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8th Annual Report

Volume 2

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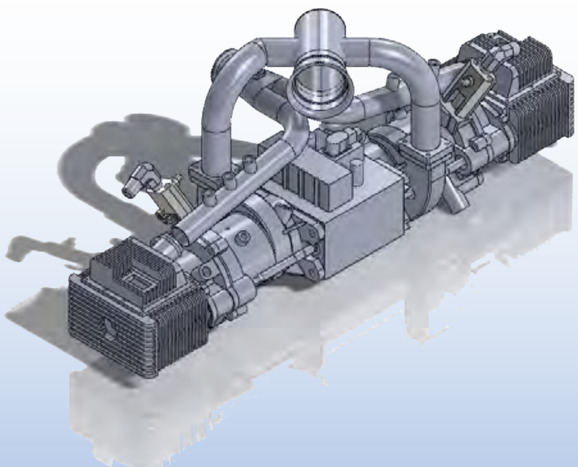
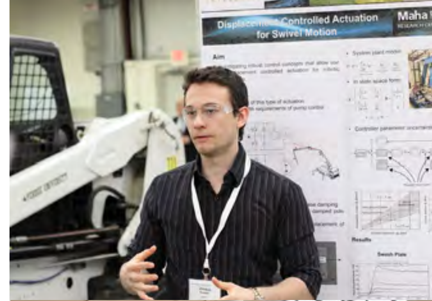




CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

University of Minnesota

Georgia Institute of Technology

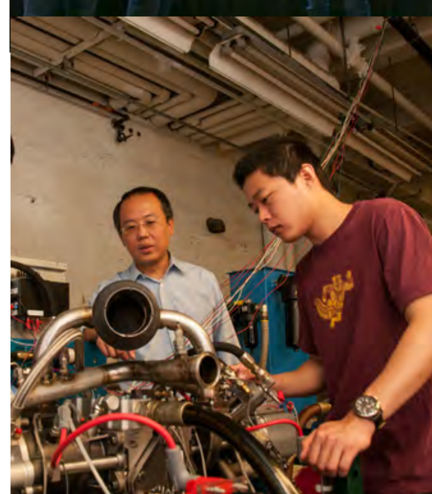
Milwaukee School of Engineering

North Carolina Agricultural & Technical State University

Purdue University

University of Illinois at Urbana-Champaign

Vanderbilt University



Dr. Kim Stelson, Director

Dr. Eric Barth, Co-Deputy Director

Dr. Zongxuan Sun, Co-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: Technology Transfer Process for Energy Management 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
1D: MicroTextured Surfaces for Low Friction / Leakage	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.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
1E.5: System Configuration & Control Using Hydraulic Transformers	Perry Li, University of Minnesota
1E.6: High Performance Actuation System Enabled by Energy Coupling Mechanism	John Lumkes, Purdue University; Monika Ivantysynova, Purdue University
1F.1: Variable Displacement Gear Machine	Andrea Vacca, Purdue University
1G.1: Energy Efficient Fluids	Paul Michael, Milwaukee School of Engineering
1J.1: Hydraulic Transmissions for Wind Energy	Kim Stelson, University of Minnesota;
A Characterization of the Pressure-Viscosity and Compressibility Response of Five Oils for a Wide Range of Temperatures	Scott Bair, Georgia Tech *Sponsors:* Deere and Company
A Characterization of the Pressure-Viscosity Response of Four lubricating Oils	Scott Bair, Georgia Tech *Sponsors:* Shell Global Solutions

Project Name	PI / Institution / Sponsor
Advances in Modeling External Spur Gear Machines and Development of Innovative Solutions	Andrea Vacca, Purdue University *Sponsors:* Casappa S.p.A.
Design of low noise emission internal gear machines	Andrea Vacca, Purdue University *Sponsors:* Confidential
Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump	Andrea Vacca *Sponsors*: Confidential
Dynamic model development for hydraulic pumps	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
Energy Saving Hydraulic System Architecture Utilizing Displacement Control	Monika Ivantysynova, Purdue University *Sponsors*: Confidential
Evaluation and Design Improvements for a Hydraulic Pump	Monika Ivantysynova, Purdue University *Sponsors*: Confidential
Evaluation of a Proprietary Gear Pump	Andrea Vacca, Purdue University *Sponsors*: Confidential
Generating of FSTI gap design input parameters	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Modeling and Analysis of Swash Plate Type Piston Motor	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Modeling of Lubricating Features of External Gear Machines and Development of Quieter Solutions	Andrea Vacca, Purdue University *Sponsors:* Casappa S.p.A.
New system concept for Electrical Hydraulic Actuation system	Andrea Vacca, Purdue University *Sponsors:* Midwest Precision
Optimal Design of a Hydro-Mechanical Transmission Power Split Hybrid Hydraulic Bus	Project Leader: Muhammad Ramdan (Kim Stelson) *Sponsors:* Malaysian Ministry of Higher Education (MOHE) and University of Science, Malaysia (USM)
Pump Dynamic Model Development	Monika Ivantysynova, Purdue University *Sponsors:* Confidential

Thrust 2 – Compactness

Project Name	PI / Institution / Sponsor
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
2B.4: Controlled Stirling Thermocompressors	Eric Barth, Vanderbilt University
2C.2: Advanced Strain Energy Accumulator	Eric Barth, Vanderbilt University
2C.3: Flywheel Accumulator for Compact Energy Storage	James D. Van de Ven, University of Minnesota
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

Thrust 3 – Effectiveness

Project Name	PI / Institution / Sponsor
3A.1: Teleoperation Efficiency Improvements by Operator Interface	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.3: Active Vibration Damping of Mobile Hydraulic Machines	Andrea Vacca, Purdue University
3D.1: Leakage/Friction 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
3E.1: Pressure Ripple Energy Harvester	Kenneth A. Cunefare, Georgia Institute of Technology
Adaptive Ride Control for Construction Machines	Andrea Vacca, Purdue University *Sponsors:* CNH America, Inc.
High Pressure Compliant Material Development	Kenneth Cunefare, Georgia Tech *Sponsors:* Danfoss
High Pressure Viscosity and Density Measurements on Diesel Fuels	Scott Bair, Georgia Tech *Sponsors:* Cummins Engine
High Pressure Viscosity and Density Measurements on Krytox Fluids	Scott Bair, Georgia Tech *Sponsors:* DuPont

Project Name	PI / Institution / Sponsor
Model Predictive Control of Pneumatic Actuators	Wayne Book, Georgia Tech *Sponsors:* National Defense Science and Engineering Graduate Fellowship (NDSEG)
New Generation Of Green, Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology	Monika Ivantysynova, Purdue University *Sponsors*: Confidential
Optimization of Valve Plate to Reduce Noise and Maintain Low Control Effort	Monika Ivantysynova, Purdue University *Sponsors*: Confidential
Rheology Modeling for Mechanical Face Seals	Scott Bair, Georgia Tech *Sponsors:* John Crane
Self-powered Leak Detection System for Pipeline Monitoring	Kenneth Cunefare, Georgia Tech *Sponsors:* Veraphotonics, Mistras

Test Beds & General Research

Project Name	PI / Institution / Sponsor
Test Bed 1: Heavy Mobile Equipment – Excavator	Monika Ivantysynova, Purdue University, School of Mechanical Engineering
Test Bed 3: Hydraulic Hybrid Passenger Vehicle	Perry Li, Mechanical Engineering, University of Minnesota
Test Bed 4: Patient Transfer Device – Hydraulics at Human Scale	Wayne J. Book, Mechanical Engineering, Georgia Tech
Test Bed 6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses)	Elizabeth Hsiao-Wecksler, MechSE, UIUC
CPS: Synergy: Integrated Modeling, Analysis and Synthesis of Miniature Medical Devices	Pietro Valdastri, Vanderbilt University *Sponsors:* confidential
EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Based Targeted Mathematics-Science Partnership	Paul Imbertson, University of Minnesota *Sponsors*: National Science Foundation (NSF); STEM Education Center - University of Minnesota
I-Corps: CO2 Insufflator for Minimally Invasive Procedures	Pietro Valdastri, Vanderbilt University *Sponsors:* confidential
Modulation of Anticipatory Postural Adjustments in Parkinson's disease Using a Portable Powered Ankle-Foot Orthosis	Elizabeth Hsiao-Wecksler, UIUC *Sponsors:* NSF IGERT Student Fellowship
NC A&T State University Regional Collaborations for Excellence in STEM	Eui Park, NC A&T Sponsors: EO Thrust A: Public Outreach

EDUCATION AND OUTREACH PROJECTS

Project Name	PI / Institution / Sponsor
EO A.1 Interactive Exhibits on Fluid Power	J. Newlin Jr, Science Museum of Minnesota
EO B.1 Research Experiences for Teachers (RET)	Alyssa Burger, University of Minnesota
EO B.3 Hands-on Fluid Power Workshops	Alyssa Burger, University of Minnesota
EO B.3b Portable Fluid Power Demonstrator and Curriculum	John Lumkes, Purdue University
EO B.4 gidaa STEM Programs	Alyssa Burger, University of Minnesota
EO B.5: BRIDGE Programs	Paul Imbertson, University of Minnesota
EO B.7 NFPA Fluid Power Challenge Competition	Alyssa Burger, University of Minnesota
EO C.1 Research Experiences for Undergraduates (REU)	Alyssa Burger, University of Minnesota
EO C.2 Fluid Power College Level Curriculum	Will Durfee, University of Minnesota
EO C.3 Fluid Power Projects in Capstone Design Courses	James Van de Ven, University of Minnesota Alyssa Burger, University of Minnesota
EO C.3a Capstone Senior Design Project	Elizabeth Hsiao-Wecksler, UIUC
EO C.3b Parker Hannifin Chainless Challenge	Brad Bohlmann, CCEFP
EO C.4 Fluid Power in Engineering Courses	James Van de Ven, Univ. 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 (SLC)	Alyssa Burger, University of Minnesota
EO C.9 / 10 Research Diversity Supplement (RDS)	Alyssa Burger, University of Minnesota Kim Stelson, University of Minnesota
EO C.11: Innovative Engineers (IE)	Paul Imbertson, University of Minnesota
EO D.1 Fluid Power Scholars/Interns	Alyssa Burger, University of Minnesota
EO D.2 Industry Student Networking	Alyssa Burger, University of Minnesota Student Leadership Council
EO D.5 CCEFP Webcast Series	Cherie Bandy, University of Minnesota Alyssa Burger, University of Minnesota Student Leadership Council
EO E Evaluation	Kim Stelson, University of Minnesota

Project Name	PI / Institution / Sponsor
NSF REU Site Award	Kim Stelson, University of Minnesota *Sponsors:* National Science Foundation
EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Based Targeted Mathematics-Science Partnership	Paul Imbertson, University of Minnesota *Sponsors*: National Science Foundation (NSF); STEM Education Center - University of Minnesota
Hand Powered Water Pumps for Developing Countries	Gary Werner, John Lumkes, Isaac Zama, Vincent Kitio McCutcheon High School/Purdue University *Sponsors:* CCEFP, Purdue University, McCutcheon HS, African Centre for Renewable Energy and Sustainable Technologies (ACREST)
NC A&T State University Regional Collaborations for Excellence in STEM	Eui Park, NC A&T Sponsors: EO Thrust A: Public Outreach
North Star STEM LSAMP Alliance	Anne Hornickel, Program Director *Grant:* LSAMP - Louis Stokes' Alliance for Minority Participation
Purdue University - SURF REU Program	Sponsor: Purdue University
Universal Fluid Power Trainer	Medhat Khalil, MSOE *Sponsor*: MSOE's Maha Fund

Project 1A.1: Technology Transfer Process for Energy Management Systems

Research Team

Project Leader:	Andrew Alleyne, UIUC
Other Faculty:	Kim Stelson, UMN
Graduate Students:	Timothy Deppen, UIUC; Jonathan Meyer, UMN
Industrial Partners:	Eaton; Danfoss

1. Statement of Project Goals

The goal of this project is to develop and implement a well-defined process for transferring energy management technology developed within the Center to industrial partners supporting the CCEFP. 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]. We have developed a formal process for transitioning the algorithms developed to practitioners and a software framework for interfacing to the available tools.

2. Project Role in Support of Strategic Plan

The project the efficiency barrier by providing a way for efficient operation algorithms developed within the Center to be readily implemented up by industrial partners. This project provides a set of “best practices” for transitioning the tools from the academic setting to the industrial setting. This will be a good approach to attracting industry support and supporting Center sustainability.

3. Project Description

A. Description and explanation of research approach

This project is the outcome of a request by CCEFP industrial advisory board members to take the CCEFP research results and put them in a form that can be easily adapted by industry members. We have created a process for moving CCEFP technology of project 1A.1 from university to industry. Project 1A.1 has developed control algorithms that use complex optimization to manage the power production, energy distribution, energy storage, and potential energy recovery in mobile hydraulic systems while maintaining performance. The goal is then to create a process with metrics and milestones that one can use to track and guide the maturation of control algorithms to the point where they can be readily used internally by industry.

Multiple energy management strategy (EMS) tools have been created within Project 1A.1 for the toolbox. The choice of tool depends on *a priori* level of knowledge of the duty cycle and performance requirements. Current tools are: 1) rule-based controllers based on deterministic dynamic programming results, 2) model predictive controllers, and 3) stochastic dynamic programming. These are given here in the order of increasing knowledge required for effective implementation. The general concept for this approach can be seen in Figure 1.

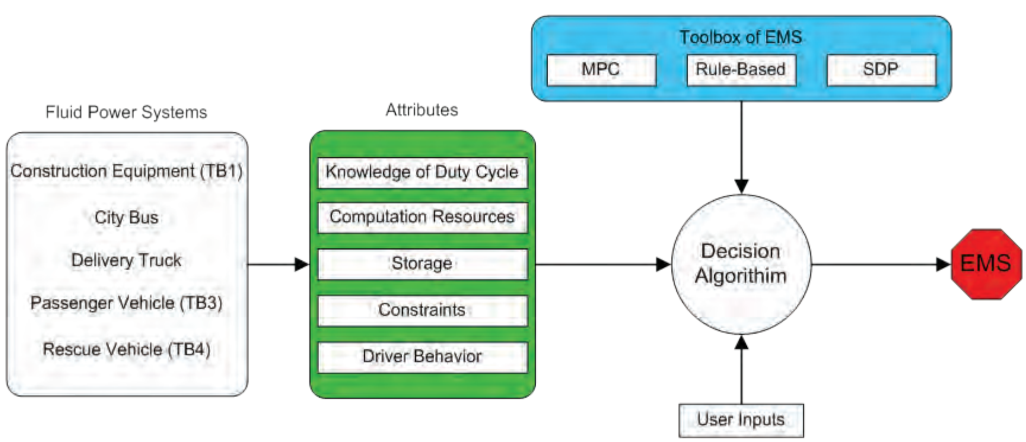

Figure 1: Implementation of the 1A.1 EMS Toolbox

The approach is a five-phase process. The first phase is to understand the 'voice of the customer'; in this case, a group of industry participants most likely to utilize the tools. The second phase, closely tied to the first, is to define a format for information entry that would be suitable for a large class of users. The third phase is to determine a suitable test platform to work out development issues. The fourth phase, which is the most challenging, is to actually create this framework using readily accessible tools. The fifth phase is to implement it on the test platform, evaluate the process utility, and iterate on any gaps in the process. The industry test group developed this tool with us and provided feedback on what worked and what could be improved.

B. Achievements

The focus a previous project was taking the simulation results of the rule-based, model predictive control, and stochastic dynamic programming and implementing them on physical hardware for a comparison study. The Augmented Earthmoving Vehicle Powertrain Simulator (AEVPS) at the University of Illinois was chosen as the experimental setup to validate the simulation results. The AEVPS is a series hydraulic hybrid architecture with accumulator for energy storage (see Figure 2). The Urban Dynamometer Drive Schedule (UDDS) was the duty cycle used for a comparison between each strategy.

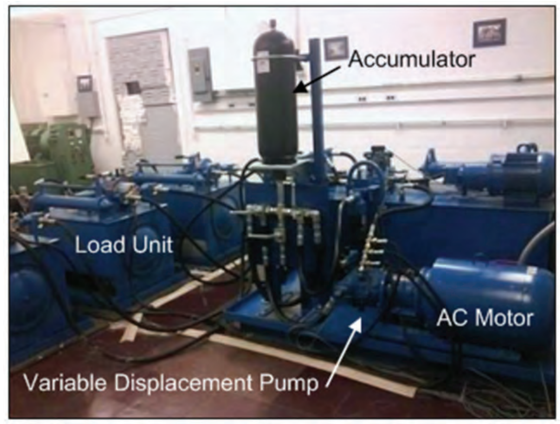

Figure 2: AEVPS System

Since all three strategies show agreement between the simulation and experimental results, simulation can be used to do further studies for which method works better for different scenarios. Using the transition probabilities developed for the SDP algorithm, 100 random drive cycles with urban driving characteristics were generated. Each of the three strategies was then simulated through each of the drive cycles. To quantify the performance of each strategy, two metrics were considered: the fuel consumption and the tracking error. The fuel consumption for each was normalized with respect to the fuel consumption of a non-hybrid vehicle for the same drive cycle. This provides a reference point to assess the relative improvement of each strategy for all drive cycles. The root mean square tracking error is a measure of how closely the vehicle speed agrees with the desired speed from the drive cycle.

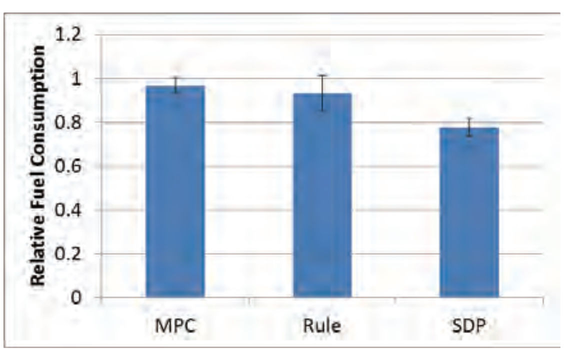

Figure 3: Mean fuel consumption relative to a non-hybrid for urban driving

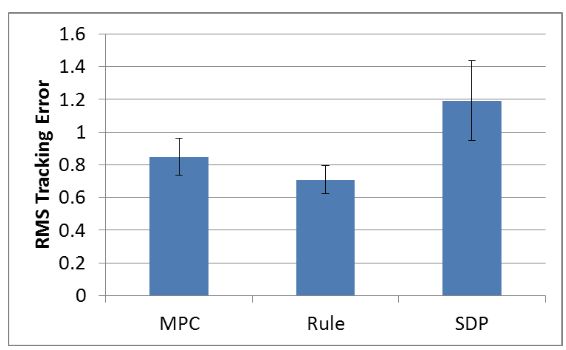

Figure 4: Mean tracking error for urban driving

Figure 3 shows the mean fuel consumption results relative to a non-hybrid vehicle. The error bars represent ±1 standard deviation from the mean. The SDP approach achieved the greatest improvement in fuel economy with small variance between urban drive cycles. The MPC and rule-based achieved similar performance but the rule-based results had larger variance. This is because the rule-based approach was tuned for a specific drive cycle. Figure 4 compares the tracking error between the three strategies for the same 100 random drive cycles. The rule-based strategy achieved the lowest tracking error while the SDP strategy had the highest error. This is due to the consequence of its sensitivity to errors in the model due to offline optimization, while the rule-based strategy incorporates a proportional-integral controller for tracking the desired speed. Based on these results, the rule-based strategy is the best compromise between fuel improvement and reference tracking.

A similar study was performed using random highway driving cycles with similar results. Summarizing, the MPC strategy is the most robust and would be best for highly uncertain applications, the SDP strategy is best suited in predictable environments with well-defined models, and the rule-based method is best suited for applications with known trajectories, such as city buses. A journal article for the ASME Journal of Dynamic Systems, Measurement and Control with these conclusions has been submitted [7].

We have held teleconferences with CCEFP member companies to gauge interest and to identify possible industrial applications as test platforms. The two companies, Eaton and Danfoss Power Systems have been engaged for detailed studies. We have determined that a set of linearized state-space equations is the best way to express the models of the physical hardware, and Matlab/Simulink software was also chosen as the best software for the development of the models.

<u>Milestones and Deliverables</u>

- Development of first-draft of toolbox (4/2013)
- Implementation of EMS strategies on industrial applications (5/2013)
- Toolbox refinement (6/2013)

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. 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.
4. 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.
5. 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.
6. Deppen, T. O., A. G. Alleyne, J. J. Meyer and K. A. Stelson, "Optimal Energy Use in a Light Weight Hydraulic Hybrid Passenger Vehicle," *Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control*, Vol. 134, no. 4, July 2012.
7. Deppen, T. O., A. G. Alleyne, J. J. Meyer and K. A. Stelson, " Comparative Study of Energy Management Strategies for Hydraulic Hybrid Vehicles," submitted to *Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control*.

Project 1A.2: Control and Prognostics for Hybrid Displacement Control Systems

Research Team

Project Leader:	Monika Ivantysynova, Purdue University
Graduate Students:	Enrique Busquets and Rohit Hippalgaonkar
Industrial Partners:	Bobcat, Sun Hydraulics, Caterpillar, Parker Hannifin, Moog, Husco, Danfoss

1. Statement of Project Goals

In the past, project 1A.2 has focused on the development of system architectures and control methods for optimal power management in multi-actuator mobile hydraulic machines using displacement-controlled linear and rotary actuators. Through this project, a 50% reduction of energy consumption for typical working cycles of multi-actuator machines has been demonstrated. In addition, a reduction in cooling capacity of up to 50% is feasible while maintaining typical working temperatures and performance. The investigation of hydraulic hybrid architectures for multi-actuator machines and the potential for further fuel savings from these systems has also been a subject of research. Simulations have shown that implementing hydraulic hybrid architectures can allow the combustion engine to be downsized to 50% of its current rated power.

Since August 2012, the project has been focused on reducing production costs, further improving system efficiency and productivity and introducing machine prognostics of highly efficient displacement controlled hydraulic machines. To achieve lower production costs and higher system efficiencies, pump switching between actuators during machine operation will be analyzed, thus reducing the number of and size of the pumps installed in the hydraulic system and ultimately leading to lower parasitic losses. Such concepts are especially important for large machines where the current design approach requires the installation of large pumps. Preliminary simulations of a single pump, two actuator displacement controlled system have shown that pump switching is a viable solution to reduce production costs of multi-actuator displacement controlled machines and increase system efficiencies. Another goal of the project is the development of effective machine prognostics concepts. These will allow for the prediction of impending failures thereby avoiding expensive machine breakdowns making displacement control a more competitive technology.

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. It also addresses the compactness barrier since displacement-controlled systems allow higher operating pressures and a reduction of interfaces and components. Displacement controlled systems with pump switching will further address the efficiency and compactness barriers by reducing the number of pumps required thereby minimizing parasitic losses. The project will provide architectures including required system control concepts for multi-actuator machines utilizing displacement control and hybrid concepts in combination with pump switching. This will support the implementation of this new energy saving technology in larger and more complex machines. The investigation of methods to predict impending failures by utilizing existing sensors will further strengthen this new technology and hopefully contribute to faster technology acceptance.

3. Project Description

Description and explanation of research approach

Traditionally in multi-actuator machines using hydraulic actuation, one or two large hydraulic pumps transmit power from the engine. Control valves downstream of the pumps are responsible for controlling actuator motion based on operator input. Such configurations incur in energy losses due to throttled flow through the valves and, additionally, do not allow energy recovery from aiding loads.

Hybrid vehicles have been studied for years in the transportation sector and recently there has been increasing interest in hybridizing off-highway applications such as in construction, mining and agricultural machines. This is a result of rising fuel costs and more stringent emission regulations. Much of the focus has been on electric hybrids and Case, Kobelco and Komatsu have released hybrid electric construction equipment to the market. Little focus, however, seems to have been placed on hydraulic hybrid systems.

Through project 1A.2, hydraulic hybrid configurations for multi-actuator machines have been investigated and combined with displacement controlled actuation for the entire system.

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 passenger vehicles. Apart from rule-based [6-8] and instantaneously optimal strategies [9, 10], extensive research has not gone in 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.

A critical factor in the development of multi-actuator displacement controlled hybrid machines is production cost. The recent project focus on new architectures and control strategies utilizing pump switching for multi-actuator displacement controlled hydraulic hybrid machine systems. A test rig with two displacement controlled actuators has been modified to allow for testing of actuator switching mode control concepts, which have been studied in simulations recently. On/off valves to allow each pump to switch between two different functions was implemented on test bed 1. The system was able to simultaneously operate the boom, stick, bucket, and swing, the primary functions, and the on/off valves switched between these and the rest of the machine's functions, the secondary functions; however, no autonomous switching or modes of operation with different cycles were analyzed. After successful testing of the pump switching control strategy on the stationary test rig the implementation in test bed 1 is planned.

A breakdown of a construction machine at the construction site often involves not only an expensive in-field service; it can disrupt the whole construction site. Machine manufacturers and end users are becoming increasingly interested in condition monitoring to allow flexible maintenance intervals and reduce machine breakdowns. More and more off-road vehicles produced today have sensors to monitor the condition of the fluid and to detect engine and electric system failures. Methods for a more complex approach of condition monitoring and fault diagnostics of hydraulic systems have been developed [11-14], but the application on mobile machines until today is mainly focused on monitoring of fluid properties and load cycles.

Condition monitoring in hydraulic systems for early failure identification and allocation are still reserved for machines producing high sequential costs in case of breakdown. In 2006, a first universal off-road vehicle condition-monitoring system based on temperature and structure vibration measurements was introduced [15]. The main focus of this work was to study how self-learning machine diagnostic methods could be implemented in very different hydraulic systems. The advantage of his approach was that condition monitoring was achieved without using extensive system modeling by introducing health indicators in combination with a set of sensors. This early work will be used to develop methods for machine prognostics for displacement controlled hybrid machine systems using the already existing set of sensors.

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

- 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 [16] 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 showing 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.
- Novel series-parallel hybrid architectures were proposed, patented and analyzed in simulation demonstrating fuel savings of at-least 20% over the prototype DC system.

- An implementable rule-based strategy which replicates the optimal trends formulated for the hydraulic hybrid using the dynamic programing technique was proposed and analyzed.
- 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 for displacement controlled system architectures.
- A complete thermodynamic model has been developed to predict the system and actuator temperature in displacement controlled multi-actuator machines. The model has been verified through temperature measurements of the test bed 1 during standard machine operation [17] and through the modeling of a valve-controlled wheel loader [18].
- A high fidelity model to study the feasibility of pump switching was developed. The main focus of the study was to investigate the pump adjustment system requirements and actuators performance.

<u>Achievements during the reporting period:</u>
Achievements include the formulation of advanced control algorithms for multi-actuator displacement-controlled machines. The efforts were focused on maximizing overall system performance and operability while increasing reliability to prevent impending system failures and reduce machine production costs. The proposed control algorithms allow for maximized performance through the compensation of unmodeled nonlinearities as well as parametric uncertainties. The addition of online parameter adaptation allows for the accurate representation of the system state and serves as a way to monitor proper machine function. Finally, the investigation of pump switching architectures allows for the minimization of production costs.

Linear Control Approach for Optimal Actuator Performance and Fault Detection through State Observers
Many fluid power researchers have focused on linear control techniques to maximize actuator performance. However, market forces directed these efforts toward valve controlled actuation systems. For displacement-controlled actuators, robust control techniques have been utilized to demonstrate that pump displacement can be utilized for accurate tracking and positioning of end-effectors and actuators over a specified range of motion. Although these results set the step forward for improved actuator performance, the investigation of more advanced control algorithms would greatly benefit displacement-controlled actuation.

For the research, the JIRA test rig at the Maha Fluid Power Research Center was utilized on which a simple pump switching architecture with one pump and two actuators was implemented.

One approach taken was the formulation of linear-time-invariant single-input-single-output LTI SISO control using modern linear control theory. To achieve accurate tracking performance of the actuator commanded position, a feedforward controller was synthetized. This controller however, relies heavily on the accuracy of the plant model to achieve best performance. For this reason, disturbances and unmodeled uncertainties cannot be overcome. A feedback controller was added to to overcome this limitation.

To evaluate the controller performance when a switch between actuators is commanded, measurements of the actuator and pump pressures were performed Figure 1 shows the actuator and pump pressures follow closely only when actuator motion is commanded. When another actuator motion or no actuator motion is commanded, the actuator pressures depend on the load. This load is effectively compensated for when additional motion is commanded. It may also be observed that the transition between actuator motion and actuator holding is smooth. This is achieved through the modification of operator commands for best performance and operability. Figure 2 shows the commanded and modified pump displacements.

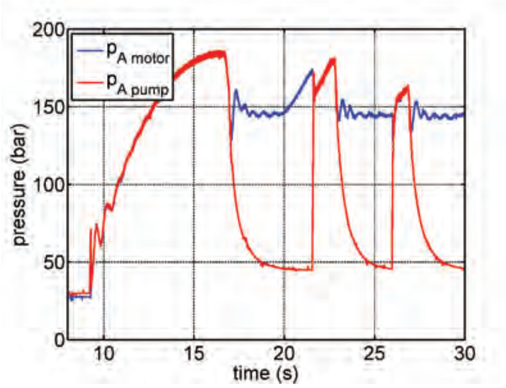

Figure 1: Actuator and pump pressures

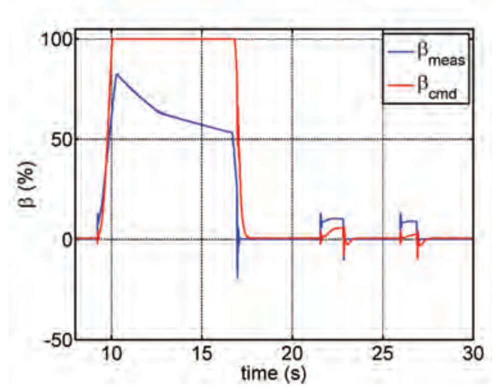

Figure 2: Commanded and modified displacements

A residual fault detection system was achieved through the use of state observers. This solution has been widely studied and utilized for a number of systems. For displacement controlled actuators, this method adds value to the system by preventing impending failures and allowing for planned maintenance intervals.

The pump switching concept was also studied for a 5-ton hydraulic hybrid excavator. In this case, nine actuators are provided with flow from 4 pumps. The current architecture however is very restrictive due to the exclusive utilization of pump flows for predetermined actuators. For this reason, a new architecture was proposed where the number of available actuators was maximized while keeping in mind the installed pump power and the machine space constraints. It is important to note that this new architecture and the control concepts derived for it are applicable to larger machines. Figure 3 shows a simplified hydraulic circuit of the proposed architecture for pump switching.

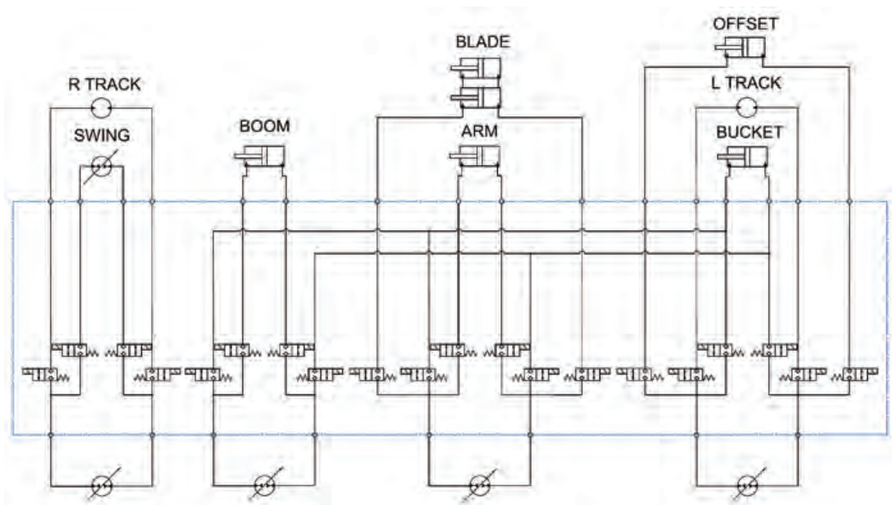

Figure 3: Proposed pump switching architecture for ERC test bed 1

Unlike the previous architecture where two predetermined machine operating modes were set and only certain actuators could be used at a time, the proposed architecture allows for sequential operation of common digging cycles where the swing, boom, arm, bucket and tracks are required.

Nonlinear Control for Optimal Actuator Performance and Fault Detection through Parameter Adaptation
Many advanced control algorithms have been developed for fluid power systems. Robust control algorithms have been widely studied due to their ability to deal with uncertainty in control due to bounded parametric uncertainties and/or disturbances. They are simple and very effective; however, fixed parameters pose a challenge to the realization of accurate control. Adaptive control algorithms exploit the use of online parameter adaptation to overcome model parametric uncertainties. These, however, only deal with the ideal cases of parametric uncertainties, which means that the system nonlinearities are

assumed to be known. Several methods have been developed to minimize the disadvantages of both techniques. A technique which overcomes the challenges of both adaptive and robust techniques is adaptive robust control (ARC) [19-22]. Advantages of this approach are the consideration of parametric uncertainties as well as disturbances through the inclusion of unknown nonlinear functions (such as unmodeled friction and other hard to model nonlinearities) and online parameter adaptation. Research has shown that this technique guarantees transient performance, final tracking to some degree as well as asymptotic output tracking.

An ARC controller was synthetized for a displacement-controlled actuator. As noted in Figure 4, a sinusoidal command was utilized to evaluate the controller response. Figure 5 shows the simulated error in the actuator position. As noted in [19-22], the degree of accuracy shown is to be expected. Furthermore, the reduction in error as the cycle continues indicates proper adaptive control action.

