.
5. Langlais, T. E., Vogel, J. H., and Chase, T. R., 2003, "Multiaxial Cycle Counting for Critical Plane Methods", *International Journal of Fatigue*, Vol. 25, No. 7, pp. 641-647.

Synergistic Activities

1. Associate Editor, ASME Journal of Mechanical Design, 9/1/04-present.
2. Level 3 Manager for Scintillator Module Design, NuMI Off-Axis υ_e Appearance (NOνA) Experiment, responsible for the design of approximately $2 million of components for neutrino detector modules (an experiment of the Fermi National Accelerator Laboratory).
3. Director of Undergraduate Studies, Mechanical Engineering Department, 2009-present.
4. Level 3 Manager for Scintillator Module Design, Main Injector Neutrino Oscillation Search (MINOS) Experiment, responsible for the design and purchase of over $1 million of components for neutrino detector modules. The MINOS Collaboration includes approximately 32 institutions internationally.
5. Member, Executive Committee, Design Engineering Division of the American Society of Mechanical Engineers, 1998-2004 (Chair, 2002-03).

Collaborators and Other Affiliations

Collaborators Over The Last 48 Months:

W. Lipinski & J. Davidson (UMN Mechanical Engineering Dept) – Solar Fuels Via Partial Redox Cycles with Heat Recovery
K. Heller, M. Marshak, E. Peterson, R. Poling (Univ of Minnesota Physics Dept) – NOνA Experiment
P. Li (Univ of Minnesota Mechanical Engineering Dept) – CCEFP Projects 1E.1, 1E.4 & TB3
E. Hsiao-Wecksler (UIUC Mechanical Engineering Dept) – CCEFP Project 2F
H. Conrad & W.-J. Seong (Univ of Minnesota Dental School) – Dental Implant Study
F. Kelso (Univ of Minnesota Mechanical Engineering Department) – Textbook project

Graduate and Postdoctoral Advisors

Ph.D. Advisor: Professor Arthur G. Erdman, University of Minnesota
M.S.M.E. Advisor: Professor Richard Budynas, Rochester Institute of Technology

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:

Graduate Students:

1. Ross Makulec, MSME, 2011
2. Tyler Kuhlmann, MSME (MTS Systems Inc.), 2010
3. Anne Fundakowski, MSME, 2010
4. David Grandall, MSME (Stefan Maier Organbuilding), 2010
5. John Robelia, MSME, 2009
6. Benjamin Nitti, MSME, 2008
7. Jackson Brandts, MSME, 2007

Total Number of Graduate Students advised: 35 (completed)

Douglas L. Cook
Applied Technology Center
Milwaukee School of Engineering

Professional Preparation

Milwaukee School of Engineering	Engineering	M.S. 2007
Milwaukee School of Engineering	Mechanical Engineering	B.S. 1998
	Electrical Engineering	B.S. 1998
Fachhochschule Luebeck	Elektrotechnik	Dipl.-Ing 1998

Appointments

2006 – Present	Research Engineer, MSOE, RP Research Principal Investigator 2005 –
2006	MSOE, ATC
1998 – 2003	Graduate Research. Asst. MSOE, RPC
1996 – 1998	Undergrad. Research. Asst. MSOE, RPC

Publications

1. John R. Brauer, Douglas L. Cook, Thomas E. Bray, "Finite-Element Computation of Magnetic Force Densities on Permeable Particles in Magnetic Separators." IEEE Transactions on Magnetics, Vol. 43, No. 8, pg. 3483-3487, August 2007. http://ieeexplore.ieee.org

2. Douglas L. Cook, Thomas E. Bray, "Flux Concentrator for Biomagnetic Particle Transfer Device." Patent No.: US 7,799,281 Issue Date: Sept. 21, 2010.

3. Gunnar Vikberg and Douglas Cook. "Voronoi Diagrams and Stress-Directed Lattice Structures Applied to Weight Reduction," Proceedings of the 6th Fluid Power Net International (FPNI) PhD Symposium. West Lafayette, Indiana (2010).

4. Douglas Cook, Bradley Knier, Vito Gervasi and Douglas Stahl, Ph.D. "Automatic Generation of Strong, Light, Multi-Functional Structures from FEA Output." Proceedings of the 21st Annual International Solid Freeform Fabrication (SFF) Symposium. Austin, Texas (2010).

5. Richard Remmers, Douglas Cook and Vito Gervasi. "Custom, Integrated, Pneumatic, Rotary Actuator for an Active Ankle-Foot Orthosis." Proceedings of the 21st Annual International Solid Freeform Fabrication (SFF) Symposium. Austin, Texas (2010).

6. Douglas Cook and Vito Gervasi. "High-Performance, Multi-Functional, Fluid-Power Components Using Engineered Materials." Proceedings of the 52nd National Conference on Fluid Power. Las Vegas, Nevada (2011).

7. Douglas Cook, Samuel Newbauer, Devin Pettis, Bradley Knier and Subha Kumpaty, Ph.D., P.E. "Effective Thermal Conductivities of Unit-Lattice Structures for Multi-Functional Components." Proceedings of the 22nd Annual International Solid Freeform Fabrication (SFF) Symposium. Austin, Texas (2011).

8. Samuel Newbauer, Douglas Cook and Devin Pettis. "Multifunctional Components Using Engineered Lattice Structures as Materials." Proceedings of the 2011 COMSOL Conference. Boston, Massachusetts (2011).

Organizations

AIAA
SIAM
SME

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Kenneth A. Cunefare
George W. Woodruff School of Mechanical Engineering
The Georgia Institute of Technology

Professional Preparation

The University of Illinois at Urbana-Champaign	Mechanical Engineering	Bachelor of Science	1982
The University of Houston	Acoustical Engineering	Master of Science	1987
The Pennsylvania State University	Mechanical Engineering	Doctor of Philosophy	1990
The Technical University of Berlin	Structural Acoustics		1990-1991

Appointments

2006-present	Professor, Georgia Institute of Technology
1997-2006	Associate Professor, Georgia Institute of Technology
1990-1997	Assistant Professor, Georgia Institute of Technology
1990-1991	F.V. Hunt Postdoctoral Fellow, The Technical University of Berlin
1988-1990	NASA GSRP Fellow, The Pennsylvania State University
1987-1988	NASA GSRP Fellow, The University of Houston
1986-1987	Senior Engineer, Exxon Company U.S.A., Houston, Texas
1984-1986	Senior Project Engineer, Exxon Company U.S.A., Midland, Texas
1982-1984	Project Engineer, Exxon Gas Systems, Inc., Houston, Texas
1981	Intern, McDonnell Douglas Aircraft Corporation

Publications

1. Jindou Wang, W. Steve Shepard* Jr., and Kenneth A. Cunefare, "Actuation of a discontinuous structure with piezoelectric actuators," Journal of Sound and Vibration, **309**(3-5), pp. 677-694, 2008.

2. F. Casadei, M. Ruzzene, L. Dozio, and K. A. Cunefare, "Broadband vibration control through periodic arrays of resonant shunts: experimental investigations on plates," Smart Materials and Structures, **19**, pp.1-13, 2010.

3. Ken Marek, Nick Earnhart, and Kenneth A. Cunefare, "Modeling and validation of an in-line silencer," Proceedings of the 6th Fluid Power Net International PhD Symposium, Lafayette, IN, June 15-19, 2010. Volume 1, pp. 101-114. CD Proceedings.

4. Benjamin S. Beck* and Kenneth A. Cunefare, "Experimental analysis of a cantilever beam with a shunted piezoelectric periodic array," Journal of Intelligent Material Systems and Structures, **20**(11), pp. 1177-1187, 2011.

5. John P. Arata, Michael J. Leamy, Jerome Meisel, Kenneth Cunefare, David Taylor, "Backward-looking simulation of the Toyota Prius and General Motors two-mode power-split HEV powertrains," SAE International Journal of Engines, June, 2011, **4**(1), pp 1281-1297.

6. Nicholas E. Earnhart* and Kenneth A. Cunefare, "Compact Helmholtz Resonators for Hydraulic Systems," accepted for publication, International Journal for Fluid Power, October, 2011

Synergistic Activities

Member, National Committee on Education in Acoustics, Acoustical Society of America. 1998-2011.

Member, National Committee on Noise, Acoustical Society of America, 1998-2013.

Integration of NSF funded (ARI grant) laboratory into ME4055, Senior Experimental Methods class.

Active recruitment of women and minorities into my research program. Eight current or former students are women or under-represented minorities (Noelle Curry, Janeen Jones, Lisa Chang, Anne Marie Albanese, Wayne Johnson, Mawuli Dzirasa, Tina Famighetti, Ellen Skow).

Collaborators and other Affiliations

Collaborators and Co-Editors: Dr. Krishan Ahuja (Georgia Tech), Dr. Mark Allen (Georgia Tech), Dr. Yves Berthelot (Georgia Tech), Scott Crane (General Electric), Brian Dater (Northrup-Grumman), Sergio DeRosa (University of Naples), Dr. Stephen Elliott (ISVR, Southampton, U.K.), Steve Engelstad (Lockheed Martin), Dr. Francesco Franco (Post Doc, University of Naples), Dr. Jerry Ginsberg (Georgia Tech), Dr. Ari Glezer (Georgia Tech), Dr. Marty Johnson (VPI), Dr. Greg Larson (Georgia Tech), Dr. Chris Lynch (UCLA), Keith Oglesby (Ford Motor Co.), Dr. Huang Pham (Newport News Shipyard), Eugene Powell (Lockheed Martin), Dr. Nader Sadegh (Georgia Tech), Dr. Manuel Collet (CNRS), Dr. Chan Il Park (Kangnung National University)

Graduate and Post-Doctoral Advisors: Dr. Ashok Belegundu (Penn State), Dr. Courtney Burroughs (Penn State, retired), Dr. Prof. Manfred Heckl (Post-Doctoral Sponsor, Technical University of Berlin, deceased), Dr. Gary Koopmann (Penn State, retired), Dr. Alan Pierce (University of Boston).

Thesis Advisor and Postgraduate-Scholar Sponsor: Dr. Anne Marie Albanese-Lerner (University of Wisconsin), Scott Crane (General Electric), Dr. Noelle Currey (Currey Acoustics), Brian Dater (Northrup-Grumman), Sergio DeRosa (Post-Doc, University of Naples), Muwali Dzirasa (Johns Hopkins), Jesse Ehnert (Arpeggio Acoustic Consulting), Mark Fowler (SY Technology), Dr.Francesco Franco (Post-Doc, University of Naples), Aaron Graf (General Motors), Dr. Mark Holdhusen (University of Wisconsin Marathon County), Dr. Wayne Johnson (Armstrong State University), Janeen Jones (deceased), Dr. Heungsoeb Kim (post-doc, Hangyang University, Korea), Dr. Nila Montbrun (Post-doc, Universidad Simon Bolivar), David Moon (Ford Motor Company), Keith Oglesby (Ford Motor Company), Dr. Victor Rastelli (Post-doc, Universidad Simon Bolivar), Ryan Rye (Motorala), Dr. William Steven Shepard, Jr. (University of Alabama), Dr. Michael Michaux (University of Southern California), Dr. Manuel Collet (post-doc, CNRS), Dr. Chan Il Park (post-doc, Kangnung National University), Tina Famighetti (Arpeggio Acoustics), Alex Michaud (Cerami & Associates), John Arata, Ken Marek (current PhD student), Nick Earnhart (current PhD student), Ben Beck (current PhD student), Flaviano Tateo (current PhD student), Ellen Skow (current PhD student), Elliott Gruber (Current MS student).

Summary: 11 Ph.D., 22 M.S., 7 Post-Doc

William K. Durfee
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

Harvard University, Cambridge, MA	A.B.	1976	Eng. & Applied Physics
M.I.T., Cambridge, MA	M.S.	1981	Mechanical Eng.
M.I.T., Cambridge, MA	Ph.D.	1985	Mechanical Eng.

Appointments

1976	Laboratory Supervisor, Harvard University.
1976-1978	Project Engineer, Harvard-MIT Rehabilitation Engineering Center.
1978-1985	Research Assistant, Department of Mechanical Engineering, MIT.
1985-1990	Assistant Professor, Department of Mechanical Engineering, MIT.
1986-1988	W. M. Keck Foundation Assistant Professor of Biomedical Eng., Dept. of Mech. Eng., MIT.
1990-1991	Associate Professor, Department of Mechanical Engineering, MIT.
1991-1993	Brit and Alex d'Arbeloff Associate Prof. of Engineering Design, Dept. of Mech. Eng., MIT.
1993-2001	Associate Professor and Director of Design Education, Dept. of Mechanical Eng., University of Minnesota.
2001-present	Professor and Director of Design Education, Dept. of Mechanical Eng., University of Minnesota. Additional appointments to the Graduate Faculty in the Department of Biomedical Engineering, the program in Human Factors and the program in Product Design.

Publications

Five Publications Related to Proposed Project:

1. KA Shorter, GF Kogler, E Loth, WK Durfee, ET Hsiao-Wecksler, A portable powered ankle-foot orthosis for rehabilitation, *J Rehab Res Dev*, 48(4):459-472, 2011.
2. L Tian, DB Kittelson and WK Durfee, Experimental tests and simulations of a 1.5 cc miniature glow-ignition two-stroke engine, *SAE 2010-32-0018, Proceedings of Small Engine Technology Conference*, Linz, Austria, 2010.
3. W Durfee, J Xia, E Hsiao-Wecksler, Tiny hydraulics for powered orthotics, *IEEE International Conference on Rehabilitation Robotics*, 1-6, 2011.
4. Tian L, Kittelson DB, Durfee WK, Miniature HCCI free-piston engine compressor for orthosis application, *Proceedings of the SAE Small Engine Technology Conference*, 2009-32-0176/20097176, 2009.
5. Durfee W, Rivard A, Design and simulation of a pneumatic, stored-energy, hybrid orthosis for gait restoration. *J Biomechanical Eng*, 127(6):1014-1019, 2005.

Five Significant Publications:

1. Durfee, W.K. and P.A. Iaizzo. Rehabilitation and muscle testing. In: *Encyclopedia of Medical Devices and Instrumentation, 2nd ed*. J.G. Webster, ed., Vol 6, pp 62-71, Hoboken, John Wiley & Sons, 2006.
2. Durfee WK, Weinstein SA, Bhatt E, Nagpal A, Carey JR, Design and usability of a home telerehabilitation system to train hand recovery following stroke. *Journal of Medical Devices*, 3(4):041003, 2009.
3. Goldfarb, M, K Korkowski, B Harrold, W Durfee, Preliminary evaluation of a controlled-brake orthosis for FES-aided gait. *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* 11(3):241-248, 2003.
4. Durfee WK, Savard L and Weinstein S, Technical feasibility of remote assessments for rehabilitation. *IEEE Trans. Neural Systems and Rehabilitation Engineering*, 15(1):23-29, 2007.

5. H Deng, WK. Durfee, DJ Nuckley, B Rheude, AE Severson, KM Skluzacek, KK Spindler, C Davey and JR Carey, Complex versus simple ankle movement training in stroke using telerehabilitation: a randomized controlled trial, *Physical Therapy*, 92(2):197-209, 2012.

Synergistic Activities

1. Technical Program Chair and co-founder, annual Design of Medical Devices Conference.
2. Former Education Co-Director, Center for Compact and Efficient Fluid Power (CCEFP), an NSF Engineering Research Center
3. Project co-leader for Test Bed 6, Wearable Fluid Power Devices in the 10 to 100 W Range, a project of the CCEFP and Project co-leader for 2B2; HCCI Engine-Compressor, a project of the CCEFP
4. Work on passive and active exoskeletons for rehabilitation
5. Collaborate with companies on product development, projects with 3M, Micro-Medical Devices, Toro, Aetrium, Augustine Medical, Donaldson, Spinal Designs, Honeywell, Select Comfort, Sulzer Medica, Enhanced Mobility Technologies, Medtronics, EnduraTEC, Machine Magic, Scimed, Sulzer Spine Tech, Andersen Windows, Hormel, Introspective, Geodigm, VivaCare, Comedicus, Hearing Components, Newco, Pando, IMI Visions, Tennant, Devicix, Lake Regent Medical , Best Buy, Graco, Nesos, Boston Scientific and others.

Collaborators & Other Affiliations

(i) Collaborators:

A. Erdman (UMN), P. Iaizzo (UMN), K. LaBat (UMN), E. Bye (UMN), K. Stelson (UMN), P. Li (UMN), C. Adams (UMN), B. Hammer (UMN), T. Ebner (UMN), J. Carey (UMN), D. Kittleson (UMN), E. Stern (UMN), E. Davis (Sister Kenny), T. Rosenthal (Systems Technology), J. Wachtel (Veridian Group), Lars Oddson (Sister Kenny) ("UMN" = University of Minnesota)

(ii) Graduate Advisor:

Dr. Michael J. Rosen, University of Vermont

(iii) Thesis and post-doc advisees in past 5 years:

A. Dittli, L. Tian, J. Xia, R. Dolid, S. Swaminathan, J. Prosise, T. Corrigan, S. Pasalar, D. Waletzko, C. Monnier, D. Bonta, D. Celotta, G. Brahmbhatt, S. Ponkshe, M. Steckler, S. Freeman, K. Vedula, P. Johnson, A. Srivasta, B. Koch, N. Carlson, J. Young, A Kangude, B. Burgstahler, R. Dargus, E. Leingang, K. Braun, M. Waddell, B. Krueger, B. Koch

Total number of advisees: 14 Ph.D., 72 MS, no post-docs

Vito R. Gervasi
Manager, Research & Development
Rapid Prototyping Research
Milwaukee School of Engineering

Professional Preparation

Milwaukee School of Eng	Manufacturing Eng Technology	B.S, 1996
Milwaukee School of Eng	Mechanical Engineering	M.S., 2003

Appointments

1993-present	Manager, Research & Development, Milwaukee School of Engineering
1985-1990	United States Air Force, honorable discharge

Publications

1. Douglas L. Cook, Vito R. Gervasi," High-Performance, Multi-Functional, Fluid-Power Components Using Engineered Materials," International Fluid Power Expo, Las Vegas, NV, March 2011.
2. D. Cook, B. Knier, V. Gervasi and D. Stahl, "Automatic Generation of Strong, Light, Mutli-Functional Structures from FEA Output," Solid Freeform Fabrication Symposium, Austin, Texas, USA, August 2010.
3. Gervasi, Vito R., Douglas Cook, "Reduction Of Complex Objects Into Manufacturable Elements Using The Shell-Slice Approach," Solid Freeform Fabrication Symposium Proceedings, Austin, Texas, August 2009
4. Gervasi, Vito R., Douglas Cook, Robert Rizza, Sheku Kamara, Xue Cheng Liu, "Fabrication of Custom Dynamic Pedorthoses for Clubfoot Correction via Additive-based Technologies," Solid Freeform Fabrication Symposium Proceedings, Austin, Texas, August 2009
5. D.C. Stahl, V.R. Gervasi, "Design and fabrication of components with optimized lattice microstructures," *NSF Design, Service, and Manufacturing Conference Proceedings*, Saint Louis, Missouri, July 2006.
6. Gervasi, Vito R., Adam Schneider, and Joshua Rocholl. 2005. "Geometry and Procedure for Benchmarking SFF and Hybrid Fabrication Process Resolution." Rapid Prototyping Journal 11(1), 4-8. (1st place poster for entire symposium)
7. Gervasi, Vito R., Douglas C. Stahl, "Fluid Power Components with Optimized Stiffness-Weight Ratio," Cooperative Research Network, National Fluid Power Association, closed webcast, April 12, 2006
8. Gervasi, Vito R., "Metalcasting Applications of Additive Fabrication and Rapid Prototyping: Brief Historical Synopsis and Look at Future Opportunities," AFS 109th Casting Congress proceedings, April 16, 2005

Synergistic Activities

Participant in NSF's new Center for Compact and Efficient Fluid Power, started June 2006. Involved primarily in thrust area two, "compactness." 2D Project leader and member of the CCEFP Executive Committee http://www.fperc.org/

Contributes to several sections of Wohler's Annual Rapid Prototyping, Tooling, and Manufacturing State of the Industry Worldwide Progress Report. Sections have included RP academic program overview and Prototype Hard and Soft Tooling update. http://www.wohlersassociates.com/

REU advisor each year of MSOE's three consecutive, NSF-funded, 5, 5, and 3-year programs. He has been involved in all student projects from 1997-2010 at various levels and advised 25 of 130 plus REU students at MSOE. http://www.msoe.edu/reu/

Promotes the activities and education of the Rapid Prototyping Consortium (RPC) industrial membership in areas of Rapid Prototyping and Rapid Tooling. 1)Has educated and trained industrial members and MSOE community on RP related topics at consortium meetings as well as at member locations. 2)Has suggested and arranged numerous RPC guest speakers for monthly meetings. 3)Conducted applied research with consortium membership on numerous RP related projects http://www.rpc.msoe.edu/

Partook in evolving SME's Rapid Prototyping Association (RPA) to the current Rapid Technologies and Additive Manufacturing (RTAM) Community, a significant progression for the education and integration of additive technologies toward the "factory of the future." Chaired one of eight sub-groups formed under RTAM. Currently involved in the RTAM Masters Exam Committee. http://www.sme.org/cgi-bin/communities.pl?/communities/rpa/rpahome.ht m&&&SME&

Co-developed an algorithm to produce 3D models of complex protein molecules from protein databank files. The method combined with new tooling developments have been used to produce the first of a number of low-cost, highly complex educational protein models, such as MHC and the GFP. Also, worked with 3D Molecular Designs, LLC to introduce the very popular WaterKit, and DNA kits. Invented the OMB system currently in use at MSOE producing amino acid models
http://www.rpc.msoe.edu/3dmd/water1.php

Collaborators & Other Affiliations

Collaborators and Co-Editors:

T. Bray, D. Cook, S. John, S. Kamara , S. Kumpaty, E. Durant, P. Michael, M. Kalchev, R. Rizza, D. Stahl, T. Wanke (MSOE); G. Hoffmann (V-tech), T. Herman (3DMD), J. Rocholl (Orbitec), T. Wohler (Wohler's & Associates), G. Hillebrand, M. Mitchell (P&G); T. Herman (3DMD); J. Wellington (SME); B. Israel (Platypus Technologies, LLC), Xue-Cheng Liu (MCW), Mark Abshire (DSM),

Graduate and Postdoctoral Advisors: G. Hoffmann (MSOE)

Elizabeth T. Hsiao-Wecksler
Department of Mechanical Science and Engineering
University of Illinois Urbana-Champaign

<u>Professional Preparation</u>

Cornell University	BS	1987	Mechanical Engineering
Rochester Institute of Technology	MS	1994	Mechanical Engineering
University of California-Berkeley	PhD	2000	Mechanical Engineering
Harvard Medical School & Boston University	Post-doc	2000-2002	Rehabilitation Engineering

<u>Appointments</u>

University of Illinois at Urbana-Champaign
Associate Professor, Dept of Mechanical Science and Engineering, 08/09 – present
Associate Professor, Information Trust Institute, 08/09 – present
Affiliate, Neuroscience Program, 03/11
Affiliate, NSF IGERT Program in Neuroengineering, 5/10
Affiliate, Center on Health, Aging and Disability, 5/08
Affiliate, Center for Autonomous Engineering Systems and Robotics (CAESAR), 11/06
Affiliate, Department of Industrial and Enterprise Systems Engineering, 10/05
Affiliate, Department of Bioengineering, 07/02
Assistant Professor, Dept of Mechanical Science and Engineering, 07/02 – 08/09

Boston University and Harvard Medical School
Post-doctoral Fellow, Integrated Rehabilitation Engineering Program, 04/00 – 6/02

Xerox Corporation, Rochester, New York
Senior Project Engineer, Low Volume Printers and Copiers Division, 07/87 - 08/94

IntelliWheels, Inc., Champaign, Illinois
Co-founder, Scientific Advisory Board member, 05/10 – present

<u>Publications</u> (from 37 peer-reviewed journal articles) *work supported by NSF

Select Related Publications:

1. Li, D.Y., Becker, A., Shorter, K.A., Bretl, T. and Hsiao-Wecksler, E.T. "Estimating System State During Human Walking with a Powered Ankle-Foot Orthosis", *IEEE/ASME Trans Mech*, accepted.*
2. Shorter, K.A., Hsiao-Wecksler, E.T., Kogler, G.F., Loth, E., and Durfee, W.K., "A Portable-Powered-Ankle-Foot-Orthosis for rehabilitation." J Rehab Res Dev, 48(4): 459-472, 2011.*
3. Chin, R., Hsiao-Wecksler, E.T., Loth, E., Kogler, G., Manwaring, S.D., Tyson, S.N., Shorter, K.A., and Gilmer, J.N. "A pneumatic power harvesting ankle-foot orthosis to prevent foot-drop", *J NeuroEng Rehab*, 6:19 (16 June) 2009. *Invited Paper*.*
4. Hsiao-Wecksler, E. T., E. Loth, G. Kogler, K. A. Shorter, J. A. Thomas, and J.N. Gilmer, "Portable Active Pneumatically Powered Ankle-Foot Orthosis", United States Patent Pending (12/898,519).*
5. Shorter, K.A., Xia, J., Hsiao-Wecksler, E.T., Durfee, W.K., Kogler, G.F., "Technologies for Powered Ankle Foot Orthotic Systems: Possibilities and Challenges", *IEEE/ASME Trans Mech*, accepted.*

Select Significant Publications:

1. Chin, R., Hsiao-Wecksler, E.T. and Loth, E. "Fluid Power Produced by Under-Foot Bellows During Human Gait" *ASME Journal of Fluids Engineering,* accepted.*
2. Hsiao-Wecksler, E.T., Polk, J.D., Rosengren, K.S., Sosnoff, J.J., and Hong, S. "A Review of New Analytic Techniques for Quantifying Symmetry in Locomotion". *Symmetry*, 2(2), 1135-1155, 2010; doi:10.3390/sym2021135*
3. DiBerardino III L.A., Polk, J.D., Rosengren, K.S., Spencer-Smith, J.B., Hsiao-Wecksler, E.T. "Quantifying complexity and variability in phase portraits of gait." *Clinical Biomechanics*, 25: 552–556, 2010.*

4. Shorter, K.A, Polk, J.D., Rosengren, K.S., and Hsiao-Wecksler, E.T. "A new approach for detecting asymmetries in gait." *Clinical Biomechanics,* 23(4): 459-467, 2008. doi:10.1016/j.clinbiomech.2007.11.009
5. Riemer, R., and Hsiao-Wecksler, E.T. "Improving joint torque calculations: optimization-based inverse dynamics to reduce the effect of motion errors" *Journal of Biomechanics,* 41(7): 1503-1509, 2008.

Synergistic Activities

- *Course development:* Whole-body Musculoskeletal Biomechanics. Elective senior/first-year grad student lecture course for engineering and advanced kinesiology students that explores the human musculoskeletal system with an emphasis on the whole-body or organism level and introduction to modeling and analysis techniques for examining human movement. It is taught every fall semester since 2003. Human and Robotic Locomotion Seminar: An interdisciplinary graduate seminar course with faculty and labs from Mechanical Engineering, Electrical Engineering, Kinesiology, Psychology, and Anthropology. Students in this course discuss issues and conduct interdisciplinary projects related to human locomotion and motor control using experimental and modeling techniques from biomechanics and robotics. This collaborative effort resulted in a NSF award (#0727083).
- *REU sponsorship:* Since 2002, I have actively included over 50 undergraduate and high school student researchers in my group; some have been in my group for 3-4 years. Nine have been supported with NSF REU funds and involved in specialized REU training programs. Their contributions have been acknowledged through authorship on conference papers, journal articles, and patents.
- *Development of research tools:* Currently conducting projects to develop techniques for (a) quantitatively assessing patterns of motion in dynamic systems with specific interest in analyzing asymmetric gait behaviors (NSF #0727083), and (b) assessing postural responses to impulse perturbations.
- *Service:* Program Chair and Program Chair-elect (2010-2012) for American Society of Biomechanics. Session co-chair and reviewer American Society of Biomechanics conferences since 2003 and International Society of Electromyography and Kinesiology Conference (2004), and symposium organizer for Society of Engineering Science Conference (2007, 2008). Reviewer for 19 journals. Ad-hoc reviewer for NIH – Musculoskeletal Rehabilitation Sciences study section (3/06, 3/09, 6/10), NSF Graduate Research Fellowship Program – Bioengineering panel, NSF – Dynamic Systems Program (ad-hoc reviewer 2007, 5/09, 12/11). NSF SBIR/STTR Emerging Opportunities in Biotechnology Future Topics invited panelist.

Collaborators & Other Affiliations

Collaborators within past 48 months:
Andrew Alleyne, UIUC; Tim Bretl, UIUC; Doug Cook, Milwaukee School of Engineering; Harry Dankowicz, UIUC; William Durfee, UMinnesota; Bo Fernhall, UIUC; Vito Gervasi, Milwaukee School of Engineering; Dominique Griffon, UIUC/Western University; Chris Hass, UFlorida; Sungjin Hong, UIUC; Gavin Horn, UIUC; Zong-Liang Jiang, North Carolina A&T; Geza Kogler, Georgia Tech; Michael Lague, Stockton College; Eric Loth, UIUC; Prashant Mehta, UIUC; Robert Motl, UIUC; Lee Nolan, Karolinska Institute, Sweden; John D. Polk, UIUC; Karl Rosengren, Northwestern; Sirinivasa Salapaka, UIUC; Jacob J. Sosnoff, UIUC; Prashant Mehta, UIUC

Graduate and Postdoctoral Advisors:
Stephen N. Robinovitch, Simon Frasier University
Lewis A. Lipsitz, Harvard Medical School
James J. Collins, Boston University
D. Casey Kerrigan, University of Virginia

Thesis Advisor and Postgraduate-Scholar Sponsor within 5 years: Total graduate students advised: 24; Total post-docs: 1. K. Alex Shorter (MS/PhD), John Jang (MS), Raziel Riemer (PhD), Richard Doyle (PhD), Andrew Bosiljevac (MS), Chantal Imbs Ragetly (PhD), Louis DiBerardino (MS/PhD), Pilwon Hur (PhD), Kiwon Park (PhD), Robin Chin (MS), Jason Thomas (MS), Manak Lal Jain (post-doc), Scott Daigle (MS), Yifan (David) Li (MS/PhD), Emily Morris (MS), Zanxi (Lloyd) An (MS), Michael Socie (MS), Mei-Kuen (Iris) Hsu (MS), Richard Kesler (MS/PhD), Mathew Petrucci (PhD), Morgan Boes (PhD), Doug Wajda (MS)

Current Support

1. UIUC Office of Public Engagement, Inspiring K-12 Students and Local Community to Engage in STEM Activities through Organized Robotics Programs, E. Hsiao-Wecksler (PI), S. Suryadevara, S.Y.Jung, M.S. Kasten, and R. Smith, $11,500, 12/11-12/12 No overlap. No salary support
2. UIUC Office of Public Engagement, Alpha Launch of an Affordable Prosthetic Arm for Upper-Extremity Amputees in GuatemalaAlpha Launch of an Affordable Prosthetic Arm for Upper-Extremity Amputees in Guatemala, E. Hsiao-Wecksler (PI), J. Naber, R. Kesler, and D. Krupa, $10,000, 12/11-12/12 No overlap. No salary support
3. US Dept of Homeland Security, Effect of SCBA Design & Firefighting Induced Fatigue on Balance, Gait and Safety of Movement, G. Horn (PI), E. Hsiao-Wecksler, B. Fernhall, K. Rosengren, R. Motl EMW-2010-FP-01606, $999,569, 8/11-7/14. No overlap. 1 month salary, 2 person month/yr effort
4. NIH, Propulsion Mechanics Variability and Shoulder Pain in Manual Wheelchair Users, J. Sosnoff (PI), E. Hsiao-Wecksler (Co-PI), $392,578. 4/1/11-3/31/13. No overlap. 1 month salary, 2 person month/yr effort
5. National Multiple Sclerosis Society, Acute exercise, spasticity and functional outcomes in MS: differential effects of duration and intensity, J. Sosnoff (PI), E. Hsiao-Wecksler & R. Motl (Co-PIs), RG4333A2/2, $295,673. 4/1/11-3/31/13. No overlap. 1 month salary, 0.3 person month/yr effort
6. National Collegiate Inventors and Innovators Alliance (NCIIA), IntelliWheels: The Continuously Variable Transmission for Manually-propelled Wheelchairs, #7596-10, 9/1/10 -1/31/12, $20,000, E. Hsiao-Wecksler (PI). No overlap. No salary support, 0.2 person month/yr effort
7. NSF, Engineering Research Center for Compact and Efficient Fluid Power, 5/18/06-5/17/14, K. Stelson, University of Minnesota (Director), (direct, Hsiao-Wecksler: Testbed - Fluid power-assisted orthoses), $130K/yr, # 0540834. 0.8 month salary, 2 person month/yr effort

Pending Support

1. Parkinson’s Disease Foundation, Facilitation of gait in Parkinson’s disease using a portable powered ankle-foot orthosis. E. Hsiao-Wecksler (PI), Colum MacKinnon (Co-PI). $165,000. 7/12-6/14. 0.2 month salary, 2 person month/yr effort
2. NSF , REU Site: Research Experiences for Undergraduates in Fluid Power, University of Minnesota, PI: Kim A Stelson, $555,750, 6/1/12 - 5/31/15. No salary support. 0.3 person month/yr effort

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Paul Imbertson
Department of Electrical Engineering
University of Minnesota

Professional Preparation
PhD, 1997, University of Minnesota, Electrical Engineering,
MS, 1994, University of Minnesota, Electrical Engineering,
BS, 1983, University of Minnesota, Electrical Engineering,

Positions

Education Director, Center for Compact and Efficient Fluid Power (CCEFP)	2011-Present
Teaching Professor, Electrical and Computer Engineering, University of Minnesota,	1997-Present
Consultant in Power Electronics and Motor Drives	1988-1997
Electrical Engineer, Power Conversion, Sperry Univac-Unisys Corp.	1983-1988

Professional Activities
Institute of Electrical & Electronic Engineers
American Society for Engineering Education
Faculty Advisor:
- National Society of Black Engineers,
- Innovative Engineers,
- Solar Vehicle Project,
- Kappa Eta Kappa, (Electrical Engineering Fraternity),
- Mad Scientists Club

Closely Related Publications
1. P. Imbertson, A. Sonnenburg, and M. Masoud "Connecting the Dots Between Engineering, Developing Nations, and Inner-City Youth with Sustainable Energy", 2010 ASEE Annual Conference.
2. P. Imbertson, M. Masoud, and A.Sonnenberg, "Energy: Bridging Developing Nations and Inner-City Youth," Minnesota Power Systems Conference (MIPSYCON), 2009.
3. T. Das, P. Imbertson, and N. Mohan, "Collaborative Learning in Laboratory Oriented Courses Using Web Conferencing for Shared Control of Physical Laboratory Experiments," ASEE Annual Conference, 2007.
4. N. Mohan, W. Robbins, P. Imbertson, R. Ayyanar, and B. Oni, "Successes with NSF CCLI-EMD and CLI-ND Grants", Proc. of the 2004 ASEE Annual Conference and Exposition, Salt Lake City, Utah, June, 2004
5. N. Mohan, W. Robbins, P. Imbertson, T. Undeland, R. Panaitescu, A. Kumar Jain, P. Jose, and T. Begalke, "Restructuring of First Courses in Power Electronics and Electric Drives That Integrates Digital Control", IEEE Trans. on Power Electronics, Vol. 18, No. 1, pp. 429-437, Jan. 2003

Other Significant Publications
1. R. Tirumala, P. Imbertson, N. Mohan, C. Henze and R. Bonn, "An Efficient, Low Cost DC-AC Inverter for Photovoltaic Systems with Increased Reliability," IECON 2002
2. P. Imbertson, and N. Mohan, "New Directions in DC-DC Power Conversion Based on Idealized Concepts Leading Ultimately to the Asymmetrical Duty-Cycle Power Converter," IEEE Transactions on Circuits and Systems, Aug 1997.
3. N. Mohan, P. Imbertson, and G. Kamath, "Panel Discussion on Future Trends in Power Electronics: Power Converters," International Power Electronics Conference (IPEC), 1995.
4. P. Imbertson and N. Mohan, "Asymmetrical Duty Cycle Permits Zero Loss Switching in PWM Circuits With No Conduction Loss Penalty," IEEE Transactions on Industry Applications (IEEE/IAS), Jan/Feb 1993.
5. U.S. Patent #5,245,520: Asymmetrical Duty Cycle Power Converter

Synergistic Activities

Senator Amy Klobuchar's Carbon Buster Award, December 2008.
Ten times awarded "Best Professor Award" from IT Student Board.
Most Inspirational Professor Award, Eta Kappa Nu, 2004
Recognized by the University of Minnesota, Board of Regents for contributions to Community-University Partnerships.
Active engagement with Minnesota communities to develop and plan for local energy needs and to heighten energy awareness.
Technical Consultant, "Designing a Clean Energy Future: A Resource Manual" for the Clean Energy Resource Teams (CERTS).
Presenter at numerous NSF-sponsored faculty workshops on Teaching of Power Electronics and Electric Drives, 2003 to present.
Education and curriculum development:

- Developed new undergraduate course "Energy, Environment, and Society".
- Developed new undergraduate course "Alternative Energy in Scandinavia", three week May-term study abroad course to Iceland Norway and Denmark.
- Developed new senior/graduate level course in electrical and computer engineering "Energy Conversion and Storage Technologies: Theory and Applications".
- Developed new cornerstone course "Engineering Basics" for new engineering students.

Prime contributor and initiator of signed Memorandum of Agreement between the Electrical and Computer Engineering Department at the University of Minnesota and the National Engineering University of Nicaragua.
Reach for the Sky: STEM outreach program for the White Earth Indian Reservation.
University on the Prairie, Southwest Research and Outreach Center (SWROC), a unit of the University of Minnesota, Lamberton, MN; 2007 to present.
Technical consultant to University of Minnesota-DOE Solar Decathlon, 2009 competition.
Arranged outreach program to North High School, an inner city minority high school in Minneapolis, MN, involving University members of the National Society of Black Engineers (NSBE).
Developing collaborative outreach/development program uniting a tribal school, an inner-city minority school, and a technical school in Nicaragua to advance STEM education, and personal empowerment using renewable energy projects as a foundation.
Developed the BRIDGE program (Building Resources and Innovative Designs for Global Energy) with the National Society of Black Engineers (NSBE), an international outreach program with activities in Minnesota and Nicaragua, featured in "Inventing Tomorrow" the magazine of the Institute of Technology, University of Minnesota.
Technical consultant to Bakken Museum's Renewable Energy Sculpture garden; 2010, and "Electrifying Minnesota" exhibit; 2007.