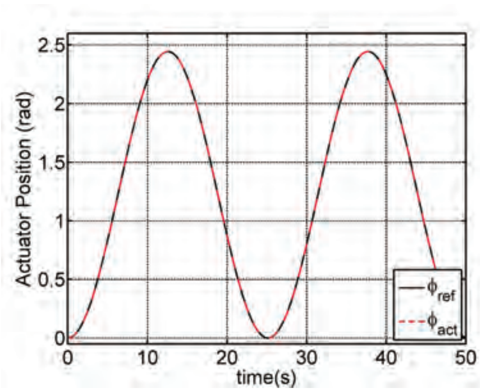

Figure 4: Actuator commanded and simulated position

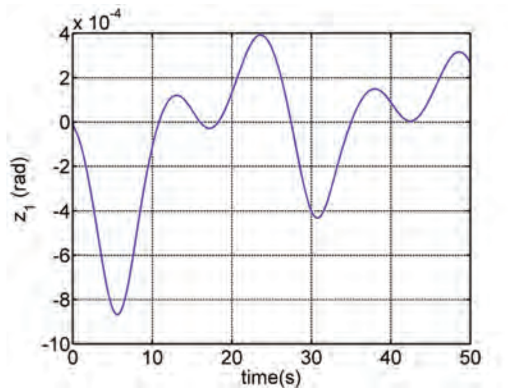

Figure 5: Actuator position error

The benefits of this control are advantageous for pump switching. Transient performance is guaranteed allowing for smooth transitions between actuators. Additionally, the scheme is robust to both uncertain nonlinearities and parametric uncertainties and, for certain cases, tracks the change in parameters reliably. Under the right conditions, a robust residual fault detection system can be derived based on this technique. Furthermore, the controller can be designed to respond to failures. Since the information from the fault detection residuals could be trustworthy, these parameters can be utilized to generate a fault-tolerant controller for certain kinds of failures.

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

- Translate the intelligent controls for handling pump switching transitions and optimal performance to the 5-ton hydraulic hybrid DC prototype. Deliverables include:
  - Optimal pump controls for pump switching transitions to minimize pressure transients resulting from opening and closing valves [05/01/2014]
  - Implementable advanced adaptive robust controls for the excavator actuators including the hybrid swing [08/01/2014]

- System prognostics design, study and simulation. Deliverables include:
  - Simulated machine fault detection system for certain modes of failure [05/01/2014]
  - Simulation results for all proposed prognostic concepts [07/01/2014]
  - Feasibility study of the utilization of a robust fault detection system [08/01/2014]
  - Simulation of fault detection system for the accommodation of certain faults [10/01/2014]
  - Implementable fault detection system with fault-tolerant controls [12/01/2014]
  - Implemented and fully functional system prognostics [01/06/2016]

The proposed work will enable in the long term, the introduction of efficient displacement-controlled hybrid systems to the market by reducing production and operation costs. Furthermore, system prognostics will make machine more effective by predicting failures using already installed sensors.

C. Member Company Benefits

The results of project 1A2 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 1A2 onto test bed 1 provides a usable prototype that can be evaluated and tested by industry members.
- The project has 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.
- The improved efficiencies and potential for reduced engine power will help OEMs meet upcoming emission regulations under the TIER emissions standards.
- The improved efficiencies 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.
- The possibility of reducing production costs will facilitate introduction of this technology to the market.
- The implementation of advanced prognostic systems will increase machine reliability over traditional systems and will make displacement controlled actuation a more competitive technology.
- Project 1A2 has led to associate projects where multiple sponsors have worked 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: Next Steps towards Digital Prototyping of Pumps and Motors

Research Team

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

1. Statement of Project Goals

The goal of this project is to help transform the design of hydraulic pumps and motors from a cumbersome task, requiring significant trial-and-error testing, to a modern approach driven by numerical simulation and digital prototyping. Previous research has developed fluid-structure-thermal simulation models which are capable of predicting the performance of critical lubricating interfaces inside axial piston machines. This research addresses three key areas which must be investigated before these models can be used in practical pump design. They are:

1. Only two of the three lubricating interface models have been directly validated with physical measurements to date. This project is constructing a test rig to measure the fluid film thickness between the slipper-swashplate and compare measured values to simulation results.
2. A good estimation of the pump leakage and discharge port temperatures are needed by the new lubrication models and this information is unknown at the design stage of a new pump or motor. The development of a pump thermodynamic model that solves for these unknown boundary temperatures is essential to enable practical virtual prototyping.
3. The latest virtual prototyping and optimization techniques will be used to propose surface/material modifications to improve pump efficiency. Simulated designs will be manufactured and physically tested to validate the computational work.

2. Project Role in Support of Strategic Plan

Piston pumps are often at the heart of many high power hydraulic systems and are especially critical in the energy saving displacement control and hydraulic hybrid architectures, both of which are concepts that have been proposed and developed in the CCEFP. By improving the efficiency of pumps and motors over a wide range of operating conditions, it enables system designs to successfully compete with alternative technologies. This project aims to complete the three goals listed above, enabling a digital prototyping approach to a new generation of pumps and motors. Virtual prototyping represents the only practical design method to create more efficient designs, utilizing new technologies for surface shaping, material coatings and other advanced manufacturing technologies.

3. Project/Test Bed Description

A. Description and explanation of research approach

Positive displacement pumps are a critical element of hydraulic systems. Although numerous pump designs exist, swash plate type axial piston machines are widely used today in industry due to their high pressure and variable displacement capabilities, and their cost to efficiency ratio. The hydraulic systems in which these machines are used demand a wide range of pump operating conditions, necessitated by system performance requirements. Unfortunately, axial piston machines reach their peak efficiency only over a limited range of operating conditions near full displacement. 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 sliding interfaces, as illustrated in Figure 1, determine in large part the achievable machine performance (speed, pressure, and maximum swash plate angle) and overall efficiency.

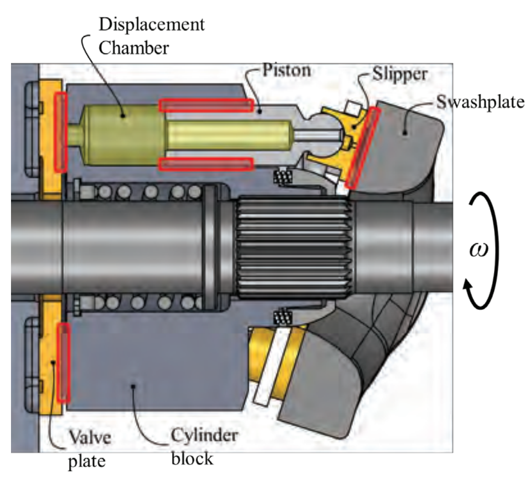

Figure 1: Swashplate axial piston machine cross section; the three lubricating interfaces in red

The energy dissipated in the sealing and bearing gaps represents up to 90% of entire machine loss at low displacement and up to 60% at maximum displacement. Advancing the development of lubrication models, which predict the gaps energy losses, to be of practical use in virtual prototyping is essential to propose better gap designs. These innovative designs will lead to better machine performance and increased efficiency especially at low displacements.

B. Achievements

Achievements prior to the reporting period

Previous work, much of which has been part of CCEFP core research projects, made significant progress advancing an initial relatively simple fluid domain - rigid body model of piston machine lubrication. Through these efforts, pressure deformation of the bounding solid bodies is now included in the model for all three critical lubricating interfaces [1, 2]. This micrometer-scale elastic deformation resulting from hydrostatic as well as hydrodynamic pressure sources is found using an integrated finite element method solver. The fluid pressure is solved using modern conjugate gradient or multi-grid methods [3]. Capturing the interaction between deformation of the solid, and fluid pressure generated due to solid deformation is resolved with a novel fluid structure interaction solver.

More recently, thermal effects have been included in the lubrication model. As the components are warmed due to the friction of lubrication, local temperature changes affect viscosity of the lubricant due to the visco-thermal effect of the fluid. Additionally, heating causes the solid bodies to elastically warp from thermal expansion, an effect especially pronounced in bi-metal components. By coupling a thermo-elastic finite element solution with the lubricating model, the entirety of physical phenomena affecting lubrication performance is captured by the multi-domain model [4].

Previous research also investigated the effects of changing elastic constraints on the solid bodies by comparing simulated to measured piston friction [5]. A secondary study was conducted comparing simulation results to temperature measurements of the lubricant between the piston and cylinder [6]. Both studies showed strong agreement between measured and simulated values, confirming the validity of the modeling approach.

Achievements during the reporting period

As previous research has shown, the lubricating performance of a piston machine is sensitive to both localized and bulk temperatures due to the thermo-viscosity dependence of the fluid. While localized heating can be calculated knowing the lubricant viscous shear and component geometry, the bulk body temperature depends on fluid inlet, outlet and case port temperatures. While the fluid inlet temperature is clearly an unknown which must be specified by design, the outlet and case port temperatures depend on the performance and design of the hydraulic pump or motor. Thus, for a given inlet temperature a problem arises to determine the working temperature of the fluid in the case and outlet volumes as a function of operating condition (speed, differential pressure and displacement). To model the temperature of these two fluid regions, first the temperature is assumed to be uniform throughout the volumes; moreover when steady state conditions prevail, time variation is not of interest and thus a lumped parameter approach is well suited to describe the problem. Thus the governing equation is the conservation of energy for an open system:

$$\sum \dot{m}_i h_i - \sum \dot{m}_o h_o + \dot{Q} - \dot{W} = 0$$

Equation 1

Equation 1 states that the difference in the rate of energy in and out the systems equals the difference in the rate of work and heat exchanged by the system with the surrounding environment. The energy balance is applied to the case and outlet control volumes in order to obtain a system of two equations, which is then solved to determine the two unknown temperatures in the case and outlet volume [7]. These two control volumes and associated heat transfer sources are illustrated in Figure 2.

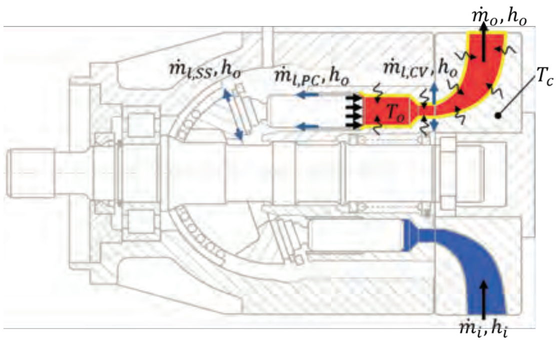
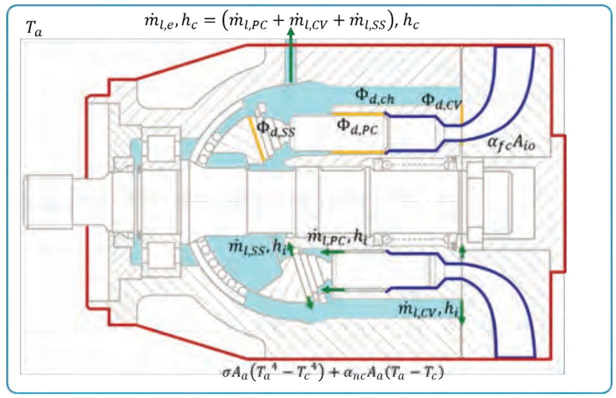

Figure 2: Outlet port thermal control volume (left), pump case/housing thermal fluid control volume (right)

Steady state measurements were taken on an existing axial piston swashplate type pump at two speeds and three pressures. Simulations were run using the parameterized pump design and the newly developed thermal model [8]. The predicted versus measured case drain fluid temperature is plotted in Figure 3. While the port temperature is at times under-predicted by up to 5°C, the model correctly predicts the trends of increasing temperature with shaft speed and pressure.

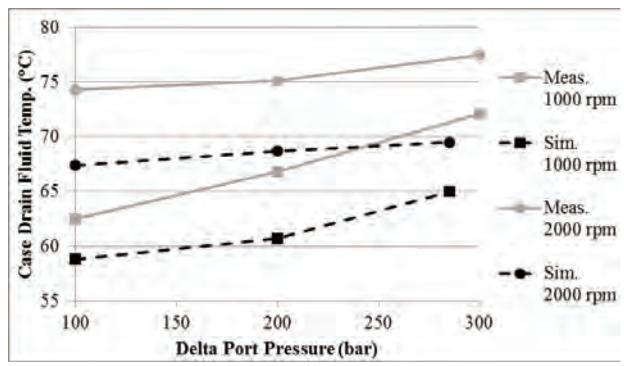

Figure 3: Measured and simulated case drain temperature

To further validate the lubrication model of the cylinder block – valve plate interface, a pump was specially modified to include 22 thermocouples located 0.5mm below the valve plate running surface (Figure 4). By locating the thermocouples close, but not through the valve plate surface, the manufactured surface finish remains intact and there is no disruption to the fluid film. The special instrumented valve plate and end case is shown below as well as a comparison between the simulated and measured temperature fields [9]. The simulation is able to correctly predict the temperature distribution both in shape and magnitude to within a few degrees. This again confirms the accuracy of the modeling approach used.

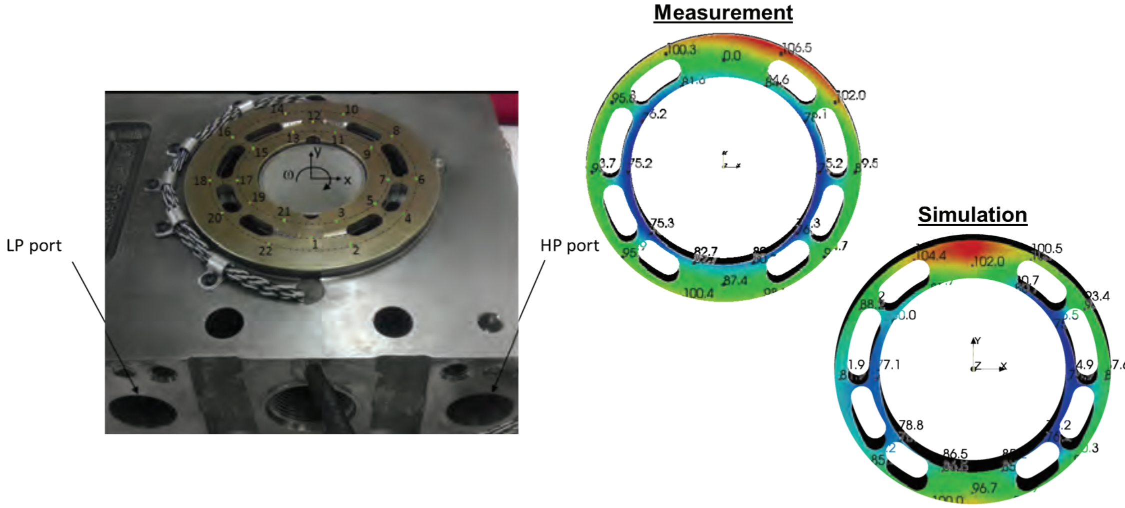

Figure 4: Thermocouple instrumented valve plate (left), Measured and simulated valve plate temperature distribution (°C) at 2000 rpm, 200 bar, 50% displacement (right)

The previously experimentally validated piston – cylinder block lubrication model was utilized to investigate the sensitivity of energy dissipation versus piston-bore clearance. The bore clearance from a commercially manufactured variable displacement swashplate type axial piston machine was varied in percentage from 30% to 130% of the nominal design. Twelve full displacement operating conditions were simulated as presented in Figure 5. It is noteworthy that the newly developed pump port temperature thermal model was utilized to aid in establishing port temperatures at the highest power operating conditions. While the nominal design is close to the theoretical optimum clearance, these simulation results indicate improvements can be made by further reducing the bore diameter. Practically however, the minimum bore diameter will be limited by machine reliability and manufacturing tolerancing.

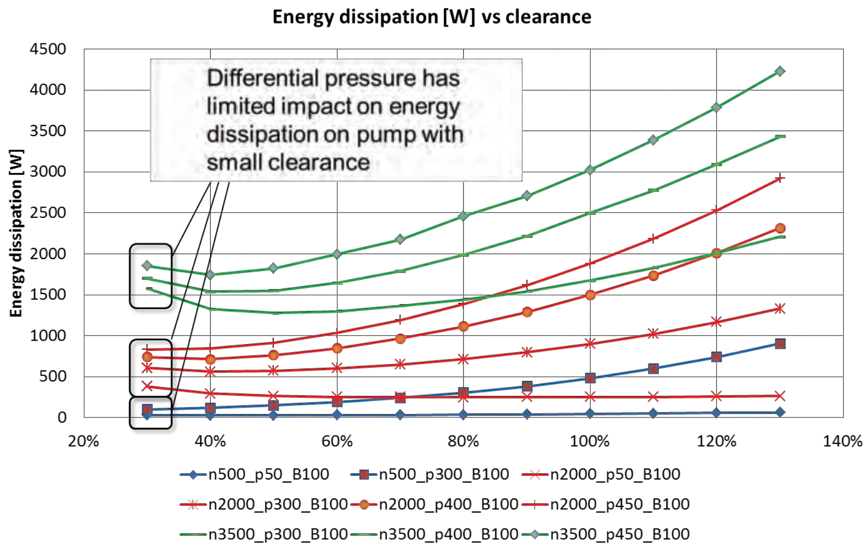

Figure 5: Piston-cylinder lubrication energy dissipation varying bore clearance

While experimental studies have been conducted to validate the piston-cylinder bore and cylinder block – valve plate lubrication models, to date the authors of this work have not directly validated the slipper – swashplate lubrication simulation model. While it stands to reason since the modeling approach utilized for the slipper is the same as the other validated models, it should be correct, the authors have decided to independently validate the slipper-swashplate lubrication model. Moreover, this validation will directly measure the dynamic fluid film thickness between the slipper and swashplate in a commercially produced axial piston machine. Due to the high pressure, fast transients, compact packaging, and fine resolution required by the sensing element, significant effort has been undertaken to pre-test and validate the intended sensor. These tests have finally settled on a customized commercially manufactured eddy-current displacement senor and a minimally invasive redesign of the swashplate body to accommodate sensor placement. Although this test rig will require slight modification of the lubricating surface directly, great care is being taken to minimize disruption from the original pump design.

Planned Achievements following the report period

With preliminary slipper fluid film thickness sensor testing completed and a design finalized, final machining of the modified swashplate is underway. Following a careful sensor installation and calibration phase, high-speed measurements will be taken at multiple operating conditions (port pressure, shaft speed, partial unit displacement). The measured film thicknesses will then be compared to simulated predicted lubricant height using the developed slipper-swashplate numerical model.

Further efforts are underway to improve the fidelity of the pump port temperature thermal model. This will include work to better capture impact of fluid enthalpy versus pressure and temperature, experimental determination of convection coefficients, and model validation using a larger sample of steady state measurement values.

Similar to the piston-bore diameter clearance study, a large scale virtual prototyping design optimization is underway to investigate the impact of piston micro-shaping on lubrication operation. This effort is not only varying the magnitude of the micro-wear but also the shape profiles. While the intent of the micro-wear study is partially to improve lubrication efficiency, it also has the potential to eliminate the necessity for machine run-in wear to achieve full film lubrication. Eliminating run-in wear would allow for the use of more sophisticated materials, tailored to specific application demands.

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 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 [10].
- Preferential patent licensing options for waved pump lubricating surfaces [11, 12].
- Project 1B.1 research has led to seven associated projects on pump modeling with different member companies with a total investment of approximately $1.1 million since 2006.

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Project 1D: Microtextured Surfaces for Low Friction and Leakage

Research Team

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Undergraduate Student:	Madeline Popelka
Industrial Partners:	Trelleborg, Eaton, Caterpillar, John Deere, Hoowaki

1. Statement of Project Goals

The goal of the project is to enhance the performance of fluid power components using microtextured surfaces that have significantly reduced friction and leakage relative to state of the art. These performance enhancements will be enabled by a fundamental understanding of lubricant behavior on microtextured surfaces, application of microtextured surfaces to fluid power components and design of viscoelastic properties of lubricants. Target applications include reciprocating rods, as well as seals and rotating components. We will fabricate and test microtextured plates, rods, and shafts. We will then integrate these components in the excavator and the orthosis test beds, and also test them in industry.

2. Project Role in Support of Strategic Plan

Our 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 testbeds. 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 fundamentally understanding lubricant/microtexture producing fluid power components that have lower friction and leakage compared to state of the art.

Until recently, there were two key technical challenges to realizing microtextured surfaces in fluid power applications. First is the inability to manufacture microtextures on real surfaces at scale, and second is the lack of design engineering design rules. Whereas other work has considered semiconductor surfaces [5], microtextured steel using photolithography and chemical etching, [2], and laser texturing [1, 3, 4], these techniques are not scalable, not applicable to curved substrates, prohibitively expensive, or 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] and is the approach used in this research. A standard industrial investment casting process is modified to incorporate microstructures into the investment mold. 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.

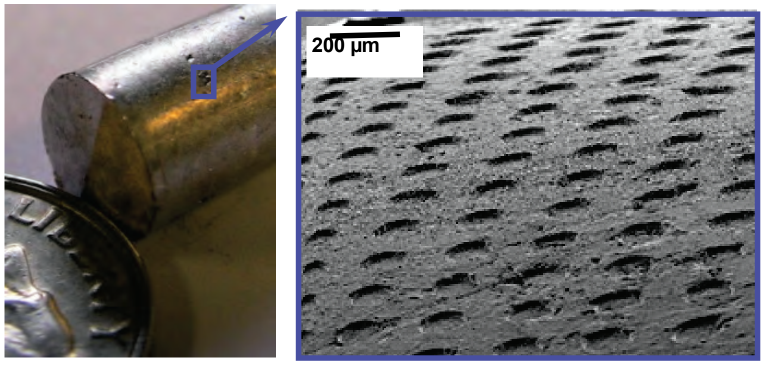

Figure 1: Metal surfaces fabricated with surface micro-textures. This surface is similar to a rod surface we will explore in the proposed research.

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.

Our objective is to develop and validate design rules. There is disagreement in literature about the exact physical mechanism but there is some experimental evidence for cavitation being the primary mechanism [11]. No prior experimental study has explored the dimensionless parameter space in terms of Reynolds number and dimensionless gap, since normal force control is more readily implemented. Our approach is to perform gap-controlled measurements of microtextured plates in shear. We use a modified rotational rheometer with customized components to achieve precision alignment of parallelism and gap thickness. This fundamental understanding will be completed by further development of the computational tool used to predict friction reduction and through constant gap experiments on a rotational rheometer. Second, after design rules have been validated for constant gap applications we will use our computational tool to develop intuition on how to design microtexture shape, orientation and asymmetry along with design of viscoelastic fluid properties to further reduce or eliminate fluid leakage.

B. Achievements:

Achievements in previous years

Under CCEFP support, the team has performed both experiments and simulations to develop the first comprehensive approach to engineering microtextures for fluid power.

Microtextured surfaces decrease friction: Tribometer experiments with controlled normal force, and computational fluid dynamics (CFD) simulations, confirm friction reduction with microtextured surfaces, validate computational modeling, and provide design rules for microtextured surfaces. The goal of these experiments was not to mimic fluid power conditions, but to validate the simulation. Friction reductions as much as 80% lower than untextured surfaces were achieved and results were published in Tribology International [10].

Microtextured surfaces improve leakage: 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 defined 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. When one surface is microtextured, there is a range of textures for which there is a significant benefit for both friction and leakage with F-L >1.

Achievements in the past year
In the past year, a novel experimental platform has been validated for gap-controlled experiments. It has contributed to the fundamental understanding of the physics of confined liquids and validated computational models of reduced friction with microtextures and Newtonian fluid.

Development of a novel gap-controlled tribo-rheometer: This instrument enables gap-controlled tests to systematically vary the appropriate dimensionless groups (which include gap thickness) involved in the co-design of microtextured surfaces and lubricant fluids for reduced friction and leakage. The instrument employs a transparent precision-aligned glass plate lower boundary for visualizing flow. Applications include friction and leakage reduction in fluid power systems; friction reduction has been measured and compares well with computational predictions [12, 13].

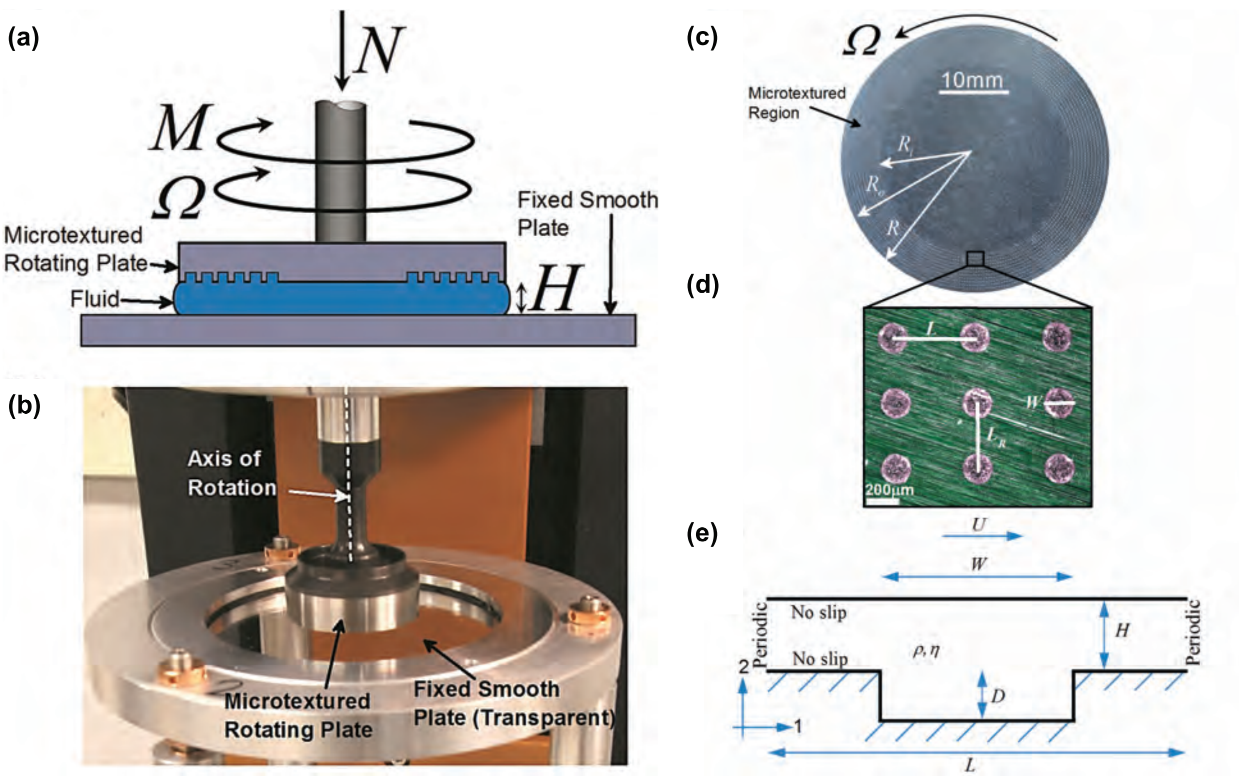

Figure 2: (a) The experimental setup uses a rotational rheometer where gap height H, angular velocity Ω, torque T and normal force N are measured or controlled. (b) Custom precision-aligned glass bottom plate with top custom microtextured plate attached. (c) Microtextured plate (full view), radius R = 20 mm. (d) Microtextures imaged with 3D optical microscopy. (e) Seven dimensional variables define the model microtexture with a Newtonian fluid

Physics of confined liquids and the influence of surface tension: The precision instrumentation has broadly impacted the study of confined liquids in shear. Striking observations have been reported elsewhere for elastic shear modulus of water, glycerol, and other simple liquids at low frequency and small gaps (Noirez et al. 2012; Noirez and Baroni 2012; Noirez and Baroni 2010). We were able to measure, and theoretically explain, that these results may actually from surface tension line forces that are amplified at small gaps. We published this in the Journal of Rheology [14]. This same effect can also cause the incorrect appearance of shear-thinning viscosity (Figure 3). The transparent plate visualization, coupled with precision alignment of the tribo-rheometer, enabled this contribution. Such effects must be considered for any small gap measures, including but not limited to fluid power applications.

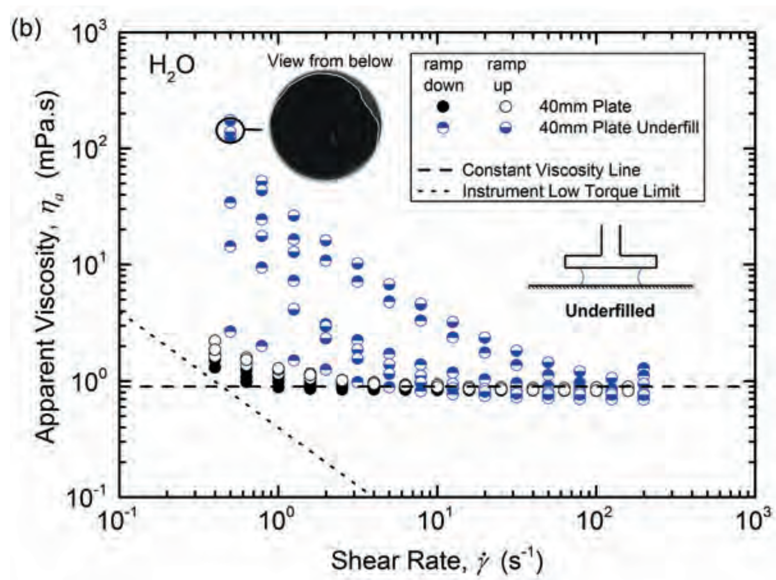

Figure 3: Anomalous shear-thinning viscosity can be explained by surface tension asymmetry, which is amplified by a slight 50 µL underfill. Visualization of the contact line ("View from below" dark circle with white line) is possible with the custom-built transparent plate of the tribo-rheometer instrument. (figure from [14])

Fundamental understanding of reduced friction with microtextures and Newtonian fluids: We have developed a dimensionless framework for understanding friction reduction, and to outline the full design space for the co-design of microtextures and fluids. Figure 4 shows three different microtextures with differing dimensional values that have the same non-dimensional geometry parameters, H*, D*, and W*. Results from simulations show that non-dimensional normal force, P*, and shear stress, T*, are equal for the three microtextures at a given Reynolds number, Re_H.

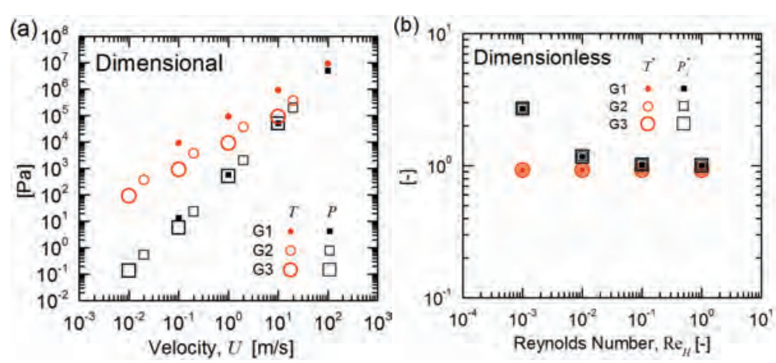

Figure 4: Non-dimensional analysis of reduction in shear friction (T*), and increase in normal pressure (P*) due to microtextures (computations). The dimensional data in (a) are replotted in (b) in terms of the dimensionless representation, which simplifies the design space. The Reynolds number Re_H depends on the gap H, which can be independently controlled in our tribo-rheometer setup.

Gap-controlled experimental results with microtextures have been performed. The results agree with computational modeling for symmetrical microtextures with Newtonian fluid, shown as dimensionless parameters in Figure 5. This validates the new experimental gap-controlled setup, as well as the computational modeling. This is required to explore more complex scenarios of asymmetric microtextures and non-Newtonian fluids, which will be pursued in the coming year.

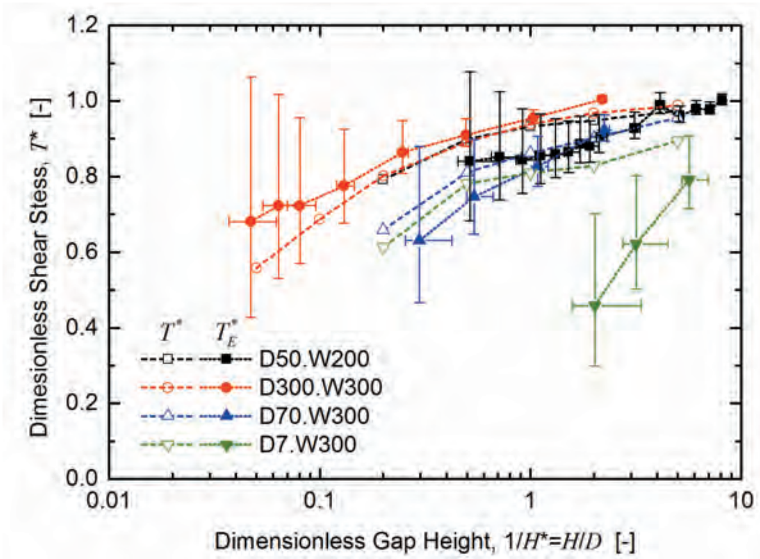

Figure 5: Gap-controlled tests to compare dimensionless friction reduction from numerical T^* and experimental T^*_E results. Geometry names D*.W* indicate depth and width, respectively, of cylindrical microtextures in units of μm.

C. Plans

Plans for the next year

Current and future work will build on the success of the past year. The new gap-controlled tribo-rheometer has been validated, and can now be used for more complex scenarios, including asymmetric microtextures and non-Newtonian fluids. These are potentially huge parameter spaces to explore. The studies will be framed with appropriate dimensionless parameters. The asymmetric microtextures to be fabricated will have asymmetric depth profiles and contour shapes. We anticipate that asymmetric textures will enhance the normal force and may also induce secondary flows that can counteract leakage. Such secondary flow can be visualized with the transparent bottom plate on the tribo-rheometer. Non-Newtonian fluids will be tested with both symmetric and asymmetric microtextures. These fluids have the potential to further increase normal force and induce secondary flows that inhibit leakage. We have also started to develop CFD capabilities that will enable us to explore the impact of viscoelastic properties on friction reduction and fluid leakage.

Expected milestones and deliverables

- Fabricate and test asymmetric microtextured plates with Newtonian fluids.
- Test non-Newtonian fluids with symmetric and asymmetric microtextures.
- Develop computational predictions for non-Newtonian fluids with microtextures.
- Explore design space and optimal conditions in the context of fluid power systems.

D. 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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Industrial Partner(s):	Eaton, Parker Hannifin, Danfoss, and others

1. Statement of Project Goals

The goal of the project is to demonstrate efficient, high performance 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). The prototype VVDPM will then be performance mapped, with operating speed/torque ranges that coincide with CCEFP test bed 3. 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 goal of increasing efficiency 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.

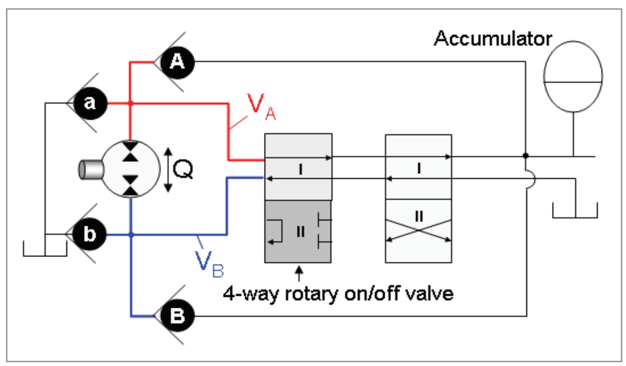

Figure 1: Hydraulic schematic of a VVDPM using a 4-way tandem rotary on/off valve. Check valves a and b prevent cavitation while check valves A and B reduce pressure spikes during transition.