Collaborators

Ned Mohan (University of Minnesota), William Robbins (University of Minnesota), Bruce Wollenberg (University of Minnesota), Jeronimo Zeas (National Engineering University of Nicaragua), Stephen Carlson (University of Minnesota), Francisco Gonzales (INATEC, Jinotega, Nicaragua), Angela Osuji (Minneapolis Public Schools), Michael Bunker (White Earth Circle of Life School)

Graduate Advisor

Ned Mohan, University of Minnesota

Graduate Advisees

Kabir Dogubo MSEE, Andrew Johnson MSEE, Ross Terhaar MSEE

Cumulative Totals:

MS advisor – 15
MS member – 2
PhD member - 6

Dr.h.c. Monika Ivantysynova, Ph.D
MAHA Professor Fluid Power Systems
School of Mechanical Engineering & Agricultural and Biological Engineering
Purdue University

Professional Preparation

Slovak Technical University of Bratislava, CZ	Mechanical Engineering	M.S.E.	1979
Slovak Technical University of Bratislava, CZ	Mechanical Engineering	Ph.D.	1983

Appointments

August 2004 – present	Maha Professor Fluid Power Systems, Director Maha Fluid Power Research Center, School of Mechanical Engineering and Agricultural and Biological Engineering, Purdue University
1999 – 2004	Professor Mechatronic Systems, Institute for Aircraft Systems Engineering, Technical University of Hamburg-Harburg, Germany
1996 – 99	Professor Fluid Power and Control, Department of Mechanical Engineering, Duisburg University, Germany
1992 -1996	Senior Researcher and Managing Director of the Institute for Aircraft Systems Engineering at Technical University of Hamburg-Harburg, Germany
1990 -1992	Senior Researcher and Project Manager at the Institute for Machine Design at Technical University of Hamburg-Harburg, Germany
1989 -1990	Project Manager for Mobile Hydraulics, Commercial Hydraulics, Hamburg, Germany
1988– 1990	Assistant Professor, Institute of Robotics, Technical University Bratislava, Czechoslovakia,
1984 – 1988	R & D Project Engineer for design and development of pumps, motors and hydraulic drive systems at ZTS VUHYM in Dubnica, Czechoslovakia
1983 - 1984	Product Development Engineer, Head of Department of Automation Systems at VEB Elektronik Gera, Germany

Awards and Honors

- Doctor Honoris Causa awarded from Slovak Technical University Bratislava, Slovak Republic, on October 20, 2010.
- Joseph Bramah Medal 2009, awarded by the Institution of Mechanical Engineers' (UK) - Mechatronics Informatics and Control Group, for outstanding commitment to international fluid power research and education, particularly in the field of hydrostatic pumps and motors.
- Seed of Success from Provost Dr. Sally Mason , Purdue University for attracting large sponsored programs to Purdue University. January 2007.
- Japan Fluid Power System Society Distinguished Service Award in honor of outstanding contribution to the JFPS International Symposium on Fluid Power on November 10, 2005.

Selected Recent Publications relevant to the Proposed Project

1. Pelosi, M. and Ivantysynova, M. 2012. A Geometric Multigrid Solver for the Piston-Cylinder Interface of Axial Piston Machines. Tribology Transactions, Vol. 55, Issue. 2, pp. 163 - 174.
2. Pelosi, M. and Ivantysynova, M. 2011. Surface Deformation Enables High Pressure Operation of Axial Piston Pumps. ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VI, USA.
3. Schenk, A. and Ivantysynova, M. 2011. An Investigation of the Impact of Elastohydrodynamic Deformation on Power Loss in the Slipper Swashplate Interface. 8th JFPS International Symposium on Fluid Power, Okinawa, Japan.- Best paper award.
4. Pelosi, M. and Ivantysynova, M. 2009. A Novel Thermal Model for the Piston/Cylinder Interface of Piston Machines. Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2782].
5. Ivantysynova, M. 2008. Innovations in Pump Design – What are future directions?. Proceedings of the 7th JFPS International Symposium on Fluid Power, Toyama 2008, pp. 59 -64. Invited lecture organized session agriculture and mining machinery.

Other Significant Publications

1. Zimmerman, J., Hippalgaonkar, R. and Ivantysynova, M. 2011. Optimal Control for the Series-Parallel Displacement Controlled Hybrid Excavator. ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VI, USA. Kumar, R. and Ivantysynova, M. 2009. An Optimal Power Management Strategy for Hydraulic Hybrid Output Coupled Power-Split Transmission. Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2780].
2. Pelosi, M. and Ivantysynova, M. 2011. Surface Deformation Enables High Pressure Operation of Axial Piston Pumps. ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VI, USA.
3. Ivantysynova, M. and Baker, J. 2009. Power Loss in the Lubricating Gap Between Cylinder Block and Valve Plate of Swash Plate Type Axial Piston Machines. International Journal of Fluid Power, Vol. 10, No. 2, pp. 29 - 43.
4. Klop, R. and Ivantysynova, M. 2011. Investigation of Noise Sources on a Series Hybrid Transmission. International Journal of Fluid Power, Vol. 12, No. 3, pp. 17 - 30.
5. Ivantysyn, J. and Ivantysynova, M. 2000. Hydrostatic Pumps and Motors, Principles, Designs, Performance, Modelling, Analysis, Control and Testing. New Delhi. Academia Books International., 512 pages, ISBN 81-85522-16-2.

Synergistic Activities

- Co-founder and member of scientific board of first virtual network in fluid power, the Fluid Power Net International (http://fluid.power.net) 1999 – present
- Member of European Fluid Power Research Centre FPCE, http://www.fpce.net 2002 - 2005
- Executive Committee Member, Thrust and Test Bed Leader, Engineering Research Center for Compact and Efficient Fluid Power (CCEFP), 2006 – present
- Founder and Editor-in-Chief of the International Journal of Fluid Power since 2000
- Developed and taught two new graduate courses in the field of Fluid Power 2005 – present
- Chair of International Engineering Panel for Aalto University Research Assessment Exercise 2009, appointed by Academia of Finland, 2009, Co-chair of the Academic Assessment Panel of PhD Program at University of Agder, Norway, 2009, Chairman Evaluation Panel of Academia of Finland to assess Finish ME Departments, 2007 -2008,
- Scientific expert and member of the Scientific Advisory Board of the Finnish Centre of Excellence (CoE) in Generic Intelligent Machines Research, 2006 – present
- Research proposal review for Natural Sciences and Engineering Research Council of Canada (NSERC), Academy of Finland, Research Council for Natural Sciences and Engineering, German Basic Research Foundation DFG and European Union – 2002 - present
- External Reviewer for Norwegian University of Science and Technology NTNU, Tampere University of Technology, Aalborg University of Denmark and Expert of the Centre of Excellence in Research IHA by the Academy of Finland.
- Member of the International Evaluation Panel, European Research Council Executive Agency, ERC.B.2 - Starting Grant, 2008 - present
- Reviewer for 20 international scientific journals.
- Chair of SAE Fluid Power Committee, 2006 – 2008, vice-chair 2009 – present
- Organizer and Chairman of the Organizing Committee of 1st International FPNI PhD Symposium, Hamburg, Germany, 2000, the 4th FPNI PhD Symposium, Sarasota Florida, 2006 and 6th FPNI PhD Symposium, West Lafayette, IN 2010.

Collaborators and Other Affiliations

(a) Collaborators in last four years:

All PI's of the CCEFP (Kim Stelson, Perry Li and Will Durfee, University of Minnesota, Wayne Book and Richard Salan, Gerogia Tech, Mike Goldfarb and Eric Barth, University of Vanderbuilt, Andrew Alleyne and Eric Loth, University of Illinois, John Lumkes Steve Frankel and Ashlie Martini, Purdue University) P.Aachten (INNAS), Mike Betz (Sauer_Danfoss), Wayne John Book (Georgia Institute of Technology), Richard Burton (University of Saskatchewan), Peter John Chapple (NTNU Norwegian University of Science and Technology), Richard Kimbel (Parker Hannifin), Joe Kovach (Parker-Hannifin), Noah Manring

(University of Missouri), Jean-Charles Mare (INSA Toulouse), Massimo Milani (University of Modena), Takao Nishiumi (National Defense Academy, Japan), Petr Noskievic (Technical University of Ostrava), Roberto Paoluzzi (IMAMOTER - C.N.R), Robert Rahmfeld (Sauer-Danfoss), Jari Rinkinen (Tampere University of Technology), Rudolf Scheidl (University of Linz), Scott Schuh (Bobcat), Jacek S. Stecki (Monash University), John Watton (Cardiff University), J. Weber (TU Dresden), Andrzej Sobzyk (Krakow University), Matti Vilenius (Tampere University of Technology), Howard Zhang (Parker-Hannifin).

(b) Thesis and Dissertation Advisor for Prof. Ivantysynova:
Prof. Paciga (TU Bratislava)

(c) Thesis or Dissertation Advisor in last five years:
Anderson St. Hilaire, Blake Adam Carl, Jonathan Baker, Shekhar Degaonkar, Reece Garret, Andrew Fredrickson, Najoua Jouini, Richard Klop, Kyle Williams, Christopher Wiliamson, Matteo Pelosi, Ganesh Seeniraj, Josh Zimmermann, Rajneesh Kumar, Shinok Lee, Rohit Kumar

Total number of graduate students supervised: 86 Postdoctoral scholars: 6 Undergraduate Research Students: 22

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Steven X. Jiang
Associate Professor
Department of Industrial and Systems Engineering
North Carolina A&T State University

Professional Preparation

East China Institute of Technology	Mechanical Engineering	BS, 1992
Nanjing University of Science & Technology	Manufacturing Engineering	MS, 1998
Clemson University	Industrial Engineering	Ph.D. 2001

Academic/Professional Appointments
Associate professor, Department of Industrial and Systems Engineering, North Carolina A&T State University, 2008-Present
Assistant Professor, Department of Industrial and Systems Engineering, North Carolina A&T State University, 2002-2008

Publications
Publications Most Closely Related to Proposal:
Hughes, K., Jiang, X. (2010), "Using Discrete Event Simulation to Model Excavator Operator Performance", International Journal of Human Factors and Ergonomics in Manufacturing and Service Industries, 20(5), 408-423.

Chung, C.,Jiang, X., Jiang, Z., Udoka, S. (2010), "Using Digital Human Modeling to Predict Operator Performance of a Compact Rescue Crawler", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Lee, A., Jiang, S. (2010), "Assessing Operator Workload for a Fluid Powered Rescue crawler", The journal of Management and Engineering Integration, 3(2), 48-53.

Hughes, K., Jiang, S., Jiang, Z., Park, E., and Mountjoy, D. (2011), "Assessment of Excavator Operator Performance Using an Integrated Human Performance Model", The journal of Management and Engineering Integration, 4(1), 88-98.

Franklin, C., Jiang, Z., Jiang, X. (2011), "Learning Curve Analysis of a Haptic Controller", The journal of Management and Engineering Integration, 4(1), 63-70.

Other Significant Publications:
Hughes, K., Jiang, X., Jiang, Z., Mountjoy, D., Park, E. (2010), "A Preliminary Study of an Integrated Human Performance Model", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Delpish, R., Jiang, X., Park, E. , Udoka, S., Jiang, Z., (2010), "Development of a User-Centered Framework for Rescue Robot Interface Design", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Jenkins, Q., Jiang, X. (2010), "Measuring Trust and Application of Eye Tracking in Human Robotic Interaction", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Liu, Y., Jiang, X., Jiang, Z., Park, E. (2010), "Predicting Backhoe Excavator Operator Performance Using Digital Human Modeling", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Osafo-Yeboah, B., Elton, M., Jiang, X., Book, W., Park, E. (2010), "Usability Evaluation of a Coordinated Excavator Controller with Haptic Feedback", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Jiang, X., Qu, X., Davis, L. (2010) "Using Data Mining to Analyze Patient Discharge Data for an Urban Hospital", Proceedings of the 6th international Conference on data mining, Las Vegas, NV, July 12-15.

Synergistic Activities

- Co-chair of Human Factors and Ergonomics Track, 2007 Industrial Engineering Research Conference (IERC)
- Co-chair of Human Factors and Ergonomics Track, 2008 Industrial Engineering Research Conference (IERC)
- Editorial Board, International Journal of Industrial Ergonomics
- Editorial Board, Journal of Management and Engineering Integration

Collaborators And Other Affiliations

Collaborators Over The Last 48 Months:
Drs. Zongliang Jiang, Eui Park, Udoka Silvanus, NCA&T, CCEFP
Dr. Wayne Book, Georgia Institute of Technology, CCEFP
Drs. Lauren Davis and Salil Desai, NCA&T
Dr. Kevin Taaffe, Clemson University

Graduate and Postdoctoral Advisors:
Dr. Anand Granmopadhye, Clemson University

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
Khaliah Hughes (SAS), Gerald Watson (US Navy), Edem Tetteh (Paine College), Paul Nuschke (Electronic Ink), Porsche Williamson (GE), Ritson Delpish (NCA&T), Yang Liu (NC A&T), Benjamin Osafo-Yeboah (NCA&T), Quaneisha Jenkins (NCA&T), Charlie Chung (Virginia Tech), Antonio Lee (NCA&T)

Total Number of Graduate Students advised: 20

Zongliang Jiang
Department of Industrial and Systems Engineering
North Carolina Agricultural and Technical State University

Professional Preparation

Shanghai Jiao Tong University (China)	Engineering Mechanics	B.S, 1999
North Carolina State University	Computer Science	M.S., 2003
North Carolina State University	Industrial Engineering	Ph.D., 2008

Appointments

2008-present	Assistant Professor, Department of Industrial and Systems Engineering, North Carolina Agricultural and Technical State University (NCAT)
2007-2008	Postdoctoral Associate, Department of Industrial and Manufacturing Systems Engineering, Iowa State University
2003-2007	Research Assistant, Teaching Assistant, Department of Industrial and Systems Engineering, The Ergonomics Laboratory, North Carolina State University

Publications

1. Franklin, C., Z. Jiang, and S. Jiang, "Learning Curve Analysis of a Haptic Controller", *Journal of Management and Engineering Integration*, 4(1): 63-70, 2011.

2. Hughes, K., S. Jiang, Z. Jiang, E. Park, and D. Mountjoy, "Assessment of Excavator Operator Performance Using an Integrated Human Performance Model", *Journal of Management and Engineering Integration*, 4(1): 88-98, 2011.

3. Liu,Y., Z. Jiang., and X. Jiang, "Development of Digital Human Model to Evaluate Excavator Operator Performance", *Journal of Management and Engineering Integration*, 2(2): 67-74, 2009.

4. Shu, Y., Z. Jiang, X. Xu, and G. A. Mirka, "The Effect of a Knee Support on the Biomechanical Response of the Low Back", *Journal of Applied Biomechanics*, 23(4), pp. 275-281, 2007.

5. Jiang, Z., Y. Shu, J. Drum, S. Reid, and G. A. Mirka, "Effects of Age on Muscle Activity and Upper Body Kinematics during a Repetitive Forearm Supination Task", *International Journal of Industrial Ergonomics*, 36(11), pp. 951-957, 2006.

Synergistic Activities

Reviewer for International Journal of Industrial Ergonomics (2007 – Present)

Reviewer for Human Factors (2010 – Present)

Collaborators & Other Affiliations

Collaborators and Co-Editors: E. Codjoe (NCAT), C. Franklin (Nuclear Regulatory Commission), E. Hsiao-Wecksler (UIUC), K. Hughes (SAS), X. Jiang (NCAT), A. Lee (NCAT), Y. Liu (NCAT), G. A. Mirka (Iowa State Univ.), C. Ntuen (NCAT), E. Park (NCAT), B. Ram (NCAT), S. Udoka (NCAT)

Graduate and Post Doctoral Advisors: S-C Fang (NCSU), G. A. Mirka (Iowa State Univ.), C. D. Savage (NCSU).

Thesis Advisor or Postgraduate-Scholar Sponsor: M.S. Students: C. Franklin; Ph.D. Students: Y. Liu, R. Pope-Ford.

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Medhat Khalil
Applied Technology Center
Milwaukee School of Engineering

Professional Preparation

Military Technical College, Cairo, Egypt	Mechanical Engineering	B.S., 1983
Cairo University, Cairo, Egypt	Mechanical Engineering	M.S., 1989
Concordia University, Montreal, Canada	Mechanical Engineering	Ph.D., 2003

Appointments

2005 - Present	Director of Professional Education and Research Development, MSOE
2003 - 2005	Hydraulic System Simulation Software Developer, Power Systems Control and Simulation Department, CAE Inc., Montreal
2003 - 2005	Adjunct Assistant Professor, Dept. of Mechanical and Industrial Engineering, Concordia University, Montreal
2000-2003	Research Assistant, Center of Industrial Control, Department of Mechanical and Industrial Engineering, Concordia University, Montreal
1996-2000	Technical Office and Training Manager, YFHE Co.
1996-2000	Egyptian Agent, Mannesmann Rexroth, Cairo, Egypt
1986-1996	Lecturer, Mechanical Power & Energy Department, Military Technical College, Cairo, Egypt
1983-1986	Maintenance Engineer, Army Vehicles Workshop, Cairo, Egypt

Publications

Journals Refereed Papers:

1. M.K. Bahr Khalil and Don Lopper, “Hydraulic System Protection against Catastrophic Line Failure using Local Safety Valve”, International Journal of Fluid Power, Vol. 9 #2, pp. 35-46, August 2008. Germany.
2. M.K. Bahr Khalil and Shajan John, “IESHYD010V01 - Hydraulic Components Sizing Calculator”, International Journal of Fluid Power, Vol. 8 #3, pp. 65-67, November 2007. Germany.
3. M. K. Bahr Khalil, J. Svoboda and R.B. Bhat, “Modeling of Swash Plate Axial Piston Pumps with Conical Cylinder Blocks”, Journal of Mechanical Design, ASME Transaction, Vol.126, pp 196-200, January 2004, USA.
4. M. K. Bahr Khalil, J. Svoboda and R.B. Bhat, “Dynamic Loads on the Drive Shaft Bearings of Swash Plate Axial Piston Pumps with Conical Cylinder Blocks”, CSME Transaction, Vol.27 #4, pp 309-318, January 2004, Canada.
5. M. K. Bahr, J. Svoboda and R.B. Bhat, “Vibration Analysis of Constant Power Regulated Swash Plate Axial Piston Pumps” Journal of Sound and Vibration, Vol. 259(5), pp1225-1236, January 2003, USA.
6. M.K. Bahr Khalil, V. Yurkevich , J. Svoboda and R. B. Bhat “Implementation of Single Feedback Control Loop For Constant Power Regulated Swash Plate Axial Piston Pumps” International Journal of Fluid Power, Vol. 3 #3, pp27-36, December. 2002, Germany.
7. M. K. Bahr, “Geometrical Analysis of Four-Nozzle Pintle Hydraulic Servovalves”, Engineering Research Bulletin, Vol. 2, pp102-115, 1991, Faculty of Engineering, Mataria, Cairo, Egypt.

Conference Proceedings:

1. M.K. Bahr Khalil, “Design Process of an Electro-Hydraulic Cylinder Position Feedback Control System” 52st National Conference on Fluid Power, International Fluid Power Exhibition, IFPE 2011 Technical Conference, March 2011, Las Vegas, NV., USA.
2. M.K. Bahr Khalil, “Interactive Analysis of Closed Loop Hydraulic Control System”, Proceedings of the Thirteenth International Conference on Aerospace Science & Aviation Technology, ASAT13, May 26 – 28, 2009, Cairo, Egypt.

3. M.K. Bahr Khalil, "Estimated versus Calculated Viscous Friction Coefficient in Spool Valve Modeling" Proceedings of the 51st National Conference on Fluid Power, International Fluid Power Exhibition, IFPE 2008 Technical Conference, March 2008, Las Vegas, NV., USA.
4. M.K. Bahr Khalil, "Innovative Tool for Custom Course Building and Delivery", 11th Annual World Conference on Continuing Engineering Education, May 2008, Atlanta, USA.
5. Khalil, M.K., Deping Li and Bhat, R.B. "Controlling of Rolling Mills Operating Conditions Using Variable Displacement Pump and Electro-Hydraulic Pressure Compensator". 12th International Conference on Applied Mechanics and Mechanical Engineering AMME-12, May 16-18, 2006, Military Technical College, Cairo, Egypt.
6. M. K. Bahr, J. Svoboda and R.B. Bhat, "Experimental Investigation on Swash Plate Axial Piston Pumps with Conical Cylinder Blocks Using Fuzzy Logic Control" International Mechanical Engineering Congress and Exposition ASME-ME2002, November 17-21, 2002, New Orleans, USA.
7. M. K. Bahr, J. Svoboda and R.B. Bhat, "Dynamic Loads on the Drive Shaft Bearings of Swash Plate Axial Piston Pumps with Conical Cylinder Blocks", CSME Forum2002, May 21-24, 2002, Queen's University, Kingston, Canada.
8. M. K. Bahr, J. Svoboda and R.B. Bhat, "Response of Constant Power Regulated Swash Plate Axial Piston Pumps to Harmonic and Random Inputs", International Conference on Multidisciplinary Design in Engineering, CSME-MDE2001, November 21-22, 2001, Concordia University, Montreal, Canada. Winner of the first prize of the student paper competition.
9. S.A. Kassem and M.K. Bahr, "Fuzzy Logic Control of Constant Power Regulated Swash Plate Axial Piston Pumps", International Mechanical Engineering Congress and Exposition ASME-ME2001, November 11-16, 2001, New York, USA.
10. S.A. Kassem and M. K. Bahr, "On the Dynamics of Swash Plate Axial Piston Pumps with Conical Cylinder Blocks", Sixth Triennial International Symposium on Fluid Control Measurement and Visualization Flucome2000, August 13-17, 2000, Sherbrooke University, Sherbrooke, Canada.
11. S.A. Kassem and M. K. Bahr, "Effect of Port Plate Silencing Grooves on Performance of Swash Plate Axial Piston Pumps", 7th Mechanical Design and Production Congress MDP7, Pergamon Press139-148, February 2000, Faculty of Engineering, Cairo University, Cairo, Egypt.

Synergistic Activities

- National Science Foundation Engineering Research Center ERC, Compact and Efficient Fluid Power Engineering Research Center, CCEFP: http://www.ccefp.org/fpcontact.html
- American Society of Mechanical Engineers, ASME. http://www.asme.org/membership/
- Canadian Society of Mechanical Engineers, CSME. http://www.csme-scgm.ca/membership.asp
- SAE fluid power committee, http://www.sae.org/servlets/index
- International Fluid Power Society, IFPS. http://www.ifps.org/Members/index.htm
- NFPA Recognized Industry Consultant, http://www.nfpa.com/OurIndustry/OurInd_AboutFP_IndustryConsultants.asp
- IFPS Certified Hydraulic Specialist, CFPHS, valid through 10/31/2013
- IFPS Certified Accredited Fluid Power Instructor, CFPAI, valid through 08/30/2014
- Introduction To University Teaching ENCS Part-Time Faculty Workshop, Center of teaching and learning services, May2002, Concordia University, Montreal, Canada.
- Hydraulic Training Course. Rexroth-International, July 1996, Lohr, Germany.

Collaborators and Other Affiliations

Collaborators and Co-Editors: None

Graduate and Postdoctoral Advisors:
M.Sc.: S. Kassem (Cairo University)
Ph.D.: R. Bhat (Concordia University)

Thesis Advisor and Postgraduate-Scholar Sponsor: None

William P. King
Department of Mechanical Science and Engineering
University of Illinois Urbana-Champaign

Professional Preparation

University of Dayton	Mechanical Engineering	B.S. 1996
Stanford University	Mechanical Engineering	Ph.D. 2002

Academic/Professional Appointments

Professor, Mechanical Science and Engineering	University of Illinois	2010-present
Associate Professor, Mechanical Science and Engineering	University of Illinois	2006-2010
Assistant Professor, Mechanical Engineering	Georgia Institute of Technology	2002-2006

Publications

Publications Most Closely Related to Proposal

1. Wei, Z., D. Wang, S. Kim, S.-Y. Kim, Y. Hu, M.K. Yakes, A.R. Laracuente, Z. Dai, S.R. Marder, C. Berger, W.P. King, W.A. deHeer, P.E. Sheehan, and E. Riedo, "Nanoscale Tunable Reduction of Graphene Oxide for Graphene Electronics," *Science* 328, 1373-1376, 2010.

2. Lee, W. K., Z. Dai, W. P. King, and P. E. Sheehan, "Maskless Nanoscale Writing of Nanoparticle-Polymer Composites and Nanoparticle Assemblies using Thermal Nanoprobes," *Nano Letters* 10, 129-133, 2010

3. Cannon, A. H., and W. P. King, "Microstructured Metal Molding Tools Fabricated via Investment Casting," *Journal of Micromechanics and Microengineering* 20, 025025, 2010.

4. Lee, J., A. Liao, E. Pop, and W. P. King, “Electrical and Thermal Coupling to a Single-wall Carbon Nanotube Device using an Electro-thermal Nanoprobe,” *Nano Letters*, 0:4, 1356-1361, 2009.

5. Park, K., Z. M. Zhang, and W. P. King, “Experimental Investigation on the Heat Transfer Between a Heated Microcantilever and a Substrate,” *Journal of Heat Transfer,* 130, 102401-1-102401-9, October 2008.

Other Significant Publications

1. Rowland, H. D., W. P. King, J. B. Pethica, and G. L. W. Cross, “Molecular Confinement Accelerates Deformation of Entangled Polymers During Squeeze Flow,” *Science*, 322, 720-724, October 2008.

2. Szoszkiewicz, R., T. Okada, S. C. Jones, T.-D. Li, W. P. King, S. R. Marder, and E. Riedo, “High-Speed, Sub-15 nm Feature Size Thermochemical Nanolithography,” *Nano Letters,* 7, 1064-1069, 2007.

3. Lee, J., T. L. Wright, T. Beecham, B. A. Nelson, S. Graham, W. P. King, “Electrical, Thermal, and Mechanical Characterization of Silicon Microcantilever Heaters,” *Journal of Microelectromechanical Systems*, 15, 1644-1655, 2006.

4. King, W. P., S. Saxena, B. A. Nelson, and B. Weeks, “Nanoscale Thermal Analysis of an Energetic Material,” *Nano Letters,* 6, 2145-2149, 2006.

5. King, W. P., T. W. Kenny, K. E. Goodson, G. L. W. Cross, M. Despont, U. Dürig, H. Rothuizen, G. Binnig, and P. Vettiger, “Atomic Force Microscope Cantilevers for Combined Thermomechanical Data Writing and Reading,” *Applied Physics Letters*, 78, 1300-1302, 2001.

Synergistic Activities

- Co-founder of Hoowaki LLC (www.hoowaki.com), a company based on technology from King's laboratory.

- Founding scientific advisor to Anasys Instruments Inc (www.anasysinstruments.com), a company based on technology from King's laboratory.

- Member, DARPA's Defense Sciences Research Council.

Collaborators And Other Affiliations

Collaborators Over The Last 48 Months:
Paul Sheehan (Naval Research Laboratory); Samuel Graham, Yogendra Joshi, Elisa Riedo (Georgia Institute of Technology); Blake Simmons (Sandia National Labs); Paul Braun, David Cahill, Joe Lyding, Eric Pop, Mark Shannon (University of Illinois Urbana-Champaign); Rob Carpick (U Penn); Jim Deyoreo (LBL Molecular Foundary); Brandon Weeks (Texas Tech).

Graduate and Postdoctoral Advisors:
Kenneth Goodson, Stanford University

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
Current: Bikram Bhatia, Andrew Cannon, Elise Corbin, Zhenting Dai, Jonathan Felts, Patrick Fletcher, Matthew Kasper, Andrew Gardner, Kyle Grosse, Patrick Harrell, Hoe-Joon Kim, Beomjin Kwon, Nicholas Maniscalco, Ryan Maclaren, James Pikul, Natasha Privorotskya, Suhas Somnath. Former: Joseph Charest, Siva Gurrum, Shinyong Eom, Marcus Elisason, Tanya Wright Haberman, Kyoung Joon Kim, Jungchul Lee, Brent Nelson, Keunhan Park, Jessica Remmert, Jun Suk Rho, Harry Rowland, Shubham Saxena, Yan Wu, Fuzheng Yang.

David B. Kittelson
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

University of Minnesota	Mechanical Engineering	B.S.	1964
University of Minnesota	Mechanical Engineering	M.S.	1966
University of Cambridge, England	Chemical Engineering	Ph.D	1972

Appointments

2003-2004	Overseas Fellow, Engineering Department, Cambridge University
2003-present	Frank B. Rowley Professorship in Mechanical Engineering
1996-present	Director, Center for Diesel Research.
1987-2005	Director, Power and Propulsion Division
1985-1986	Overseas Fellow, Engineering Department, Cambridge University
1980-present	Professor, Department of Mechanical Engineering
1976-80	Associate Professor, Department of Mechanical Engineering
1970-76	Assistant Professor, Department of Mechanical Engineering

Publications

1. Tian, Lei, David B. Kittelson, William K. Durfee, 2009. Miniature HCCI Free-Piston Engine Compressor for Orthosis Application, JSAE paper number 20097176.
2. Aichlmayr, H. T. Kittelson, D. B. and Zachariah, M. R., 2003 "Micro-HCCI Combustion: Experimental Characterization and Development of a Detailed Chemical Kinetic Model with Coupled Piston Motion" Combustion and Flame Vol. 135, No. 3, pp. 227-248, 2003.
3. Aichlmayr, H. T., D. B. Kittelson, and M. R. Zachariah, "Miniature Free-Piston Homogeneous Charge Compression Ignition Engine-Compressor Concept-Part I: Performance Estimation and Design Considerations Unique to Small Dimensions," Chemical Engineering Science Vol. 57 No 19, pp. 4161-4171, 2002.
4. Aichlmayr, H. T., D. B. Kittelson, and M. R. Zachariah, "Miniature Free-Piston Homogeneous Charge Compression Ignition Engine-Compressor Concept-Part II: Modeling HCCI Combustion in Small-Scales with Detailed Homogeneous Gas Phase Chemical Kinetics," Chemical Engineering Science Vol. 57 No. 19 pp. 4173-4186, 2002.
5. Franklin, Luke M.; Anil S. Bika; Winthrop F. Watts; and David B. Kittelson, 2010. Comparison of Water and Butanol Based CPCs for Examining Diesel Combustion Aerosols, Aerosol Science and Technology, 44:629–638.
6. Gidney, J.T.; N. Sutton; M.V. Twigg; and D.B. Kittelson; 2010, Exhaust inorganic nanoparticle emissions from internal combustion engines, Internal Combustion Engines: Performance, Fuel Economy and Emissions, Chandos Publishing, Oxford, pp 133 – 146.
7. Gidney, Jeremy T., Martyn V. Twigg, and David B. Kittelson, 2010. Effect of Organometallic Fuel Additives on Nanoparticle Emissions from a Gasoline Passenger Car, Environmental Science and Technology, v 44, n 7, p 2562-2569.
8. Swanson, Jacob and David Kittelson, 2010. Evaluation of thermal denuder and catalytic stripper methods for solid particle measurements, Journal of Aerosol Science, Volume 41, Issue 12, Pages 1113-1122.
9. Swanson, Jacob; Kittelson, David B.; Pui, David Y. H.; Watts, Winthrop, 2010. Alternatives to the gravimetric method for quantification of diesel particulate matter near the lower level of detection, Journal of the Air and Waste Management Association, v 60, n 10, p 1177-1191.
10. Watts, Winthrop F., David D. Gladis, Matthew F, Schumacher, Adam C. Ragatz, and David B. Kittelson, 2010. Evaluation of a Portable Photometer for Estimating Diesel Particulate Matter Concentrations in an Underground Limestone Mine, Ann Occup Hyg 54(5): 566-574.
11. Apple, James, David Gladis, Winthrop Watts, and David Kittelson, 2009. “Measuring Diesel Ash Emissions and Estimating Lube Oil Consumption Using a High Temperature Oxidation Method,” SAE Int. J. Fuels Lubr. 2(1): 850-859, 2009, also SAE paper number 2009-01-1843.

12. Bika, Anil Singh, Luke Franklin, and David Kittelson, 2009. Hydrogen as a Combustion Modifier of Ethanol in Compression Ignition Engines, SAE paper number 09FFL-0209.
13. Boies, Adam, Steven Hankey, David Kittelson, Julian Marshall, Peter Nussbaum, Winthrop Watts, and Elizabeth Wilson, 2009. Reducing Motor Vehicle GHG Emissions in a State that is not California, Environ. Sci. Technol., 2009, 43 (23), pp 8721–8729.
14. Gidney, J T , N Sutton, M V Twigg and D B Kittelson, 2009. Exhaust Inorganic Nanoparticle Emissions From Internal Combustion Engines, in Internal Combustion Engines: Performance, Fuel Economy and Emissions", Chandos Publishing, Oxford, pp 133 – 146.
15. Johnson, Jason P., David B. Kittelson, and Winthrop F. Watts, 2009. The Effect of Federal Fuel Sulfur Regulations on In-Use Fleets: On-Road Heavy-Duty Source Apportionment, Environ. Sci. Technol. 2009, 43, 5358–5364

Synergistic Activities
We maintain and active research program on engine combustion and emissions.

Collaborators and Other Affiliations
Collaborators and Co-Editors: Aichlmayr, H. T., Sandia National Labs; Baltensperger, U., Paul Scherrer Institute; Bischof, Oliver F., TSI, Inc.; Bukowiecki, N., Paul Scherrer Institute; Burtscher, H., Paul Scherrer Institute; Caldow, Robert, TSI, Inc.; Cao, Feng, University of Minnesota; Carter, J., University of Rochester; Collings, Nick, Cambridge University; Couderc, J. Univ. of Rochester; Cox, C., Univ. of Rochester; Dallas, Andrew, Donaldson; Docherty, Kenneth S., UC Riverside; Driscoll, K., University of Rochester; Eberly, S., Univ. of Rochester Elder, A. C., University of Rochester; Finkelstein, J., University of Rochester; Frampton, M., University of Rochester; Gelein, R., University of Rochester; Goersmann, C., Johnson-Matthey; Goodier, S. P., British Petroleum; Grose, M., TSI, Inc.; Hands, Tim, Cambustion, Ltd.; Higgins, K.J., University of Minnesota; Hopke, P. K., Clarkson College; Ische, E. E., University of Minnesota; Jacobson, M. Z., Stanford; Jeong, C-H., University of Rochester; Johnson, J. P., University of Minnesota; Johnson, Tim, TSI, Inc. Jung, Heejung, UC Riverside; Kasper, A., Paul Scherrer Institute; Kim, E., University of Rochester; Kuehn, T.H., University of Minnesota; Kumarathasan, P., University of Rochester; Lawson, D. R., NREL; Lee, D., University of Minnesota; Liu, W., University of Rochester; Liu, Z. Gerald, Fleetguard; Ma, Hongbin ,Cummins; McMurry, P. H., University of Minnesota; Miller, Arthur, NIOSH ; Mirme, Aadu, TSI, Inc. ; Morgan, C. G., Johnson-Matthey. Plc.; Murray, I. P., Johnson-Matthey. Plc.; Ng, Iam Pou, Cummins; Nickolaus, Chris, Cambustion, Ltd.; Niemelä, Ville, Dekati; Oberdörster, G., University of Rochester; Ortiz, M., Corning; Park, Kihong, University of Minnesota; Paul, Schaberg, Sasol; Payne, M. J., British Petroleum; Phipps, R., University of Rochester; Pöcher, Arndt, TSI, Inc.; Premkumari K., University of Rochester; Preston, H., British Petroleum; Ramachandran, G. J., University of Minnesota; Remerowki, M. L., University of Minnesota; Roberts, J.T., University of Minnesota; Rowntree, C. J., British Petroleum; Sakurai, Hiromu, University of Minnesota; Savstrom, J. C., Donaldson Company; Schauer, J., University of Wisconsin; Sem, Gilmore J., TSI, Inc.; Stolzenburg, M. R., Univ. of Minnesota; Swanson, Jacob, Univ. of Minnesota; Swor, Thaddeus, Fleetguard; Tobias, Herbert J., UC Riverside; Twigg, Martyn, Johnson-Matthey, plc.; Utell, M., University of Rochester; Vasys, Victoria N., Fleetguard; Vincent R., University of Rochester; Walker, A. P., Johnson-Matthey; Warrens, C. P., British Petroleum; Watts, W., Univ. of Minnesota; Weingartner, E., Paul Scherrer Institute; Xia, X., Univ. of Rochester; Yang, C.H., University of Minnesota; Zachariah, Michael R.. University of Maryland; Zareba W., Univ. of Rochester; Zarling, Darrick D., University of Minnesota; Zhao, W., University of Rochester; Zhuo, L..University of Rochester; Ziemann, Paul J., UC; Riverside; Zink, U., Corning.

Graduate and Post Doctoral Advisors: M.S. – Edward Fletcher, University of Minnesota
Ph.D. – Alan Hayhurst, Cambridge University

Thesis Advisor and Postgraduate-Scholar Sponsor: (last 5 years) Jason Johnson, TSI Inc.; Jeffrey Campbell, US State Department; Jacob Swanson, UofM; Andy Tan, Cummins; David Hall, Phillips Temro; Brad Dana, MTS; John Dixon, Cummins; Suwandi Iskak, M.S., University of Minnesota; Jason Johnson, M.S. Donaldson; Hamed Kebriaei, M.S. Cummins; Junghwan Kim, M.S., University of Wisconsin; Bamidele Fayemi, M.S., Nigeria; Arthur Miller, Ph.D., NIOSH; Hongbin Ma, Post-doc., Cummins; Jake Savstrom, M.S., Donaldson Co.; Heejung Jung, Ph.D., UC Riverside; Matt Cambio, M.S., ThermoKing;

John Debauche, M.S., ; Thomas Robert, M.S., Thermo-King; Iam Pou Ng, M.S., Cummins; Qiang Wei, Ph.D., Horiba; Hans T. Aichlmayr, Ph.D., Sandia National Labs

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John H. Lumkes Jr.
Associate Professor
Agricultural and Biological Engineering Department
Purdue University

Professional Preparation

Calvin College	Engineering	B.S.E., 1990
University of Michigan-Ann Arbor	Mechanical Engr.	M.S.E, 1992
University of Wisconsin-Madison	Mechanical Engr.	Ph.D., 1997

Academic/Professional Appointments

Associate Professor, Agricultural and Biological Engineering Department Purdue University, West Lafayette, Indiana	2010-present
Assistant Professor, Agricultural and Biological Engineering Department Purdue University, West Lafayette, Indiana	2004-2010
Associate Professor, Mechanical Engineering Department Milwaukee School of Engineering, Milwaukee, Wisconsin.	2001-2004
Assistant Professor, Mechanical Engineering Department Milwaukee School of Engineering, Milwaukee, Wisconsin.	1997-2001

Publications

Publications Most Closely Related to Proposal:

1. Batdorff, M., and Lumkes, J. (2009). High fidelity magnetic equivalent circuit in an axisymmetric electromagnetic actuator. *IEEE Transactions on Magnetics*, 45(8):3064-3072.
2. Garcia, J., Lumkes, J., Heckaman, B., and Martini, A. 2011. Viscosity Dependence of Static Friction in Lubricated Metallic Line Contacts, *Tribology Transactions*, 54: 3, 333 — 340
3. Mahrenholz, J. and Lumkes, J., (2009). Coupled Dynamic Model for a High Speed Pressure Balanced 3-way On/Off Hydraulic Valve. *J. Dyn. Sys., Meas., Control*, 132, 10p.
4. Lumkes, J., Batdorff, M., and Mahrenholz, J. (2009). Characterization of losses in virtually variable displacement pumps. *International Journal of Fluid Power*, 10(3) pp. 17-27.
5. Merrill, K., Holland, M., Batdorff, M., and Lumkes, J. 2010. Comparative Study of Digital Hydraulics and Digital Electronics. *International Journal of Fluid Power*, 11(3) pp. 45-51.