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.

The approach of the project is to develop novel on/off valves that use continuous rotary motion to generate on/off switching [10]. 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.

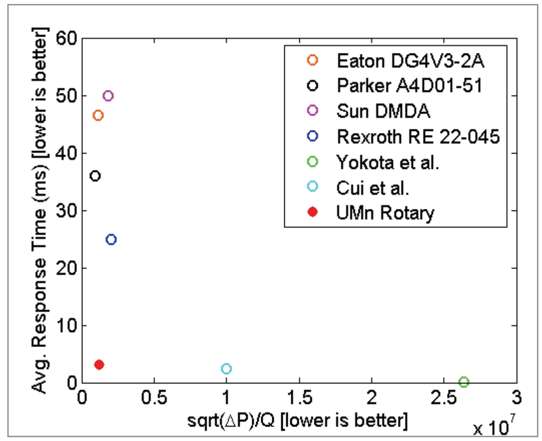

Figure 2: Effective flow area and response times of existing on/off valves

B. Achievements

Achievements in previous years

An analysis-driven design of a virtually variable displacement pump/motor based on a rotary valve was completed in Year 6 of the center. No further funding for this project was requested after Year 6. However, a prototype was constructed using carry-forward funding. The prototype is based on the spool valve architecture that has been under development since the inception of the CCEFP [10, 17]. 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 [13, 16]. The prototype utilizes a commercially available fixed displacement bent-axis pump. It was combined with the rotary valve by re-packaging it in a custom case.

Efficiency testing was attempted at a Danfoss lab. Unfortunately, the rotary valve seized during this trial. The valve continued to be plagued with seizing issues for the next year after returning it to Minnesota, so the efficiency of the VVDPM has yet to be mapped successfully.

Achievements in the past year

Achievements over the past year include replacing the rotary valve spool with an improved spool, removing contaminants in the valve, inspecting the rotary spool and sleeve, and operating the prototype successfully as a motor in manual mode. These achievements are described below.

We suspected that seizing of the spool was attributable to material incompatibility between the stainless steel spool and steel sleeve. A new spool was plated with a diamond-like carbon (DLC) surface treatment to resolve this issue. The new spool can be seen in Figure 3.

Contamination was found inside the prototype which caused damage to the previous spool and to the ID of the sleeve. This was addressed by changing both the pressure and return filters in the hydraulic power unit and purging the contaminated oil. In addition, a high pressure filter was added immediately before the pump/motor. The sleeve was honed to remove the scratch marks.

All the bearing surfaces of the spool and sleeve were measured with a coordinate measuring machine for roundness and cylindricity. This showed that the current spool and sleeve fit together as designed, even after surface treatment, with proper mechanical clearance, while also being tight enough to hold high pressure.

Figure 3: The DLC plated 4-way spool

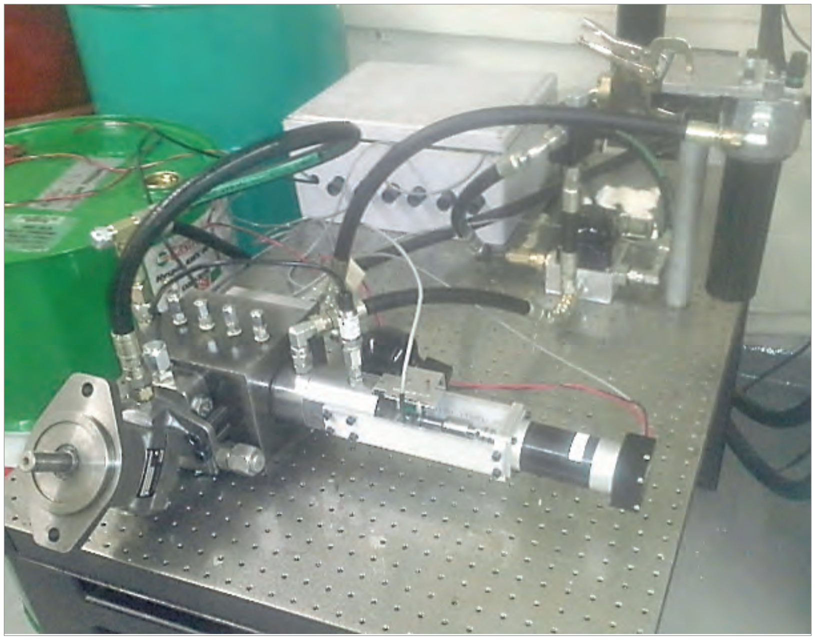

Figure 4: Prototype setup. Filter on supply oil can be seen on the right.

The prototype has now operated successfully as a motor. Figure 4 shows the prototype set up for further testing. We learned that the motor shaft needs sufficient inertia to average out the pulses attributable to the valve. The motor shaft without any inertia tended to slow or stop during the time when the valve was "off" (when the motor ports are connected). This causes a shuddering motion of the shaft. A wheel was rigged to a hub to add inertia to the motor shaft, and the motor then operated as expected at various speeds. This test was qualitative in nature to show that the seizing issues have been addressed, and that the spool porting is correct. While the system was designed with an automatic controller to set the spool position, the speed has been set by manually pushing the spool in and out during de-bugging.

a) Plans for the next year

This project is nearing completion. No additional funding is expected through the CCEFP. Now that the pump/motor prototype is completed, its efficiency will be evaluated. First, the controller to set the axial position of the rotary spool will be re-installed. Then, a pump/motor test stand available at the University of Minnesota will be utilized to create a performance map of the device. Next, the Generation I Hydraulic Hybrid Vehicle will be used to create a torque-speed profile corresponding to a drive cycle. This profile will be used to drive the pump/motor test stand in a hardware-in-the-loop configuration to evaluate the average efficiency of the prototype device in the context of a real application.

If results are sufficiently promising, further development of an improved "ring valve" implementation of the device may be pursued through external funding sources.

b) Expected milestones and deliverables

- Torque-speed performance map of pump-motor generated (4/30/14)
- Efficiency for hardware-in-the-loop simulation of pump/motor using HHPV drive cycle measured (3/1/15)

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. Also, the practical knowledge gained and challenges to be overcome in turning the concept of a PWM controlled VVDPM into a working prototype will be an asset as high speed on/off hydraulic valve technology evolves.

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

Research Team

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Graduate Students:	Farid El-Breidi, Tyler Helmus
Industrial Partners:	Eaton, Parker Hannifin, Poclain, Danfoss

1. Statement of Project Goals

The goal of this project is to translate the successful fundamental research of pump chamber voiding and the test bench experimental results of a three piston digital pump/motor to implementation on a test bed (hydraulic vehicle or excavator) for demonstration and eventual industrial commercialization. This requires two outcomes: the development of optimal control strategies that allow the digital pump/motor to switch seamlessly between operating modes (flow limiting/flow diverting) while maintaining optimal efficiency and minimal noise, and the compact integration of valves and embedded controls to enable mobile operation. During the previous cycle, full four quadrant operation was demonstrated in all proposed operating modes, and efficiency and noise tradeoffs were characterized for each mode. The results have been encouraging and provide motivation for a focused effort to implement a digital pump/motor on a test bed.

2. Project Role in Support of Strategic Plan

The project will overcome a major system efficiency limitation in the fluid power industry by improving the efficiency and dynamic performance of piston pump/motors. Regardless of the fluid power system, overall efficiency is limited by the efficiency of the primary pump/motor. Project goals will be achieved by leveraging the test bench, simulation, and experimental results from the previous grant cycle to migrate the pump/motor design to a test bed. Current test bed results have demonstrated higher operating efficiencies at lower displacements, four quadrant operation, high displacement control bandwidth, and high operating pressures.

The project directly supports Thrust 1: Efficiency, and improves Test Bed 1 and Test Bed 3 overall performance. It also impacts Thrusts 2 and 3, Compactness and Efficiency, respectively. Specifically, this project overcomes the following technical barriers for each thrust:

- Efficient Components and Systems (improve pump/motor efficiency at low displacements)
- Efficient Control (real-time optimal control flexibility)
- Efficiency Energy Management (piston-by-piston control of energy)
- Leak Free (positive sealing poppets replacing port plates)

3. Project Description

A. Description and explanation of research approach

Current state-of-the-art variable displacement pump/motors have high efficiencies when operating at high displacements. However, as the displacement of the pump/motor is reduced, the efficiency significantly decreases due to 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 fixed and 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). By actively controlling high speed on/off valves connected to each piston cylinder displacement chamber, digital pump/motors can increase the efficiency and potential applications within fluid power systems by minimizing leakages, friction losses and compressibility losses.

There are ongoing international research activities related to digital pump/motors. A primary motivation is that digital pump/motors allow the displacement chambers to remain at low pressure when not needed, reducing the losses [1]. Artemis Intelligent Power Ltd. used a radial piston configuration and mounted two electro-hydraulic latching poppet valves for each displacement chamber. This allows the valves to be latched in the open state and divert the fluid in the piston chamber to the low pressure port achieving variable displacement flow. In this unit, the compressibility, shear and leakage losses scale more closely with displacement [2]. The overall efficiency of this unit was high throughout a wide range of displacement [3]. However, the valves can't be actuated against high pressure, so this allows having only one high pressure port and one low pressure port, which prevents the Artemis unit from self-starting when motoring without adding additional valves.

The design of the project's digital pump/motor allows for expansion into other state-of-the-art efficiency designs with few modifications. The versatility of this design comes from the ability to independently control the fluid flow of each piston chamber. Individual control allows each piston to act as an independent pump/motor depending on conditions in the hydraulic system. With this type of control and minimal additions, control structures can be implemented to allow for different pressure outputs, energy recovery by motoring on certain pistons and pumping on the others, and energy storage to and recovery from accumulators independently as described in the work of Linjama and Huhtala [4] and experimentally validated by Heikkila *et al* [5]. This can produce differing pressures from the same pump/motor and could thus be used to replace and improve the dual pump/motors found in the Integrated Energy Recovery system [6].

B. Achievements

Previous work in Project 1E.3 developed a coupled dynamic model of a digital hydraulic pump/motor and an experimental test stand that is crucial for understanding the design tradeoffs and operating characteristics of the digital pump/motor [7-9]. The simulation model was used to characterize and predict the efficiency, define the dynamic response and flow requirements of the on/off valves, and perform design optimization studies. The model has been used to characterize different operating strategies (flow limiting and flow diverting) and the effects on pump/motor efficiency and flow ripple. The three-piston pump/motor unit was used to experimentally validate the model, design, and operating strategies of a digital pump/motor. A schematic of the test bench setup is shown in Figure 1. This is a regenerative circuit. If the digital unit is pumping the regenerative unit acts as a motor and puts power back onto the shaft. The electric motor then only has to make up the losses of the two units and there is less heat generated and less electrical power required to run the test stand.

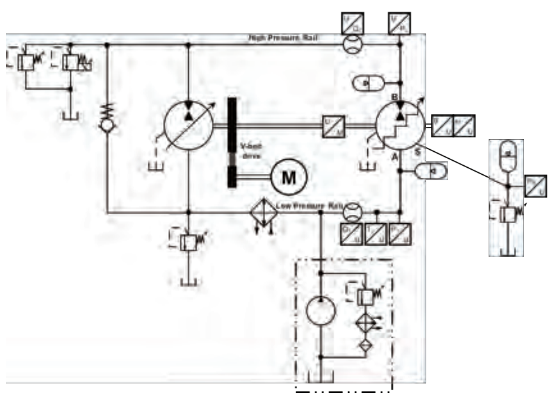

Figure 1: Schematic of test stand.

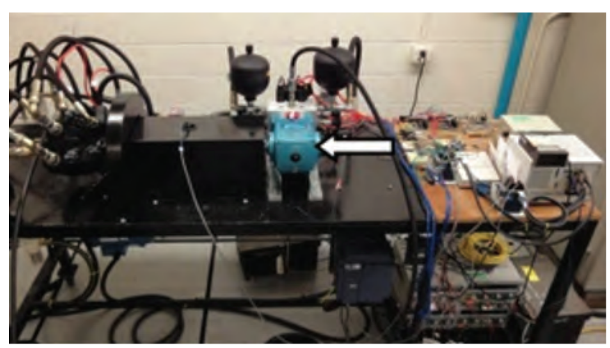

Figure 2: Research test stand.

The 3-piston digital pump/motor (light blue, arrow) and test stand is shown in Figure 2. Each piston has two on/off valves, one at the low pressure side and one at the high pressure side. There are three 2,000 Hz pressure transducers measuring the pressure in each of the displacement chambers. A check valve is connected to the displacement chamber to provide a safe release of the displacement chamber pressure in the case of missed valve timing. There are different methods to achieve partial displacement for pumping and motoring in digital pump/motors with two on/off valves. These methods, partial flow-diverting and partial flow-limiting, were described by Nieling *et al* [10]. Simulation and experimental tests have successfully characterized the efficiency and noise tradeoffs of the different operating strategies (flow diverting/limited, sequential/partial stroke). Sequential flow-diverting operates on a piston-by-piston cycle, where all the flow from the displacement chamber is either diverted to tank or to system pressure. Another method of operation is sequential flow-limiting. This is similar to the sequential flow-diverting method described, but instead of diverting the piston flow the piston chamber is voided for a complete cycle. This method either completely voids a chamber or the piston does a complete pumping cycle depending on the displacement desired from the sequential algorithm. Construction of the digital pump/motor test stand has allowed the testing of fundamentally new operating strategies in pump/motors, similar to how camless engines in combustion research labs are used to explore new internal combustion strategies. This adds a fundamental contribution to the design of pump/motors beyond the development of a prototype unit (i.e. pump chamber voiding, verified on the test stand, could become the foundation for a new class of variable displacement pump/motors not currently envisioned by conventional designs).

Figure 3 shows the flow-diverting operation strategy of both sequential flow diverting (F-D) operation and partial F-D operation running at 700 rpm and 103 bar (1500 psi) pumping. The simulation efficiency results are 5% higher at full displacement to 20% higher at 25% displacement than the measured results due to variation in valve characteristics (based on static PQ tests and dry tests of valve position dynamics). The sequential flow limiting (F-L) and partial F-L operation strategies were comparable to the F-D results, as seen in Figure 4. However, as expected both the simulated and measured F-L results had better efficiency than the F-D results.

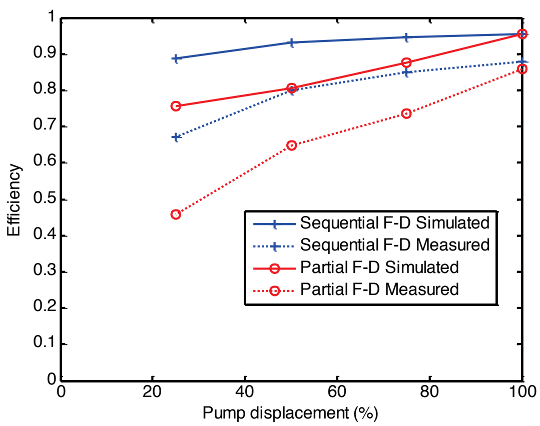

Figure 3: Sequential and partial flow-diverting, measured and simulated.

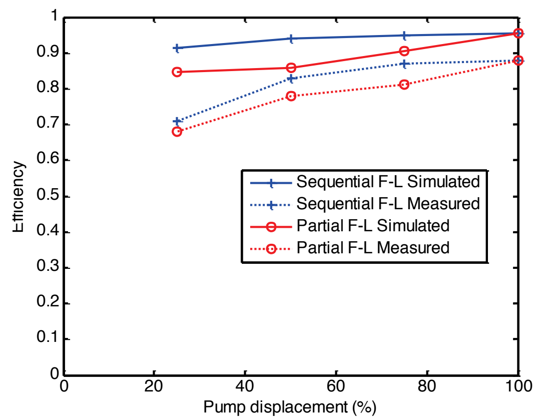

Figure 4: Sequential and partial flow-limited, measured and simulated.

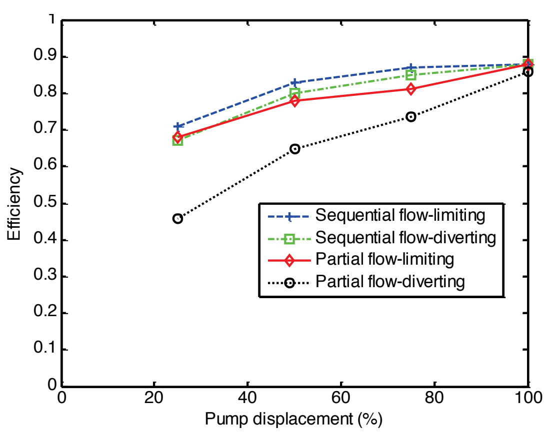

Figure 5: Measured results of 4 operating strategies at 700 rpm and 103 bar.

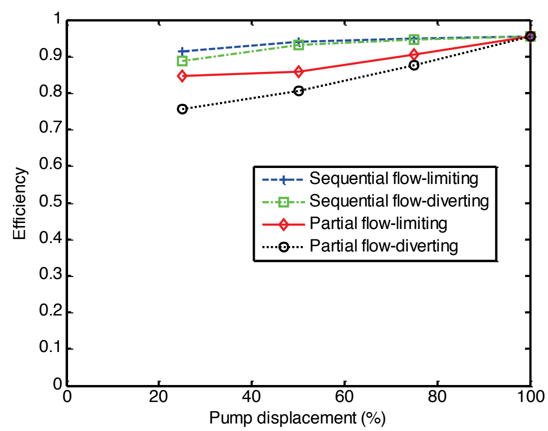

Figure 6: Simulated results of 4 operating strategies at 700 rpm and 103 bar.

Figure 5 shows the measured results of all four operating strategies when the digital pump is running at 700 rpm and 103 bar (1500 psi). The trends of the operating strategies are similar to the simulation results of the four operating strategies seen in Figure 6. The operating strategy with the best efficiency for the conditions and parameters stated in this work is sequential F-L, followed by sequential F-D, next is partial F-L and the worst efficiency is partial F-D.

The individual losses of the pump/motor are shown in Figure 7. With the 3-piston digital pump/motor, the friction loss due to the positive sealing on the piston does not scale with displacement and will result in a larger percentage loss when operating at a lower displacement of 25%. Since normally closed on/off valves were used, the electrical losses will be less for the sequential and partial F-L strategy because no electrical consumption is required when the piston's flow is being limited. The valve throttling loss is quite significant for the partial F-D and partial F-L operation strategy. This higher throttling loss is due to the valves relatively slow transition time and small flow area.

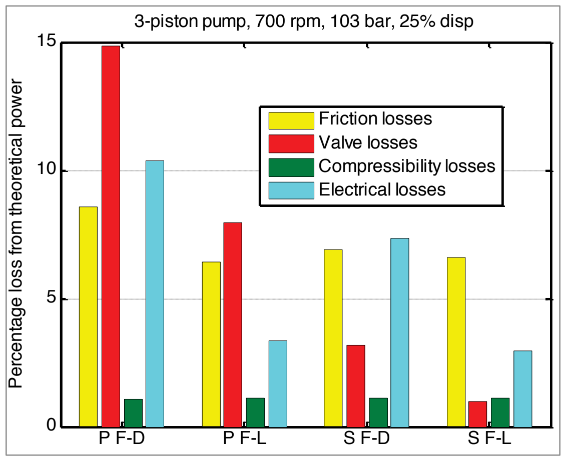

Figure 7: Simulation loss results, 700 rpm, 103 bar, and 25% displacement.

C. Plans

Plans for the next year

There are two primary tasks for next year. The first task is to develop and implement a real-time valve correction algorithm that uses pressure curves to automatically adjust the timing of signals to open or close the valves. These algorithms will initially be experimentally tested on the digital pump/motor test stand before being included on the embedded electronics of the mobile digital pump/motor prototype. An example cylinder pressure curve is shown in Figure 8. An overshoot or undershoot, caused by valves opening and closing early or late, would be detected by the algorithm and corrected on the subsequent piston cycle. Preliminary results obtained by manually editing the valve timing based on the overshoot and undershoot in the pressure curves yielded an improvement greater than 5% in efficiency.

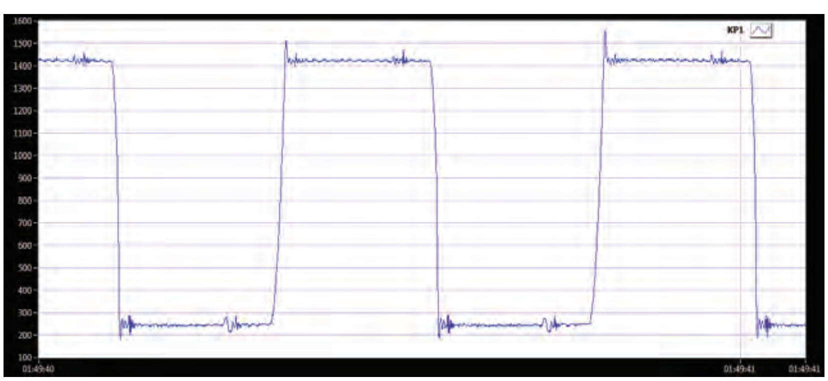

Figure 8: Pressure response curve for cylinder 1.

The second task is to investigate and develop the mode switching algorithm. Depending on the pressure and flow requirements, different operating modes are more efficient than others. The goal is real-time switching between operating strategies (partial flow diverting/limiting and sequential) based on the condition required (flow ripple, heat, torque ripple, efficiency...) with the goal of maximizing system efficiency and keep noise under allowable levels. Although this is easy to demonstrate on the test bench by manually selecting the operating mode, if the pump/motor is to be successfully implemented on a test bed, the controller must do this in real-time and while minimizing any feedback to the system during the actual mode switch.

Expected milestones and deliverables

Project Deliverables:

- Task 1: Develop and implement a real-time valve correction algorithm [6 months]
    - Use cylinder pressure curves to account for overshoot/undershoot
    - Experimentally validate efficiency improvement
- Task 2: Investigate and develop mode switching algorithm [6 months]
    - Real-time switching between operating strategies (partial flow diverting/ limiting and sequential) based on the condition required (flow ripple, heat, torque ripple, efficiency...)
- Task 3: Investigate the use of project 1E.6 valves [4 months]
    - Validate further efficiency improvement by using faster and less non-linear on/off valves, test valve transition shaping using the 1E.6 proportionality for minimal noise and maximum efficiency
- Task 4: Design and construct a test bed ready digital pump/motor prototype [12 months]
    - Integrate the electronics, valves, and rotary group into a mobile prototype
- Task 5: Implementing the portable prototype into an actual machine [4 months]
    - Implement digital pump/motor on TB1 or TB3
    - Coordinate with test bed owner and experimentally validate operational capability and energy savings

Milestones:

- Validated simulation and design tool for digital pump/motors [Completed]
- Multiple piston digital pump/motor test stand designed and built [Completed]
- Experimental characterization of digital p/m and operating strategies [Completed]
    - Confirmation of research hypothesis that digital pump/motors are capable of high efficiency over a wide operating range [Completed]

New for Y9/Y10

- Experimentally validated optimal control algorithms for maximum efficiency and minimal noise [September 2014]
- Experimentally validated mode switching algorithm [Feb. 2015]
- Design of test bed ready mobile digital pump/motor unit with integrated electronics, sensors, and rotary group [Oct. 2015]
- Construction of test bed ready mobile digital pump/motor unit with integrated electronics, sensors, and rotary group [Feb. 2016]
- Implementation of mobile digital pump/motor prototype on a test bed [June 2016]

D. 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 1E4: Piston-by-Piston Control of Pumps and Motors Using Mechanical Methods

Research Team

Project Leader:	Perry Li, Mechanical Engineering, University of Minnesota
Other Faculty:	Thomas Chase, Mechanical Engineering, University of Minnesota
Graduate Students:	Mike Rannow, Chad Larish, John Dekarski
Industrial Partner:	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. The focus is on creating a variable displacement pump/motor that can meet or exceed existing designs in peak efficiency, and demonstrate less of a 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 competing research approaches.

2. Project Role in Support of Strategic Plan

The need for efficient hydraulic components is 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 will also facilitate the realization of practical hydraulic hybrid powertrains in both on-highway and off-highway vehicles. The key element to the new design 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 pump or motor, which are typically variable displacement in order to reduce power losses in throttling valves. In existing designs, the efficiency of variable pumps and motors dramatically decreases as the displacement decreases. 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. In the majority of variable pumps and motors the 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, leakage and friction losses remain approximately 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 with displacement is the piston-by-piston variation method. Research that was initiated at the University of Edinburgh, and has continued with the start-up company Artemis Intelligent Power, 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. With separate valves controlling the fluid in and out of each piston, the constant losses associated with the valve plate are also eliminated.

The latching check valves have advantages over other types of valves with respect to actuation power. They also have ideal timing for pumping. However, they do not allow the device to be configured as a self-starting motor. CCEFP project number 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 does rely on multiple high-speed, electronically controlled valves per pumping piston, which can create cost and robustness challenges.

In project 1E.4, 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 CCEFP 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.

Using a mechanical control method offers many advantages. The first is simplicity: only a single control input, the axial position of the rotary valve, is needed. The second and third are robustness and cost: the pump-motor does not require solenoids, wires and current drivers for each piston. The fourth is low actuation power: the rotary valve does not need to be accelerated and decelerated, and it does not require a constant holding power as is typically the case in electrical valves. The fifth is repeatability: the valve is mechanically coupled to the drive shaft, thereby ensuring repeatable timing. The sixth is contamination resistance: significant torque is available to spin the valve through contaminated oil. The approach does also suffer one disadvantage: control flexibility is reduced as a result of replacing flexible electric controls with fixed mechanical controls. 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 were used to 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 was carried out with assistance from an industry champion (Danfoss), who has agreed to donate prototype parts.

B. Achievements

Achievements in previous years

The initial phase of this project, completed in 2011, was to examine 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 models used to generate this comparison were designed for a pump 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 was 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 clearly demonstrate that 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 approach removes the tradeoff between sealing and load bearing that exists in a typical valve plate.

In 2012, the rough design concept was developed into a detailed prototype design. The selected on/off valve concept was designed to fit into a custom pump housing for a wobble-plate style pump-motor. The design incorporates elements from a donated pump prototype, along with 25 custom designed parts. The detailed design of the pump/motor components was an iterative process that included dynamic modeling as well as computational fluid dynamics (CFD) analysis.

Achievements in the past year

A design review was held with industry champion, Danfoss, during which we received some helpful feedback on the design. The primary design changes resulting from the review centered on material selection and heat treatment options.

The current status of the design is that all but two of the custom parts have been received, and the drawings for the remaining parts have been sent to a prototyping shop to be manufactured. The parts that have been received have been partially assembled to ensure proper fits and clearances. After fixing some minor defects, all received parts fit together as designed (see Figure 1). The remaining components for conducting a test of the functionality and efficiency of the pump/motor prototype are being collected, with testing expected to begin early in Q3 of 2014.

Figure 1: Picture of partially constructed discrete piston pump/motor prototype

Throughout the project, modeling of the power losses has been updated to provide an estimate of the overall efficiency of a pump/motor using the piston-by-piston control approach. In simulating the designed valve control concept, it was found that the power losses in the motoring case are expected to be significantly higher than in the pumping case (see Figure 2). This is due primarily to the energy lost when compressing a low pressure volume of oil up to high pressure so that it can perform work on the pistons. A mechanical device that will automatically adjust the valve timing in pump and motor modes to eliminate the efficiency difference between the two modes has been designed. While this adjustment mechanism will not be included in this prototype, the pump/motor was designed to have flexible timing so that the effect of the timing adjustment can be quantified.

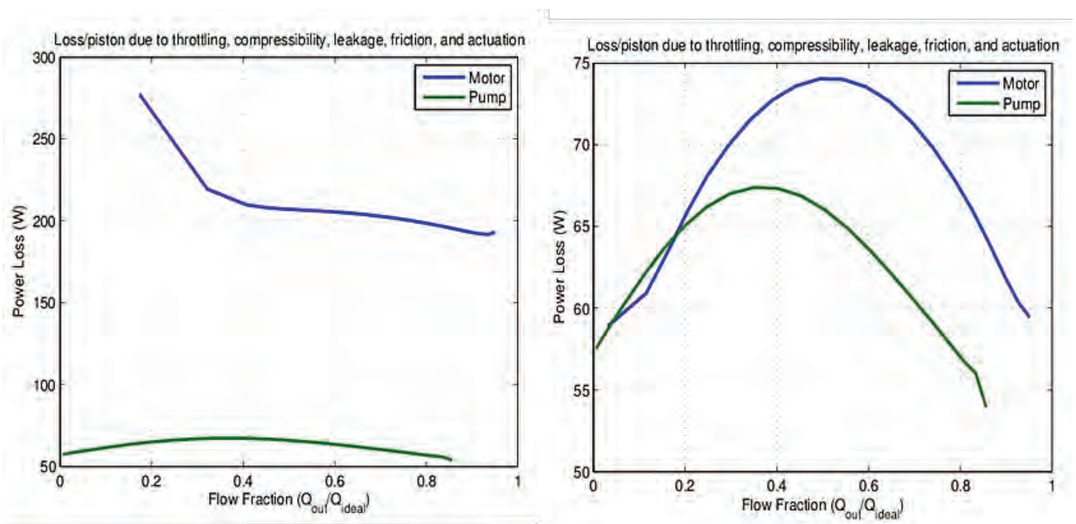

Figure 2: Power losses in the piston control valves without (left) and with (right) timing adjustment for the motoring case.

C. Plans

Plans for the next year

Assembly of the prototype pump/motor will be completed by May 2014. Three months are then allotted for ``shake-down'' testing and debugging. The pump/motor will be tested for efficiency and dynamic performance using a test stand available at the University of Minnesota. If the results are as expected, it will be taken through a torque-speed profile obtained using the Hydraulic Hybrid Passenger Vehicle in a hardware-in-the-loop configuration on the test stand. At that point, the original project plan will be complete.

If the efficiency tests are as promising as expected, member companies will be contacted to seek follow-up funding to further develop the technology. A logical next step for this research is to investigate whether the approach can be extended to a piston-by-piston transformer.

Expected milestones and deliverables

- 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 (complete)
- Analyze flow paths using Computational Fluid Dynamics (complete)
- Hold design review with Danfoss (complete)
- Complete construction of prototype (5/14)
- Complete de-bugging of prototype (8/14)
- Test efficiency of pump/motor and document with performance maps (12/14)
- Document results and seek follow-up external funding (5/15)

D. 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 1E.5: System Configuration and Control Using Hydraulic Transformers

Research Team

Project Leader:	Perry Li, Mechanical Engineering, University of Minnesota
Graduate Students:	Sangyoon Lee, Pieter Gagnon
Industrial Partners:	Eaton, Case New Holland, Takako Industries, iRobot

1. Statement of Project Goals
This project investigates how hydraulic motion control systems can best make use of hydraulic transformers to improve efficiency while maintaining control performance. Various existing and novel transformer designs and system architectures are modeled, analyzed and evaluated. Control approaches that maximize both efficiency and precision will be developed and demonstrated. These control approaches will be experimentally implemented on a transformer test bench and on the patient mover test bed (TB4).

2. Project Role in Support of Strategic Plan
Hydraulic transformers address the efficiency goal of the Center by providing a throttle-less and regeneration capable means to control hydraulic actuators. Transformers may also be amenable to compact integration with actuators. Efficient and high performance control of actuators with appropriate form factors could expand the use of hydraulics in human scale robotic applications. Demonstration of transformer performance in the new test bed 4 (patient mover) is targeted, although transformers also have applications in hydraulic hybrid vehicles, excavators, energy storage systems, and in small scale human wearable devices as well.

3. Project Description
A. Description and explanation of research approach
In a typical hydraulic system with a centralized hydraulic supply and multiple services (actuators), throttling valves are still being used predominantly due to their simplicity and capability for precise control. While a load sensing pump can reduce the throttling loss for the service with the highest pressure requirement, throttling losses are inevitable for other services with lower pressures. Moreover, energies associated with over-running loads are generally not recoverable in throttling circuits. In both construction equipment and mobile robot applications, large differences between pressure requirements amongst the various services and opportunities for regenerative energy exist. For this reason, alternative means to throttling for controlling services that are more efficient, allow for energy to be recovered, and capable of high control performance, are needed.

Hydraulic transformers are devices that transform hydraulic power conservatively from one pressure/flow combination to another pressure/flow combination. They are hydraulic equivalents of gear-sets (mechanical transformers) and AC magnetic transformer and power converters (electrical transformers). Fundamentally, a traditional hydraulic transformer consists of a hydraulic pump and a hydraulic motor that are mechanically coupled. As such, it is the inversion of a hydro-static transmission (HST). Since throttling is not used to achieve pressure change, a hydraulic transformer with variable ratios is a potentially efficient means to distribute and control power from a single hydraulic power source to multiple functions.

One aim of this project to gain understanding of how the intrinsic properties of the transformer impact overall system performance and provide guideline for the future design and optimization of transformer devices. Innas has introduced a transformer that uses a rotatable 3 ported port plate and a single rotating piston group (as in a swash plate pump/motor) [1, 2, 6-10]; and Digital Hydraulics has introduced a transformer based on a linear displacer with discretely selectable areas [3]; a PWM switched inertance transformer was proposed in [4]; the switched model hydraulic transformer as a hydraulic equivalence of switched mode electronic power converter was proposed in [5]. In each of these configurations, elements that perform the function of the pump, the motor, the connecting inertia, and varying the pump and motor displacements can be discerned. By developing experimentally validated models of transformer configurations with these intrinsic elements, their contributions to efficiency and performance can be identified.

Another aim of this project is to develop control strategies and control algorithms for hydraulic transformer based systems for efficient and precise control. While most rigorously developed advanced hydraulic control concepts are based on flow control (e.g., via control of valves and displacements pump at relatively constant speeds) [11-14], transformers are in contrast pressure control devices. Therefore, control strategies and methods for analysis can be quite different from the more conventional hydraulic systems.

Finally, effective and precise control using transformers will be demonstrated experimentally on the lab bench and on the patient mover test bed in a human power amplifier mode.