Other Significant Publications:

1. Lumkes, J., Control Strategies for Dynamic Systems, Design and Implementation, Marcel-Dekker Inc., 616 pages, 2002, ISBN: 0—8247—0661—7.
2. Sosnowski, T., Lucier, P., Lumkes, J., Fronczak, F., and Beachley, N. (1998). Pump/motor displacement control using high-speed on/off valves. SAE Transactions, Journal of Commercial Vehicles, 107(2): 153-161.
3. Brauer, J., and Lumkes, J. (2002). Coupled model of a magnetically-actuated valve controlling a hydraulic cylinder and load. IEEE Transactions on Magnetics, 38(2):917-920.
4. Branson, D., Lumkes, J., Wattananithiporn, K., and Fronczak, F. (2008). Simulated and experimental results for a hydraulic actuator controlled by two high-speed on\off solenoid valves. International Journal of Fluid Power, 9(2) pp. 47-56.
5. Lumkes, J. and van Doorn IV, W. (2008). Design and testing of a dual path front hydrostatic drive-by-wire off road vehicle. Transactions of the ASABE, 51(4): 1165-1175.
6. McKinley, C. and Lumkes, J. (2009). Quantitative evaluation of an on-highway trucking fleet to compare #2ULSD and B20 Fuels and their impact on overall fleet. Applied Engineering in Agriculture, Vol. 25(3): 335-346.

Synergistic Activities

Faculty Advisor, PI: CCEFP Outreach and Education projects including the Portable Fluid Power Demonstrator kits, advising REU, RET, and high school students participating in laboratory experiences. Outreach programs have been offered to over 500 pre-college students since 2009 (over 50% of participants have been from under-represented groups).

Faculty Advisor: Cameroon, Africa, African Center for Renewable Energy and Sustainable Technology (ACREST). Organize and advise student design teams focused on renewable energy, food and water, and affordable transportation projects for developing countries. Students from Agricultural and Biological Engineering, Agricultural Systems Management, Chemical Engineering, Mechanical Engineering, and Mechanical Engineering Technology have participated on projects including hydroelectric site analysis and turbine design, low cost wind turbine designs, and the design of basic utility vehicles using parts found locally in western Africa and requiring only basic tools and fabrication skills. Nineteen students have traveled to ACREST at the conclusion of their design projects.

Faculty Advisor: Study abroad class—China: Globalization, the Environment, and Agriculture. Organize and teach a study abroad class for Purdue students for a Maymester travel experience in China. Approximately 20 students participate each offering and travel has included Tibet, Beijing, Xi'an, Chongqing, and Shanghai. Various farms, universities, and factories are visited.

SAE International Professional Society Activities: SAE Fluid Power Committee (2006-2010), SAE Aerospace Program Office (APO) Committee (2003-2006), SAE Aero Design Competition Rules Committee (2003-present), Board of Directors, Position of Vice Chair of Student Activities, Milwaukee Section of SAE (2003-2004), SAE Aero Design and Formula Design faculty advisor (1998-2004), SAE Chapter Faculty Advisor (1998-2004).

Musto, J., Lumkes, J., and Carnell, W., A Freshmen Programming Course for Mechanical Engineers Using Mechatronics Applications, Proceeding of the 2004 American Society for Engineering Education Annual Conference and Exposition, Salt Lake City, UT, June, 2004.

Lumkes. J. (2010). Survey of Three Different Methods of Delivering Engineering Content in Lectures. *J. Educational Technology Systems*, 38(3):349-366.

Collaborators And Other Affiliations

Collaborators Over The Last 48 Months:
Gary Krutz (Professor, ABE Dept. Purdue University)
Monika Ivantysynova (Professor, ABE and ME Dept, Purdue University)
Nancy Denton (Professor, MET, Purdue University)
Ashlie Martini (Asst. Professor, ME, Purdue University)
Klein Ileliji (Assoc. Professor, ABE, Purdue University)
Rabi Mohtar (Director of Global Engineering Programs, Purdue University)
Betty Bugusu (Director of Food Security Technology Center, Purdue University)

Graduate and Postdoctoral Advisors:
Ph.D. Advisor, Frank Fronczak, University of Wisconsin—Madison

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
Mark Batdorf (MSE, PhD), Bill VanDoorn (MSE), Prashant Desai (MSE), RJ Evans (MSMET), Adam Flaugh (PhD), Cody McKinley (MSE), Greg Long (MSE), John Mahrenholz (MSE), John Andruch (MSABE), Jose Garcia (PhD), Michael Holland (PhD), Kyle Merrill (PhD), Lington Sun (MSME), Gabe Wilfong (MSE), Ronald Evans (MSMET), Jingjing Guo (PhD), Shaoping Xiong (PhD)

Ashlie Martini
Assistant Professor
University of California – Merced, School Engineering

Professional Preparation

Northwestern University	Mechanical Engineering	B.S. 1998
Northwestern University	Mechanical Engineering	Ph.D. 2007

Appointments

8/11 – present	Assistant Professor, Engineering, University of California Merced
8/08 – 8/11	Assistant Professor, Mechanical Engineering, Purdue University

Publications

Closely Related to Proposed Project

Garcia J, Lumkes J, Heckaman B and Martini A (2011) "Viscosity dependence of static friction in lubricated metallic line contacts", Tribology Transactions, 54, 333.

Vadakkepatt A and Martini A (2011) "Confined fluid compressibility predicted using molecular dynamics simulation", Tribology International, 44, 330.

Greco A, Martini A, Liu Y-C, Lin C, and Wang QJ (2010) "Rolling Contact Fatigue Performance of Vibro-Mechanical Textured Surfaces", Tribology Transactions, 53, 610.

Martini A and Vadakkepatt A (2010) "Compressibility of Thin Film Lubricants Characterized Using Atomistic Simulation", Tribology Letters, 38, 33-38.

Martini A and Bair S (2010) "The Role of Fragility in EHL Entrapment", Tribology International, 43, 277-282.

Other Significant Publications

Moon R, Martini A, Nairn J, Simonsen J and Youngblood J (2011) "Cellulose Nanomaterials Review: Structure, Properties and Nanocomposites", Chemical Society Review, 40, 3941.

Li Q, Dong Y, Perez D, Martini A and Carpick RW, “Speed dependence of atomic stick-slip friction in optimally matched experiments and molecular dynamics simulations: The role of dynamics vs. energetics,” Physical Review Letters 106 (2011) 126101.

Dong Y, Li Q, Wu J and Martini A, “Friction, slip and structural inhomogeneity of the buried interface,” Modeling and Simulation in Materials Science and Engineering 19 (2011) 065003.

Perez D, Dong Y, Martini A and AF Voter, “On the Rate Theory Description of Atomic Stick-Slip Friction,” Physical Review B 81 (2010) 245415.

Martini A, Roxin A, Wang Q, Snurr RQ and Lichter S (2008) "Molecular Mechanisms of Liquid Slip", Journal of Fluid Mechanics, 600, 257-269.

Synergistic Activities

- Society of Tribologists and Lubrication Engineering, Board of Directors (May 2011-present)
- Society of Tribologists and Lubrication Engineers, Nanotribology Technical Committee: Vice-Chair (2010-present); Secretary/Treasurer (2009-2010); Paper Solicitation Chairperson (2008-2009)
- Technical Editor, Tribology and Lubrication Technology (2009-present)
- ASME/STLE IJTC Conference Planning Committee, Nanotribology Track Chair, Student Poster Track Chair (2008-present)
- STLE Young Tribologists Committee, Originator and Chairperson (2008-2011)

Collaborators and Other Affiliations

Collaborators and Co-Editors

Georgia Tech: S. Bair

Los Alamos National Laboratory: A. F. Voter, D. Perez

Milwaukee School of Engineering: P. Michael

Northwestern University: Prof. S. Lichter

Purdue University: M. Ivantysynova, J. Lumkes, F. Sadegi, J. Youngblood, P. Zavattieri

Southern Illinois University: S. Aouadi

United States Forest Service: R. Moon

University of Wisconsin Milwaukee: E. Tysoe

University of Pennsylvania: R. Carpick, Q. Li

Graduate and Post Doctoral Advisors

Professor Q. Jane Wang, Northwestern University, Department of Mechanical Engineering

Professor Randall Q. Snurr, Northwestern University, Department of Chemical and Biological Engineering

Thesis Advisor and Postgraduate-Scholar Sponsor

Gao, Zhenjia – MS, Mechanical Engineering, 8/2009

Garcia, Jose – PhD, Agricultural and Biological Engineering, 3/2011

Gylfadóttir, Hildur – MS, Mechanical Engineering, 7/2010

Udupa, Anirudh – MS, Mechanical Engineering, 4/2011

Wu, Jianguo – MS, Mechanical Engineering, 4/2011

Brandt, Daniel – Current MS Student

Dong, Yalin – Current PhD Student

Gao, Hongyu – Current PhD Student

Wu, Xiawa – Current PhD Student

Ye, Zhijiang – Current PhD Student

Paul Michael
Research Chemist
Milwaukee School of Engineering
Fluid Power Institute

Professional Preparation

University of Wisconsin, Milwaukee	Chemistry	BS, 1987
Keller Graduate School	Business	MBA, 2001

Academic/Professional Appointments

2005-present	Research Chemist, MSOE Fluid Power Institute, Milwaukee, WI
1987-present	Part-time Faculty, MSOE Fluid Power Institute, Milwaukee, WI
1993-2005	Technical Director, Benz Oil, Milwaukee, WI
1987-1993	Applications Chemist, Benz Oil, Milwaukee, WI

Publications

Publications Most Closely Related to Proposal

Michael, P. Garcia, JM. Bair, S. Devlin, MT, Martini, A. "Lubricant Chemistry and Rheology Effects on Hydraulic Motor Starting Efficiency," Tribology Transactions (in press)

Michael, P. Guevremont,J. K. Devlin, M. and Ziemer, C. "Tribological Film Formation in Hydraulic Motors," Proceedings of the STLE/ASME International Joint Tribology Conference, Paper IJTC2011-61029 (2011)

Burgess, K. Michael, P. Wanke, T. and Ziemer, C. "Starting Efficiency in Hydraulic Motors," Proceedings of the 52nd National Conference on Fluid Power – National Fluid Power Association, Paper NCFP I11-9.1, Las Vegas, NV (2011)

Bair, S. and Michael, P. "Modelling the Pressure and Temperature Dependence of Viscosity and Volume for Hydraulic Fluids," International Journal of Fluid Power, Vol. 11, N 2, pp 37-42 (2010)

Michael, P. Wanke, T. Kimball, A. and Blazel, B. "Atomic Force Microscopy of Geroler Motor Wear Debris Ferrograms," Journal of ASTM International, Vol. 6, N 1, Paper ID JAI101628, (2009)

Other Significant Publications

Michael, P. and Wanke, T. "Hydraulic Fluid and System Standards," Handbook of Hydraulic Fluid Technology, 2nd Edition, G.E. Totten and V.J. De Negri Ed., CRC Press, Boca Raton, (2012)

Michael, P. Blazel, B. Reuchel, R. and Harville, X. "Hydraulic Fluid Compatibility and Filterability," Proceedings of the 52nd National Conference on Fluid Power – National Fluid Power Association, Paper NCFP I11-35.2, Las Vegas, NV (2011)

ASTM D7752 - 11 "Standard Practice for Evaluating Compatibility of Mixtures of Hydraulic Fluids"

Synergistic Activities

Chairman, Hydraulic Fluid Compatibility Section D02.N0.09, ASTM International
Chairman, Fluids Committee, National Fluid Power Association
REU Advisor in 2011, 2010, 2009, 2008 & 2007 (4 of the 5 students were from underrepresented groups)
RET Advisor in 2009 & 2008
Member and Certified Lubrication Specialist, Society of Tribologists and Lubrication Engineers
Technical Editor, "Tribology and Lubrication Technology" (TLT)

Collaborators And Other Affiliations

Collaborators Over The Last 48 Months:

Ashlie Martini, University of California, Merced – Static Friction Studies
Bill King, University of Illinois, Champaign, Urbana – Surface Texturing of Geroler Motors
Eric Dorn, Sauer Danfoss – Hydraulic Motor Research
Gilles LeMaire, Poclain Hydraulics – Hydraulic Motor Research
Jeffery Mordas, MP Filtri – Filtration Research
Jill Tebbe, US Army – Hydraulic Fluid Research
Jose Garcia, Illinois Institute of Technology – Static Friction Studies
Mark Devlin, Afton Chemical – Boundary Lubrication Research
Matt Simon, Parker Hannifin – Geroler Motor Research
Scott Bair, Georgia Tech – High Pressure Rheology
Steve Herzog, Rohmax USA – Hydraulic Fluid Research
Tomasz Young, Exxon-Mobil – Hydraulic Fluid Research

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
Graduate Students:

Kelly Heathcote, General Dynamics
Aaron Kimball, Cobham Mission Systems
Total Number of Graduate Students advised: 2

Undergraduate Research Assistants that have advanced to graduate school: 5

Chelsey Ericson, University of Wisconsin
Dan Schick, University of Wisconsin
Kelsey Whittaker, University of California, Riverside
Michael McCambridge, Arizona State University
Ricardo Rivera Lopez, University of Pittsburgh

Christiaan J.J. Paredis
School of Mechanical Engineering
Georgia Institute of Technology

Professional Preparation

Katholieke Universiteit Leuven (Belgium),	Mechanical Engineering,	B.S./M.S., 10/83-7/88
Université de Liège (Belgium),	Business Administration,	B.S., 10/88-7/89, 10/90-7/91
Carnegie Mellon University,	Electrical and Computer Engineering,	M.S., 8/89-9/90
Carnegie Mellon University,	Electrical and Computer Engineering,	Ph.D., 1/92-8/96

Appointments

7/08 – present	Associate Professor, Georgia Institute of Technology, Mechanical Engineering
8/02 – 6/08	Assistant Professor, Georgia Institute of Technology, Mechanical Engineering
6/98 – 7/02	Research Scientist, Carnegie Mellon University, Inst. for Complex Eng. Systems
8/96 – 5/98	Visiting Research Engineer, Carnegie Mellon University, Inst. Complex Eng. Syst.

Related Publications

1. R.J. Malak, Jr, and C.J.J. Paredis, "Using Support Vector Machines to Formalize the Valid Input Domain of Predictive Models for Systems Design Problems."*Journal of Mechanical Design*, 132(10): 101001 (2010).
2. R.J. Malak, Jr, and C.J.J. Paredis, "Using Parameterized Pareto Sets to Model Design Concepts." *Journal of Mechanical Design*. 132(4) 041007 (2010).
3. Shah, A.A., C.J.J. Paredis, R. Burkhart, and D. Schaefer, "Combining Mathematical Programming and SysML for Component Sizing of Hydraulic Systems." *Proceedings of IDTEC/CIE 2010*, paper no. DETC2010-28960, Montreal, Canada, August 15-18 (2010).
4. A.A. Shah, A.A. Kerzhner, D. Schaefer and C.J.J. Paredis, "Multi-View Modeling to Support Embedded Systems Engineering in SysML." in Gregor Engels, Claus Lewerentz, Wilhelm Schäfer, Andy Schürr, Bernhard Westfechtel (Eds.): *Graph Transformations and Model-Driven Engineering - Essays Dedicated to Manfred Nagl on the Occasion of his 65th Birthday,* LNCS 5765, Springer-Verlag, Berlin/Heidelberg (2010).
5. Kerzhner, A.A. and C.J.J. Paredis, "Model-Based System Verification: A Formal Framework for Relating Analyses, Requirements, and Tests." *Proceedings of the Workshop on Multi-Paradigm Modeling (MPM'10)*, Satellite Event for MODELS'10, Oslo, Norway, October 3 (2010).

Other Significant Publications

1. R.J. Malak Jr. and C.J.J. Paredis, "Modeling Design Concepts under Risk and Uncertainty using Parameterized Efficient Sets," *SAE International Journal of Materials and Manufacturing,* 1(1): 339-352 (2009).
2. R.A. Conigliaro, A.A. Kerzhner, and C.J.J. Paredis, "Model-Based Optimization of a Hydraulic Backhoe using Multi-Attribute Utility Theory," *SAE International Journal of Materials & Manufacturing,* 2(1): 298-309 (2009).
3. R.J. Malak Jr, L. Tucker, and C.J.J. Paredis, "Compositional Modeling of Fluid Power Systems using Predictive Tradeoff Models," *International Journal of Fluid Power*, 10(2): 45-56 (2009).
4. A.A. Kerzhner, and C.J.J. Paredis, "Using Domain Specific Languages to Capture Design Synthesis Knowledge for Model-Based Systems Engineering," in *Proceedings of IDETC/CIE 2009*, paper no. DETC2009-87286, San Diego, CA (2009).
5. C.J.J. Paredis, "An Open-Source Modelica Library of Fluid Power Models," *Bath/ASME Symposium on Fluid Power and Motion Control,* Bath, UK, September 10–12 (2008).

Synergistic Activities

- Past Chair, ASME Computer and Information in Engineering Division; Executive Committee Member since 2002; Chair of the division from July 2007–June 2008; Chair of the 2007 CIE Conference; Program Chair of the 2006 CIE Conference.
- Associate director of the Model-Based Systems Engineering Center at Georgia Tech.
- Member of the Technical Advisory Board, Integrated Model-Centric Engineering Program, Jet Propulsion Laboratory.
- Member of the INCOSE Vision 2025 team, defining the vision for the future of Systems Engineering practice, research and education.
- Chair of the OMG (Object Management Group) Finalization Task Force for the SysML-Modelica Transformation Specification. Lead author of the specification.