B. Achievements

Prior year accomplishments:

At the time of last annual report (first 6 months of the project), we had begun a comprehensive comparison between the three traditional pump/motor (P/M) transformer configurations (Figures 1-3) and the 3-ported Innas hydraulic transformer configuration (IHT) with respect to size (as measured by overall displacement), flow/pressure ripples and efficiencies. Average and piston-by-piston kinematic models were created for both configurations assuming axial piston rotating units. With these models, it was concluded that to achieve similar flow capabilities across the range of transformation ratios, P/M transformers would need to be 33%-65% larger than IHT. However, IHT would have significantly larger flow and torque ripples than P/Ms that decrease slowly with increasing pistons. This is a consequence of the port switching when the piston flows are non-zero for the IHT case.

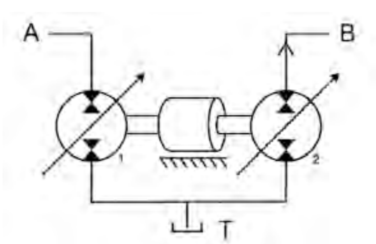

Figure 1: P/M Transformer Tank port Shared

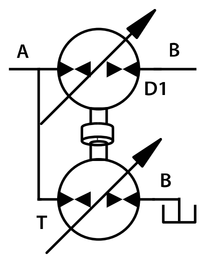

Figure 2: P/M Transformer Output Port Shared

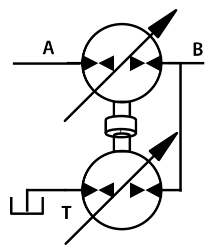

Figure 3: P/M Transformer Input Port Shared

Current year accomplishments:

Improved compactness and efficiency through port-switching: A scenario in which the three P/M transformer configurations can be switched into one another has been considered. This capbility reduces the overall displacements of the P/M transformer to only 17% larger (from 33%-65%) than IHT. Such a switched P/M utilizes input shared and output shared configurations with switching at transformation ratio of 1. Because each P/M configuation is most efficient at different transformation ratios (see below), port-switching also has advantage of improving the overall efficiency of P/M transformer.

Efficiency comparison of transformers configurations: Piston-by-piston energy loss models were created for traditional P/M configurations and IHT in order to evaluate their efficiency characteristics. Friction and leakage within the piston chambers, between the valve plate and barrel, and piston shoe / swash plate friction, fluid compressibility and throttling loss valve are included based upon models in the literature [16-18]. Experimental validation of the P/M model was also carried out on a fixed ratio transformer setup (Figure 11). The resulting efficiency maps for one set of parameters are shown in Figures 4-7. They show that the IHT has a higher peak efficiency than P/M configurations. They also show that the three P/M configurations have advantages in different ranges of transformation ratios. For example, input shared P/M is better for pressure bucking while output share P/M is better for pressure boosting. This suggests that if port switching is allowed, efficiency improvement can be achieved over a broad range of transformation ratios.

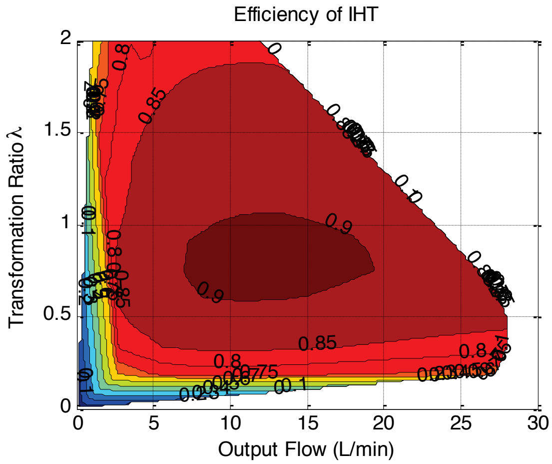

Figure 4: IHT Efficiency

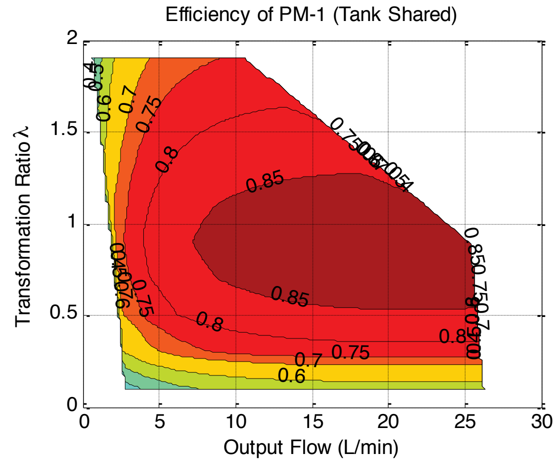

Figure 5: PM (tank shared) Efficiency

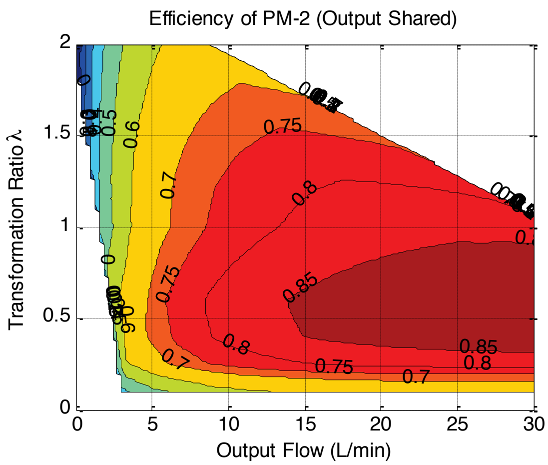

Figure 6: PM (input shared) Efficiency

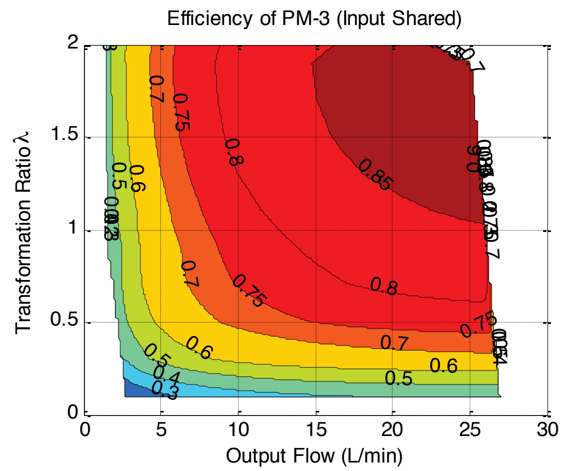

Figure 7: PM (output shared) Efficiency

System Level Case Study: Besides reducing throttling loss, transformers can be used to boost system pressure, to increase flow rates, and to regenerate energy from an over-running load. These capabilities have system level consequences, e.g., boosting pressure and increasing flow rates allow actuator and supply pump size to be reduced respectively, resulting in a more compact system; regenerating energy from loads can further increase system-level efficiency.

To study the potential system level efficiency improvement of a hydraulic transformer system, a case study was performed to compare a throttling valve based system with a transformer based system. The two approaches were designed and simulated for a leg-robot (Figure 8) duty cycle which was generated using published human gait data [19]. In this case, energy regeneration is not utilized and the designs were not optimized exhaustively. In the simulations, transformer efficiency models developed earlier are used. The required input powers for the two approaches are shown in Figure 9. Table 1 shows that even without utilizing energy regeneration, efficiency is increased by 5 folds. Further, supply pressure can be reduced from 200 bar to 138 bar illustrating a system level opportunity that transformers can offer.

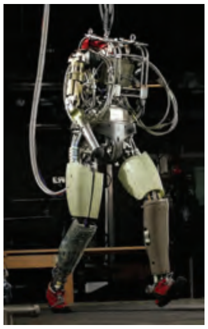

Figure 8: Leg Robot Simulated

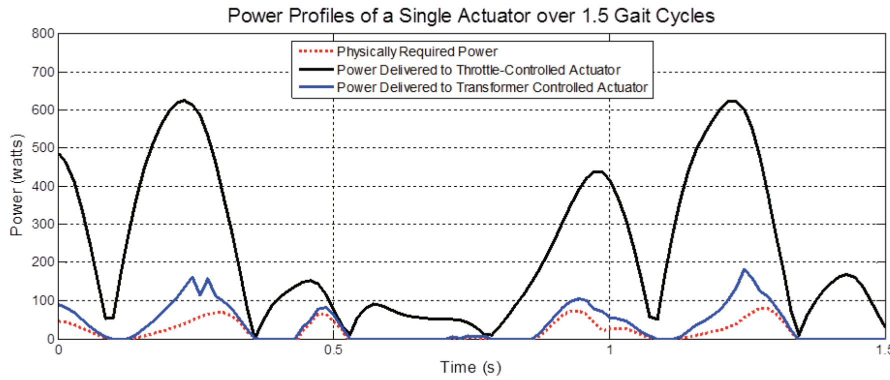

Figure 9: Power Profile of Simulated Robot

Table 1: System Efficiency Comparison

	Throttle (200 bar)	Transformer (138 bar)
Hip Actuator Efficiency	9.5%	68.28%
Knee Actuator Efficiency	8.38%	51.76%
Ankle Actuator Efficiency	15.63%	61.48%
Total Efficiency	**11.03%**	**58.7%**

Experimental Results and Prototyping A test bench was constructed to allow experimental validation of the efficiency model. The first prototype utilized two fixed-displacement micro-piston pumps donated by Takako Industries (Figure 10). The pump displacements were 0.8 cc/rev and 1.6 cc/rev, allowing the transformer model to be validated for the small, compact units needed for human-scale robotic applications. Figure 11 shows that the model was able to predict the efficiency adequately.

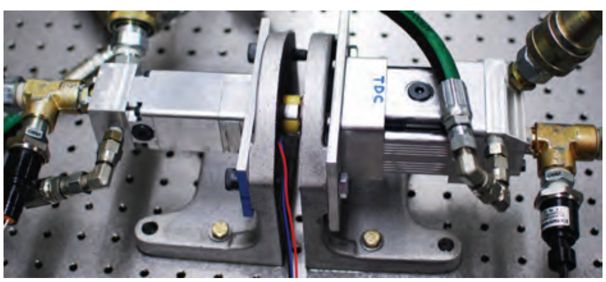

Figure 10: Preliminary Test Stand

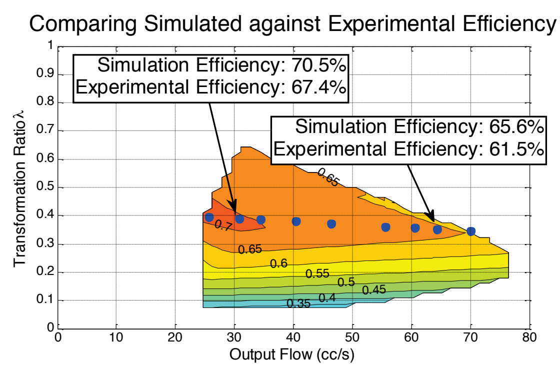

Figure 11: Model efficiency map and experimental results

A manually controlled variable pump/motor hydraulic transformer prototype was recently made and donated by Takako Industries. The device (Figure 12) consists of two variable displacement 3.15 cc/rev units in the traditional pump/motor configuration. Characterization of the physical dynamic model of the prototype is currently underway. The variable transformer will also be converted to allow for computer control. This setup will be used for control algorithm development and testing.

Figure 12: Takako's P/M Transformer

<u>Trajectory tracking control</u> In the case of a P/M transformer with two variable displacement pump/motors, a preliminary trajectory tracking control for driving an actuator with an inertial load (Figure 14) has been developed. In Figure 14, a tank shared P/M is shown but other P/M transformers can also be used. A backstepping control design approach is taken to meet the flow demand for the actuator and to regulate the transformer speed at the predetermined value [20]. The control law was designed based upon ideal models but it was simulated with MATLAB including losses. Figures 14-16 show that the control is able to achieve trajectory tracking and regulation of the transformer speed. This controller will be tested on the experimental setup when it is ready. Control for human power amplification and approaches for the determining appropriate transformer speeds will be considered next.

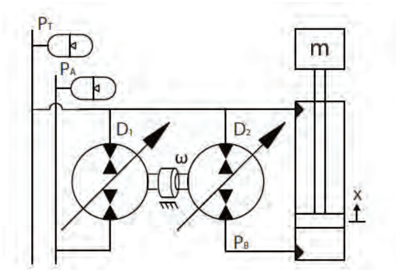

Figure 13: Transformer based control circuit (simplified)

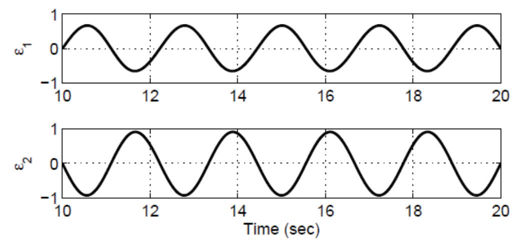

Figure 14: Displacements (control input)

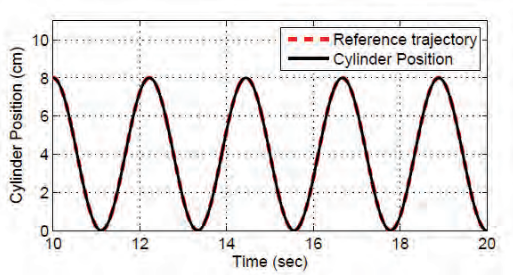

Figure 15: Desired and achieved actuator position

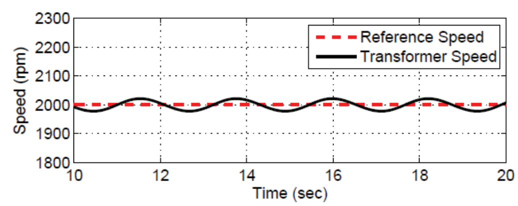

Figure 16: Desired and achieved transformer speeds

<u>**Future Plans**</u>

The immediate plan is to experimentally characterize the variable transformer prototype and to convert it into a computer controlled unit. This will be used for testing control algorithms for trajectory tracking and for human power amplification. Implementation on test bed 4 (patient mover) will proceed afterwards. Realization of the port-switching concept will also be developed and implemented on the prototype. The system level humanoid robot case study will be extended to include energy regeneration, optimal sizing of the components and variable pressure rails.

C. Member company benefits

Member companies can benefit from learning benefits of hydraulic transformers to save energy, and how to apply and control hydraulic transformers in applications. The project may also provide guidance on transformer configurations as a product.

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Project 1E.6: High Performance Valves Enabled by Kinetic Energy

Research Team

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Graduate Students:	Dan Skelton, Shaoping Xiong
Undergraduate Student:	Jordan Garrity
Industrial Partners:	Moog, Parker-Hannifin, Sun Hydraulics

1. Statement of Project Goals

The goal of the project is to develop high performance actuation mechanisms to enable high bandwidth valves and improve the performance and efficiency of existing systems. The concept is based on coupling energy storage mechanisms with translational movement to increase the speed and controllability of linear actuators. The high speed linear actuation method is being applied to hydraulic proportional valves. The stored actuation energy (such as a rotating mass) is intermittently coupled and decoupled to produce linear or rotary motion in the primary actuator. The project will develop the bidirectional proportional control algorithms for the Energy Coupler Actuated Valve (ECAV), integrate the ECAV with both a poppet and a spool valve body and experimentally investigate the pressure-flow-time performance, and develop an integrated electrical systems (driver circuits and sensor), actuator, and valve system that can be easily incorporated into center and industry projects.

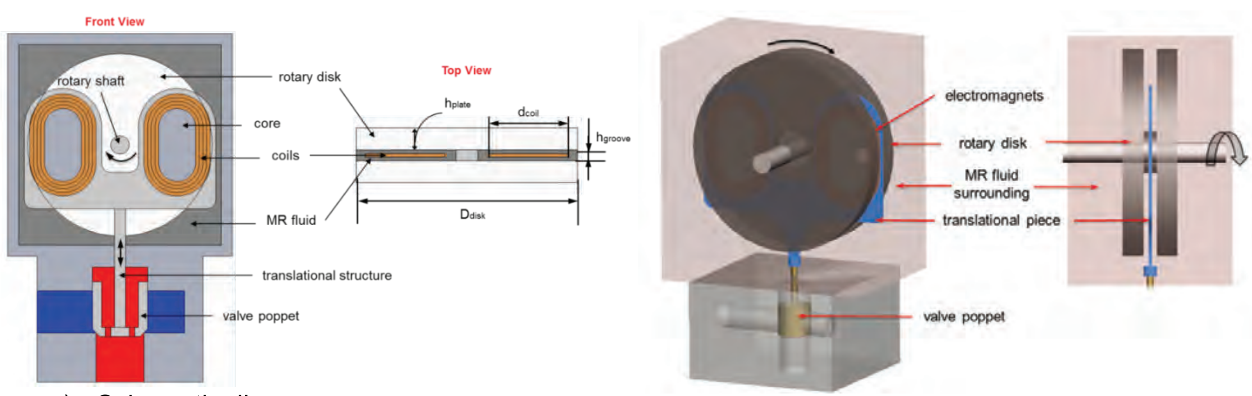
2. Project Role in Support of Strategic Plan

This project addresses the technical barriers of efficient components and is an enabler for efficient and effective systems. Hydraulic valves are found on nearly every fluid power system in production. The core technology developed in this project: compact, modular, high performance, proportional and scalable valves are enablers or enhancers for every test bed in the center. Test beds 1 & 3 would benefit from high efficiency pumps/motors enabled by these valves, or from increased bandwidth displacement control when using current state-of-the-art variable displacement units.

3. Project Description

A. Description and Features of Energy Coupler Actuator (ECA)

The project focuses on the development of a promising new concept of a valve actuation mechanism to solve the trade-off between fast switching and large nominal flow rates in the design of high speed valves, the energy coupler actuator (ECA). The fundamental principal of the valve actuation system is to couple a kinetic energy source with a translational valve poppet or spool. Valve positions can be controlled by intermittently coupling or decoupling the translational component from the energy source. Figure 1 illustrates the ECA design. When the MR fluid is not magnetized, the liquid viscous friction forces between the rotary disk and the translational components are small [1]. If the left side coil is energized, magnetic flux will be generated in the gap and will cause the MR fluid to thicken. As the fluid thickens, it creates a shearing force. The rotating disk will clutch the translational piece and bring it upwards thereby opening the valve. Similar mechanisms apply to the valve closing.



a) Schematic diagram b) 3D rendering

Figure 1: MR fluid energy coupler actuator valve.

The ECAV design has the following advantages: High pressure can be at either port; Large and scalable actuation forces; Large stroke; Proportional control; Small moving mass; System pressure-independent performance; Low leakage; Compact axial stacking of valves. Figure 2 shows a stack valve with multiple MR fluid energy coupler actuators.

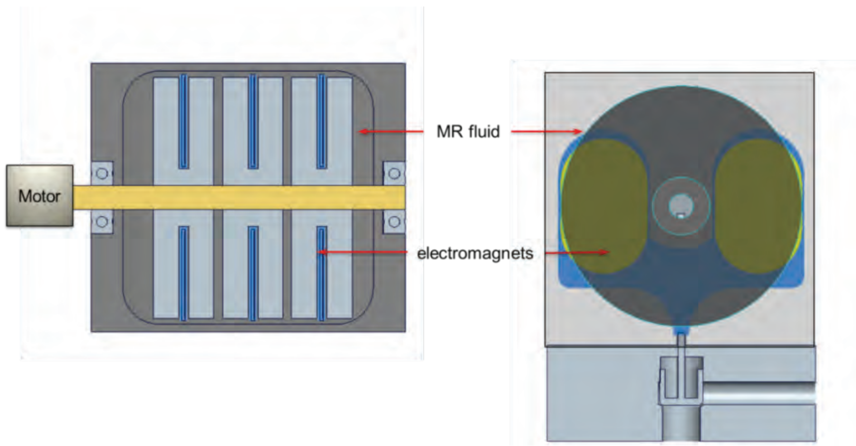
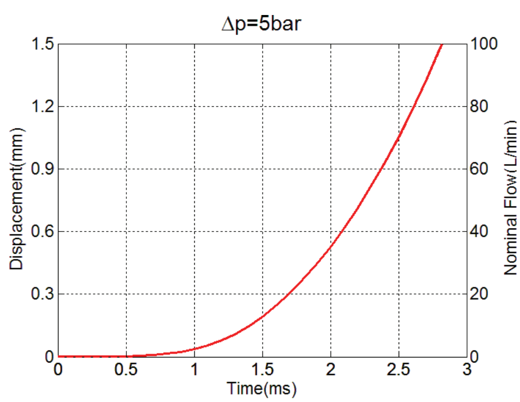


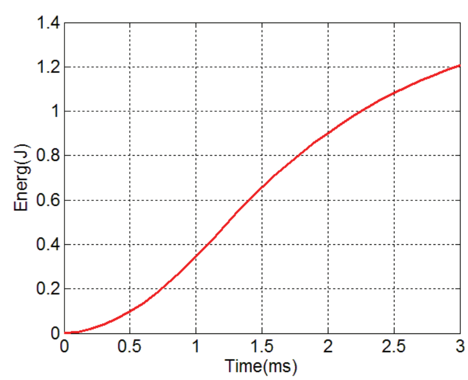
Figure 2: ECAV stack valves configuration.

B. Achievements

Results from Y7/Y8: A simulation study was used to optimize the design and performance of the ECAV in terms of holding forces, response time and electric energy consumptions. Using a 96V, 1ms peak and 5V hold voltage produces the valve motion profile and corresponding energy consumption curve shown in Figure 3.



(a) Valve stroke



(b) Electric energy consumptions

Figure 3: Simulated dynamic ECAV performances.

The ECAV response time for 1.5mm stroke (100L/min nominal flow) was predicted to be 2.8ms and the resulting electric energy consumption was evaluated as 1.2J electric power per switch.

Experimental Testing Results from Y7/Y8: Experimental tests were conducted to test the dynamic performance of a prototype MR fluid ECA. Figure 4 shows the displacement trend plots during one stroke. It achieved 4.5ms for a 1.5mm stroke, using about 1.4J of electrical energy (Figure 5). The prototype ECA achieved a 7mm stroke in 10ms, which demonstrates the significant potential for large stroke high bandwidth actuators. Simulated results matched the experimental results quite well.

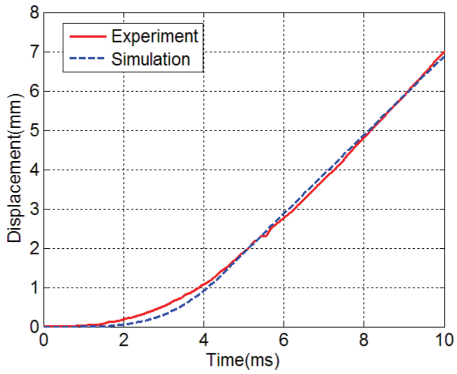


Figure 4: MR fluid ECA displacement trend plots.

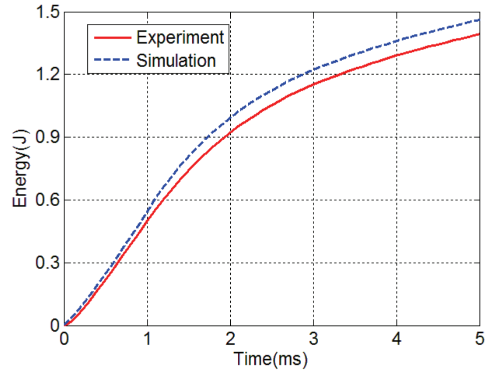


Figure 5: Coil electric energy consumptions.

Figure 6 shows the achievement of bidirectional capability in the ECAV. In Y9/Y10 a position sensor will be integrated into the valve body to achieve bidirectional and proportional position control.

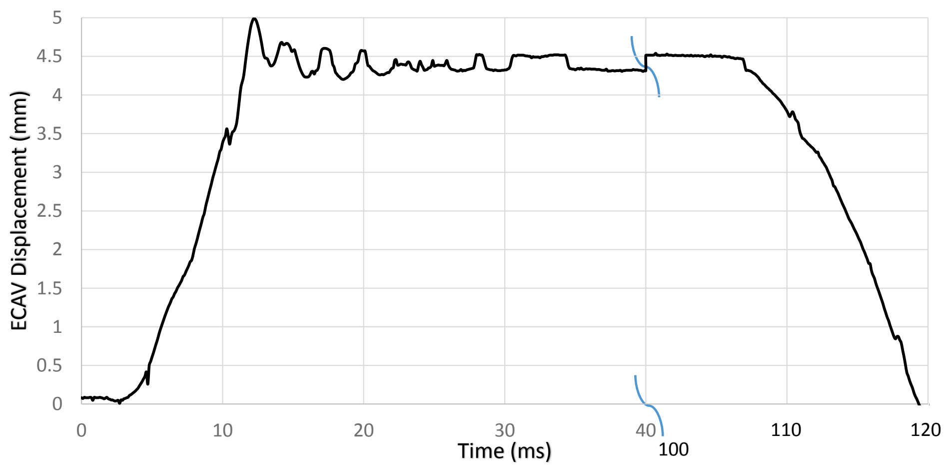


Figure 6: The switch-on, hold, switch-off cycle for the MR fluid ECA.

The prototype developed in Y7/Y8 and whose results are shown here used aluminum plates to hold the coil set (for ease of constructing in the lab), which required an increase in the groove gap h_{groove}, coil wire diameter d_{wire}, and coil thickness h_{coil}. The magnetic resistance of aluminum is 3 to 5 times larger than MR fluids, which significantly reduced the resulting flux density and hence shear forces at a rated power, and resulted in a larger moving mass than necessary. Using a different coil design on a second prototype, and leveraging the knowledge gained in Y7/Y8, the ECA concept has the potential for achieving even faster responses while using less power.

C. Proposed Work for Y9/Y10

Milestones: The proposed work for Y9/Y10 includes task 1) to develop the bidirectional proportional control algorithms for the Energy Coupler Actuated Valve (ECAV), task 2) integrate the ECAV with both a poppet and a spool valve body and investigate experimentally the pressure-flow-time performance, and task 3) develop an integrated electrical system (driver circuits and sensor), actuator, and valve system that can be easily incorporated into center and industry projects.

Tasks 1 & 2 will be completed concurrently in the first year of the project. The control algorithms will initially be developed on the existing actuator prototype while the valve poppet and spool, and associated housings, are developed. Task 3 is to develop and test integrated valve units with embedded electronics, working towards the goal of incorporating high performance valves into test bed supporting projects like digital pump/motors, control of swash plate displacement, and for enabling new energy storage configurations [2]. Another outcome of task 3 and possible application is the integration of the ECAV on the digital pump/motor test stand, as shown in Figure 7. This would provide a great multi-valve testing platform while improving the overall efficiency, controllability, and operating envelope of the digital pump/motor.

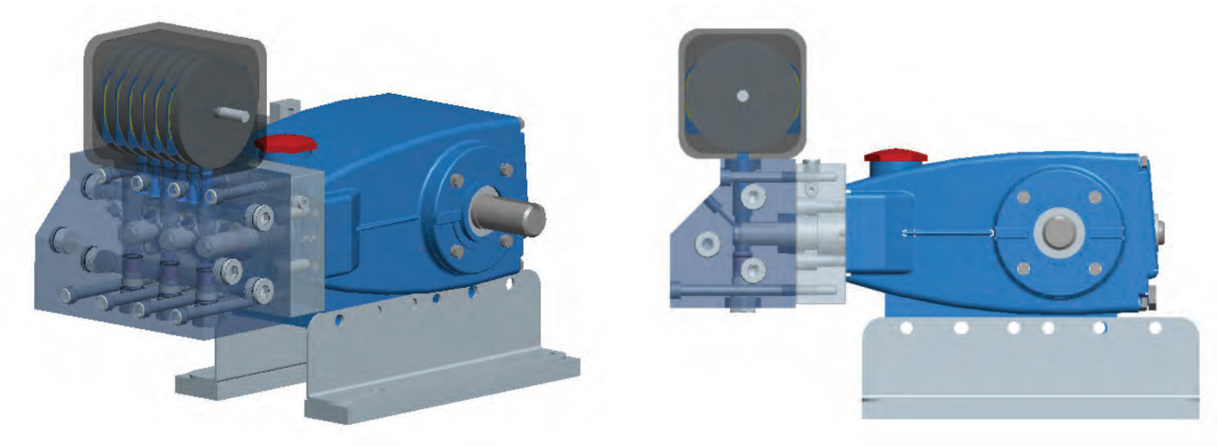


Figure 7: ECAV Digital Pump/Motor Concept

D. Member Company Benefits

These valves would enable a higher efficiency for pumps/motors and would greatly benefit test beds 1 & 3, or the efficiency could be improved by increasing the bandwidth displacement control by using state-of-the-art variable displacement units.

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Project 1F.1: Variable Displacement Gear Machine

Research Team

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1. Statement of Project Goals

The primary goal of this project is to formulate and develop a unique concept for variable displacement external gear machines (VD-EGMs). The new innovative design of the machine will preserve the well-known advantages of current fixed displacement EGMs such as ease of manufacturability, low cost high pressure range of operation and good operating efficiency. To reach the primary goal, the project also proposes a general and innovative design method for EGMs that surpasses the current empirical design approach used to design such units. Particularly, the project will take into consideration unconventional designs, such as non-involute or helical gear profiles. Therefore the goals of the project can be mentioned objectively as:

Objective one: Formulate a new design principle for VD-EGM

Objective two: Propose a novel and general design methodology for EGMs.

2. Project's Role in Support of Strategic Plan

The proposed research directly addresses the technical barriers "efficient components" and "efficient systems" by introducing a new concept for a VD hydraulic machine. CCEFP is extensively researching new system concepts to minimize energy consumption of the fluid power applications, and many solutions are based on the potentials of VD units. However, the diffusion of efficient system layout architectures based on VD units is not as broad as it should be, due to the inherent high cost factor associated with VD pumps and motors. Therefore, research toward more cost effective solutions for VD units is needed in the fluid power field. By proposing a new VD design concept, this project will support the ongoing research on novel architecture and will permit a wider diffusion on more efficient systems also in low cost fluid power machines. With a strong fundamental component on the approach for designing EGMs, the research aims to surpass the current empirical methods that limit the possibilities of formulating new design concepts for EGMs.

3. Project Description

A. Description and explanation of research approach

External gear machines (figure 1) are one of the most widely used positive displacement machines in numerous hydraulic applications. The strong-point of these machines lies in their good reliability, operating efficiency, compact size and low cost. Despite these advantages, EGMs are fixed displacement and they cannot be used as primary energy conversion units in modern energy efficient layout configurations based on variable flow supplies, such as in load sensing systems, hydrostatic transmissions or in displacement controlled systems [1, 2].

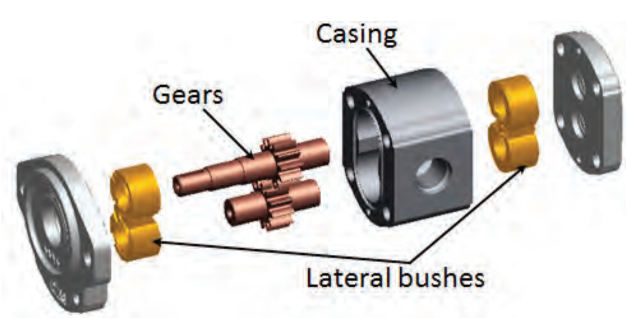

Figure 1: Parts of an external gear machine

With the exception of cases where the unit operates at fixed pressure and flow rate, the energy consumption of fluid power circuits based on fixed displacement units can be as much as 70% higher than standard VD system layouts. For this reason, both industry and academia have been dedicating effort in formulating VD design solutions for EGMs, with the aim of preserving the advantages of limited cost (about 10 times lower than existing VD units with the same capacity) and reliability. Representative of the past efforts are given by references [3-11]. All these past effort share the idea of realizing an axial or radial relative motion between the gears to obtain a variable output flow. However, the motion of the gears, which are the most loaded elements in an EGM, involves major problems such as: sealing the tooth space volume; guaranteeing a smooth meshing process and a good balance of the gears avoiding contacts. A good solution for mentioned aspects generates complexities which increase the cost of the unit and penalize its reliability. For these reasons, none of the solutions proposed for VD-EGMs have found successful commercial application.

The proposed solution for VD-EGM

Variable displacement in EGMs can be obtained by proposing an innovative concept of variable timing of connections between the displacement chambers (tooth space volumes, TSVs) and the inlet and the outlet ports. A schematic representation of this idea is shown in Figure 2.

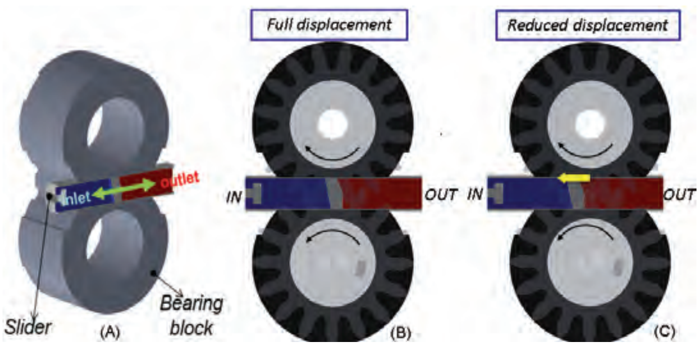

Figure 2: (A) Slider placed on the bearing block for the proposed VD-EGM. The position of the slider determines the timing of the connections of each TSV with inlet/outlet ports (Patent pending for the design of the gears and recesses in the slider for the proposed VD-EGM) (B) Position of the slider to achieve 100% (C) Position of the slider to achieve 65% displacement.

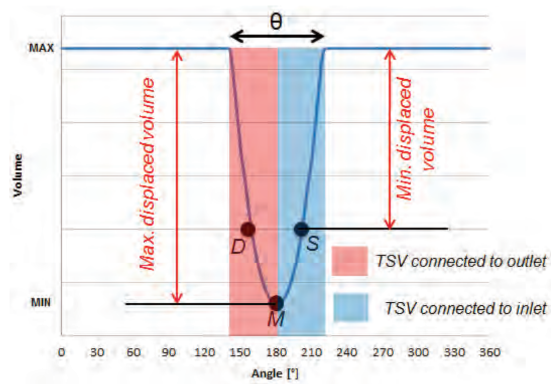

Figure 3: EGM tooth space volume and its value as a function of shaft angle. The meshing process realized the displacing action in the angular interval θ, for a portion of the meshing process (between D-S), the volume is trapped between points of contacts.

In this design, the delivery and the suction grooves are machined on a slider which is a part of the lateral bush as shown in Figure 2. Displacement variation is achieved by moving the element. When the movable element is moved to the left, the volume of the fluid which is trapped between the contact points of the teeth of the gears is connected to the delivery for a larger interval of time as shown by the timing diagram.

B. Achievements

Achievements prior to the reporting period:

Prior to the reporting period, the research team has developed an omni-comprehensive simulation tool for the simulation of EGMs. The tool, named HYGESim (HYdraulic GEar machines Simulator) [12] is capable of simulating the operation of gear pumps and motors, including elasto-hydrodynamic deformation effects in the lubricating gaps [13]. HYGESim permits the understanding of the influence of the design parameters on the EGM performance in terms of efficiencies, power losses, local pressure peaks and cavitation, flow pulsations etc. HYGESim is a multi-domain simulation tool built in LMS.AMESIM® platform to facilitate complete hydraulic systems and it consists of several parts (Figure 4): a) Geometrical Model capable of generating the various details necessary for the lumped parameter model from CAD drawings, b) a lumped parameter fluid dynamic model for the study of the main flow through the unit, c) a mechanical model to study the radial balance of the gears considering the micro motions of their axis d) a fluid-structure thermal interaction model to study the lubricating gap between gears and lateral bushes and the axial balance of the machine.

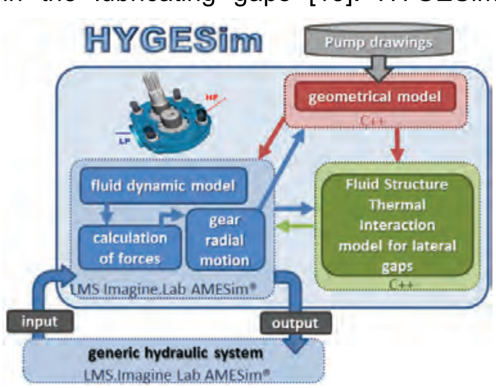

Figure 4: Sub-models of HYGESim simulation tool.

Achievements during the reporting period:
Started from summer 2012, the research has made significant progress in addressing the research objectives one and two.

1. **Geometrical model** of HYGESim has been extended to include a gear generator capable of designing asymmetric gears. A lateral bush designer has also been developed which is capable of designing complicated shapes of the grooves. With the introduction of asymmetric gears, the geometrical model has been modified to calculate the different geometrical features necessary for the calculations by the other sub-model of HYGESim
2. An **optimization workflow** for the simultaneous design of asymmetric gears and lateral bushes was developed. This workflow uses HYGESim as a virtual test rig to evaluate the performance of the machine. The objectives of the optimization are: 1) Maximize the reduction in displacement 2) Minimize pressure pulsations, 3) Minimize internal pressure peaks and localized cavitation effects and 4) Maximize volumetric efficiency. In order to aid faster convergence, a hybrid algorithm of multi-objective genetic algorithm with response surface methodology. This algorithm aids in the fast evolution of new designs at every iteration especially since there are more than one objective functions and they lack analytical expressions in terms of the design variables.

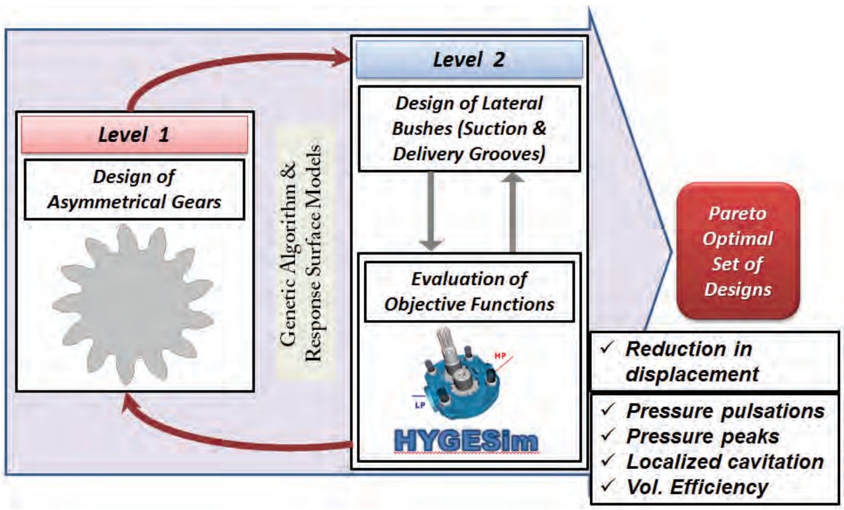

Figure 5: Optimization workflow.

3. **Optimal design of the gears** which reduced the displacement from 100% to 68% was identified with the help of the optimization workflow. The optimal design of the lateral bushes which optimized the performance of the machine as a whole was also identified as shown in figures 6 and 7.

Figure 6: Optimal design of the gears.

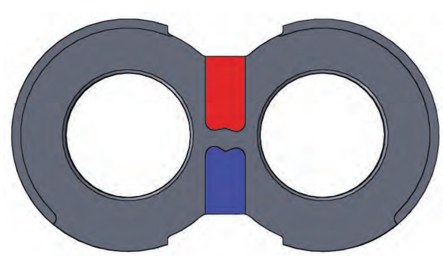

Figure 7: Optimal design of the grooves in the lateral bushes.

4. ***Proof of concept tests*** were performed using the multi-purpose test rig at the Maha Fluid Power Research Center of Purdue University. The optimal design of the gears shown in figure 6 was

machined using wire electric discharge machining. For the proof of concept testing, two different configurations of the lateral bushes were machined: 1) for maximum displacement and 2) for reduced displacement using conventional milling process. The final machined prototypes are shown in figure 8. Steady state measurements were performed with the asymmetric gears and the bearing bloc for maximum displacement at first. Following the testing for maximum displacement, the pump was disassembled and the bearing block for minimum displacement was switched in place of the one for maximum displacement. Pressure ripple measurements at the delivery of the machine was also evaluated and compared with that of the reference commercial design as shown in figure 9.

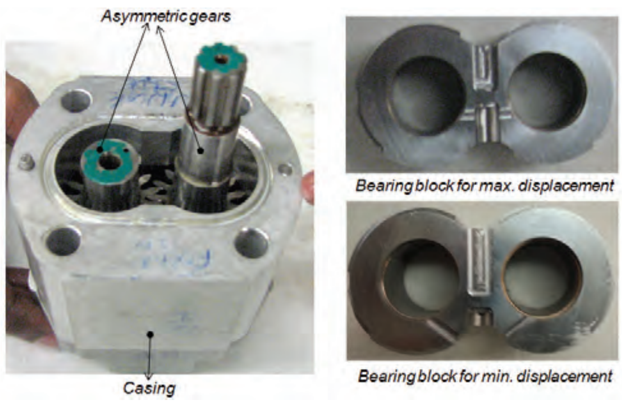

Figure 8: Prototypes machined for the proof of concept tests.

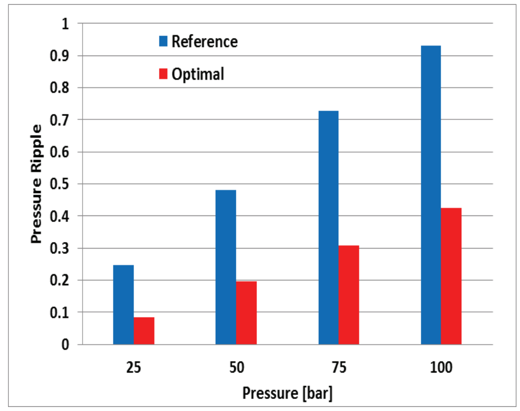

Figure 9: Measured pressure ripple for the reference and the optimal design (figure 6).

It can be seen from figure 9, that the introduction of asymmetric gears has significantly reduced the pressure ripple at the delivery of the pump, thereby reducing the fluid generated noise emissions. From figure 10, it is evident that the variable displacement concept is successful in reducing the flow rates. It can also be seen that the input torque has also reduced proportionally thereby consuming lower power as compared to the maximum displacement.

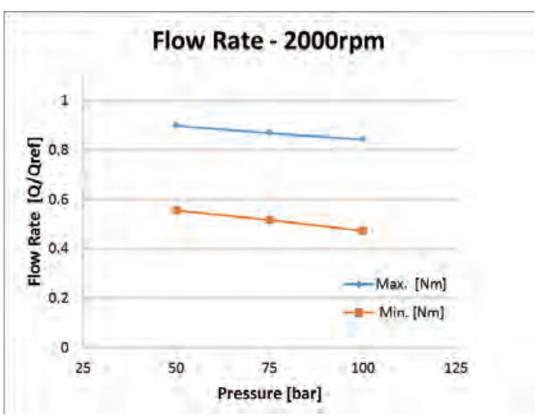

Figure 10: Experimental flow rate for max. and min. displacement.

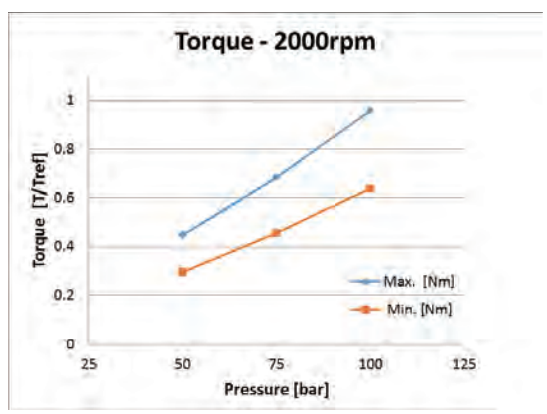

Figure 11: Experimental input torque for max. and min. displacement.

Planned achievements following the report period

- Deliverables:
  - Preliminary design for the actuation system for changing the displacement in the proposed VD-EGM design, with manual control of the displacement (April 2014)
  - Testing of VD-EGM prototype and model validation (May 2014)
  - Possible integration in TB.1 - fan drive system (fall 2014)
  - Extension of the research to parametric unconventional multi involute profiles (May 2014)

- ○ Drawings and simulation model for the optimal solution with unconventional multi involute profiles (May 2014)
- ○ Simulation results purporting the benefits of unconventional designs over standard designs (fall 2014)

C. Member company benefits

- The CCEFP member will gain a more deep understanding of the principle of operation of external gear machines
- The novel design approach used to quantify the performance of the EGM (see objective functions above) is general could be used for the evaluation of other positive machines. This would bring to new design approaches for hydrostatic units.
- The members will understand the fundamentals of the application of unconventional gear profiles to gear machines and the benefits in doing so.
- Licensing options for the novel variable displacement external gear machine design

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Project 1G.1: Energy Efficient Fluids

Research Team

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Industrial Partners:	Afton Chemical, Danfoss, Evonik, Idemitsu Lubricants, Gates, Lubrizol, Parker Hannifin, Poclain Hydraulics

1. Statement of Project Goals

The goal of this project is to bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power components. This will be accomplished by characterizing fluids in benchtop instruments, analyzing fluid efficiency effects in a hydraulic dynamometer, and modeling fluid-component interactions in Matlab Simulink. Improvements in bulk modulus, boundary friction, and shear stability properties are expected to yield a 10% increase in overall system efficiency. Non-Newtonian fluids will be formulated and characterized throughout 2014. Dynamometer studies of bulk modulus, boundary friction, and shear stability effects will be conducted Q3 2014 through Q2 2016. These results will be used to develop and validate a system efficiency model that incorporates the properties of advanced hydraulic fluids.

2. Project Role in Support of Strategic Plan

This project will increase system efficiency by advancing hydraulic fluid technology. The CCEFP has identified system efficiency as a major technical barrier that must be overcome to achieve the Test Bed performance objectives. Increased system efficiency also makes possible the use of smaller, more compact valves, pumps, and motors. This project, which incorporates the high-pressure viscosity research of Professor Bair (3D.2), improved the low-speed mechanical efficiency properties of the test fluid for Professor Chase (TB3) by at least 10%.

3. Project Description

A. Description and Explanation of Research Approach

This project seeks to improve efficiency by studying the fluid properties that impact system-wide efficiency. In our earlier work we found that a reduction in static and boundary friction can yield double-digit improvements in hydraulic motor starting efficiency [1]. The low-speed efficiencies of geroler, axial piston, and radial piston motors also benefited from low viscosity-pressure coefficients [2]. In pumps, viscosity modifiers (VM) have been found to reduce leakage flow losses [3]. Resistance to permanent viscosity loss due to shear has also been identified as a key requirement [4]. The interactions of additives and base oil properties on system-wide efficiency, however, are not well understood. In this project, a hydraulic dynamometer and bench-top tribometers are used to develop models for the rational design of energy efficient hydraulic fluids.

B. Achievements

<u>Achievements in previous years</u>

Previously we found that the starting and low speed efficiency of hydraulic motors was related to the static friction, boundary friction, pressure-viscosity, and thermal conductivity properties of the hydraulic fluids. The best motor performance at start-up was obtained by formulating a fluid with low static and boundary friction coefficients and the smallest viscosity change at increased temperature and pressure. Boundary film formation, friction, and surface topography studies were conducted in benchtop tribometers and hydraulic motors to investigate additive-surface interactions. The addition of a friction modifier to an ashless hydraulic fluid increased the low-speed mechanical efficiencies of geroler, radial-piston and axial-piston motors. EDX analysis of tribometer and motor surfaces revealed tribochemical films from the hydraulic fluid additives. The benchtop test results were consistent with surface examinations on end of test hydraulic motor parts. These findings are significant because they provide insights towards the development of fluids that enhance hydraulic motor efficiency.

Achievements in the past year

A new expression for the relationship between hydraulic motor efficiency and Stribeck number has been developed that incorporates the Michaelis-Menten chemical kinetics model [5]. The Michaelis-Menten biochemical model is used to describe enzyme reactions [6]. Enzyme reactions are initiated by a bond between the substrate and enzyme. The rate of this reaction depends upon the available substrate surface area. Boundary lubrication in hydraulic motors is also dependent upon chemical kinetics of surface reactions. In fluid power, surface interactions are also influenced by dimensionless viscosity.

Efficiency measurements in a hydraulic dynamometer have been used to evaluate the Michaelis-Menton model adaptations. Newtonian, Non-Newtonian, and friction-modified fluids were evaluated. The volumetric efficiency equation (Equation1) includes a leakage flow constant (LP). The mechanical efficiency equation (Equation 2) includes constants for boundary lubrication (BL), viscous shear losses (SL), and the torque to rotate (TTR). The BL parameter in the mechanical efficiency equation is particularly helpful because it accounts for variations in the boundary friction characteristics of different hydraulic fluid formulations.

Equation 1
$$\eta_{VM} = \frac{\left(ZN/p \right)}{\left(ZN/p + C_{LP} \right)}$$

Equation 2
$$\eta_{TM} = \frac{\left(ZN/p \right)}{\left(ZN/p + C_{BL} \right)} - C_{SL}\left(ZN/p \right) - C_{TTR}$$

The volumetric efficiency results for Newtonian and Non-Newtonian Fluids in an axial piston motor at 50°C and 80°C are shown in Figure 1. Normally Stribeck analysis is not used to evaluate Non-Newtonian Fluids because the Stribeck number does not account for shear-dependent viscosity behavior. To compensate for differences in viscosity stability, the model incorporates the viscosity after permanent shear losses have occurred as measured in the ASTM 40- minute sonic shear test.

Mechanical efficiency results for a conventional and a friction-modified fluid in an axial piston motor at 50°C and 80°C are shown in Figure 2. Model results for a conventional HM46 fluid are shown. The FM additive improved efficiency at low Stribeck numbers and exhibited lower levels of boundary friction in benchtop tribometer tests. The model can be adjusted to account for differences in boundary friction by adjusting the parameter C_{BL}.

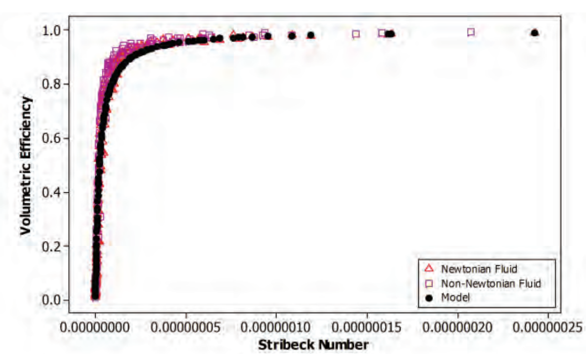

Figure 1: Volumetric efficiency curves for Newtonian and Non-Newtonian fluids in an axial piston motor.

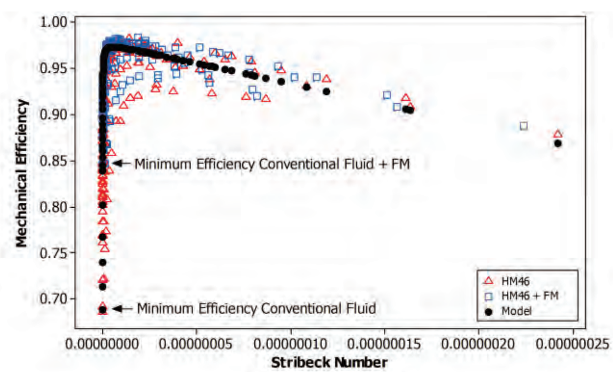

Figure 2: Mechanical efficiency curves for a conventional and friction modified fluid in an axial piston motor.

A Matlab Simulink model has been developed that uses the Michaelis-Menten efficiency equations to predict pump flow rates and system pressures as a function of motor torque output and speed. Flow rates and operating pressures were simulated and measured for a range of hydraulic motor conditions. It was found that friction modifiers reduce the pressure required to achieve a given level of torque, and viscosity modifiers reduce the flow rate required to achieve a given level of motor speed.

Pump and system-wide models for fluid efficiency are being developed. In typical piston pump efficiency tests, the swash-plate angle is fixed so that the pump displacement can be determined. In the fluid efficiency test, the swash-plate is allowed to compensate for changes in the system flow rate. Pump overall efficiency was determined from the ratio of the pump flow rate and outlet pressure to the ratio of pump input torque and speed. As shown in Figure 3, pump overall efficiency varies with the Stribeck number in a similar manner to the motor. Fluctuations in pump efficiency arise from changes in displacement, speed and temperature. System-wide efficiency tests have also been conducted on a series of fluids. In this investigation, system-wide efficiency is defined as the ratio of the motor output power (torque and speed) to the pump input power (torque and speed). As shown in Figure 4, system-wide efficiency increases with the Stribeck number. Pump speed affects system-wide efficiency, but less than the motor speed. These results will be incorporated into the fluid efficiency model to bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power systems.

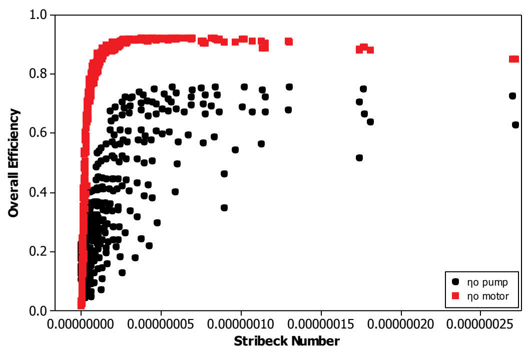

Figure 3: Overall efficiency curves for an axial-piston pump and an axial piston motor.

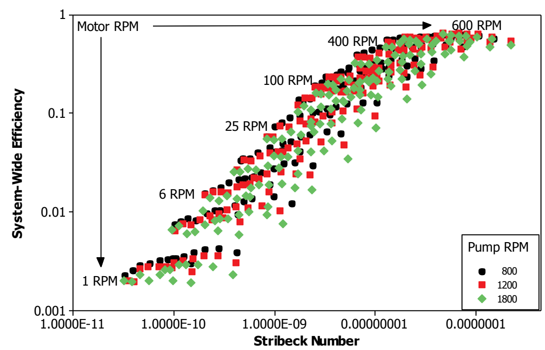

Figure 4: System-wide efficiency for the axial-piston pump and motor combination.

C. Plans

Plans for the next year

- Task 1: Evaluate the high bulk modulus fluid [3 months]
- Task 2: Blend and “age” Non-Newtonian fluids [3-6 months]
- Task 3: Evaluate shear-thinning effects of VM [6-12 months]
- Task 4: Conduct dynamometer and bench-top experiments on prototype hydraulic fluids to probe the effects of bulk modulus, shear stability, and boundary friction on hydraulic system efficiency [1-24 months]

Expected milestones and deliverables

- Completion of high bulk modulus fluid testing [Q3 2014]
- Completion of shear thinning characteristics [Q3 2015]
- Completion of pump model [Q2 2016]

D. Member Company Benefits

This research has benefited additive and hydraulic fluid manufacturers in the center by providing insights towards the development of fluids that enhance pump and motor efficiency. This research has benefited equipment manufacturers in the center by facilitating the use of smaller power units.

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Project 1J.1: Hydraulic Transmissions for Wind Power

Research Team

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Undergraduate Student:	Becca Trietch, Yale University
Industrial Partners:	Bosch Rexroth, Danfoss, Linde, Eaton, Clipper Windpower

1. Statement of Project Goals

Wind power is a plentiful, renewable source of energy, able to produce emission-free power in the kilowatt to megawatt range. The US Department of Energy has a goal of having 20% of the nation's energy come from wind by 2030. Land-based or off-shore wind farms can provide wind energy to the grid. However, these facilities require expensive power transmission lines and typically incur significant construction and maintenance costs. A small wind facility is a cost-effective method of power generation for areas with limited power needs, such as farms or factories. Most mid-sized turbines are designed as fixed speed machines which reduce costs by eliminating the power converter. However, fixed speed operation does not allow the rotor to capture the maximum energy as wind speed varies. To capture wind energy more efficiently, a continuously variable transmission (CVT) is required.

A hydrostatic transmission (HST) functions as a continuously variable transmission and eliminates the need for the gearbox. Gearbox reliability is a major issue and gearbox replacement is quite expensive. In a recent study by Reliawind, it was reported that the major components contributing to low reliability and increased downtime of wind turbines are the gearbox, power electronics and pitch systems. An HST has the potential to increase system efficiency, improve system reliability and decrease the lifetime cost of energy. The application of HST is mainly on the mid-sized wind turbine since most commercially available hydraulic components (pumps and motors) match that power level well. This reduces the technology risk of developing new hydraulic components for the turbine.

The objective of this project is to investigate the possibility of applying HST to the mid-sized wind turbine, identify the technical barriers of the hydrostatic wind turbine, explore different control methods and energy strategy to maximum energy capture, and establish a hydrostatic wind turbine test platform in the lab.

2. Project Role in Support of Strategic Plan

The project aligns with the Center's efficiency thrust and addresses the transformational barrier of efficient components and systems. The system efficiency of a wind turbine has three components: aerodynamic efficiency (converting the wind stream to power in the rotor shaft), drivetrain efficiency (transferring the rotor shaft power to the generator; usually includes increasing rotation speed) and electrical efficiency. Replacing the gearbox in a wind turbine with an HST lowers drivetrain efficiency, but substantially reduces maintenance and repair costs. In addition, the HST will allow the aerodynamic efficiency and generator efficiency to increase resulting in a higher system efficiency. Finally, this project focuses on creating a new market for fluid power and, thus, strongly supports the Center's goal of making the use of fluid ubiquitous.

3. Project Description

A. Description and explanation of research approach

Conceptual analysis of hydrostatic transmission for off-shore, utility scale wind turbine: This research is to support Eaton Corporation with the subject concept development and evaluation program proposed under Department of Energy Award No. DE-EE0005190. The overall objective of the project is to reduce the technical risk for a hydrostatic transmission based drivetrain for high power utility scale wind turbines and validate the potential for reduction of COE for the wind turbine. Although this study targets the utility scale off-shore turbine, some concepts and analysis are still applicable to the mid-sized hydrostatic wind turbine.

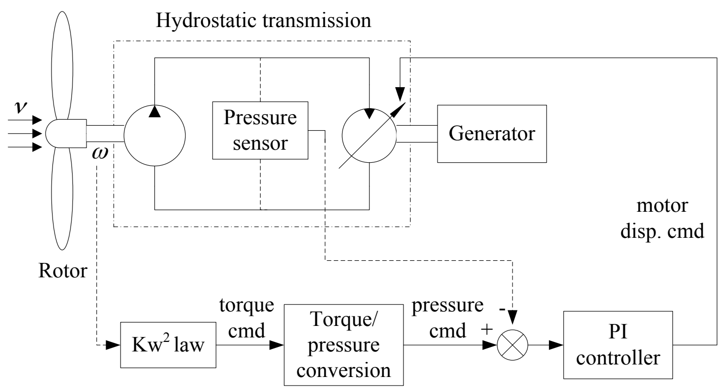

Figure 1: Control schematic of a hydrostatic wind turbine.

B. Accomplishments:

1. Develop a dynamic simulation model to verify the performance for the drivetrain;
2. Perform sensitivity analysis of system parameters to assist with design decisions and optimize the drivetrain design;
3. Develop a control methodology for the hydrostatic wind turbine;
4. Calculate the annual energy production of the hydrostatic wind turbine and compare it with the commercially available gearbox turbine;
5. Identify control challenges for the proposed drivetrain concept based on the simulation study;
6. Explore the possibility of short-term energy storage of the hydrostatic wind turbine.

Simulation results show that although the annual energy production (AEP) of the hydrostatic wind turbine is slightly lower than the gearbox turbine, the cost of energy (COE) is still lower than the gearbox turbine, which owes to the higher reliability and lower initial cost of hydrostatic drives. The slightly lower annual energy production is due to the lower efficiency of the hydrostatic transmission compared to the gearbox transmission. With modern advanced pump and motor technology such as Digital Displacement control, the improved pump and motor efficiency at low displacement fraction would improve the AEP of the hydrostatic wind turbine. Preliminary study shows that it is possible to capture the turbulent wind energy by using a hydraulic accumulator.

Short-term energy storage for mid-sized hydrostatic wind turbine: Mid-sized wind turbine, typically defined as 100 kW to 1 MW, fits into the sweet spot of HST applications since the components needed for this application are commercially available in this power range. Preliminary study demonstrated the need and advantages of using hydrostatic transmissions in mid-sized wind turbines. It is shown that a variable ratio hydrostatic wind turbine can produce more power than a fixed ratio and fixed speed gearbox turbine even given the lower efficiencies of the HST. But most modern wind turbines are variable speed, pitch controlled turbines. In this case, commercially available off-the-shelf hydrostatic drives may not be able to compete with gearbox drives in energy production even though the lifetime cost of energy may be lower owing to the higher reliability and lower initial cost of hydrostatic drives.

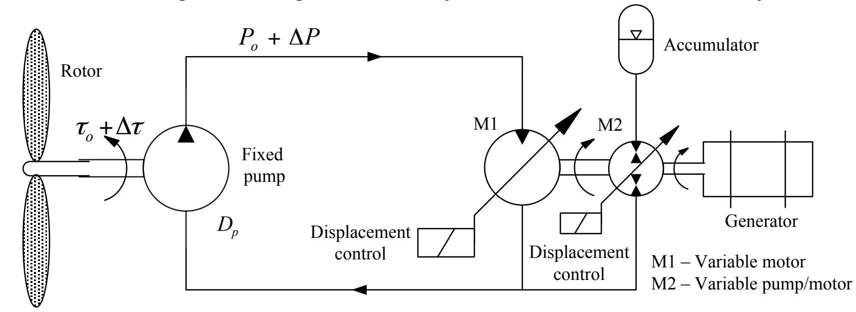

Figure 2: Hydraulic schematic of a hydrostatic turbine with short-term energy storage.

To make hydrostatic drives more attractive, this study investigates the use of short-term energy storage using hydraulic accumulators to increase the Annual Energy Production (AEP). The use of short-term energy storage during turbulent wind oscillations is focused on the region around the rated wind speed (between region 2 and region 3).

Accomplishments:

1. Propose a system configuration for the energy storage of the hydrostatic wind turbine;
2. Develop a rule-based control strategy for the proposed energy storage system;
3. Obtain a turbulent wind profile based on FAST code;
4. Build a dynamic simulation model to verify the energy storage concept;
5. Conduct a sensitivity study of the accumulator size on the annual energy production;
6. Compare the AEP between the systems with and without the energy storage system.

The target application of this concept study is mid-sized wind turbines. The hydrostatic wind turbine model consists of turbine blade aerodynamics, HST and generator. Characteristics of AOC 15/50 were chosen for blade aerodynamic turbine model. AOC 15/50 is a 50 kW wind turbine manufactured by Atlantic Orient Corporation. The aerodynamic model of AOC 15/50 was incorporated using FAST code. Simulation results show that the AEP increases with the accumulator size until it reaches a point of diminishing return. For a 50 kW wind turbine the optimum accumulator size was found to be 60 liters which increases the AEP by 4.1%.

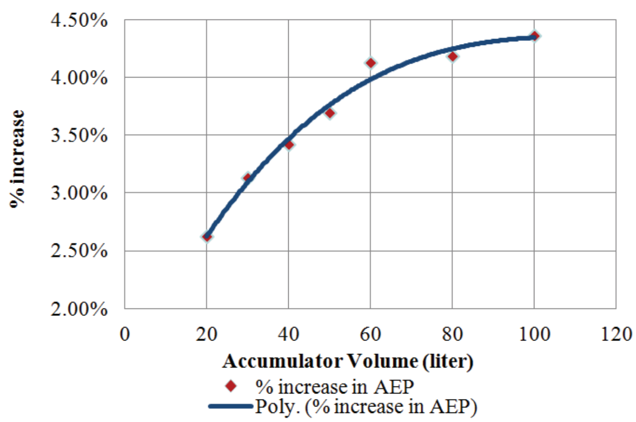

Figure 3: Sensitivity study of accumulator size on AEP in a 50 kW turbine.

Hydro-mechanical transmission for mid-sized wind turbine: Preliminary study shows that a variable transmission such as a hydrostatic transmission (HST) is needed to capture wind energy more efficiently. Yet, the low efficiency of an HST compared to gearbox drives often makes it undesirable. Therefore, a hydro-mechanical transmission (HMT), combining the high efficiency of a gearbox and the variable ratio function of an HST, offers a more competitive solution for mid-sized turbines.

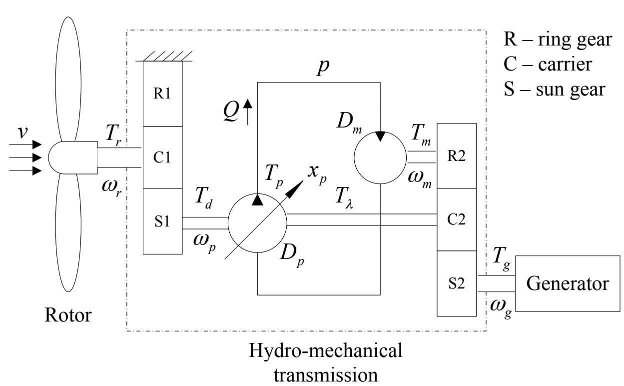

Figure 4: Schematic diagram of a hydro-mechanical wind turbine.

Accomplishments:

1. Propose a hydro-mechanical transmission drivetrain configuration for mid-sized wind turbine;
2. Conduct a theoretical analysis to understand how the power is transferred through the HMT at different wind and rotor speeds;
3. Conduct a parameter study to determine the components sizing;
4. Build a dynamic simulation model of the HMT wind turbine;
5. Compare the drivetrain efficiency and generator power production between the HMT and HST wind turbines.

Due to the variable ratio characteristics of the HMT, the rotor speed can be adjusted with the varying input wind speed so that the optimum tip-speed ratio and maximum rotor power coefficient can always be obtained. The high efficiency of the planetary gear improves the overall drivetrain efficiency and increases the generator power output. Simulation results are compared with the theoretical results based on steady-state characteristics. As predicted, the ratio of the rotor power transferred through the mechanical path increases with the increasing wind speed. This is desired since higher wind speeds have more power than lower wind speeds. The drivetrain efficiency and the generator power of the HMT and HST wind turbines are compared. Simulation results show that an HMT turbine has higher drivetrain efficiency and generator output power than an HST turbine. If the additional cost is low enough, a hydro-mechanical transmission could be a more cost effective solution than a hydrostatic transmission for mid-sized turbines.

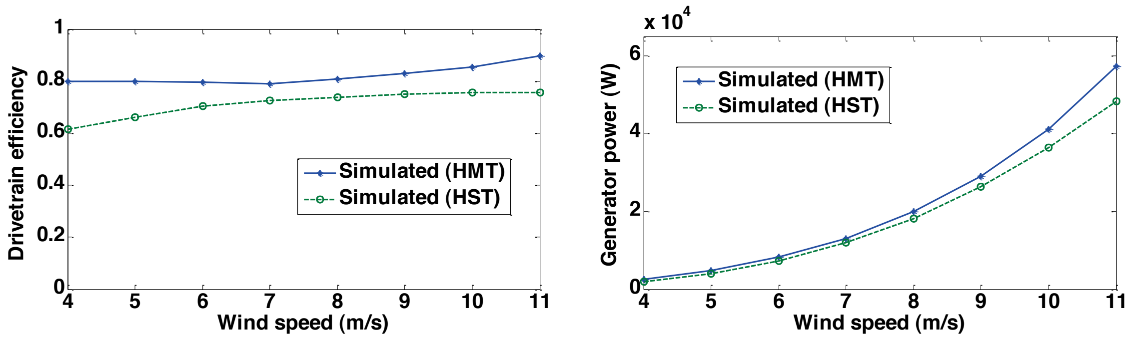

Figure 5: Drivetrain efficiency and generator power comparisons between HMT and HST turbines

Power regenerative test platform for mid-size hydrostatic wind turbine: To validate the proposed ideas, a power regenerative midsize hydrostatic turbine test platform is being built at the University of Minnesota, providing a powerful tool to investigate the related research topics about the midsize turbines. The hydraulic schematic of the test platform is shown in Figure 6. The block in dark gray is the hydrostatic transmission under test and the block in light gray is the hydrostatic drive (HSD) simulating the virtual rotor. The virtual rotor is simulated at the input of HST and the turbine output is simulated at the output of HST.

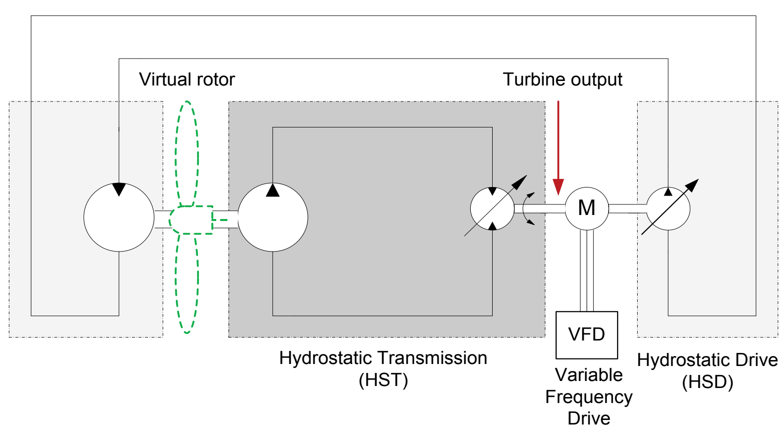

Figure 6: Hydraulic schematic of power regenerative test platform for mid-size hydrostatic wind turbine.