Collaborators & Affiliations

Collaborators:
J. Allen (GaTech), A. Alleyne (UIUC), E. Barth (Vanderbilt), W. Book (GaTech), B. Bras (GaTech), T. Bray (MSOE), R. Burkhart (Deere), T. Chase (UMN), K. Cunefare (GaTech), W. Durfee (UMN), S. Ferson (Applied Biomathematics), S. Frankel (UMN), S. Friedenthal (Lockheed Martin), P. Fritzson (Linköping U), V. Gervasi (MSOE), L. Ginzburg (Applied Biomathematics), M. Goldfarb (Vanderbilt), A. Griffin (GaTech), E. Hsiao-Wecksler (UIUC), M. Ivantysynova (Purdue), X. Jiang (NCAT), S. John (MSOE), M. Kaltchev (MSOE), M. Khalil (MSOE), D. Kittelson (UMN), P. Krus (Linköping U), P. Li (UMN), E. Loth (UMN), J. Lumkes (Purdue), S. Mantell (UMN), S. McCary-Henderson (NCAT), D. McDowell (GaTech), L. McGinnis (GaTech), C. McMahon (U Bath, UK), P. Michael (MSOE), F. Mistree (GaTech), L. Mongeau (McGill), D. Mountjoy (NCAT), Z. Mourelatos (Oakland U), E. Park (NCAT), R. Peak (GaTech), G. Poncia (UTRC), D. Rosen (GaTech), M. Ruzzene (GaTech), R. Salant (GaTech), T. Simpson (Penn State), M. Shofner (GaTech), K. Stelson (UMN), S. Udoka (NCAT), J. Van De Ven (UMN), S. Wereley (Purdue), H. Zhu (GaTech).

Graduate Advisor:
Pradeep Khosla (Carnegie Mellon University)

Thesis Advisor & Postgraduate-Scholar Sponsor: 14 MS, 9 PhD, 1 Postdoc
Khaled Al-Ajmi (Riyad Bank, Saudi Arabia), Jason Aughenbaugh (UT, Austin), Morgan Bruns (UT, Austin), Michael Collins (Software Engineering Institute), Antonio Diaz-Calderon (Draper Labs), Sebastian Herzig (GaTech), Soshi Iba (Honda R&D), Jonathan Jobe (OFS), Thomas Johnson (D.R. Cash), Aleksandr Kerzhner (GaTech), Ben Lee (GaTech), Vei-chung Liang (US Patent Office), Jay Ling (U Nebraska, Lincoln), Richard Malak (Texas A&M U), Roxanne Moore (GaTech), Jitesh Panchal (Washington State U), Axel Reichwein (GaTech), Tarun Rathnam (Google), Steven Rekuc (Royalox), Aditya Shah (Deere & Co), Rajarishi Sinha (IC Mechanics), Stephanie Thompson.

Eui H. Park
Department of Industrial and Systems Engineering
North Carolina Agriculture and Technical State University

Professional Preparation

Yonsei University, Korea	Physics	B.S. 1972
Mississippi State University	Industrial Engineering	M.S. 1978
City University	Business Administration	M.B.A. 1980
Mississippi State University	Industrial Engineering	Ph.D. 1983

Appointments

1983 – present	Assistant/Associate/Full Professor, Department of Industrial and Systems Engineering, North Carolina A&T State University
1990 – 2005	Chairperson, Department of Industrial and Systems Engineering, North Carolina A&T State University
1978 – 1982	Senior Engineer, Division of Engineering Computing Systems, Boeing Commercial Airplane Company, Seattle, Washington
1985	Summer Faculty, Information Productions Division, IBM - Charlotte, NC
1983 – present	Consulted with ConVatec, Kaplan, Panel Concepts, Brayton International, Longwood, Guilford County Public Health, Korean Institute of Metals and Machinery, Hyundai, and Korean Management Association.

Publications

1. X. Jiang, B. Osafo-Yeboah, and E. Park, "Using the Callsign Acquisition Test (CAT) to Investigate the Impact of Background Noise, Gender, and Bone vibrator Location on the Intelligibility of Bone-Conducted Speech," International Journal of Industrial Ergonomics, International Journal of Industrial Ergonomics 39, pp. 246-254, (2009).

2. Park, E., J. Park, Celestine Ntuen, Daebum Kim, and Jendall Johnson, "Forecast Driven Simulation Model for Service Quality Improvement of the Emergency Department in the Moses H. Cone Memorial Hospital," The Asian Journal on Quality, Vol 9, No 3.

3. Kim, D. E. Park, Celestine Ntuen, and Younho Seong, "An AGV Dispatching Algorithm with Look-ahead Procedure for a Tandem Multiple-load AGV System," The Journal of Management and Engineering Integration, Winter 2009.

4. Seong, Y., E. Park and H. Lee, "Sensemaking and Human Judgment Under Dynamic Environment," Journal of the Ergonomics Society of Korea, Vol. 25, No.3, pp. 1-12, August 2006.

5. Park, E. & C. Ntuen," A Model for Predicting Human Reliability under Workload and Skill Performance," 2006 INFORMS International Conference, Hong Kong, China, June 2006.

6. Ntuen, C. & E. Park, "Human Performance in Monitoring Linear Automation Behavior," Proceedings of 15th Triennial Congress of the International Ergonomics Association, Seoul, Korea, August 2003.

7. Ntuen, C. & E. Park "Supporting Courses of Action Planning with Intelligent Management of Battle Assets,", Proceedings of Command & Control Symposium, National Defense University, July 2003.

8. Ntuen, C., S. Eastman & E. Park, "CAAD: The Commander's Battle Plan Assistance, Handbook of Human-Computer Interface for Military Application (M. Vassillious & T. Huang), Computer Society Press , Chapter 21, pp.237-257, 2001.

9. Park, E., Q. Jenkins, and X. Jiang, " Measuring Trust of Human Operators in New Generation Rescue Robots," Proceedings of 2008 JFPC International Symposium on Fluid Power, Toyama, Japan, September 2008.

10. Ntuen, C. and E. Park, " Predicting Human Reliability under Workload and Skill," Proceedings of the 10th IFAC Symposium on Information Control Problems in Manufacturing, Seoul, Korea, Aug. 2007

Synergistic Activities
Fellow, Institute of Industrial Engineers, since 2000, Board of Directors, Member, Piedmont Triad Center for Advanced Manufacturing, 1997 – 2005, Director, Manufacturing Initiatives, North Carolina A&T State University, 1989 – 1995, Co-Program Chair, Symposium on Human Interactions with Complex Systems, five times since 1991., Principle Investigator in 22 awarded funded research projects totaling over $7 million in the past eleven years.

Collaborators
Dr. Earl Barnes – School of Industrial & Systems Engineering, Georgia Institute of Technology, Dr. Wayne Book – School of Mechanical Engineering, Georgia Institute of Technology, Dr. Daebuem Kim and Young Park – Kangnam University, Korea, Dr. Xiaochun Jinag, Dr. Celestine Ntuen, Dr. Bala Ram, Dr. Sanjiv Sarin, and Dr. Younho Seong – Industrial & Systems Engineering, North Carolina A&T State University, Dr. Gary Rubloff – Institute of Systems Research, University of Maryland

Graduate Advisors: Drs. Larry Brown and Fazli Rabbi (Mississippi State University); Dr. Joe Tanchoco (Purdue University)

Richard F. Salant

Georgia Institute of Technology

Professional Preparation

M.I.T	Mechanical Engineering	BS 1963
M.I.T.	Mechanical Engineering	MS 1963
M.I.T.	Mechanical Engineering	ScD 1967

Appointments

Georgia Power Distinguished Professor	Georgia Institute of Technology	2001- Present
Professor	Georgia Institute of Technology	1987 - 2001
Manager - Fluid Mechanics & Heat Transfer Dept.	Borg Warner Research Center	1972 - 1987
Associate Professor	M.I.T.	1972
Assistant Professor	M.I.T.	1968 - 1972
Assistant Professor	University of California/Berkeley	1966 - 1968

Most Relevant Publications

Yang, B. and Salant, R. F., "Soft EHL Simulations of U-cup and Step Hydraulic Rod Seals," Journal of Tribology, Vol. 131, pp. 021501 -1 – 021501-7, 2009.

Thatte, A. and Salant, R. F., "Elastohydrodynamic Analysis of an Elastomeric Hydraulic Seal during Fully Transient Operation," Journal of Tribology, Vol. 131, pp. 031501-1 - 031501-11, 2009.

Salant, R. F., Yang, B. and Thatte, A., "Simulation of Hydraulic Seals," Journal of Engineering Tribology, Vol. 224, pp. 865-876, 2010.

Thatte, A. and Salant, R. F. "Visco-Elastohydrodynamic Model of a Hydraulic Rod Seal during Transient Operation," Journal of Tribology, Vol. 132, pp. 041501-1 – 041501-13, 2010.

Yang, B. and Salant, R. F., "EHL Simulation of O-ring and U-cup Hydraulic Seals," Journal of Engineering Tribology, Vol. 225, pp. 603-610, 2011.

Other Significant Publications

Salant, R. F., Maser, N. and Yang, B., "Numerical Model of a Reciprocating Hydraulic Rod Seal," Journal of Tribology, Vol. 129, pp. 91-97, 2007 and STLE/ASME Tribology Conference, San Antonio, pp. Trib-06-1052, 2006.

Yang, B. and Salant, R. F., "Numerical Model of a Reciprocating Rod Seal with a Secondary Lip," Tribology Transactions," Vol. 51, pp. 119-127, 2008 and 62nd Annual Meeting, STLE, 2007.

Rocke, A. H. and Salant, R. F., "Elastohydrodynamic Analysis of a Rotary Lip Seal Using Flow Factors, Tribology Transactions, vol. 48, pp. 308-316, 2005 and 60th Annual Meeting, STLE, 2005.

Shen, D. and Salant, R. F., "A Transient Mixed Lubrication Model of a Rotary Lip Seal with a Rough Shaft," Tribology Transactions, vol. 49, pp. 621-634, 2006 and 61st Annual Meeting, STLE, 2006.

Thatte, A. and Salant, R. F., "Transient EHL Analysis of an Elastomeric Hydraulic Seal," Tribology International, Vol. 42, pp. 1424-1432, 2009.

Synergistic Activities
Associate Editor, Journal of Tribology (1993-1999)

Associate Editor, Tribology Transactions (2010-present)

Member of Editorial Board: J. of Engineering Tribology, 2006-present; Sealing Technology, Elsevier, 1993-present; Mechanika (Lithuania), 2006-present

ASME – Fellow (1990), Henry R. Worthington Medal (1996), Machine Design Award (2003), Mayo D. Hersey Award (2009).

STLE – Fellow (1997), Edmond E. Bisson Award (2000), Frank P. Bussick Award (2002, 2005, 2007).

Collaborators in Last 48 Months
Jia, X. (Tsinghua U.), Wang, Y. (Tsinghua U.), Jung, S. (U. of Stuttgart), Haas, W. (U. of Stuttgart), Flitney, R. (BHR Group), Castleman, L. (Trelleborg).

Graduate Advisor
Tau-Yi Toong, MIT (retired)

Thesis Advisees Over the Last 5 Years*
Shen, D. (Parker); Maser, N. (Pratt and Whitney), Wang, L (Apogee Interactive), Yang, B. (GM), Thatte, A. (GE), Scope, K. (Bettis Nuclear Laboratory), Huang, Y.

Total number of advisees: 22

***** If no affiliation is given, the affiliation is Georgia Tech.

Zongxuan Sun
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

Southeast University, China	Automatic Control	B.S. 1995
University of Illinois at Urbana-Champaign	Mechanical Engineering	M.S. 1998
University of Illinois at Urbana-Champaign	Mechanical Engineering	Ph.D. 2000

Appointments

8/2007 - present	Assistant Professor, Department of Mechanical Engineering, University of Minnesota
11/2006 – 8/2007	Staff Researcher, Research and Development Center, General Motors Corp.
9/2000-10/2006	Senior Researcher, Research and Development Center, General Motors Corp.
7/1999 – 9/2000	Senior Engineer, Western Digital Corp.
8/1996-5/2000	Research Assistant, University of Illinois at Urbana-Champaign

Publications

1. Li, K. and Sun, Z., "Stability Analysis of a Hydraulic Free Piston Engine with HCCI Combustion", Proceedings of the 2011 Dynamic Systems and Control Conference, Arlington, VA, DSCC2011-5983, Nov., 2011.
2. Sadighi, A., Li, K. and Sun, Z., "A Comparative Study of Permanent Magnet Linear Alternator and Hydraulic Free Piston Engines", Proceedings of the 2011 Dynamic Systems and Control Conference, Arlington, VA, DSCC2011-6041, Nov., 2011.
3. Li, K. and Sun, Z., "Modeling and Control of a Hydraulic Free Piston Engine with HCCI Combustion", Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV, pp.567-576, March 2011.
4. Li, K., Santiago, W. and Sun, Z., "Modeling of a Two-Stroke Free-Piston Engine with HCCI Combustion", Proceedings of the 2010 Dynamic Systems and Control Conference, Boston, MA, DSCC2010-4267, September, 2010.
5. Sun, Z., Zhang, Z. and Tsao, T.-C., "Trajectory Tracking and Disturbance Rejection for Linear Time-Varying Systems: Input/Output Representation", Systems and Control Letters, 58, pp.452-460, 2009.
6. Kuo, T., Sun, Z., Eng, J., Brown, B., Najt, P., Kang, J., Chang, C. and Chang, M., "Methods of HCCI and SI Combustion Control for a Direct Injection Internal Combustion Engine", US patent 7,275,514, 2007.
7. Sun, Z. and Kuo, T., "Transient Control of Electro-Hydraulic Fully Flexible Engine Valve Actuation System", IEEE Transactions on Control Systems Technology, Vol. 18, No. 3, May, 2010.
8. Zhang Z. and Sun, Z., "A Novel Internal Model-Based Tracking Control for a Class of Linear Time-Varying Plants", ASME Transactions on Journal of Dynamic Systems, Measurement and Control, Vol. 132, 011004, January, 2010.
9. Sun, Z., "Electro-Hydraulic Fully Flexible Valve Actuation System with Internal Feedback", ASME Transactions on Journal of Dynamic Systems, Measurement and Control, Vol. 131, 024502, 2009.
10. He, X., Durret, R. and Sun, Z., "Late Intake Valve Closing as an Emission Control Strategy at Tie 2 Bin 5 Engine-Out NO_x Level", SAE International Journal of Engines, 1(1), pp.427-443, 2008.

Synergistic Activities

- Guest editor, "Active Automotive Safety Systems", IEEE Control System Magazine, 2010.
- Board member, SAE twin cities section, 2010-2011.
- Session organizer, "HCCI Control", The 2010 SAE World Congress.
- Session organizer, "Engine Control", The 2009 SAE Powertrain and Fluid Systems Conference.
- Advisor for minority undergraduate student, North Star STEM Alliance program, University of Minnesota, 2009.

Collaborators & Other Affiliations

Collaborators and Co-Editors: Shih-Ken Chen, Burak Gecim, Kumar Hebbale, Chi-Kuan Kao (GM), T.-C. Tsao (UCLA), G. Zhu (MSU), David Kittelson, Kim Stelson, Michael Manser, Juergen Konczak (UMN), Sonja Glavaski, Qinghui Yuan, Ben Morris (Eaton)

Graduate Advisors and Postgraduate Sponsors: T.-C. Tsao (UCLA)

Thesis Advisor or Postgraduate-Scholar Sponsor:
Graduate Students: P. Gillella, M. McCuen, Y. Wang, X. Song, C. Wu, A. Zulkefli, V. Gupta, A. Heinzen, W. Santiago, K. Li, Y. Yoon, M. Koester, V. Mallela (UMN)
Total Number of Graduate Students advised: 13

Postdoctoral Fellows: Dr. Z. Zhang, Tsinghua University, Dr. A. Sadighi, University of Minnesota
Total Number of Postdoctoral Scholars Sponsored: 2

Silvanus Johnson Udoka
Department of Industrial and Systems Engineering and Department of Business Administration
North Carolina Agriculture and Technical State University

Professional Preparation

Weber State University	Manufacturing Engineering Technology	B.S., 1982
Oklahoma State University	Industrial Engineering & Management	M.S., 1984
Oklahoma State University	Industrial Engineering & Management	Ph.D., 1989

Appointments

1997 - Present	Associate Professor (Tenured), Department of Industrial & Systems Engineering and Department of Business Administration (Joint Appointment), NC A&T State University.
2000	Summer Faculty Intern, Consilium, An Applied Materials Company, Mountain View, CA.
1999	Summer Faculty Research Fellow, GE Corporate Research and Development, Niskayuna, NY
1992 - 1997	Assistant Professor, Department of Industrial & Systems Engineering and Department of Business Administration (Joint Appointment), NC A&T State University.
1989 - 1992	Assistant Professor, Department of Industrial Engineering, University of Wisconsin-Platteville, Platteville, WI.
1985 - 1989	Instructor of Industrial Engineering & Management Oklahoma State University, Stillwater, OK
1984 - 1985	Distribution Manager, Sunmark Inc., Carrolton, TX

Publications

1. Sanders, J. H. and S. J. Udoka “A Step-Wise Search for Statistical Significance in Establishing a Manufacturing Process Window. “ To be Presented at the FAIM 2007 Conference, Philadelphia, PA, June 17-20, 2006.

2. Huff, Jimmy and S. J. Udoka “Analysis of Peak Picked Detections of Sonar Signals Derived From Simulations of Sonar Beam Intensities.” To be presented at the 2007 Industrial Engineering Conference, Nashville, TN, May 19-23, 2007.

3. Udoka, S. J. “Lean Six Sigma: A Roadmap to Systematic Process Improvement.” Proceedings of the 7th Africa-USA International Conference on Manufacturing Technology” Port Harcourt, Nigeria, July 12-14, 2004.

4. Udoka, S. J. “A Framework for a Confluence of Six-Sigma, Lean Strategies and SCOR.” Proceedings of the 2004 Industrial Engineering Conference (IERC), Houston, TX. May 15-19, 2004.

5. McGee, A. A. and S. J. Udoka, “A Process Model for Interdisciplinary Virtual Teams,” Proceedings of the 2003 Industrial Engineering Research Conference (IERC), Portland, Oregon, May 17-21, 2003.

6. Sanders, J. and S. J. Udoka, “Development of the “Science” of Micro Lithography Glass Grinding & Polishing Using Virtual Manufacturing.” Proceedings of the 13th International Conference one Flexible Automation & Intelligent Manufacturing (FAIM) 2003, Tampa Florida, June 9-11, 2003.

7. Franceschini, Ricardo J., Silvanus J. Udoka, and Frederick Ferguson, “A Rational Standard for Design of Living and Experimental Modules for Sustained Space Habitation.” Proceedings of the 2001 Industrial Engineering Research Conference (IERC), Dallas, TX, May 20-22, 2001.

8. Udoka, S. J., E. H. Park and C. A. Ntuen "Adaptations of Virtual Reality and Augmented Reality to Manufacturing Applications: Implications for Developing Economies." Proceedings of the 5[Th] Africa-USA Conference on Manufacturing Technology, Abuja, Nigeria, July 10-14, pp. 38-45, 2000.

Synergistic Activities

"*A Framework for Optimizing Manufacturing Task Performance Utilizing a Virtual Environment."* Doctoral Dissertation under my supervision (Janet H. Sanders, Ph.D. Candidate)

"Mixed Reality Development in a Scalable Visualization Environment." A Project funded under Title III Grant for Ph. D. student development.

Interdisciplinary Learning, Discovery and Engagement of Students through Integrated Virtual Team Projects: The Interdisciplinary Virtual Team (IVT) Project was initiated and implemented starting in the 2002-2005 academic year and is ongoing in my courses in the Department of Industrial and Systems Engineering in cooperation with Dr. Chi Anyansi-Archibong in courses in the Department of Business Administration.

Collaborators and Other Affiliations

Collaborators:
Dr. Marc Goetschalckx – Georgia Institute of Technology, Dr. Paul Stanfield – North Carolina A&T State University

Graduate Advisors:
Dr. John W. Nazemetz – Oklahoma State University, Dr. Allen C. Schuermann – Oklahoma State University, Dr. David E. Mandeville – Oklahoma State University

Graduate Students Supervised (As Chair) For Thesis Or Project:
Kula Bwamba – Masters Project (Completed May 1997), Charles Ehule – Masters Project (Completed April 1998), Ricardo Franceschini – Masters Thesis (Completed July 2000), Aquaris Moore - Masters Thesis (Completed June 2000), Kristin E. Bell - Masters Thesis (CompletedJune 2001), Alecia A. McGee – Masters Project (Completed - May 2003), Nicole Champion – Masters Project (Completed July 2004), Janet Sanders – Ph. D. Dissertation (Completed July 2007), Jimmy Huff - Ph. D. Dissertation (In Progress)

Jun Ueda
Georgia Institute of Technology

Professional Preparation

Kyoto University, Japan	Mechanical Engineering	B.S.,	1994
Kyoto University, Japan	Mechanical Engineering	M.S.,	1996
Kyoto University, Japan	Mechanical Engineering	Ph.D.,	2002

Appointments
2008-Present Assistant Professor, Mechanical Engineering, Georgia Institute of Technology
2010-Present Adjunct Faculty, Applied Physiology, Georgia Institute of Technology
2006 Lecturer, Mechanical Engineering, Massachusetts Institute of Technology
2005-2008 Visiting Scholar, Mechanical Engineering, Massachusetts Institute of Technology
2002-2008 Assistant Professor, Information Science, Nara Institute of Science and Technology, Japan
1996-2000 Senior Research Scientist, Advanced Technology R&D Center, Mitsubishi Electric Corporation

Publications

(i) Five publications most closely related to the proposed project

1. Schultz, J. and Ueda, J., "Analysis of antagonist stiffness for nested compliant mechanisms in agonist-antagonist arrangements," *the 2011 ASME Dynamic Systems and Control Conference* (DSCC'11).
2. MacNair, D. and Ueda, J. David MacNair and Jun Ueda, "A Fingerprint Method for Variability and Robustness Analysis of Stochastically Controlled Cellular Actuator Arrays," *The International Journal of Robotics Research*, Volume 30, Issue 5, pp. 536 - 555, April 2011.
3. Ueda, J.; Ming, D.; Krishnamoorthy, V.; Shinohara, M.; Ogasawara, T. "Individual Muscle Control Using an Exoskeleton Robot for Muscle Function Testing," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol.18, no.4, pp.339-350, Aug. 2010.
4. Ueda, J.,Secord,T., Asada,H. "Large Effective Strain Piezoelectric Actuators Using Nested Cellular Architecture with Exponential Strain Amplification Mechanisms", *IEEE/ASME Transactions on Mechatronics,* Vol. 15, No. 5, pp. 770-782, 2010.
5. Ueda, J., Yoshikawa, T., "Force Reflecting Bilateral Teleoperation with Time Delay By Signal Filtering," *IEEE Transactions on Robotics and Automation*, Vol. 20, No. 3, pp.613- 619, June, 2004.

(ii) Five other significant publications

1. Schultz J.and Ueda, J. "Experimental Verification of Discrete Switching Vibration Suppression," *IEEE/ASME Transactions on Mechatronics*, *in Press*.
2. Ueda, J., Kondo, M., Ogasawara, T " The Multifingered NAIST-Hand System for Robot In-hand Manipulation," *Mechanism and Machine Theory*, Volume 45, Issue 2, Pages 224-238*,* February 2010.
3. Ueda, J., Odhner, Asada, L., H. Harry, "Broadcast Feedback of Stochastic Cellular Actuators Inspired by Biological Muscle Control," *The International Journal of Robotics Research*, Volume 26, Issue 11-12, pp. 1251--1265, November-December 2007.
4. Ueda, J.,, Ikeda, A., Ogasawara, T., "Grip-force Control of an Elastic Object by Vision-based Slip Margin Feedback during the Incipient Slip", *IEEE Transactions on Robotics*, Vol.21, Issue 6, pp.1139- 1147, December, 2005.
5. Ueda, J., Yoshikawa, T., "Mode Shape Compensator for Improving Robustness of Manipulator Mounted on Flexible Base", *IEEE Transactions on Robotics and Automation*, Vol. 20, No. 2, pp. 256- 268, April, 2004.

Synergistic Activities

1. Early Academic Career Award in Robotics and Automation from IEEE Robotics and Automation Society, for fundamental contributions to robust control of robot dynamics including time-delayed telerobotics, flexible robots, cellular actuator devices, and rehabilitation robots May 2009
2. Associate Editor for *IEEE/ASME Transactions on Mechatronics* April 2008 –Present
3. Associate Editor and Committee Member for *2011 IEEE International Conference on Robotics and Automation* (ICRA 2011), *the 2010 IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics* (BioRob 2010), *2010 Robotics Science and Systems Conference* (RSS 2010), *2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics* (AIM 2009), and *ASME Dynamic Systems and Control Conference* (DSCC 2009, 2010, 2011, 2012).
   a. Organized a panel discussion session on Mechatronics for Biosystems and Healthcare at AIM 2009
   b. Organized a workshop on Biologically Inspired Actuation with Dr. Stefanini at ICRA 2011
   c. Organizes a workshop on Biosystems and Healthcare at DSCC 2011
   d. Serves as Students and Young Members Chair for DSCC 2012
4. Best Automation Paper Finalist *at the 2008 IEEE International Conference on Robotics and Automation* (ICRA 2008) May 2008
5. Training Faculty, National Institute of Child Health & Human Development, "Training Movement Scientists: Focus on Prosthetics and Orthotics" (1T32 HD055180-01A1) at the School of Applied Physiology, Georgia Institute of Technology Feb 2010-Present

Collaborators & Other Affiliations

(i) Collaborators and Co-Editors

Shinohara, M., (Applied Physiology, Georgia Institute of Technology), Kogler, G.(Applied Physiology, Georgia Institute of Technology), Stilman, M (Interactive Computing, Georgia Institute of Technology), Christensen, H. (Interactive Computing, Georgia Institute of Technology), Book, W. (Mechanical Engineering, Georgia Institute of Technology), Krishnamoorthy, V.(Emory University), Webster, R.(Vanderbilt University), Barth, E. (Vanderbilt University), Asada, H. (Massachusetts Institute of Technology), Ogasawara, T. (Nara Institute of Science and Technology, Japan), Takemura, H.(Tokyo University of Science, Japan), Kurita, Y.(Hiroshima University, Japan), Haga, N. (University of Tokyo Hospital, Japan), Burdet, E. (Imperial College, London, UK); Gennisson, J. (ESPCI ParisTech, France); Kaneko M (Osaka University, Japan); Mihailidis, A. (University of Toronto), Gao, D. (General Motors), Stefanini , C. (Biomedical Engineering, Scuola Superiore Sant'Anna, Italy).

(ii) Graduate and Postdoctoral Advisors

Graduate advisor: Yoshikawa, T., Ritsumeikan University, Japan (formally Kyoto University)
Postdoctoral Advisor: Asada, H. Mechanical Engineering, Massachusetts Institute of Technology

(iii) Thesis Advisor and Postgraduate-Scholar Sponsor

Graduate thesis advisor:
Joshua Schultz, Ph.D. Candidate, Mechanical Engineering, Georgia Institute of Technology
David MacNair, Ph.D. Candidate, Robotics Ph.D. Program, Georgia Institute of Technology
Billy Gallagher, Ph.D. Candidate, Robotics Ph.D. Program, Georgia Institute of Technology
Melih Turkseven, Ph.D. Student, Mechanical Engineering, Georgia Institute of Technology
Gregory Henderson, M.S. Student, Mechanical Engineering, Georgia Institute of Technology
Timothy McPherson, M.S. Student, Mechanical Engineering, Georgia Institute of Technology
Ellenor Brown, Ph.D. Student, Applied Physiology, Georgia Institute of Technology

Postdoctoral scholar:

Dr. Yuichi Kurita, Assistant Professor of Nara Institute of Science and Technology, Japan
Dr. Ding Ming, Postdoctoral Fellow, the Science University of Tokyo, Japan

Robert J. Webster III
Department of Mechanical Engineering
Vanderbilt University

Professional Preparation

Clemson University	Electrical Engineering	B.S., 2002
John Hopkins University	Mechanical Engineering	M.S., 2004
John Hopkins University	Mechanical Engineering	Ph.D., 2007

Appointments
2008 – Present Assistant Professor in Mechanical Engineering, Vanderbilt University

Publications
1. E. M. Boctor, M. A. Choti, E. C. Burdette, and R. J. Webster III. Three-dimensional ultrasound-guided robotic needle placement: An experimental evaluation. International Journal of Medical Robotics and Computer Assisted Surgery, 4(2):180–191, 2008.

2. R. J. Webster III, J. M. Romano, and N. J. Cowan. Mechanics of precurved-tube continuum robots. IEEE Transactions on Robotics, 25(1):67–78, 2009.

3. R. J. Webster III, T. E. Murphy, L. N. Verner, and A. M. Okamura. A novel twodimensional tactile slip display: Design, kinematics and perceptual experiments. ACM Transactions on Applied Perception, 2(2):150–165, 2005.

4. R. J. Webster III. Object capture with a camera-mobile robot system: An introductory robotics project. IEEE Robotics and Automation Magazine, 13(1):85–88, March 2006.

5. R. J. Webster III, N. J. Cowan, G. S. Chirikjian, and A. M. Okamura. Nonholonomic modeling of needle steering. International Journal of Robotics Research, 25(5/6):509–526, May/June 2006.

Other Publications
1. R. A. Lathrop, T. T. Cheng, and R. J. Webster III. Laparoscopic image guidance via conoscopic holography. ASME Journal of Medical Devices, 57(6), 1497-1506, 2010.

2. D. C. Rucker and R. J. Webster III. Parsimonious evaluation of concentric-tube continuum robot equilibrium conformation. IEEE Transactions on Biomedical Engineering Letters, 56(9), 2308-2311, 2009.

3. P. Valdastri, R. J. Webster III, C. Quaglia, M. Quirini, A. Menciassi, and P. Dario. A new mechanism for meso-scale legged locomotion in compliant tubular environments. IEEE Transactions on Robotics, 25(5), 1047-1057, 2009.

4. D. C. Rucker, B. A. Jones, and R. J. Webster III. A Geometrically Exact Model for Externally Loaded Concentric Tube Continuum Robots. IEEE Transactions on Robotics, 26(5), 769-780, 2010.

5. E. M. Boctor, R. J. Webster III, H. Mathieu, A. M. Okamura, and G. Fichtinger. Virtual remote center of motion control for needle placement robots. Journal of Computer Assisted Surgery, 9(5):175–183, 2004.

Synergistic Activities
ASME Dynamic Systems and Controls Division, Robotics Technical Committee, SPIE Medical Imaging Program Committee.

Reviewer for Journals: IEEE Transactions on Robotics, IEEE/ASME Transactions on Mechatronics, IEEE Sensors, Robotica, Applied Bionics and Biomechanics, The International Journal of Robotics Research.

Reviewer for Conferences: IEEE International Conference on Robotics and Automation, IEEE/RSJ International Conference on Intelligent Robots and Systems, Medical Image Computing and Computer Assisted Intervention,

Best Poster, ASME Design of Medical Devices Conference 2009, Best Paper Finalist at IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, 2006.

Recent seminars at given at: Duke University, Carnegie Mellon University, University of Georgia, Scuola Superiore Sant'Anna, and Johns Hopkins University.

Collaborators and Other Affiliations

Recent Collaborators – Michael Goldfarb (Vanderbilt University), Gabor Fichtinger (Queens University), Pietro Valdastri (Vanderbilt University), Brian Jones (Mississippi State University), Emad Boctor (Johns Hopkins University), Robert Labadie (Vanderbilt University), J. Michael Fitzpatrick (Vanderbilt University), Robert Galloway (Vanderbilt University), Ron Alterovitz (University of North Carolina), Clif Burdette (Acoustic MedSystems, Inc.).

Graduate Advisors – Allison Okamura and Noah Cowan (Co-Advisors, Johns Hopkins University).

Advisees – Ph.D. Primary Adviser (7): D. Caleb Rucker (2011), Ray Lathrop (expected 2012), Jenna Gorlewicz (expected 2013), Louis Kratchman (expected 2014), Philip Swaney (expected 2015), Hunter Gilbert (expected 2015), Richard Hendrick (expected 2016).

Advisees – Ph.D. Co-Adviser (1): Jadav Das (2010).

Advisees – M.S. Primary Adviser (2): Diana Cardona (expected 2011), Byron Smith (expected 2011).

Lisa J. Wissbaum
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

University of Minnesota	College of Liberal Arts	B.I.S., 2001
University of Minnesota	Humphrey Institutute of Public Affairs	MPA, 2008

Appointments

2009-present	Administrative Director, NSF Engineering Research Center for Compact and Efficient Fluid Power
2008-2009	Executive Office and Administrative Specialist, IPrime - Chemical Engineering Department, Univ. of Minnesota
2006-2008	Administrative Fellow, NSF IGERT, Dept. of Mechanical Engineering, Univ. of Minnesota
1985-2006	Travel Manager, Account Manager, Travel Agent - TravelCorp, Minnesota

Publications

Anders, Deena, J. Burza, C. Coslin, P Kresser, E. Messiou, S. Nelson-Salcedo, A. Morris, M. Pidduck, K. Sharpe, K. Sowards, L. Wissbaum, "Immigration Policy and Law in the Post-9/11 Era: A study of Civil and Human Rights Concerns," published in *Law Enforcement Executive FORUM, 2007 7(7), p.33.*

Synergistic Activities

- Candidate for Department Administrator, University of Minnesota, Sponsored Projects Administration Spectrum Program. Completion expected in 2013
- Member of Project and Change Management Collaborators Group, University of Minnesota, since 2011.
- Certificate candidate for Project Management; University of Minnesota, College of Continuing Education (CCE), Completion expected in 2013.
- Supervisory training through University of Minnesota, Office of Human Resources (OHR) through the Office Organizational Effectiveness, completed November 2011
- Certificate in Travel management (CTC), 1998

Collaborators & Other Affiliations

Graduate Advisors: Hubert Humphrey Institute of Public, advisors, G. Edward Schuh, Gary DeCramer.

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Data Management Plan

This document presents the plan followed by the CCEFP ERC in the management of data generated by the activities of the award. It specifies the tools used to ensure that all data relevant to reporting are stored in the system. It also details the types of repositories required for dissemination of the data generated by the Center and its partners in the conduct of the program.

Expected Types of data

Research results of every project have a variety of different formats for raw data. There is no general rule to justify raw data formats. These data will be stored locally and every project leader needs to have access to raw data for generating higher level of data that will be stored in the CCEFP Project Center. They are expected to be in the form of spreadsheets, presentations, images and rich-text documents. Final project review presentations representing ERC outcomes are saved on our secure website.

Format and Content Standards

To manage data generated in the CCEFP, we have designed a web-based reporting system for record keeping.

The web-based reporting system at www.ccefp.net is designed to a) track all research and education activities, b) provide a means for project review, and c) foster data dissemination among the collaborating scientists, students and affiliated personnel. The system is based on a data schema developed by the ERC Administrative Directors' Data Collection Workshop. This system is built on Drupal, an open-source system that allows a network of ERC centers to easily develop and implement new reporting and management features, and thus make a wide range of data available to stakeholders.

Additional information includes the following:

1. Personal reporting information - (publications, courses, meetings outreach events, etc. -used in Table 1 of Annual Report)
2. Personnel information (includes faculty, staff, consultants, and temporary employees)
3. Students and alumni (includes a history of CCEFP fellowships, stipends, employment and gender/minority /disabled status)
4. Industrial memberships (includes a history, level and length of membership along with notes and documentation)
5. Invention disclosures, patents and licenses
6. Donations, technology transfer or translational research support
7. Capital equipment and assets (purchased and donated) - under development
8. Financial records
9. Base award, amendments, supplemental awards, associated awards from other agencies
10. Inventories (e.g., CCEFP computer hardware and software, licensing agreements)
11. Records of research, educational outreach and industrial activities necessary for CCEFP performance evaluation.

Access and Sharing

All research data generated in the course of conducting the projects of the CCEFP will be stored locally by the organization that generates the data. Each organization will be responsible for protecting the data in accordance with the governing university standards and the center's bylaws. As all universities retain rights to data and other intellectual property generated in the course of its research (in accordance with the Bayh-Dole Act), each participant has the obligation to protect such data and share it with other participants and stakeholders formally and informally during presentations throughout the year, and formally annually via a written report to our sponsors, and in accordance with the center by-laws.

The reporting system has a built-in data repository used for annual reports. Access to data is secured by user name and password. There are four levels of user access: confirmed participant, PI, site content manager, and site technical admin. Site access is provided to basic users, known as confirmed participants, by the site technical admin users and is limited to administrative tasks (create, delete, and update their own data only). PIs have access to these same administrative tasks, but they can also delete and update data for those students who are working on their projects, and have limited access to students' profiles. The site content manager has access to view and edit fields. The site technical admin is the only level that has access to the full Administration Menu, where changes to the layout of the site itself can be made. A choice few individuals on the Administrative team at CCEFP headquarters have been granted Site Technical Admin access.

Period of Retention

All data generated by the Center are retained for a period of no less than five years beyond the end date of the award.

Data Storage and Preservation

Each participating institution is responsible for their own data storage and preservation in accordance with their own university's policies and standards.

The CCEFP Project Center serves as a central repository for the data necessary to be shared among participants for ongoing project activities. The data is maintained in a secure MySQL database provided by CCEFP's web hosting service. The database is backed up to a local archive once a day, and to a second remote server once a week. Additionally, DBeck Creative (the website's development firm) creates and archives a snapshot of the entire server once a month during routine maintenance.

CCEFP headquarters houses research project and administrative information throughout the year. This data is housed on a secure server on the University of Minnesota campus, and backups are completed daily. An identical hard drive of data is stored off-site and swapped out for a fresh backup on a regular basis.