Instead of dissipating the turbine output power, a variable frequency drive electric motor is coupled to the turbine output shaft. The turbine output power and the electric motor power are combined to power the hydrostatic drive, which constitutes a power regenerative circuit. With the power regeneration, the electric motor only needs to make up for the losses in both the HST and the HSD, enabling the turbine power simulation with smaller electric power supply. Another benefit is to use the grid to regulate the turbine output shaft speed, which is the real condition while connecting these turbines to the grid. This also avoids using high cooling demand power dissipative electric components such as resistors as the load.

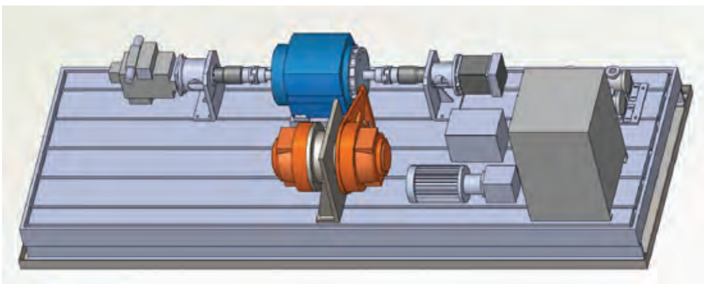


Figure 7: Regenerative wind turbine test platform in construction.

Currently the test platform is under construction. The electric power and chilled water infrastructure is in place. The final designs of data acquisition and control systems are underway. The next step is to get the hardware and control system ready for the initial start-up.

C. Plans

Planned future work:

- Complete the hydrostatic wind turbine test platform
- Simulate the steady-state and dynamic wind characteristics
- Validate the proposed control strategy for the HST turbine at wind speeds below that required to achieved rated generator output
- Test the HST efficiencies at different steady-state wind speeds
- Investigate the dynamic behaviors of the HST turbine during wind turbulence
- Implement the short-term energy storage concept on the test platform
- Explore other energy storage scheme and implement it on the test platform
- Investigate the possibilities of using other more efficient hydraulic transmissions

D. Member company benefits

Wind energy drivetrains represents a large new potential market for fluid power. Although the hydraulic drivetrain solution is robust and cost-effective, there are no wind turbines with HST or HMT drivetrains commercially available today. Several of the Center's member companies have investigated applying hydrostatic transmissions to wind turbines. More than one has approached the Center to investigate working with Center researchers to move the technology toward commercialization and one DOE funded project was completed. Given the increased government focus on renewable and sustainable energy and the advantages fluid power brings to wind energy, we believe that the Center's researchers and their industry partners are in a position to facilitate the adoption of fluid power technology to wind energy thus opening a large new market for our members.

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

Research Team

Project Leader: David Kittelson, Mechanical Engineering, University of Minnesota
Other Faculty: William Durfee, Mechanical Engineering, University of Minnesota
Graduate Student: Dustin Johnson

1. Statement of Project Goals

This project has two goals. The first is to generate new knowledge about the science and engineering of homogeneous charge compression ignition (HCCI) in free piston engine-compressors on a small scale. Such devices would be suitable as tiny power supplies for fluid power systems. The second goal is to design, build, evaluate and deliver a tiny, high-efficiency free-piston air compressor that delivers approximately 20W of cold compressed air and runs on cartridges of clean-burning dimethyl ether (DME) fuel. The engine compressor will be suitable for projects in CCEFP Test Bed 6, such as the Portable Pneumatic Ankle Foot Orthosis, and other small scale mobile pneumatic fluid power devices including hand tools and robots.

2. Project Role in Support of Strategic Plan

This project supports CCEFP's goal of developing new fluid power supplies that are one to two orders of magnitude smaller than anything currently available (10 W – 1 kW). This in turn 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 that prevents these new applications of fluid power is the lack of a compact, light, high energy density source of pressurized fluid. This project addresses this problem with an internal combustion free-piston engine coupled with an air 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 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. Using experimental results, appropriate models with fitted parameters can be chosen to better simulate the engine-compressor, 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>Achievements in previous years</u>

The project started September, 2008. A second prototype has been fabricated, which is about 12 cm long with 12.5 mm bore size in the engine and air compressor, and weights 260 grams. Various unique design features improved upon the first prototype to ensure alignment of components and reduced friction, while maintaining relatively good sealing.

Experimental data were compared with the simulation model and verified that the model was able to predict key engine-compressor characteristics. Analysis of experiments performed with the free-piston engine prototype showed that the rate of combustion was slow compared to the expansion process, leading to reduced efficiency. The relatively slow combustion was associated with glow plug ignition and traditional flame propagation. HCCI is associated with very fast flameless combustion and should lead to significant efficiency improvements.

The free-piston engine compressor was designed to be self-regulating without active control, but cyclic variation has led to inconsistent running. Cyclic variation occurs in all engines but it is worse in two-stroke designs where the quantity of trapped charge (fuel-air mixture) may vary from cycle to cycle. As a result of the free-piston's lack of mechanical constraints, its range of travel depends on the strength of combustion. A weak charge causes a shorter stroke which hinders scavenging. In order to minimize this problem, the piston assembly was designed to over-stroke by 2 mm, ensuring that the scavenging ports are uncovered to provide a fresh charge for each cycle. But then a stronger combustion will cause the pistons to move beyond their normal stroke, which may cause physical damage to the engine if the extra energy is not controlled. In a longer stroke the compressor and rebound spring absorb more energy but rubber bumpers were also built into the prototype to absorb the remaining energy and prevent damaging metal-to-metal collisions. At higher output pressure, the compressor can absorb more of the extra energy from stronger cycles; however, there is also an increased chance that the engine will stall during weak cycles. Ongoing design issues associated with this problem include improving scavenging to reduce cyclic variation and developing a better bumper material.

The current generation II prototype uses the piston and liner from an AP Hornet .09 model aircraft engine. Piston material is hyper-eutectic aluminum alloy with high silicon content in the alloy for lubricity. The cylinder liner is brass, with a thin layer of chrome plating. Measurement showed that at room temperature the cylinder liner has negative clearance around the top dead center (TDC) position and tapers off towards bottom dead center (BDC). As a result, model aircraft engines are tight to turn over the TDC position when they are cold. This isn't a problem for model aircraft engines as enough force is used to turn the crankshaft during start up to overcome the tightness, and the momentum of the crankshaft and flywheel is adequate during warm-up to keep the engine running. As the engine warms up, the top of the liner heats up and expands more than the bottom, thus counteracting the liner taper, and resulting in a straight bore and good seal against the piston.

The negative tolerance around TDC is a problem for a free-piston engine during starting, as there is no force to overcome the tightness at TDC. The only force available during starting up is from the rebound spring, which is not enough to overcome the tightness of negative clearance and achieve high enough compression ratio. The negative clearance problem has been addressed by reducing the taper of the liner. The compressor liner was reamed from a diameter of 12.48 mm at TCD to 12.55 mm. The diameter of the engine liner was increased from 12.48 mm at TDC to 12.51 mm to provide good piston-cylinder fit in the engine for cold starting. However, after the engine warms up, thermal expansion of the top of the liner results in increased clearance, causing poor sealing. Scuffing and piston-cylinder seal deterioration are still present and limit run time to a maximum of approximately five minutes.

Achievements in the past year

In the current reporting year, the project went through a transition in personnel. Lei Tian finished his Ph.D. and left the project at the beginning of January 2013 and Dustin Johnson joined the project in September 2013. Progress this year was focused on working towards improved reliability and performance of the engine compressor by addressing the hardware issues. The primary concerns are with the interaction between the piston and cylinder liner. Reducing friction and wear will greatly increase the run time of the engine, making it more reliable and useful for further studies of small-scale HCCI, one of the goals of this project. These problems are being addressed by changing the materials of the piston and liner. These new materials are also expected to improve sealing.

In order to gauge the effectiveness of improvements made to the engine-compressor, thorough testing was done with the current prototype. The prototype was run with glow-plug ignition using methanol-based model airplane fuel. While starting and running, the in-cylinder pressure and piston position were continuously monitored and recorded. A sample of these data can be seen plotted in Figure 1. The compressor was connected to an air reservoir to measure its output.

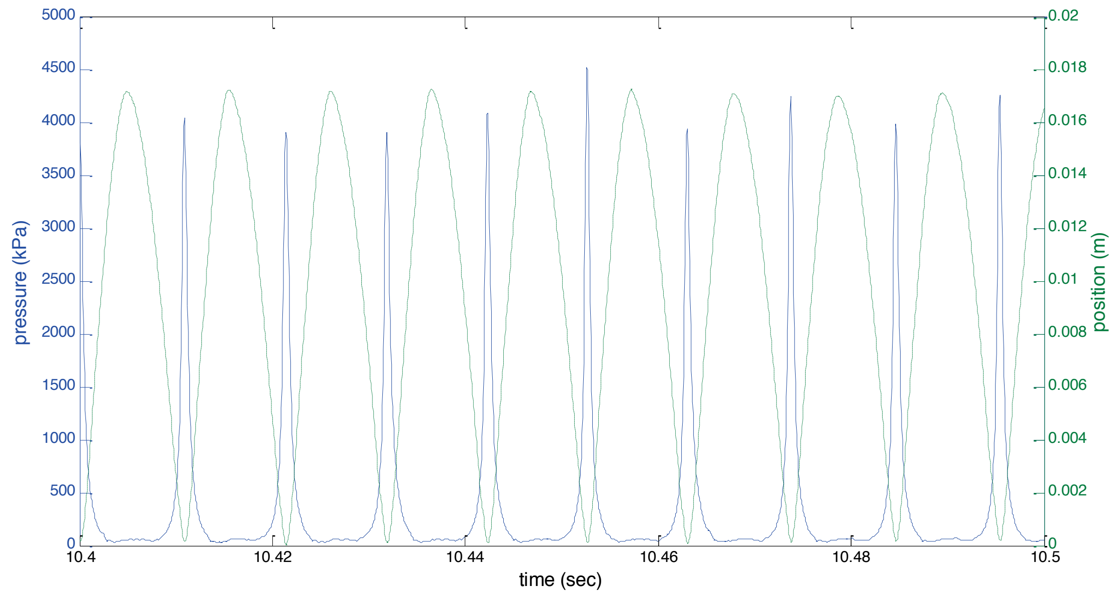

Figure 1. Typical data for pressure and piston position while the engine is running. The pressure, represented by the solid line, peaks during combustion events. The position, represented by the dashed line, is measured down from the top of the stroke; therefore it is near zero at full compression.

During a typical 20 sec. run, the free-piston engine compressor pressurized a 530 mL air reservoir from atmospheric pressure to approximately 3.4 bar (50 psig). Assuming that this air has cooled to room temperature, the stored energy can be calculated by finding the work it would do in an adiabatic expansion to atmospheric pressure. It was found that the pressurized air had about 200 J of energy. Averaging over 20 s – the time it took to compress the air – the average power output is found to be about 10 W.

The engine ran continuously for a maximum time of about 20 seconds. It was successfully restarted multiple times without replacing any parts, so the reason for it stalling cannot be due to excessive scuffing of the piston. We believe that heat transfer causes more thermal expansion of the cylinder than the piston, increasing the clearance and causing excessive leakage. After cooling for a short time, the clearance is reduced so that leakage is low enough to allow successful engine operation.

As a first attempt at reducing friction and wear in the engine side of the prototype, a ceramic piston coating will be used. The piston's sides will be coated with a dry lubricant material by PolyDyn. This hard and slippery coating will allow the piston to run with less friction, reducing energy loss. This also will reduce wear, increasing the life of the piston and the runtime of the engine-compressor. There will also be a thermal barrier ceramic coating added to the top of the piston, which is directly exposed to the heat of the combustion process. This will reduce heat absorbed by the piston, resulting in less thermal expansion.

Since this device is intended to be used in close proximity to people, its noise level, vibration, and heat output need to be considered. While running the engine compressor, the sound level was measured to be approximately 100 dB at a distance of one foot. There are various silencing options for small two-stroke engines which will be examined. Due to short run time, the engine has not heated up to the expected steady state operating temperature; when it runs for a longer time, detailed temperature measurements will be taken.

C. Plans

Plans for the next year

The pistons with ceramic coatings will be installed in the engine, and testing will be repeated to look for improve performance. The volume of airflow from the compressor during steady state operation, and the rate of fuel consumption will both be measured directly to further quantify the prototype's output. Depending on initial results, further steps may be taken to improve performance. Using the same material piston and cylinder liner might cause the expansion factor to match up better, resulting in consistent clearance and sealing over a wide temperature range.

Hardware improvements are needed for the compressor, as well. Since it does not experience the elevated temperatures of combustion, PTFE material could be a good candidate for eliminating compressor side friction and piston scuffing while improving sealing. The compressor check valves also need to be addressed. In the current prototype, the valves are fabricated from thin stainless steel foils and suffer deformation and cracking after several minutes of running. In order to solve this fatigue problem, stops need to be added to prevent exaggerated motion of the valves. When oil flows through the valves it causes extra stress. More seals are needed to prevent excessive liquid from the engine side seeping into the compressor.

Expected milestones and deliverables

Task 1: Improve engine-compressor performance

- In order to move towards the goals of this project, a reliable prototype will need to start and run consistently. It should be sufficiently durable that it can run continuously for several hours and survive multiple runs without replacement of major parts.
- A number of hardware improvements are necessary. Parts that are more refined will allow for longer running with less wear, and they will reduce mechanical losses during operation.
- Problems that should be addressed are: piston wear and scuffing, piston-cylinder sealing, fuel delivery and scavenging, and compressor valve sealing and fatigue.

Task 2: Implement HCCI

- Pure homogeneous charge compression ignition (HCCI) will greatly improve cycle efficiency due to much faster combustion than glow plug ignition. HCCI requires a higher compression ratio, so piston-cylinder leakage must be minimized and design considerations made to achieve adequate compression.
- Appropriate fuels that work well for HCCI should be used. One of these is dimethyl-ether (DME), which is a clean and renewable. DME has physical properties similar to propane and butane, existing as a gas under ambient conditions but stored as a liquid in a pressurized cartridge similar to that used in butane lighters.
- A better fuel delivery system will be required for the engine. The use of fuel from a pressurized cartridge could provide more consistent fuel flow metering than the current carbureted system.

D. Member company benefits

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

Project 2B.3: Free Piston Engine Hydraulic Pump

Research Team
Project Leader: Zongxuan Sun, Mechanical Engineering, University of Minnesota
Graduate Students: Ke Li, Chen Zhang
Industrial Partner: Ford Motor Company, Individual Project Champion: John Brevick

1. Statement of Project Goals

The goal of this project is to provide a compact and efficient fluid power source for mobile applications (10 kW-500 kW), including on-road vehicles and off-road heavy machineries. This is achieved through the development of a hydraulic free-piston engine (HFPE).

2. Project Role in Supporting of Strategic Plan

The project will address two transformational barriers as outlined in the CCEFP 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

Fluid power is very effective at energy transmission due to its superior power density and flexibility. The current practice for energy storage is using hydraulic accumulators to store high-pressure fluid. However, applications of fluid power are limited by the relatively low energy density of the hydraulic system. An alternative approach is to store the energy in the form of hydrocarbon fuel and convert it to fluid power in real time. This configuration offers the ultimate power density and energy density, and therefore become extremely attractive for mobile applications. However, to realize this concept, it is necessary to convert the chemical energy into fluid power in real time to match the dynamic power demand. The hydraulic free piston engine (HFPE) is a promising candidate due to its fast dynamics (output can be changed on a cycle-to-cycle basis in milliseconds), resulting from its unique architecture, low inertia and modular design. A schematic diagram of the HFPE is shown in Figure 1.

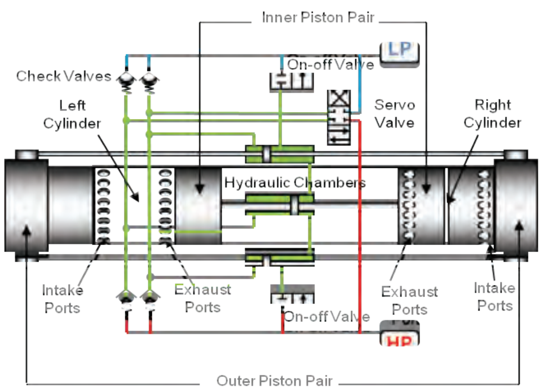

Figure 1: Schematic of the Free Piston Engine Driven Hydraulic Pump.

A major technical barrier for the wide spread of the FPE technology is the lack of robust and precise control of piston motion, which is determined by the complex dynamic interactions between the combustion and the load in real time [1-10]. Unlike a conventional ICE with the crankshaft to maintain its piston trajectory, a FPE without such a mechanism is exposed to large cycle-to-cycle variation, especially during transient operation. To address the above challenge and push the FPE technology forward to a new frontier, the research is divided into three steps: a) development of precise piston motion control; b) efficient and reliable operation of the HFPE; c) optimization of the HFPE operation for on-road and off-road applications using a hardware-in-the-loop system.

B. Achievements

<u>Achievements in previous years</u>

To address the challenge mentioned above, an active control was designed previously to act as a “virtual crankshaft”, which regulates the piston to follow any reference trajectory using the energy from the storage element [11-15]. By adjusting the opening of the servo valve, the virtual crankshaft controls the hydraulic forces acting on the piston pair in real time, and therefore regulates the piston motion. Engine subsystems that are necessary to conduct experiments were designed and installed in the test cell, and the virtual crankshaft mechanism has been developed and implemented on the FPE as well. Figure 2 shows the related experimental motoring and firing test results, which demonstrates the effectiveness of the virtual crankshaft mechanism.

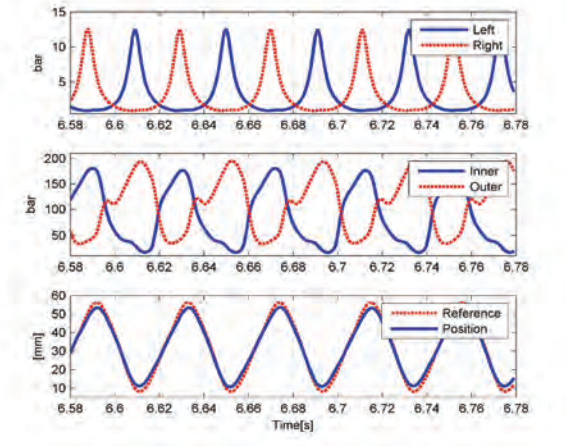

Figure 2(a). Engine motoring results (from top to bottom: gas pressure, hydraulic pressure, tracking performance).

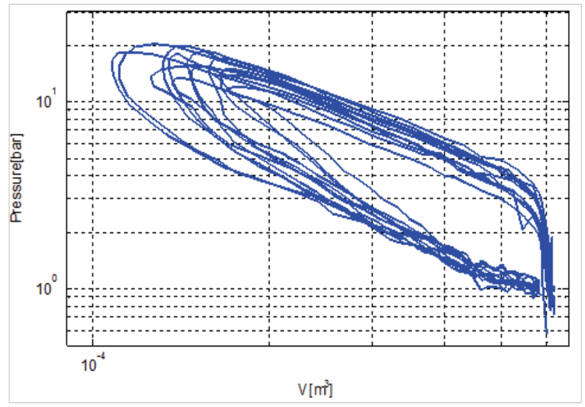

Figure 2(b). Combustion tests with the regulation of the virtual crankshaft.

Achievements in the past year

As shown in Figure 2(a), the virtual crankshaft is able to produce repeatable engine motoring. However, when switched from motoring to engine firing, a transient period is observed as shown in Figure 3(a). To ensure continuous engine operation, a transient control method which involves the design of a combustion detection mechanism and modification of the existing active control algorithm, has been developed [16]. The experimental results demonstrating the effectiveness of the transient control are shown in Figure 3(b).

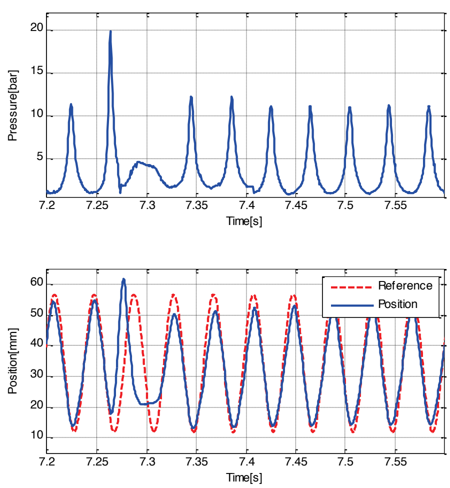

Figure 3(a). Transient period when engine switch from motoring to firing: pressure trace (top) and tracking performance (bottom).

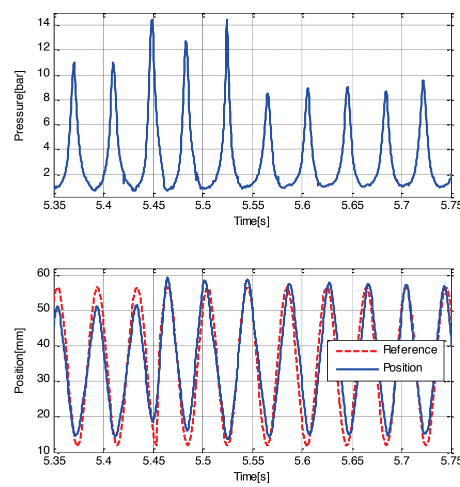

Figure 3(b). System behaviour after applying the transient control.

To enhance the system capability for comprehensive tests, we have updated the existing hardware. Specifically, a heating plug has been installed to adjust the intake air temperature. And a thermal control unit has been designed and integrated with the HFPE, which allows us to control the engine wall temperature from 35˚F to 200˚F with ± 1˚F accuracy. Not only does the thermal unit offers a stable boundary condition for repeatability of the firing tests by maintaining a constant wall temperature, it also provides an opportunity to study the influence of the wall temperature on the engine operation.

In the past year, a major milestone of our project is the achievement of the continuous operation of the HFPE with the virtual crankshaft mechanism. Figure 4 shows the continuous engine operation with transition from motoring to firing. The experimental results offer valuable information for future

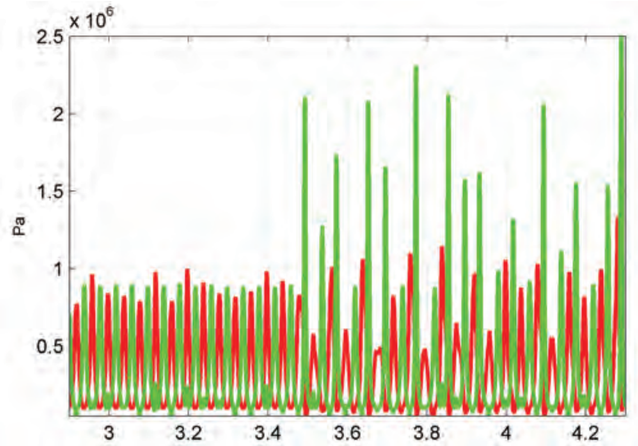

Figure 4. Continuous HFPE operation.

HFPE research, as no previous experimental results have been published in the literature on FPE operation with opposed-piston-opposed-cylinder (OPOC) architecture. Based on the results, we are able to obtain the mechanical loss of the engine operation. At the same operating point, the mechanical loss of a conventional ICE, which is measured by the friction mean effective pressure (FMEP), is 140 kPa [17], whereas for the HFPE, the mechanical loss is equivalent to 50 kPa. We are currently working on the quantification of the engine efficiency. However, the results readily reveal the advantage of the HFPE over the conventional ICE. Note the results also show the cycle-to-cycle variation of the combustion, which is mainly due to the low pressure of the current fuel injection system that causes insufficient fuel atomization and mixing. Construction of a custom high pressure direction injection system is currently ongoing.

C. Plans

Plans for the Next Years

1) *Transient control methodology development*
   Beside the aforementioned control method which addressed the transient performance from the motoring to firing process, the transient control will be fortified with the capability to address the engine on off operation, load transition and miss fire recovery, so that the HFPE will be ready for transient operations in both on-road and off-road applications. Additionally, feedforward control will be designed and integrated to the existing active control to further enhance the tracking performance of the piston motion.
2) *Enhancement of HFPE System Capability*
   To further improve the HFPE system performance and flexibility, new engine subsystems will be integrated with the existing hardware. Specifically, a high pressure direct injection (DI) fuel system will be custom-designed, and piston synchronization using high speed digital valves will be investigated.
3) *Optimization of HFPE driven vehicle and machinery*
   For mobile applications with the HFPE, since the load is not connected to the HFPE mechanically, accumulators and hydraulic motors are required to mobilize the vehicles, which is similar to the series hybrid vehicles. However, due to the high modularity of the HFPE, the system architecture can be drastically different from the conventional ones. Therefore, a novel system level optimization strategy that ensures smooth operation, optimal efficiency and reduced emissions, will be developed in this part of the project.

   The optimization strategies will be implemented in a Hardware-in-the-loop platform, which consists of a load emulating system, virtual vehicle and driveline dynamics and the HFPE. As in the case of a passenger vehicle powered by the HFPE, the vehicle dynamics as well as the drivetrain dynamics will be modeled [18-19], and this virtual system is run in real time parallel to the actual HFPE to emulate the numerous loading conditions of the HFPE. Extensive experiments will be conducted for various applications with different architectures under different drive cycles.

Expected milestones and deliverables

- Task 1: Transient control methodology development [10 months]
  - Designing transient control methodologies for on off operation, transient load change and miss fire recovery [12/31/2014]

- Implementation of the transient control methodologies on the FPE [3/31/2015]

- Task 2: Enhancement of HFPE system capability [12 months]
  - Installation and testing of the high pressure DI system [9/30/2014]
  - Installation and testing of the digital hydraulic valves [5/31/2015]

- Task 3: Optimization of HFPE driven vehicle and heavy machinery [14 months]
  - Optimization of HFPE driven vehicle and heavy machinery [9/30/2015]
  - Implementation using a hardware-in-the-loop system [5/31/2016]

Milestones:

- Transient control methodology development [month 10]
- Enhancement of HFPE system capability [month 12]
- HFPE driven vehicle and heavy machinery optimization [month 24]

D. 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 the Center.

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Project 2B.4: Controlled Stirling Themocompressors

Research Team

Project Leader: Eric Barth, Vanderbilt University, Mechanical Engineering
Graduate Student: Anna Winkelmann

1. Statement of Project Goals

The goal is to design and build a second generation Stirling thermocompressor as a design evolution of the first generation device that has already been completed with CCEFP funding. The research goals are: 1) design and experimentally validate a Stirling thermocompressor for untethered fluid power applications, as driven by the challenging and representative requirements of the ankle-foot-orthosis test bed (TB6), 2) continue to pursue a dynamic model-based design approach for a Stirling-based thermocompressor based on validated models from the generation 1 device, 3) experimentally characterize the generation 2 device for model validation purposes and performance, and 4) study the scalability of technology developed for the Stirling thermocompressor from miniature pneumatic power supplies up to industrial pneumatic compressors, particularly with respect to enhancing heat transfer within the compressor to enhance efficiency. The goals of the project will be achieved by paying attention to the lessons learned from the generation 1 device from both a model-based / fundamental standpoint, as well as from an implementation standpoint.

2. Project Role in Support of Strategic Plan

This project contributes to two thrusts within the Center: compactness and efficiency. Enhanced compactness is particularly needed at the scale of TB6 (10-100W). This project will contribute to the Center’s goal of breaking the barrier of low energy density power sources for untethered devices. The efficiency thrust is addressed as a by-product of requiring high heat transfer within the device. The novel in-cylinder heat exchangers already developed in this project have been shown to be very effective, and their inclusion on larger scales will be investigated through model-scaling. The ultimate goal of this work is to fulfill the CCEFP’s strategic vision of providing a source of power for untethered fluid power devices in a way that will open up whole new applications and whole new markets in robotics – specifically utilizing pneumatics.

3. Project Description

A. Description and explanation of research approach

The scientific contribution of this project will be a much needed fundamental understanding of the system dynamics underlying Stirling devices. The literature contains a body of knowledge that is primarily either quasi-statically thermodynamic in nature, or of a CFD nature. The literature is also characterized as presenting very few experimental platforms. The scientific gap that will be filled by this research is a first-principles based understanding of the lumped parameter system dynamics that is experimentally validated. Filling this gap will provide model-based design and control tools for the improved design of such future devices. This will be accomplished by designing, modeling, fabricating, and testing a second generation Stirling thermocompressor. The research will also pursue a novel configuration of a Stirling machine that has shown promise in the first two years of this research by operating at 800° C (required for high efficiency) and achieving a pressure ratio of 1.6 (a sign of excellent heat transfer characteristics). [1].

Stirling machines have long held the promise of being an efficient, clean, reliable, and nearly maintenance-free source of power. However, after more than a century of research, the reality of Stirling engines has unfortunately fallen far short of these promises, except in a few application areas. Why is this the case? The primary reason appears to be low power density – a heavy engine producing small amounts of useable power – particularly at the sub 10kW scale. Free piston Stirling machines are recognized as possibly holding the key to increasing power density without sacrificing the Stirling cycles’ characteristic high efficiency. Historically, the design of the Stirling engine (where the output is mechanical work rather than compressed air for a Stirling thermocompressor) has progressed from its original purely kinematic arrangement, where the motion of the displacer and the power piston are kinematically constrained, toward a purely dynamic arrangement – such engines are called free-piston Stirling engines. By replacing bulky, complicated kinematic linkages with small, lightweight dynamic elements, free-piston arrangements can be significantly lighter, more compact and operate with fewer losses, and thereby possess higher power densities than their kinematic cousins. Perhaps one of the strongest reasons for miniaturization of the Stirling thermocompressor and the reason for its proposed application to TB6 (the ankle-foot orthosis), is that heat transfer rates are enhanced as the device becomes smaller, thereby increasing power density. Our generation 1 device employed novel in-cylinder heat exchangers that further enhance this advantage of scale. The in-cylinder heat exchangers designed and implemented in the first two years of this project showed nearly a 4x increase in heat transfer over not using them. [1]

The problem with the current state-of-the-art in the design of Stirling engines, and Stirling machines more generally, arose when purely dynamic, or free-piston, Stirling engines began to be considered. In the early 1960's William Beale determined that kinematic linkages were not a necessity for a Stirling engine to operate [2]. The invention of Beale's free-piston Stirling engine was the first dynamic Stirling engine. Primary advantages of a free-piston arrangement include the ability to completely seal the engine, the elimination of side forces on the pistons, and the ability to pressurize the engine to obtain higher power densities [3, 4] – all are necessities for advancing Stirling machines. However, since the time of Beale, inadequate design and analysis tools have prevented the design of free-piston Stirling engines from escaping a large degree of trial and error selection of the system parameters. Here, the analysis technique has largely continued down the path of an assumed solution in time, but due to the lack of kinematic linkages altogether, the task of selecting such an assumed solution becomes all encompassing. This is where the "design" of free-piston Stirling engines becomes less constructive. Instead of a constructive design method that reveals intuition and insight regarding the effect of each engine parameter on the metric of interest (such as power, efficiency or indeed even whether the engine will run or not), the designer is left to test each candidate set of design parameters in a trial-and-error manner. Extensive numerical codes exist for this purpose [5, 6, 7, 8]. Although accurate, these codes are unfortunately no better for gaining insight into a particular design than simply building the machine and seeing if it runs, seeing how much power it produces, or seeing how efficient it turns out to be [9]. Despite this, certain dynamic Stirling configurations have been constructed and shown to work, such as many of Beale's arrangements [10, 11], the Harwell Thermomechanical Generator [12, 11, 13], or even the ingenious liquid piston Fluidyne Stirling engine by West [14, 15], among many others. When such free-piston engines have been constructed that run, the selection of their parameters, and their ability to run with respect to the sensitivity of their parameters, is not generally well understood [11]. The combination of this fact, along with the numerical simulation based trial-and-error nature of the current design strategy, results in engine designs that are not robust (do not continue to oscillate for certain load variations) and do not have well understood parameter-sensitive properties.

So although free-piston Stirling machines show promise in increasing the power density and reducing the size scale over kinematic Stirling machines, thereby opening them up to a host of small scale and mobile applications, they are subject to a very difficult constraint. That constraint is that they must self-oscillate. Kinematic Stirling machines are constrained to get the phase of the displacer motion correct with respect to the power piston in order to keep the engine running. Conversely, typical free-piston Stirling machines utilize their own pressure variations to drive the displacer piston. Free-piston Stirling machines must achieve the correct phase dynamically, and due to this, the phase is coupled to other dynamics that change over time. The dynamic condition of self-oscillation is therefore sensitive to the parametric properties of the engine (which are difficult to design accurately), and to the load (which is difficult to hold within acceptable bounds). Although understanding of this sensitivity has received recent attention by researchers such as Bamieh [16], it is a difficult constraint that limits the design freedom of the overall machine. This difficulty can be overcome by directly controlling the displacer piston of the machine. By doing this, the delivery of the output power is decoupled from, and does not affect, the motion of the displacer piston. This allows more design degrees of freedom and ensures that the device is insensitive to load or internal dynamics variations. Finally, as a general characterization of the literature regarding Stirling machines, many papers treat theoretical aspects of Stirling machines and simulate novel designs, yet a very small fraction of the papers present an experimental device. Even fewer present an experimental device in the context of a novel design.

B. Achievements

Achievements in previous years

The first generation device, shown conceptually in Fig 1, was a multi-stage thermocompressor where each stage would progressively increase the pressure. This had appeal by being a true thermocompressor – meaning that the working fluid (air) was also the output fluid. Based on this, the compressor was designed to have multipe stages, where each stage would feed compressed air into a smaller chamber which in turn would compress the air even further.

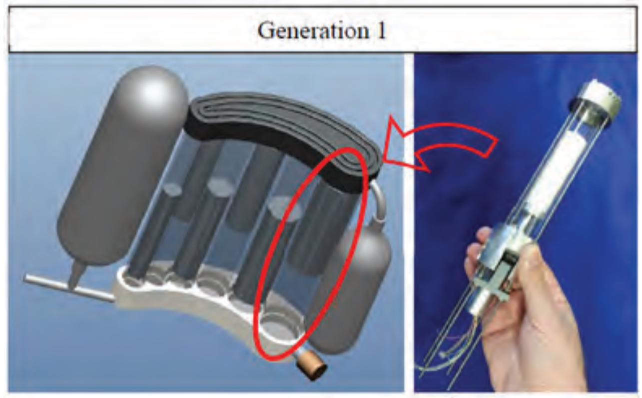

Figure 1: Generation 1 device.

The design of a single stage is shown in Fig. 2. The displacer was driven by controlling a brushless DC motor. This was done to decouple the displacer motion and thus divorce from the idea of using the output pressure to drive the displacer, and all of the complexities associated with this requirement. The motor was used to drive a continuous linear reciprocating screw, onto which the displacer piston is affixed. The reciprocating screw is similar to a lead screw but differs in that the screw has a "criss-crossed" left-handed and right-handed thread, and a turn-around at the end of the threads to enable reciprocating motion of the nut with unidirectional screw rotation. This enables the reciprocating screw to be driven in one direction while achieving reciprocating motion of the displacer piston. This is beneficial since the use of the reciprocating screw reduces motor power consumption. The displacer piston was made from Macor machinable ceramic, which was selected for its low thermal conductivity (1.46 W/mK at 25°C), high service temperature (1000°C), and machinability. The working fluid is bound between the heat source and the sink by a fused quartz cylinder which was chosen because of its ability to withstand high temperature and its low thermal conductivity (for reduced heat flow along the cylinder walls). Two check valves in the cooler section near the motor allow the pumping of the working fluid into or out of the thermocompressor.

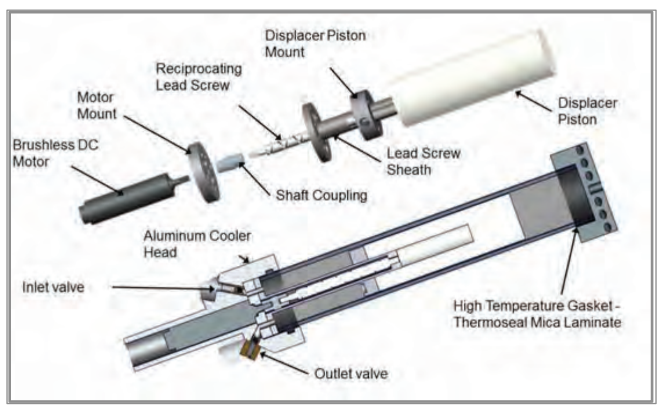

Figure 2: Design of a single stage of Generation 1.

Following from this initial design, an experimental prototype was designed, constructed, and experimentally tested. Some initial model validation was completed that showed a critical dependence on heat transfer.

Achievements in the past year and Plans for this year

In order to increase the heat transfer, heat exchangers were developed for and implemented in the thermocompressor. As shown in Figure 3, the heat exchangers are stacks of thin (0.002''), circular stainless steel shim stock. The key is that these in-cylinder heat exchangers dramatically increase the surface area of heat transfer (from 4.57 cm^2 to 1300 cm^2 on the hot side [1]) while not contributing to dead volume due to their compact collapsed configuration when the space they occupy is displaced by the piston. While expanded, convective heat transfer is dramatically increased due to a large increase in surface area. When compacted, the disks touch and transfer heat from the heater head (or to the cooler head on the bottom) through conduction. This unsteady convection/conduction mechanism needs further modeling.

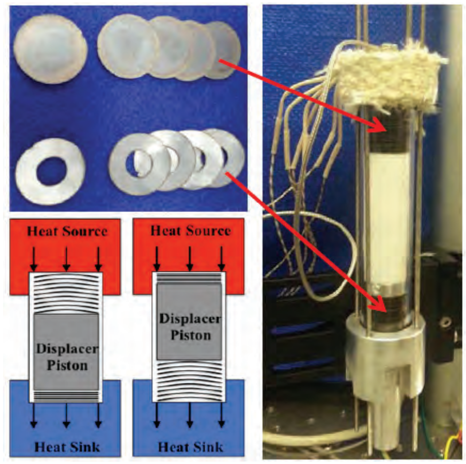

Figure 3: In-cylinder heat exchangers.

Experiments with the thermocompressor [1, 17] were conducted with heater temperatures between 200°C and 800°C, and at frequencies from 0.25 Hz up to 2.8 Hz (where the reciprocating lead screw mechanism became the bottleneck for higher frequencies). The results from the in-cylinder heat exchangers were very good, showing nearly a 4x increase in the total heat transfer and results in adequate heat transfer to operate the device up to 40Hz. The generation-1 device also showed a pressure ratio of 1.6 at 800°C and 2.8 Hz – a result that was lower than expected and would lead to a low boost pressure ratio. A detailed breakdown of the model with physical parameters of the prototype revealed that dead-space around the lead screw mechanism was the culprit. Based on the prototype validated a dynamic simulation, the generation-1 thermocompressor would require more compression stages than acceptable to reach the target output pressure [17]. In addition to this, the motor power required to drive the reciprocating lead screw was found to be much higher than expected due to friction in the mechanism. From these results it was clear that although heat transfer was adequate, the architecture of a multi-stage true thermocompressor needed to change. It was also clear that the driver mechanism for the displacer piston also needed to change.

The multi-stage architecture became untenable in the face of the mechanical complexity encountered in the single stage prototype. Therefore, the generation 2 device will be of single-stage, pre-pressurized architecture with a separate compressor stage. This architecture has two major advantages.

1. A sealed, pre-pressurized engine section can use helium as the working fluid for maximum efficiency and power.
2. Pre-pressurizing the Stirling engine to 500 psig will increase the working density [J/(m^3·stroke)] by more than two orders of magnitude, allowing the single stage engine/compressor unit to be able to pump up to 120 psig.

The separate compressor stage, seen in Figure 4, utilizes the differential pressure swing inside the engine section to pump air above the target output pressure of 80 psig. While the pressure in the driving chamber oscillates with the pressure in the engine, the pressure in the return chamber is kept at an average pressure of the engine via a simple needle valve (see Fig. 5). Known technology of rolling diaphragms and standard diaphragm pump design will be used to pump air to its desired output pressure. When the pressure in the driver chamber is higher than in the return chamber, the rod moves down and compresses the air in the lower pumping chamber. Conversely, when the pressure is higher in the return chamber, the rod moves up, compressing the air in the upper pumping chamber.

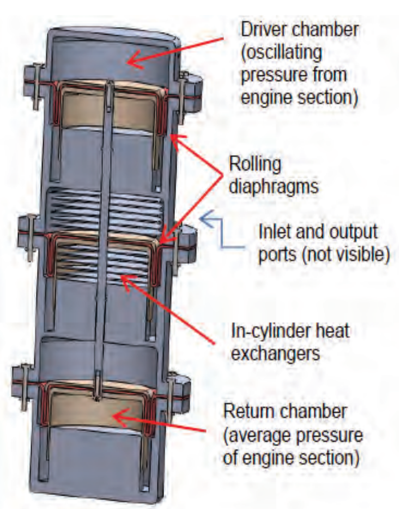

Figure 4: Compressor Section.

To improve the linear drive mechanism of the displacer piston, the DC motor and the reciprocating lead-screw will be replaced by a compact COTS linear actuator (Faulhaber). A linear spring located in between the displacer piston and the linear motor will act as a restoring force such that the system will move at its natural frequency.

Experiments of the generation 1 device revealed a slow leak resulting from the high temperature seal between the fused quartz glass and the heater head. To avoid a leak, the generation 2 device will have an engine cylinder made of Inconel 625 as opposed to fused quartz. This will be tougher and able to be welded, thus solving the sealing problem at the hot end.

The pressurized Stirling Thermocompressor with its separate compressor section has been designed and modeled. Results of the dynamic simulation show that the system can pump 120 psig when the initial pressure inside the engine is at about 500 psig. After analyzing the dynamic model in more detail, parts will be ordered, the pressurizer and compressor fabricated and assembled such that the dynamic model can be experimentally characterized.

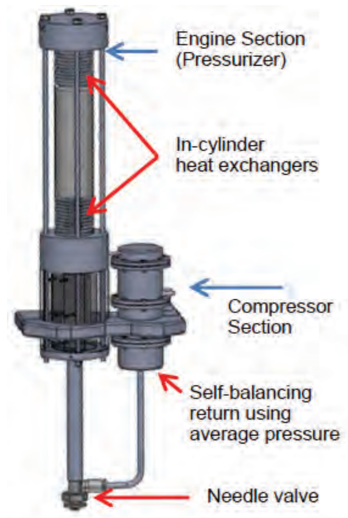

Figure 5: Generation 2 device.

<u>Completed and Expected Milestones and Deliverables</u>

- *Milestone 1:* Generation 1 device initially designed and constructed. [Completed]
- *Milestone 2*: Generation 1 device pressure ratio experimentally characterized [Completed]
- *Milestone 3*: System Modeled and Validated [Completed]
- *Milestone 4*: Pressurizer and Compressor stage designed and modeled [06/2014]
- *Milestone 5*: Pressurizer experimentally characterized and dynamic model validated [01/2015]
- *Milestone 6*: Compressor stage experimentally characterized and dynamic model validated [01/2015]
- *Milestone 7*: First full thermocompressor system modeled and validated [06/2015]
- *Milestone 8*: Design and fabricate the hydrocarbon fueled heater [01/2016]
- *Milestone 9*: Final full thermocompressor system completed [05/31/2016]

C. Member company benefits

The first two years of this work on the device intended for the Ankle-Foot Orthosis will be of interest to a future emerging market having to do with power prostheses and orthoses. As work matures on powered versions of these devices, it is expected that the need will materialize for more capable portable power sources. Companies manufacturing these devices should have future interest in this technology. The second part of this work after the second year will be of interest to industrial pneumatic companies given the increasing incentives for energy savings. Enfield has expressed interest along these lines.

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Project 2C.2: Advanced Strain Energy Accumulator

Research Team

Project Leader:	Eric Barth, Mechanical Engineering, Vanderbilt University
Graduate Students:	Josh Cummins
Undergraduate Students:	Andrew Voss, Daniel Awogbemlia
Industrial Partners:	Case New Holland, Lord Corporation, US Army Aberdeen Proving Ground

1. Statement of Project Goals

The objective of this research is to extend the current state of knowledge in the use of strain energy elastomeric materials in the design of compact energy storage devices. Specifically, this project seeks a low cost, low maintenance, high energy density accumulator targeted toward a fluid powered automotive regenerative braking system (hydraulic hybrid) or a pneumatic ankle foot orthosis medical assist device. This project will focus on improving the energy storage capabilities of accumulators for the specific purpose of storing large amounts of hydraulic or pneumatic energy with an energy density appropriate for applications such as regenerative braking in passenger vehicles or medical assist devices and will be appropriate for either series or parallel configurations.

The metric for success of the hybrid version 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. In the pneumatic version of the accumulator an efficiency increase of 25% over existing configurations is the threshold for success. Additional potential benefits of this research include solutions to more traditional accumulator problems including cost, pre-charge issues, fluid contamination from gas diffusion through the bladder and in the pneumatic case a reduction in exhaust gas noise.

2. Project Role in Support of Strategic Plan

This project contributes to the Center's strategic goals of compact and efficient energy storage. The tasks of designing new compact and efficient 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". Compact energy-dense storage solutions are critical to the success of this migration. This project addresses the knowledge level of this goal 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.[1] The hydraulic version of the accumulator will aim to demonstrate on the SUV test bed (TB3).

In this past year, 2013, the pneumatic version of the accumulator was realized in pneumatic systems. There exists a great potential for energy savings, and hence increased efficiency, in pneumatic systems, particularly industrial pneumatics. A pneumatic prototype was designed for and implemented on the Ankle-Foot Orthosis (AFO) test bed (TB6).

3. Project Description

A. Description and explanation of research approach

This project seeks to investigate, design and experimentally implement a compact strain energy accumulator with elastomeric materials not traditionally utilized in existing accumulators. A control strategy and control laws for regulating power flow will be developed and implemented. Efficiency of the hydraulic pump/motor is out-of-scope of the accumulator effort and will be left to members of the Center focusing on efficiency. Hydraulic accumulators are energy storage devices commonly used to provide supplementary fluid power and absorb shock. An 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 current spring piston accumulators that prohibits them from being used in HRB is their low gravimetric energy density. Using linear analysis, steel and titanium alloy accumulator springs have a gravimetric energy density of around 1-1.5 kJ/kg.[2] 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 paramount, including such a heavy component is impractical.

Gas bladder accumulators and piston accumulators with a gas pre-charge (PAGPs) use gas for energy storage and are therefore much lighter than their spring piston counterparts. In gas bladder accumulators, a gas occupies one side of a container and is separated by a bladder or piston divider where the other side is filled with an incompressible fluid. As fluid is forced into the container, the gas inside the separated volume is compressed and energy is converted and stored in the form of thermal energy (kinetic theory of gasses). This method of energy storage has two major disadvantages: 1) inefficiency through heat losses, and 2) gas diffusion across the bladder and into the hydraulic fluid. The inefficiency resulting from heat loss is less of a concern when compared to the gas diffusion which results in high maintenance costs due to frequent "bleeding" of the gas out of the fluid.

In the event that the thermal energy stored in the compressed gas of the accumulator is not retrieved shortly after initial compression, the heat flow from the gas to its immediate surrounding results in large thermal losses and subsequently less energy being retrieved. Pourmovahed et al.[3] showed that in as little as 50 seconds between gas compression and expansion, a piston-type gas accumulator's efficiency can fall to about 60%. Several methods to mitigate these heat losses have been proposed. One method for PAGPs involves placing an elastomeric foam in the gas side of the accumulator. The foam serves as a regenerator by absorbing the heat generated during gas compression and returns the heat to the gas during expansion. Pourmovahed et al. showed that "the insertion of an appropriate amount of elastomeric foam into the gas enclosure…[can] virtually eliminate thermal loss."[3] Incorporation of elastomeric foam has shown how accumulator efficiency can be vastly improved with a slight modification. This modification however, still does not solve the issue of frequent and costly maintenance associated with gas diffusion.

The purpose of the current proposed strain energy accumulator is to investigate a new method of energy storage in hydraulic and pneumatic accumulators by using strain energy resulting from the hyperelastic nature of elastomer as the primary mechanism for energy storage. An elastomeric bladder or other deformable shape will be designed and tested to determine its capacity to store and return energy by stretching in response to a hydraulic or pneumatic fluid being pumped in and out of it. This approach presents a new and unconventional method that simultaneously greatly reduces heat losses and eliminates gas diffusion inherent to gas pre-charged accumulators. Strain energy accumulators have a higher gravimetric energy density than that of metallic spring piston accumulators. This design also avoids the gas diffusion problem since the pressure gradient between gas and hydraulic fluid is opposite that of the gas charged accumulator. Additional advantages include relatively low cost and simplicity.

Material Selection

The selection of an appropriate energy storing material for 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 period 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 has an order a magnitude better volumetric energy density than steel, and two orders of magnitude better gravimetric energy density than steel (Cambridge Engineering Selector, 2008). Polyurethane's large elongation percentage of 500% to 700% allows for an 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).

Previously an elastomeric material with an experimentally measured energy density of 15 kJ/l and an efficiency of 81-84% was selected. The aforementioned material properties database shows much higher capacities than those of the commercially available elastomer that was selected. An elastomer expert at ExxonMobil confirmed that such an elastomeric material can be engineered with similar or lower hysteresis than the one selected for initial proof of concept tests. 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 on the energy returned in a hydraulic cycle, as opposed to energy stored.

B. Achievements

Achievements in Previous Years

A low pressure prototype demonstrated nearly constant pressure behavior that 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 with an 85% total efficiency 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. Further investigation into the model revealed an effective transmission ratio between wall thickness of the bladder and the hydraulic pressure of the fluid inside the inflated bladder. The thinner the accumulator wall thickness, the more evenly the strain was distributed in the material. A thinner wall however, results in a lower allowable hydraulic pressure in the bladder.

The lower allowable bladder pressure necessitates a change in bladder geometry from the original shape in order to utilize the full material energy density while maintaining high pressure. The new geometry must uniformly strain the material to its maximum thin wall limit in order to maximize material energy density and enabling high pressures. Ideal configurations allow pressures that are higher than elastomer accumulator material maximum allowable stresses. Several configurations of the device have been conceptualized as can be seen in Figures 1 through 3.

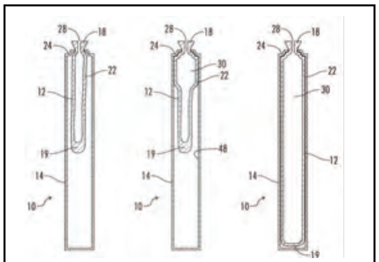

Figure 1: Original PCT patent application.

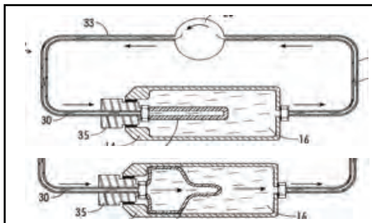

Figure 2: Integrated Reservoir PCT application.

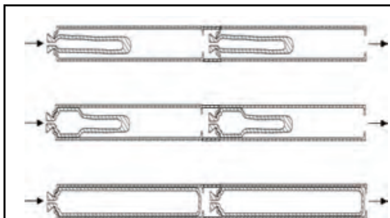

Figure 3: Series configuration to multiply pressure. PCT application filed jointly with Georgia Tech.

Much of the early work focused on a concept called the “distributed piston accumulator” because of its energy storage dependent cross sectional area (Figure 4),This concept encompasses the features of the three balloon concepts above into a single device.

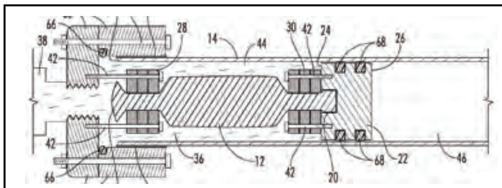

Figure 4: Distributed Piston Accumulator PCT patent application.

The “balloon” concept exhibits a nearly flat P-V curve after the initial radial expansion. While this is desirable, there are two limitations. First, as the wall thickness of the balloon increased, the strain gradients in the radial direction became more severe. This limits the effective strain energy density of the material as not all of the material is fully utilized. A second limitation was that the hydrostatic pressure inside the balloon could not be larger than the maximum local stress experienced in the material.

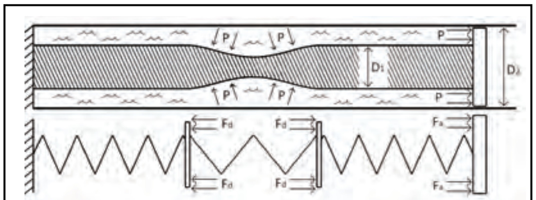

Figure 5: “Inverse ballooning”

The distributed piston accumulator design shown in Figure 5 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. 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 5 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. 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 which is under that of common hydraulic systems. 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 the dent to grow. The dent gives rise to an increased distributed area that continues to localize the effect. In this case it has a similar effect of "rolling out" the material so that the pressure upon extension remains mostly flat.

Work on the Distributed Piston Elastomeric Accumulator (DPEA) approach has developed geometry-based design equations[5] that yield design tradeoffs for different configurations. A prototype DPEA accumulator was constructed and experimentally evaluated with two different polyurethane materials. Experimental testing of polyurethane bladders and uniaxial tension specimens was conducted, with the highest performers exhibiting an energy density of 15 kJ/l and 17% loss through hysteresis. These experimental results were used to make projections for a full scale device and were compared to an idealized gas-charged accumulator.

Five separate cases were considered for comparison: two conventional gas charged accumulators, and three DPEA accumulators. The design equations and the material testing data were then utilized to calculate the system energy density and maximum strain for a range of material energy densities and pressures and are illustrated in Figures 6 and 7 below. As expected, a higher material strain energy density gives rise to a higher system energy density. Recent progress by Otte, et al.[6] in developing a fully composite piston accumulator indicate a weight savings of 70% to 80% over typical steel piston accumulators. Implementing a composite shroud to house a DPEA accumulator with a high energy density elastomeric material offers the potential of a compact and lightweight energy density system.

In addition to the hydraulic version, the previous reporting year saw the strain energy accumulator applied to a pneumatic device – the Ankle-Foot Orthosis (AFO) test bed (TB6). A balloon-in-shroud version of the strain energy accumulator was designed and constructed to recycle the exhaust air of the pneumatic rotary actuator of the test bed. It was experimentally demonstrated to have an initial energy savings of 17.5% relative to operating with no accumulator. This pneumatic accumulator used in the AFO test bed is shown below in Figure 8, fully integrated into the test bed.

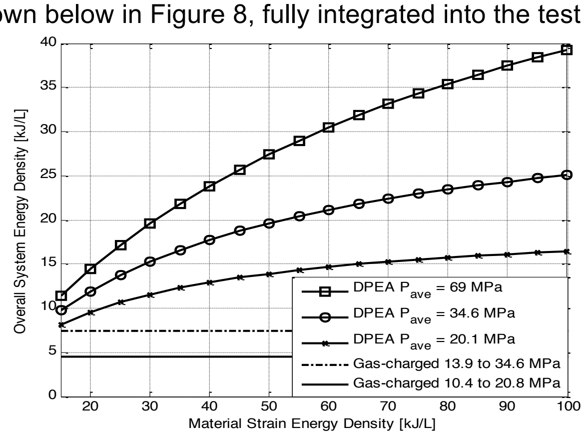

Figure 6: System energy density of DPEA at three different average pressures compared to two conventional gas-charged accumulators.

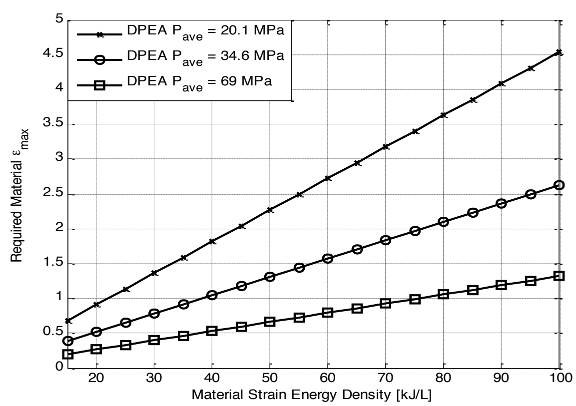

Figure 7: Required material elongation (maximum strain) as a function of material strain energy density operating at three different average pressures.

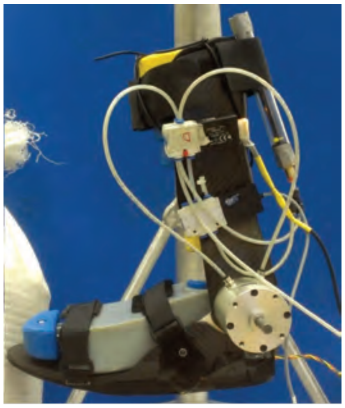

Figure 8: Pneumatic strain energy accumulator in TB6.

Achievements in Past Year and Plans for this Year

Having made significant progress on the pneumatic accumulator and with modeling advances in the hydraulic accumulator a decision was made to focus on developing and selecting an elastomer designed specifically for this application having a high energy density with minimal hysteresis. It was determined that it is best to focus on elastomer formulation and selection prior to finally tackling manufacturing issues with the hydraulic accumulator so that when the time comes to work through the manufacturing issues we have the elastomer that will be used in the final version of the accumulator, eliminating any further manufacturing issues.

One of the steps taken in finalizing an elastomer formulation was the addition of Dr. Douglas Adams, Vanderbilt University's Department of Civil Engineering chair. Dr. Adams brings to the table an extensive knowledge of non-linear systems and a strong relationship with Lord Corporation a worldwide leader in elastomers and other non-linear systems. In discussions with Lord Corporation a letter of support was given to support elastomer selection and assistance in addressing the manufacturing issues in the continued effort of developing the strain energy accumulator.

One idea put forward to the addition of Carbon Nanotubes (CNTs) to the elastomer. When CNTs first came onto the scene researchers looked into the effects of adding CNTs to elastomers. Among the most important benefits of adding CNTs is improved strength, electrical and electro-magnetic interference (EMI) shielding properties. At the time some of these initial studies were performed CNTs were still in their relatively early stages so cost was high, purity was not great, and lengths were relatively small compared to the lengths achievable today. Today CNTs can be grown much purer and longer in bulk quantities; one such company able to accomplish these metrics is General Nano. Ensuing discussions with General Nano indicated support in integrating their product into the strain energy accumulator.

A researcher here at Vanderbilt University, Dr. Florence Sanchez, has investigated the dispersion of CNTs in viscous materials, or in her application concrete. It is believed that the results obtained by Dr. Sanchez are directly applicable to the strain energy accumulator. With the desired team in place, Lord Corporation to assist in elastomer formulation, General Nano to support integration of CNTs and Dr. Sanchez to guide CNT dispersion in the chosen elastomer we hope to have an improved CNT elastomeric strain energy accumulator by the end of year ten. This approach of assembling a team of subject matter experts to develop a final version of the accumulator has gained the attention of the US Army at their Aberdeen proving ground as a candidate technology for use in some of their applications as was indicated in their letter of support for the next two years of NSF funding support.

Expected Milestones and Deliverables

- Redesign and fabricate DPA with lessons learned [1/1/2015] In-progress
- Fabricate DPA unit(s) to be tested on TB2 [3/1/2015]
- Coordinate with UMN and begin to install DPA in TB2. [4/1/2015]
- Metrics measured on TB2 [7/15/2015]
- Final Evaluation of DPA [11/31/2015]
- Integrate embedded CNTs into elastomeric accumulator and test [7/15/2016]

C. Member company benefits

The results of this project will provide an alternative to current accumulators. The pneumatic and hydraulic strain energy accumulator variants under development have a high energy density, simple configuration, inexpensive material costs, are easy to manufacture, are less susceptible to leaks, are safe, require no pre-charging, and do not experience gas diffusion into the hydraulic fluid. Member company Case New Holland has expressed their interest and support in the latest proposal. Potential new members have been identified in Lord Corporation and the US Army who have offered letters of interest in the latest round of proposals and verbal support has been given by General Nano. Additional discussions are ongoing with Parker Hannifin Corporation.

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Project 2C.3: Flywheel Accumulator for Compact Energy Storage

Research Team
Project Leader: James D. Van de Ven, Mechanical Engineering, University of Minnesota
Graduate Student: Kyle Strohmaier

1. Statement of Project Goals

The goal of this project is to develop a high-energy-density hydraulic storage system, the hydraulic flywheel accumulator. The system will be demonstrated in a bench top prototype with an energy density of 18 kJ/kg, which is three times higher than a conventional carbon fiber-wrapped accumulator [1]. The target round-trip efficiency for the prototype energy storage device is >80%.

2. Project Role in Support of Strategic Plan

The project's goal is to significantly increase hydraulic storage energy density while maintaining good round-trip (storage-regeneration) efficiency. Overcoming the energy density barrier is one of CCEFP's transformational barriers and is a key enabler for implementing a commercially successful hydraulic hybrid powertrain in a passenger vehicle.

3. Project Description

A. Description and explanation of research approach

The focus of this project is the hydraulic flywheel accumulator, a novel device that stores energy in the hydro-pneumatic and rotating kinetic energy domains. The energy density of the hydraulic flywheel accumulator is theoretically more than an order of magnitude higher than conventional accumulators [2]. This is due to the high energy density of rotating kinetic energy storage, which reaches 325 kJ/kg for high performance flywheels [3]. Furthermore, the ability to store energy in two modes decouples the system pressure from of the state of charge, allowing the system pressure to be actively controlled. The changing volume of hydraulic fluid in the device results in a variable flywheel inertia that creates coupling between the energy domains.

The hydraulic flywheel accumulator (HFA), which has been granted a full utility patent [4], is a cylindrical piston-style accumulator rotated about its central axis and coupled to a pump/motor, Figure 1. Hydraulic fluid enters and exits the HFA at the center of one end of the cylinder. The opposing side of the piston is occupied by nitrogen gas at a precharged pressure.

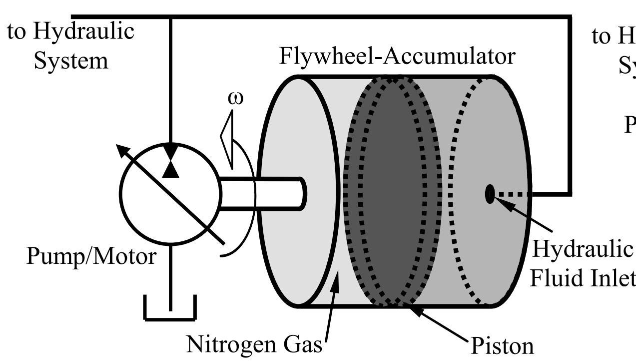

Figure 1. Diagram of the hydraulic flywheel accumulator. The pump/motor is coupled to the flywheel-accumulator directly or through a geared connection. The hydraulic inlet is at the center of the opposite end.

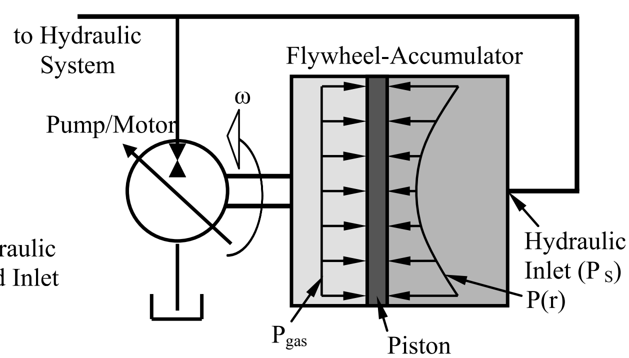

Figure 2. Pressure distributions of the gas and hydraulic fluid in the device. Due to the centripetal acceleration and density of the hydraulic fluid, a parabolic pressure distribution is formed.

Energy can be added or removed from the HFA in two ways, either through an applied torque or by adding or removing hydraulic fluid. When hydraulic fluid is added to the device, the piston compresses the gas, increasing the pneumatic energy storage, and the moment of inertia increases. In the absence of an applied torque, the increase in inertia creates a decrease in the angular velocity as described by the conservation of angular momentum. If the quantity of hydraulic fluid in the HFA remains constant as a torque is applied, the angular velocity increases, causing a decrease in the hydraulic system pressure. This unique coupling allows the hydraulic system pressure to be directly controlled by modulating the method of energy storage.

Prior to CCEFP support, a simple model and a low-energy density bench top prototype had been developed. The model, which assumed rigid body behavior, was used to predict the hydraulic fluid pressure gradient and demonstrated that the flywheel-accumulator can increase energy storage capacity by more than an order of magnitude [2]. A low-energy bench top prototype with a transparent cylinder was constructed and instrumented to demonstrate the concept and explore physical phenomena. The measured pressure gradient results confirmed the steady-state pressure distribution model [5].

B. Achievements in the past year

During the past year of CCEFP funding, significant research progress has been made towards a high energy density prototype. Figure 3 shows a conceptual design, which utilizes a center tie-rod. The center tie-rod eliminates the aerodynamic drag of external tie-rods and provides a high bearing ratio (bearing length/diameter) for the piston, preventing binding. In order to better understand the influence of geometric and operating parameters on the HFA performance, a model was generated of the stress in all of the components of the system due to applied pressure and centripetal acceleration. Using these models and a simple constant pressure regulation control strategy, the flywheel-accumulator was simulated in a hydraulic hybrid power train performing the EPA Urban Dynamometer Driving Schedule in charge-depleting mode. This simulation was run in a multi-objective genetic algorithm in order to optimize the design parameters. The optimization objectives were to minimize the HFA mass and minimize the energy converted through the kinetic domain. The latter was used as a preliminary optimization objective; short of employing a comprehensive set of energy loss models, it is assumed that converting energy through the pump/motor to the rotating kinetic domain is less efficient than using the hydro-pneumatic domain. One energy loss component not well understood during this study was the viscous dissipation in the fluid during angular velocity transients.

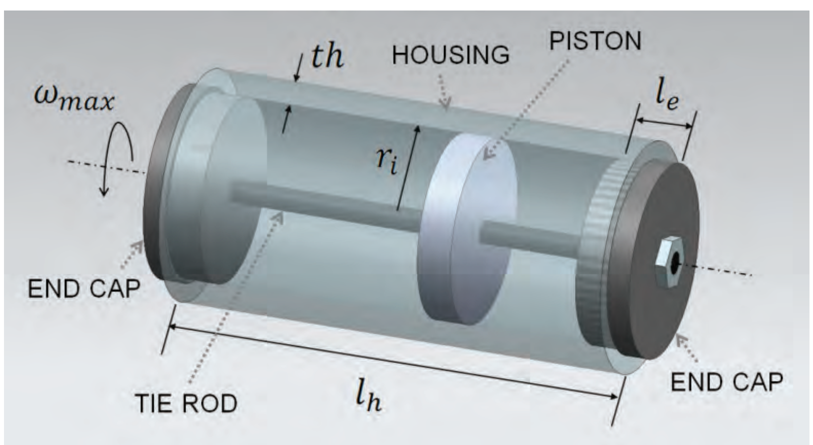

Figure 3. Conceptual design and optimization variables of energy dense HFA using a center tie-rod.

Multiple optimizations were run using various materials for the HFA housing and the same maximum angular velocity. The Pareto optimal solution sets are shown in Figure 4a. The x-axis is the mass of the HFA as a proportion of total vehicle mass, and the y-axis is the energy converted through the kinetic domain as a proportion of total energy converted during the drive cycle. Solutions in the upper left approach pure flywheels and solutions at the lower right approach traditional accumulators. The materials with higher strength to density ratios, such as carbon fiber and titanium provide superior performance. The Pareto optimal fronts for titanium operated with different limits on maximum angular velocity are shown in Figure 4b. To the lower right, all of the Pareto fronts converge, as these solutions are not speed limited. However, in the other areas of the solution space, higher angular velocities yield solutions that are superior with respect to both objectives [6].

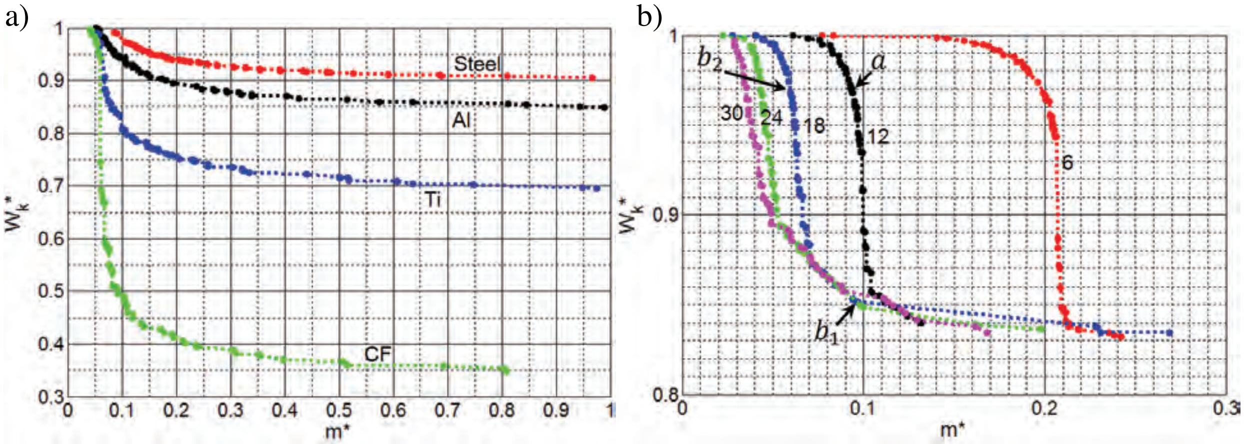

Figure 4. Pareto optimal solutions to the HFA parameter optimization for a) maximum angular velocity of 18,000 rpm with different materials and b) titanium housing with different maximum angular velocities (1,000s of rpms) [6].