Current and Pending Support

Investigator: Andrew Alleyne	Other agencies to which this proposal has been/will be submitted: NONE

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support
Project/Proposal Title: Engineering Research Center for Compact and Efficient Fluid Power
Source of Support: University of Minnesota (NSF)
Total Award Amount: $2,079,944 Total Award Period Covered: 6/1/06-5/31/12
Location of Project: University of Illinois at Urbana-Champaign
Person-Months Per Year Committed to the Project. Cal: 1.00 Acad: 0.00 Sumr: 0.00

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support
Project/Proposal Title: Dynamic Simulation of Transport Refrigerations Baseline Model
Source of Support: ThermoKing
Total Award Amount: $413,872 Total Award Period Covered: 1/1/07-8/15/13
Location of Project: University of Illinois at Urbana-Champaign
Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.50

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support
Project/Proposal Title: NSEC: Center for Nano-Chemical-Electrical-Mehcanical Manufacturing Systems
Source of Support: NSF
Total Award Amount: $229,204 Total Award Period Covered: 10/1/08-9/30/13
Location of Project: University of Illinois at Urbana-Champaign
Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support
Project/Proposal Title: Customized Load-Bearing Scaffolds Using Multiscale Porosity and Multi-Material Domains (Co-PI)
Source of Support: NSF
Total Award Amount: $437,576 Total Award Period Covered: 8/1/09-7/31/12
Location of Project: University of Illinois at Urbana-Champaign
Person-Months Per Year Committed to the Project. Cal: 0.20 Acad: 0.00 Sumr: 0.00

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support
Project/Proposal Title: Workshop on Building Systems Champaign-Urbana Illinois May 2010
Source of Support: NSF
Total Award Amount: $49,000 Total Award Period Covered: 3/15/10-2/29/12
Location of Project: University of Illinois at Urbana-Champaign
Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

Current and Pending Support

Investigator: Andrew Alleyne	Other agencies to which this proposal has been/will be submitted: NONE

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support
Project/Proposal Title: IPower
Source of Support: Technical University of Denmark
Total Award Amount: $105,690 Total Award Period Covered: 2/1/11-7/1/16
Location of Project: University of Illinois at Urbana-Champaign
Person-Months Per Year Committed to the Project. Cal: 1.00 Acad: 0.00 Sumr: 0.00

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support
Project/Proposal Title: Thermodynamics Based Optimization and Control of Vapor Compression Cycle Systems
Source of Support: University of Dayton (Research Institute)
Total Award Amount: $75,424.00 Total Award Period Covered: 8/16/11-8/15/13
Location of Project: University of Illinois at Urbana-Champaign
Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.50

Support: [X] Current [ ] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support
Project/Proposal Title: Header Height Control - GPS Based Feedforward Augmentation
Source of Support: John Deere & Co.
Total Award Amount: $50,000 Total Award Period Covered: 9/1/11-8/31/12
Location of Project: University of Illinois at Urbana-Champaign
Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

Support: [ ] Current [X] Pending [ ] Submission Planned in Near Future [ ] *Transfer of Support
Project/Proposal Title: SBIR Phase II: Dynamic Vapor Compression Cycle Modeling and Simulation Support
Source of Support: PC Krause & Assoc (Air Force)
Total Award Amount: $156,441 Total Award Period Covered: 1/1/12-12/31/13
Location of Project: University of Illinois at Urbana-Champaign
Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 1.00

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Eric J. Barth

Other agencies (including NSF) to which this proposal has been/will be submitted.
NSF

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Engineering Research Center for Compact and Efficient Fluid Power,
Project 2B.1: Free-Piston Engine-Compressor

Source of Support: NSF and Industrial Collaborators, subcontracted through University of Minnesota

Total Award Amount: $760,925 Total Award Period Covered: 06/01/06 – 05/31/12

Location of Project: Vanderbilt University

Person-Months Per Year Committed to the Project. Cal: Acad: 0.582 Sumr: 0.862

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Engineering Research Center for Compact and Efficient Fluid Power,
Project2C.2: Advanced Strain Energy Accumulator

Source of Support: NSF and Industrial Collaborators, subcontracted through University of Minnesota

Total Award Amount: $545,226 Total Award Period Covered: 06/01/06 – 05/31/14

Location of Project: Vanderbilt University

Person-Months Per Year Committed to the Project. Cal: Acad: 0.7 Sumr: 0.38

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

CPS: Medium: Self-Sustaining CPS for Structural Monitoring

Source of Support: NSF

Total Award Amount: $499,992 Total Award Period Covered: 10/1/10-9/30/13

Location of Project: Vanderbilt University

Person-Months Per Year Committed to the Project. Cal: Acad: 0.45 Sumr: 0.0

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Engineering Research Center for Compact and Efficient Fluid Power,
Stirling Thermocompressors

Source of Support: NSF and Industrial Collaborators, subcontracted through University of Minnesota

Total Award Amount: $260,058 Total Award Period Covered: 06/01/12 – 05/31/14

Location of Project: Vanderbilt University

Person-Months Per Year Committed to the Project. Cal: Acad: 0.0 Sumr: 0.25

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Engineering Research Center for Compact and Efficient Fluid Power, Project 2G: Fluid-Powered Surgery & Rehabilitation via Compact, Integrated Systems

Source of Support: NSF and Industrial Collaborators, subcontracted through University of Minnesota

Total Award Amount: $189,876 Total Award Period Covered: 06/01/12 – 05/31/14

Location of Project: Vanderbilt University

Person-Months Per Year Committed to the Project. Cal: Acad: 0.0 Sumr: 1.4

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Eric J. Barth	Other agencies (including NSF) to which this proposal has been/will be submitted. NSF

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
REU Site: Research Experiences for Undergraduates in Fluid Power

Source of Support: NSF
Total Award Amount: $555,750 Total Award Period Covered: 06/01/12 – 05/31/15
Location of Project: University of Minnesota (PI: Kim Stelson)
Person-Months Per Year Committed to the Project. Cal: 0.0 Acad: 0.0 Sumr: 0.0

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
GOALI: Model-Based Design and Control of Fully-Actuated Free-Piston HCCI Engines

Source of Support: NSF
Total Award Amount: $340,905 Total Award Period Covered: 09/01/12 – 08/31/15
Location of Project: Vanderbilt University
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: 0.45 Sumr: 1.0

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

NSF Form 1239 (10/99) USE ADDITIONAL SHEETS AS NECESSARY

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Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Wayne Book

Other agencies (including NSF) to which this proposal has been/will be submitted. (none)

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:
Multi-modal operator interface and test bed

Source of Support: NSF
Total Award Amount: $270,506 Total Award Period Covered: June 1, 2010-May 31, 2011
Location of Project: Atlanta, GA
Person-Months Per Year Committed to the Project. Cal: 2 Acad: Sumr:

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:
Multi-modal operator interface and test bed

Source of Support: NSF
Total Award Amount: $243,456 Total Award Period Covered: June 1, 2011 to May 31, 2012
Location of Project: Atlanta, GA
Person-Months Per Year Committed to the Project. Cal: 2 Acad: Sumr:

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:
Simultaneous Control of Large Arrays of Actuators with Reduced Control Inputs for Shape-Haptic-Tactile Input-Output HMIs

Source of Support: NSF
Total Award Amount: $$497,841 Total Award Period Covered: January 1, 2010 to December 31, 2013
Location of Project: Atlanta, GA
Person-Months Per Year Committed to the Project. Cal: 4 Acad: Sumr: 1

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

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*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

NSF Form 1239 (10/99) USE ADDITIONAL SHEETS AS NECESSARY

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Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Thomas R. Chase	Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: X Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Solar Recycling of CO2 to Fuels (PI: J. Davidson)

Source of Support: Institute for Renewable Energy & The Environment
Total Award Amount: $450,000? Total Award Period Covered: 7/1/10-6/30/13
Location of Project: UMN
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.25

Support: X Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Solar Fuels via Partial Redox Cycles with Heat Recovery (PI: W. Lipinski)

Source of Support: Department of Energy ARPA-E Program
Total Award Amount: $1,851,522 Total Award Period Covered: 12/15/11-12/14/14
Location of Project: UMN
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 1

Support: x Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Helical Ring On/Off Valve Based 4-Quadrant Virtually Variable Displacement Pump/Motor (PI: P. Li)

Source of Support: NSF-CCEFP
Total Award Amount: $235,000? Total Award Period Covered: 6/1/10-5/31/12
Location of Project: UMN
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.25

Support: X Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Piston-by-Piston Control of Pumps and Motors Using Mechanical Means (PI: P. Li)

Source of Support: NSF-CCEFP
Total Award Amount: $236,000? Total Award Period Covered: 6/1/10-5/31/12
Location of Project: UMN
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.25

Support: X Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: MEMS Proportional Pneumatic Valve

Source of Support: NSF-CCEFP
Total Award Amount: $190,000? Total Award Period Covered: 6/1/10-5/31/12
Location of Project: UMN
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.5

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

NSF Form 1239 (10/99) USE ADDITIONAL SHEETS AS NECESSARY

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Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Thomas R. Chase

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: X Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Hydraulic Hybrid Passenger Vehicle (PI: P. Li)

Source of Support: NSF-CCEFP
Total Award Amount: $490,000? Total Award Period Covered: 1/1/08-5/31/12
Location of Project: UMN
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.25

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

NSF Form 1239 (10/99) USE ADDITIONAL SHEETS AS NECESSARY

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Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Ken Cunefare

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: X Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Passive noise control in fluid power

Source of Support: NSF

Total Award Amount: $119,771 Total Award Period Covered:

Location of Project: Georgia Tech

Person-Months Per Year Committed to the Project. 1 Cal: Acad: Sumr: X

Support: Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: CSUV Advanced Electric Drive Vehicle Education Program

Source of Support: DoE

Total Award Amount: $200,000 Total Award Period Covered: 1/10-12/12

Location of Project: Georgia Tech

Person-Months Per Year Committed to the Project. 1 Cal: Acad: Sumr: X

Support: ☐ Current ☐ Pending Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

NSF Form 1239 (10/99) USE ADDITIONAL SHEETS AS NECESSARY

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Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Paul Imbertson

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Center for Reforming Undergraduate Education in Electric Energy Systems – A Critical Infrastructure for National Security (PI: N. Mohan; Co-PIs: W. Robbins, B. Wollenberg, P. Imberson, T. Posbergh)

Award # N00014-06-1-0381

Source of Support: USDOD NAVY

Total Award Amount: $1,285,746 Total Award Period Covered: 06/01/2006 – 09/30/2012

Location of Project: University of Minnesota

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.50

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

A Nationwide Consortium of Universities to Revitalize Electric Power Engineering Education by State-of-the-Art Laboratories (PI: N. Mohan, Co-PI with 2 others)

Source of Support: Department of Energy

Total Award Amount: $2,500,000 Total Award Period Covered: 07/30/10 – 07/29/13

Location of Project: University of Minnesota

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.50

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

ERC: NSF Funds: CCEFP E&O (PI: K Stelson; Co-PI: P Imbertson with 6 others)

Award# EEC-0540834

Source of Support: NSF

Total Award Amount: $25,872,136 Total Award Period Covered: 05/15/06-05/31/14

Location of Project: University of Minnesota

Person-Months Per Year Committed to the Project. Cal: Acad: 1 Sumr: 1

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Based Targeted Mathematics-Science Partnership

Source of Support: NSF

Total Award Amount: $8,000,000 Total Award Period Covered: 1/1/13 – 12/31/18

Location of Project: University of Minnesota

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 1

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

NSF Form 1239 (10/99) USE ADDITIONAL SHEETS AS NECESSARY

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Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: David Kittelson

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: x Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Performance and Emissions of a Second Generation Biofuel - DME

Source of Support: IREE

Total Award Amount: $500000 Total Award Period Covered: 07/01/10 – 06/30/13

Location of Project: U of M

Person-Months Per Year Committed to the Project. 0 Cal: Acad: Sumr:

Support: x Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Biofuels for the Farm

Source of Support: IREE

Total Award Amount: $107000 Total Award Period Covered: 5/31/1010-8/31/2012

Location of Project: U o M

Person-Months Per Year Committed to the Project. 0 Cal: Acad: Sumr:

Support: x Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Engine and Emission Research

Source of Support: General Motors

Total Award Amount: $150000 Total Award Period Covered: 9/30/2010 -9/29/2013

Location of Project: U of M

Person-Months Per Year Committed to the Project. 0.33 Cal: 0.11 Acad: Sumr: 0.11

Support: x Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Operation of a Diesel Generator on Producer Gas from a Biomass Gasifier

Source of Support: DOE NETL

Total Award Amount: $161000 Total Award Period Covered: 6/10/2010-1/31/2012

Location of Project: U of M

Person-Months Per Year Committed to the Project. 0.23 Cal: 0.23 Acad: Sumr: 0.23

Support: x Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Reactive-Flash Volatilization JP-8 Reformer

Source of Support: Creare, Inc.

Total Award Amount: $75000 Total Award Period Covered: 1/01/2010-12/31/2011

Location of Project: U of M

Person-Months Per Year Committed to the Project. 0.23 Cal: 0.23 Acad: Sumr: 0.23

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*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

NSF Form 1239 (10/99) USE ADDITIONAL SHEETS AS NECESSARY

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Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: David Kittelson	Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: x Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Development of a Precise and High Speed Hydrostatic Dynamometer System

Source of Support: NSF

Total Award Amount: $808000 Total Award Period Covered: 1/01/2010-12/31/2011

Location of Project: U of M

Person-Months Per Year Committed to the Project. 1.38 Cal:0.69 Acad: Sumr: 0.69

Support: x Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Real-Time Ash Measurements

Source of Support: BP

Total Award Amount: $275000 Total Award Period Covered: 10/31/2007-12/31/2012

Location of Project: U of M

Person-Months Per Year Committed to the Project. 0.2 Cal: 0.05 Acad: Sumr: 0.05

Support: x Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Center for Compact and Efficient Fluid Power

Source of Support: NSF

Total Award Amount: $21370000 Total Award Period Covered: 05/15/2006-05/31/2014

Location of Project: U of M and others

Person-Months Per Year Committed to the Project. 2.54 Cal: 0.63 Acad: Sumr: 0.63

Support: ☐ Current x Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

High Efficiency Enabled by Hydrous Ethanol use in Dual-Fuel Diesel Engines

Source of Support: Minnesota Corn Growers

Total Award Amount: $118500 Total Award Period Covered: 06/01/2012-05/31/2013

Location of Project: U of M

Person-Months Per Year Committed to the Project. 0.35 Cal: 0.35 Acad: Sumr: 0.35

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

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*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

NSF Form 1239 (10/99) USE ADDITIONAL SHEETS AS NECESSARY

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Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Perry Y Li

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

EFRI-Novel Compressed Air Approach for Offshore Wind Energy Storage

Source of Support: NSF

Total Award Amount: $2,000,000 Total Award Period Covered: 9/2010-8/2014

Location of Project: U of Minnesota

Person-Months Per Year Committed to the Project. Cal: Acad: 0.5 Sumr: 1

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

NSF Engineering Research Center for Compact and Efficient Fluid Power (CCEFP) – testbed 3 Hydraulic Hybrid Passenger Vehicle

Source of Support: NSF

Total Award Amount: $380,000 Total Award Period Covered: 6/2010-5/2012

Location of Project: U of Minnesota

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 1.0

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

NSF Engineering Research Center for Compact and Efficient Fluid Power (CCEFP) – Project 1E.1 Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor

Source of Support: NSF

Total Award Amount: $260,000 Total Award Period Covered: 6/2010-5/2012

Location of Project: U of Minnesota

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.5

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

NSF Engineering Research Center for Compact and Efficient Fluid Power (CCEFP) – Project 1E.4 On/off Valve Based Piston-by-Piston Control of Pumps and Motors Using Mechanical Methods

Source of Support: NSF

Total Award Amount: $260,000 Total Award Period Covered: 6/2010-5/2012

Location of Project: U of Minnesota

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.5

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

NRI-Large: Theory of Human Assistive Machines

Source of Support: NSF

Total Award Amount: $2,331,000 Total Award Period Covered: 9/2012-8/2016

Location of Project: U of Minnesota

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 1.0

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Christiaan Paredis

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☒ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: EFRI-ODISSEI: Scalable Elastic and Morphable Structures (SEAMS)

Source of Support: NSF

Award Amount (or Annual Rate): $ 2,000,000 Period Covered: 8/15/2012 – 8/15/2016

Location of Project: Georgia Institute of Technology

Person-Months Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 1.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: ERC: Center from Compact and Efficient Fluid Power

Source of Support: NSF

Award Amount (or Annual Rate): $ 15,000,000 Period Covered: 06/01/06 - 05/31/12

Location of Project: University of Minnesota (sub-contract for GaTech)

Person-Months Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 1.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: Establishing a Logical Vehicle System Architecture in SysML

Source of Support: Ford Motor Company

Award Amount (or Annual Rate): $ 75,697 Period Covered: 05/15/11 - 05/31/11

Location of Project: Georgia Institute of Technology

Person-Months Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.75

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: Development of iFAB Manufacturing Process and Machine Capability Library

Source of Support: DARPA

Award Amount (or Annual Rate): $ 1,468,644 Period Covered: 05/01/11 - 4/31/12

Location of Project: Georgia Institute of Technology

Person-Months Committed to the Project. Cal: 0.00 Acad: 1.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: EFRI-SEED: Risk-Conscious Design and Retrofit of Buildings for Low Energy

Source of Support: NSF

Award Amount (or Annual Rate): $ 1,960,113 Period Covered: 8/1/2010 – 7/31/2014

Location of Project: Georgia Institute of Technology

Person-Months Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.75

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Christiaan Paredis

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: Modeling of Mechatronic Systems using SysML4Modelica

Source of Support: Siemens

Award Amount (or Annual Rate): $ 65,981 Period Covered: 7/15/2011 – 05/31/2012

Location of Project: Georgia Institute of Technology

Person-Months Committed to the Project. Cal: 0.00 Acad: 0.50 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title: Model-Based Systems Engineering for Aerospace Manufacturing — MBSEAM

Source of Support: Boeing

Award Amount (or Annual Rate): $ 900,000 Period Covered: 8/01/2011 – 07/31/2014

Location of Project: Georgia Institute of Technology

Person-Months Committed to the Project. Cal: 0.00 Acad: 1.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ * Transfer of Support

Project/Proposal Title:

Source of Support:

Award Amount (or Annual Rate): $ Period Covered:

Location of Project:

Person-Months Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Richard F. Salant

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: X Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:
PWR Reactor Coolant Pump Seal Improvement Project

Source of Support: EPRI
Total Award Amount: $159,679 Total Award Period Covered: 1/1/2012-12/31/2012
Location of Project: Georgia Institute of Technology
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 2

Support: ☐ Current X Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:
PWR Reactor Coolant Pump Seal Improvement Project

Source of Support: EPRI
Total Award Amount: $157,204 Total Award Period Covered: 1/1/2013-12/31/2013
Location of Project: Georgia Institute of Technology
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 2

Support: ☐ Current Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

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Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Kim Stelson	Other agencies (including NSF) to which this proposal has been/will be submitted. None

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
Engineering Research Center for Compact and Efficient Fluid Power

Source of Support: NSF
Total Award Amount: $21,912,328.00 Total Award Period Covered: 6/1/2006 – 5/31/2016
Location of Project: University of Minnesota
Person-Months Per Year Committed to the Project. Cal: Acad: 1 Sumr: 2

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
IREE – Hydrostatic Transmission for Windpower

Source of Support: University of Minnesota
Total Award Amount: $44,406 Total Award Period Covered: 9/1/2009 – 12/30/2011
Location of Project: University of Minnesota
Person-Months Per Year Committed to the Project. Cal: 0 Acad: Sumr:

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
Reliable Lightweight Transmission

Source of Support: Eaton Corporation
Total Award Amount: $151,496 Total Award Period Covered: 9/30/11 – 4/30/12
Location of Project: University of Minnesota
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
Engineering Research Center for Compact and Efficient Fluid Power

Source of Support: National Science Foundation
Total Award Amount: $12,475,600 Total Award Period Covered: 6/1/2012 – 5/31/2016
Location of Project: Lead Institution—University of Minnesota
Person-Months Per Year Committed to the Project. Cal: Acad: 1 Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

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Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Zongxuan Sun

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
GOALI Collaborative Research: A Control Oriented Charge Mixing and Hybrid Combustion Model for SI-HCCI Dual Mode Engines
Source of Support: NSF
Total Award Amount: $204,747 Total Award Period Covered: 9/1/2010-8/31/2013
Location of Project: University of Minnesota
Person-Months Per Year Committed to the Project. 0.5 Cal: Acad: Sumr:

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
CAREER: Control of Mechatronic Automotive Propulsion Systems
Source of Support: NSF
Total Award Amount: $400,000 Total Award Period Covered: 6/1/2012-5/31/2017
Location of Project: University of Minnesota
Person-Months Per Year Committed to the Project. 1 Cal: Acad: Sumr:

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
Free Piston Engine Hydraulic Pump
Source of Support: CCEFP
Total Award Amount: $227,939 Total Award Period Covered: 6/1/2010-5/31/2012
Location of Project: University of Minnesota
Person-Months Per Year Committed to the Project. 1 Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

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