The optimization study described above created significant insight into a physically feasible design and trade-offs between design parameters and performance (much more detail on the parameter study is available in this citation [6]). For the purposes of designing a prototype, however, a full set of energy loss models must be incorporated into the drive cycle simulation. While the aerodynamic drag, bearing friction, rotary union losses, and vacuum pumping losses can be modeled relatively easily, the complex fluid motion in the HFA makes it challenging to predict the viscous dissipation during angular velocity transients.

The relative flow of the hydraulic fluid in the cylinder during transience is quite three-dimensional, with the end walls playing an extremely important role [7]. Due to the no-slip condition, an increase in the container angular velocity creates a thin layer of fluid at the endcaps and cylinder walls that rotates faster than the core flow. These thin layers of fluid are subject to a centrifugal field that overcomes the prevailing pressure gradient (the pressure gradient imposed by the rotation of the core flow). Consequently, fluid at the end walls is accelerated radially outward in an Ekman boundary layer. To satisfy continuity, the radial outflow is accompanied by an axial inflow to the Ekman layer along the longitudinal axis of the cylinder. Fluid leaving the Ekman layer at the outer radius is turned and travels axially within the sidewall boundary layer. Near the meridian, the flow is turned again, such that it travels radially inward to replace the axial inflow to the Ekman layer. The radial inflow at the meridian can be envisioned as fluid rings which approximately conserve angular momentum; as they travel inward, their angular velocity increases, tending to spin-up the fluid. Thus, the dominant mechanism for fluid spin-up is advective, not viscous. As a result, *spin-up is accomplished approximately three orders of magnitude faster* than it would if viscosity was the dominant mechanism (as occurs in an infinitely long cylinder) [8]. Based on these results, baffles that impede azimuthal flow are no longer being considered. Instead, parallel discs uniformly spaced in the fluid volume are being considered to aid fluid acceleration by promoting Ekman boundary layer formation.

Though conceptually useful, the theory developed in Ekman spin-up literature treats discrete spin-up events between steady conditions and is insufficient to model transient HFA behavior. Furthermore, the literature does not treat the viscous energy dissipation required to accomplish a spin-up event. Thus, the literature was used to justify modeling assumptions and guide the form of an experimentally constructed empirical model. Using the Buckingham-Pi Theorem, non-dimensional groups were formed and fit to experimental data generated from angular velocity transients with the system shown in Figure 5. The viscous dissipation and time constant terms fit the data well, with a coefficient of determination (R^2) of > 0.99 [8].

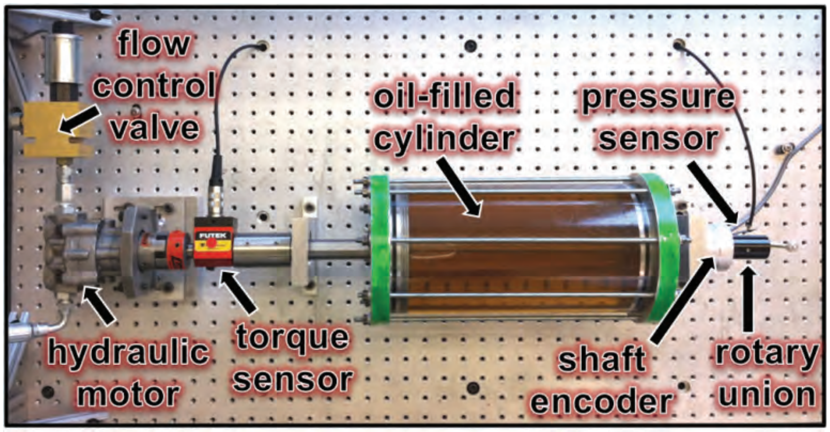

Figure 5. Experimental system used to generate transient fluid behavior model.

In addition to this empirical viscous energy loss model, all major forms of energy loss have recently been modeled and incorporated into a drive cycle simulation of HFA performance. In the simultion,the HFA is housed in a vacuum/containment chamber, uses ceramic ball bearings, and uses a clearance type high-speed rotary union (HSRU). The loss mechanisms include aerodyanamic drag on the surface of the HFA, which is a function of vacuum pressure, vacuum pumping losses, friction in the ceramic ball bearings, inefficiencies in the variable displacement pump/motor, and viscous dissipation, leakage, and pipe flow losses in the HSRU. The dominance of the variable displacement pump/motor (VDPM) energy loss for an example simulation is illustrated in Figure 6. The HFA design parameters were NOT optimized for this simulation.

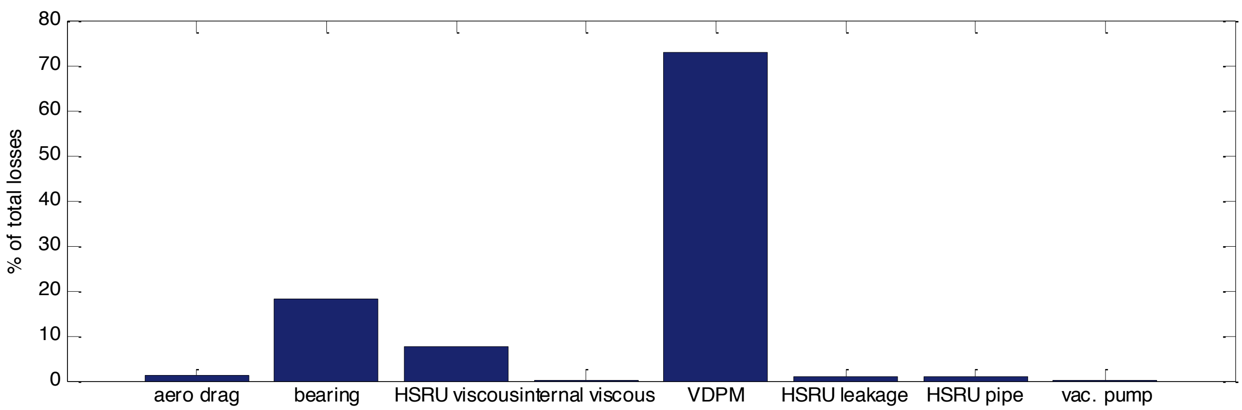

Figure 6. Energy loss contributions during a drive cycle.

The preliminary results from the un-optimized case are quite promising, illustrating that the well understood pump/motor losses dominate the other energy losses during a drive cycle. For reference, the simulated system has a maximum speed and pressure of 17,000 rpm and 35 MPa respectively, a pump/motor displacement of 0.2 cc/rev (will be higher when driven through a gear train to reduce speed), an energy density of 26 kJ/kg, and an resultant efficiency, defined as $1-\frac{E_{losses}}{E_{converted}}$, of 84%.

C. Plans

The project plan to demonstrate the hydraulic flywheel accumulator in a bench top prototype includes the following tasks during the following two years:

- Task 1: Conduct viscous dissipation experiments.
- Task 2: Optimize the HFA parameters for operation on a standard drive cycle.

- Task 3: Perform a detailed design of prototype HFA.
- Task 4: Fabricate the HFA prototype
- Task 5: Perform designed experiments with the HFA prototype.

Milestones:

- Empirical fluid model constructed from viscous dissipation experiments complete [month 8]
- Drive train simulation with revised models operational [month 9]
- Optimal solution for prototype selected [month 12]
- Detailed design of HFA prototype complete including detail drawings of all parts [month 18]
- HFA prototype fully operational [month 20]
- Testing and characterization of HFA prototype completed [month 24]

D. Member company benefits

A utility patent for the hydraulic flywheel accumulator has been granted and can be licensed by member companies. The technology holds the promise of creating a more compact and energy dense method for storing energy in hydraulics systems. Its implementation could create new applications and markets for hydraulics, such as a hydraulic hybrid passenger car.

E. References

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Project 2F: MEMS Proportional Pneumatic Valve

Research Team

Project Leader:	Thomas Chase, Mechanical Engineering, University of Minnesota
Graduate Student:	Nebiyu Fikru
Industrial Partners:	Enfield Technologies & Parker Hannifin

1. Statement of Project Goals

The goal of this project is to create extremely efficient proportional valves for pneumatic systems by exploiting Micro-Electrical Mechanical Systems (MEMS) technology. The valves are expected to require under 5 milliwatts of actuation power to hold them in the fully open state while producing a maximum flow rate of 40 slpm when venting from a pressure of 6 bar to 5 bar. They are also compact: the target envelope of the valves is 4 cc. Supporting goals include leveraging the potential of piezoelectric materials such as “PZT”, developing MEMS-scale sealing technologies and developing position sensing strategies for the MEMS scale devices.

2. Project Role in Support of Strategic Plan

This project has breakthrough potential toward the Center’s transformational strategic goal of developing efficient fluid power components. While we are developing generic proportional valves, the extremely low power requirements and compactness of these valves make them especially attractive for portable and mobile applications. The project also contributes to the Center’s goals of developing leak-free systems and compact integrated systems. A major thrust of the project involves developing original sealing technologies for MEMS scale valves, a technology necessary for bringing MEMS valves to commercial markets. The valve technology was originally inspired by, and will be showcased on Test Bed 6, the Ankle-Foot Orthosis.

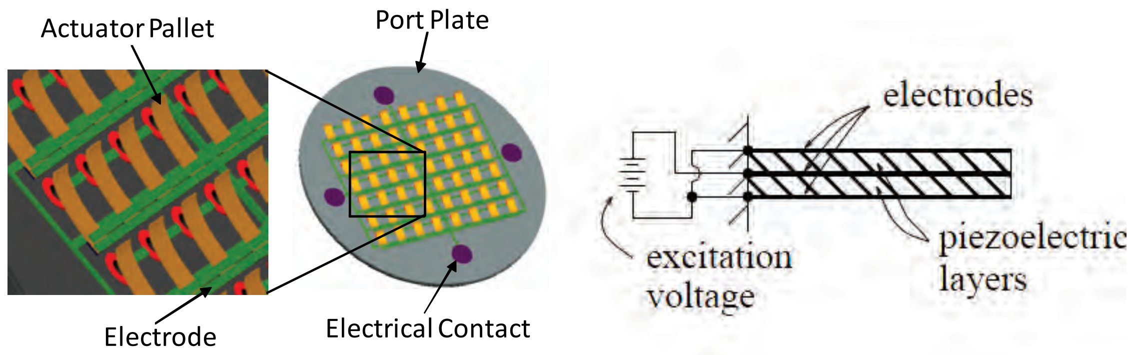
3. Project Description

A. Description and explanation of research approach

Currently available microvalves can only deliver flow rate on the scale of milliliters per minute. We have developed a unique parallel architecture to achieve macro scale flow in our MEMS based devices. The basic concept underlying our novel valve design is illustrated in Fig. 1(a). The valves utilize an array of tiny orifices and actuators to replace a single large orifice and actuator. The actuators constitute simple cantilever beam type pallet valves. Reducing the orifice size reduces the force on each actuator. This makes it possible to reduce the actuator size to the MEMS scale. Ganging an array of orifices and actuators in parallel, including potentially several hundred on our MEMS devices, enables the valve to produce macro flow rates.

A question that was raised concerning the valve concept was whether utilizing an array of small orifices in place of a single large orifice will lead to increased pressure drop. Using our in-house built ISO 6358 compatible test stand [1], we experimentally demonstrated during Year 6 that an array of multiple orifices will yield the same flow rate as a single large orifice having equivalent area. Therefore, the concept of parallelizing the flow using multiple miniature orifices and actuators is sound. Since each actuator has extremely low mass, the valves are expected to have exceptional bandwidth. MEMS batch fabrication methods are expected to enable manufacturing the valves at low cost when taken to the commercial production scale.

The valves will utilize a “bimorph” piezoelectric architecture, illustrated in Fig. 1(b). Two layers of the piezoelectric material are sandwiched between electrodes. The two layers have the same polarity, but they are subjected to reverse voltages. As a result, the bottom layer expands and the top layer contracts, causing the actuator to deform as a cantilever beam subjected to pure bending. The first MEMS scale piezobenders are being constructed as “unimorphs”, which replace one of the active layers with a passive layer of dissimilar material. The unimorph suffers a performance penalty relative to a bimorph but it simplifies fabrication.



(a) (b)

Figure 1. (a) MEMS valve concept. (b) Piezoelectric bimorph.

All actuators are shown connected in parallel in Fig. 1(a). Common electrical contact points are used to supply electric current to all actuators simultaneously. As the supply current is increased, deflection of the actuator pallets increases, thereby increasing the flow rate. An alternative wiring scheme would vary the flow rate by fully opening sub-groups of actuators in binary combinations (one, two, four, eight, etc.). Two valves have been identified in the literature which utilize a parallel actuator/orifice strategy similar to our valve. However, the first [2] utilizes electrostatic actuation of diaphragms rather than piezoelectric actuation of pallets and the second [3] is not practical for commercial implementation due to high leakage.

B. Achievements

Achievements in previous years

This project was initiated in Year 5-6 and extended to Year 7-8. Accomplishments during the first three years include: performing a literature review on pneumatic MEMS valves, constructing an ISO compatible test stand, demonstrating the valve concept on a "meso-scale" version of the MEMS valve, integrating a capacitive displacement sensor on the meso-scale valve, fabricating and testing a MEMS port plate and developing a new compressible flow model. Two of these accomplishments are explained in greater detail below, while others are expanded on in the following section.

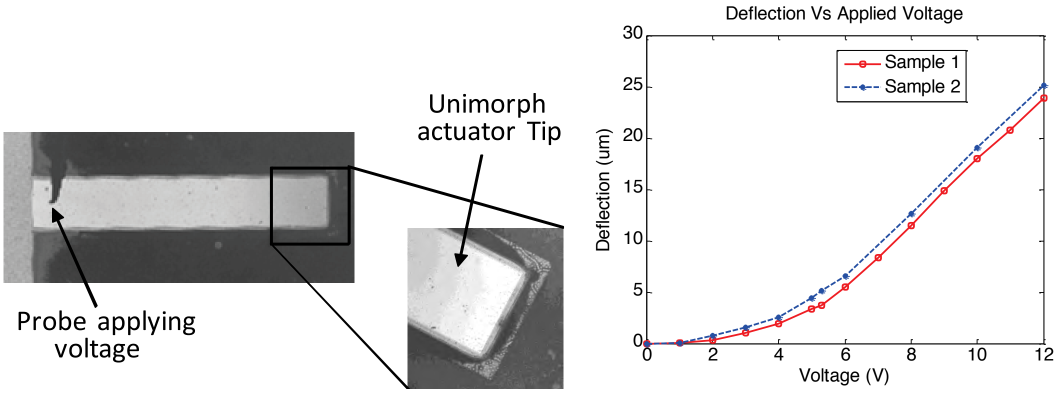
A thorough literature review on miniature valve actuation technologies [4] directed us toward piezoelectric actuation for our MEMS valve due to its low power requirements and fast response. We constructed a "meso-scale" concept demonstration prototype of our valve, which is an order of magnitude larger than a MEMS device, using conventional machining techniques. The meso-scale valve utilized a commercially available piezobender. We discovered the revolutionary power savings potential of selecting lead zirconate titanate, or PZT, as the piezoelectric material of choice by measuring the current required by the meso-scale valve. PZT constitutes the enabling technology for scaling actuators to the MEMS valves.

The MEMS valve consists of two main parts as shown in Fig. 1(a): the port plate and the actuator array. Successful fabrication of the silicon based port plate, including a micro-orifice array that meets target specifications of pressure and flow rate, constituted a break-through achievement in the third year of the project. The port plate fabrication required the development of unique MEMS process designs.

Achievements in the past year

Accomplishments since February 2013 include: fabricating and testing of functional unimorph PZT actuators, completing the installation of a capacitive displacement sensor on the meso-scale valve, and improving flow and actuator models. These accomplishments are described in order below.

Fabricating functional piezobenders has proven to be the most challenging aspect of the project. We are aware of only one facility in the United States that can fabricate thin film PZT for MEMS applications: the Nanofabrication Lab of Pennsylvania State University [5]. We have formed a synergetic association with that facility, and the primary graduate student has made several trips to PSU to participate in the PZT fabrication processes.



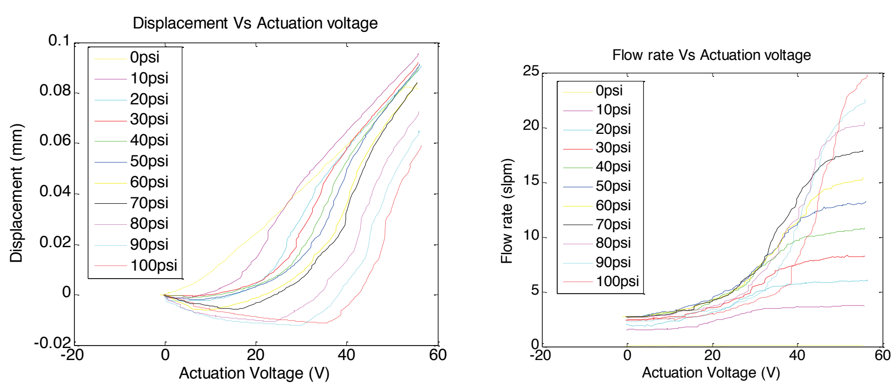
(a) (b)

Figure 2. (a) Unimroph actuator with probe touching top electrode. (b) Deflection versus voltage measured for the unimorph actuator illustrated in (a).

We suffered three "false starts" before producing a functional unimorph piezobender. Our first effort failed when we discovered that the PZT layer would not adhere to the material used for a base layer. Our second effort failed when an insulating layer required for routing the top electrodes was deposited using a process called "plasma enhanced chemical vapor deposition" (PECVD). We discovered that this process chemically damaged the PZT. Our third attempt failed when our masks for etching the electrodes caused shorting between them.

A second break-through achievement occurred on the fourth attempt, which produced successful unimorph piezobenders. A scanning electron microscope image of one of these actuators is illustrated in Fig. 2(a). Each cantilevered piezobender has a length of 2 mm, a width of 700 µm and a thickness of 17 µm. The deflection versus applied voltage was experimentally measured and is illustrated in Fig. 2(b). We deduced from this plot that the effective transverse piezoelectric coefficient of our thin film PZT is 20-30% of that of bulk PZT (190x10−12 m/V [6]). Our collaborators at PSU report consistent results in their work. The effect of this difference is that a larger voltage must be applied to obtain the same deflection as for the bulk material. While the piezoelectric coefficient is still superior to alternative materials, it forces us to adjust our intended bender operating parameters to obtain equivalent valve performance.

At the time of submitting our Year 7 report, we were in the process of installing a miniature capacitive displacement sensor on our meso-scale valve. We are now able to measure the displacement of the meso-scale actuator under operating conditions (see Fig. 3(a)). The test stand also includes a flow sensor (see Fig. 3(b)). The instrumented meso-scale valve will continue to be used to better understand the behavior and control of valves which utilize piezobenders.



(a) (b)

Figure 3. (a) Plot of Meso-scale PZT actuator deflection versus actuation voltage. (b) Plot of Meso-scale valve flowrate versus actuation voltage.

Lastly, we have been enhancing our analytical models of the valve system. We have developed an improved one dimensional model to relate actuator displacement with flow. The model iteratively solves coupled friction and isentropic compressible flow models. We are seeing good agreement with our meso-scale valve test results. Rudimentary steady-state actuator deflection and force models have also been developed. The models relate applied voltage to tip displacement and force of the piezobender. The two models will be combined and validated by testing with the meso-scale hardware to give us a comprehensive model that relates applied voltage to flow.

C. Plans

Plans for next year

The pioneering nature of this project has resulted in several unanticipated delays. In particular, establishing a working relationship with the Nanofabrication Lab at Penn State required several months. Additionally, we have suffered from delays when specialized MEMS fabrication equipment required for our processes have gone out of service, at times for several weeks in a row. Nevertheless, the recent breakthroughs of producing successful orifice plates and actuator arrays justifies re-scoping our schedule Our revised plans are presented below.

The immediate plan is to fabricate and test a bimorph PZT actuator. We will utilize processing recommendations such as deposition temperature from a group that had fabricated a PZT bimorph actuator for different application at Penn State [7].

Next, three steps in the actuator fabrication process where additional refinement is required will be addressed. The first concerns precisely controlling the thickness of the actuator. The second involves introducing new actuator geometries. These are necessary because we have discovered that the orifices act as stress concentrators, so their minimum diameter must be set large enough to prevent fracture of the orifice plate. The forces generated by the actuators must be increased to match those resulting from the larger orifices. The third addresses managing residual stresses in the material to control unwanted deformations of unexcited actuators.

Once refined actuators become available, we will be ready to address combining the actuator array with the valve plate. This will enable us to package the actuator and orifice arrays into a working valve, at which time they can be demonstrated on the Ankle-Foot Orthosis (TB6). Following that, we will develop strategies for reliably sealing the actuators to the orifices when the valve is in the “off” state. Our final goal is to integrate position sensors into the valve, enabling its conversion to a servo-valve. Once these base technologies are developed, we will be ready to seek funding to commercialize the valves.

Expected Milestones and Deliverables

- Demonstrate “unimorph” MEMS actuator array ~~[4/30/13]~~ → [1/15/14] (completed)
- Demonstrate first “bimorph” MEMS actuator array ~~[7/31/13]~~ → [3/31/14]
- Demonstrate complete packaged MEMS device [8/31/14]
- Demonstrate MEMS pneumatic valve on Ankle-Foot Orthosis (Test Bed 6) ~~[3/31/14]~~ →[10/31/14]
- Demonstrate MEMS valve with integrated position feedback [5/31/16]

D. Member company benefits

CCEFP member companies will benefit from this research in three ways. First, the valve constitutes a new concept for constructing a miniature pneumatic valve 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 and meso level flow devices.

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

Research Team

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High School Teachers (RETs):	Gabe Sterling, Sean Donnelly
Industrial Partner:	Enfield Technologies

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.

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.

3. Project Description

A. Description and explanation of research approach

Fluidic energy transmission is the only effective way of transmitting energy during imaging in an MRI. 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.

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 enable the surgeon to visualize the position of instruments in relation to sensitive subsurface blood vessels, nerves, tumors, etc. and enable the robot to directly position a tool at a desired target specified in a medical image. Both 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 ability to clearly show soft-tissue boundaries and structures which are not visible in other imaging modalities. Fluid power 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 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 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.

B. Achievements

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

<u>Invention of novel, non-invasive approach to access and treat the hippocampus</u>

Together with our collaborating neurosurgeon at VU Medical Center, we have designed a radiofrequency (RF) ablator and an accompanying concentric tube needle [3]. This device is designed to enable a novel, non-invasive access path through the foramen ovale, a natural opening in the skull base at the top of the patient's cheek. This access path is a new approach and is highly advantageous since the soft tissue will seal the access path and prevent contamination of the brain through it.

<u>Needle tip accuracy using 5-DOF precision pneumatic robotic platform</u>

Prior to in-scanner experiments, an initial benchtop assessment of cannula tip accuracy was needed. Thus, tip position measurements were acquired for 28 robot poses using an optical tracking system. Three optical markers were affixed to the robot front plate. Manufactured from acrylic using a laser cutter, the plate includes pin-sized holes to assist in placing the markers at precisely known positions. Five multi-modality fiducial markers were similarly added for registration with MRI images. An optical marker was fixed to the cannula tip for bench testing with the optical tracker; it will be removed for in-scanner experiments. Figure 1 shows the active canula robot.

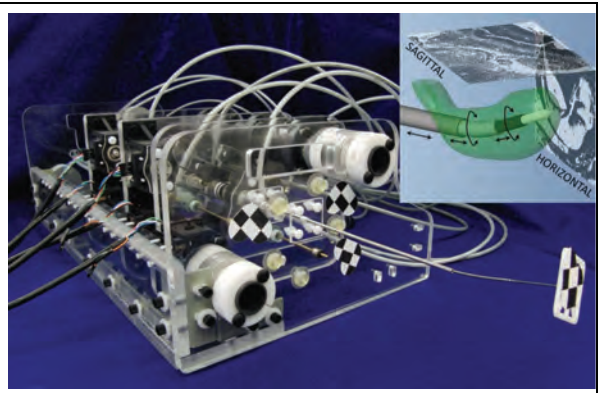

Figure 1: Active cannula robot. Inset shows CAD model of cannula and ablator inside hippocampus.

Image registration from optical tracker to robot was achieved using point-based registration of the markers on the robot's front plate. Then, for each robot pose, the expected cannula tip position was determined from the robot's forward kinematics. Tip error was taken as the difference between measured tip position and tip position expected from the cannula model. The tip position of the steerable needle was measured for 28 different poses of the needle, and the mean error compared against the kinematic model was 1.18 mm [4].

<u>Invention of intrinsically-safe, MRI-compatible pneumatic stepper actuator</u>

While the model-based precision pneumatic controller is closed-loop stable, there are contingencies (e.g. valve failure) in which the piston could travel the full stroke of the cylinder and potentially endanger the patient. Therefore, we have done some preliminary work to create our own fluid power actuator that is intrinsically safe and MRI compatible. A first prototype was jointly designed at Vanderbilt and MSOE for manufacture by selective laser sintering (SLS); this additive manufacturing process enabled compact integration of actuator components, resulting in a small footprint for the device (1.75 inch diameter, 3.75 inch length). The non-magnetic prototype was made from nylon powder on an SLS machine at MSOE, and a photograph of the device is shown in Figure 2. Employing an inchworm-like behavior, this linear actuator can advance or retract the needle in discrete steps, and is thereby intrinsically safe. Its actuating bellows is hermetically sealed (no sliding seals) to prevent contaminants such as blood or cerebrospinal fluid from entering pneumatic circuitry. The precision pneumatic controls previously developed for the multi-DOF robotic platform were used to position control the bellows, providing mean steady-state positioning error of 0.025mm [5]. A provisional patent on this invention was jointly filed by Vanderbilt and MSOE [6].

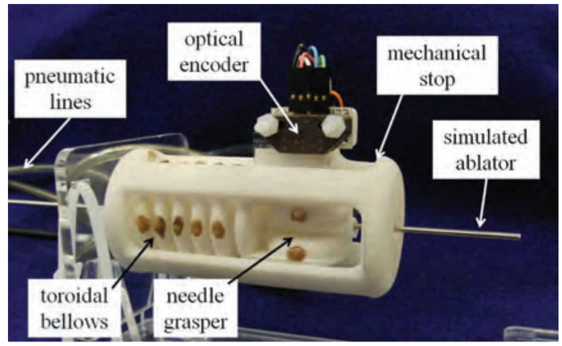

Figure 2: Intrinsically safe, flexible fluidic actuator prototype. [5]

Building upon these promising preliminary results, a modular, two-degree-of-freedom version of the intrinsically safe actuator is currently under development. It is designed to both translate and rotate the base of a single tube of the steerable needle. Because the steerable needle is made of multiple, nested tubes, the actuator design is modular, allowing for several modules to be cascaded together, one for each tube of the needle.

<u>MRI compatibility and preliminary in-scanner experiments</u>

Several experiments were recently conducted with the 5-DOF robotic platform inside a 3-Tesla MRI scanner at Vanderbilt University Institute for Imaging Science. A photograph of the robot with the scanner is shown in Fig. 3. A portable setup for the robot controller electronics was developed to interface the controller with the scanner in an MRI compatible manner. Located outside the scanner room, this electronics cart houses the pneumatic control valves, pressure transducers, printed circuit boards, data acquisition cards, and computers dedicated to controlling the robot. Optical position encoders on the robot interface with the controller via 30-foot-long double-shielded cables connecting through the patch panel's low pass filter. Piston-cylinder actuators on the robot interface with the pneumatic controls components via 20-foot-long transmission lines passing through a wave guide port in the scanner room wall.

Figure 3: 5-DOF robotic platform on 3T MRI scanner bed.

Using this experimental setup, the MRI compatibility of the 5-DOF robot was quantified. While the robot was inside the scanner, images of a water-based gelatin phantom were obtained under several conditions: robot powered off, robot powered on but not moving, and robot powered on with joints in full motion. Reduction in signal-to-noise ratio (SNR) was only observed with the robot joints in full motion; in this case, SNR loss was 10 percent and attributed to the low-level electronics

(a) (b) (c)

Figure 4: MRI images acquired during testing: a) needle inserted by robotic platform into gelatin phantom, b) Z-shape fiducial frame for image registration between robot coordinate space and scanner coordinate space, and c) single slice of the Z-shape fiducial frame, as used to calculate the registration transformation.

of the optical encoder modules. Figure 4 shows some MRI images acquired by the scanner during the preliminary testing.

fMRI Compatible Force Sensor and Haptic Interface

The Georgia Tech group has developed a pneumatically driven, tele-operated platform for the rehabilitation of hemiparesis in Y6-7.[7] A rotary displacement sensor and plastic force sensor has been integrated to this interface to provide quantitative feedback along with the brain activity of the subject. The interface design was improved with a new, more compact prototype, as seen in Figure 5. A more compact and sensitive version of the MRI-compatible force sensor was also generated. The latest version has a thinner compliant body; reducing its resistance, hence making it suitable for the tests related to fine motor skills.

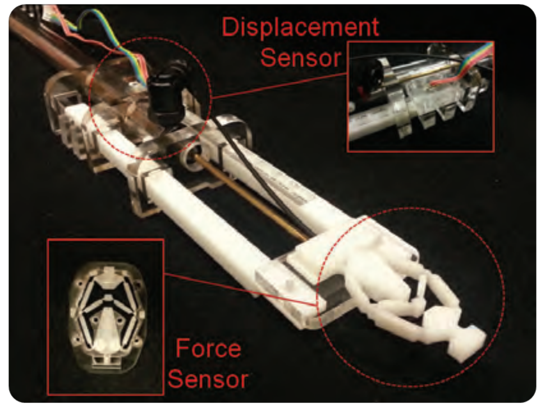

Figure 5: MRI Compatible Haptic Interface

Modeling of pneumatic line transmission delay and attenuation:

The tele-operated haptic interface requires connecting tubes, typically more than 5 meters long, between the ferromagnetic system components and the MRI-compatible actuator isolated in the MRI room. Pressure dynamics of pneumatic actuators is significantly affected by the length of those transmission lines and the delay of air pressure control could potentially destabilize the closed-loop control. Therefore, a further analysis for the systems that involve a transmission line of more than 5 meters is necessary. In Y7, we have confirmed that the delay is approximately proportional to the length of tubing, divided by the speed of sound. According to our initial calculation, the pure time delay due to a pneumatic line of 6m will be approx. 17ms. Ueda and Turkseven obtained an accurate nonlinear model that captures the characteristics of pressure dynamics with a long transmission line.

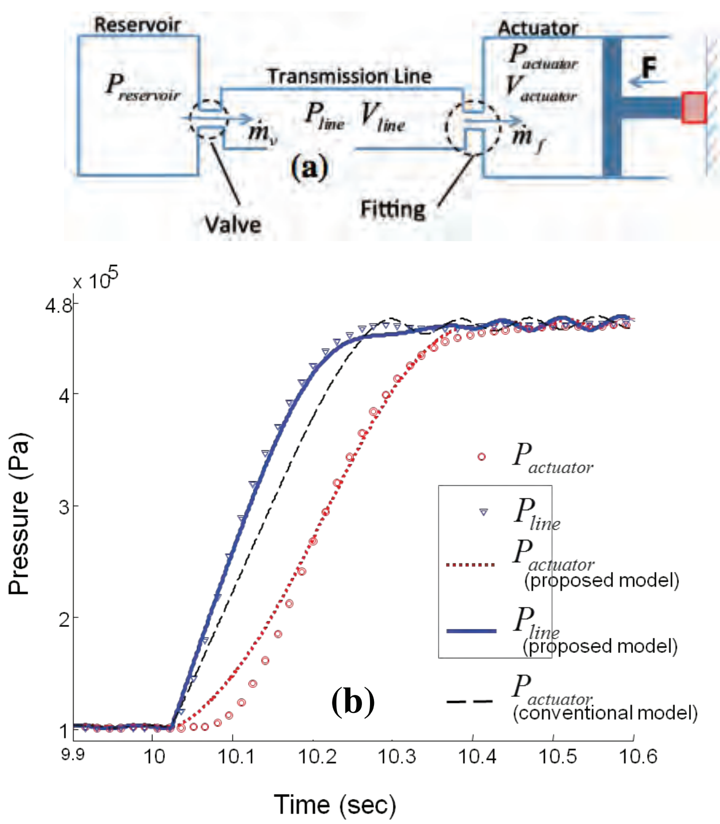

Figure 6: a) The serially connected chamber model proposed by Georgia Tech group b) Pressures estimated by both models. Experimental data points are added for comparison.

The transmission lines add a resistance on the air flow creating a pressure gradient between the valve and the actuator and therefore limiting the mass flow rate. Apart from that, there is an inevitable difference in the pressure response of the line and the actuator due to the geometry of the connection (fitting) between the transmission line and the actuator.

A new method that regards the transmission line and the actuator as two separate chambers was proposed to improve the accuracy in the open loop pressure estimation. The new model accounts for the dynamic relation between the chamber and the transmission line.

The transmission line was assumed as an intermediate chamber connected to the reservoir and the actuator in series as shown in Figure 6a. The flow from the reservoir to the line or from the line to ambient (m_v) is provided via the valve and a typical model of spool valve is used to characterize that connection. The time delay attributed to the length of the line is preserved and added to the model. We assumed another orifice on the fitting that connects the line to the chamber of the actuator in order to capture the dynamic relation between them. The rate of mass flow to the chamber (m_f) and the developed pressure in the line (P_{line}) are calculated accordingly. The intermediate chamber between the source and the actuator prevents rapid changes in the mass flow rate when there is a sudden change on the input.

The impact of the new model was observed on the fixed-volume chamber tests. A 7.25 meters long tube between the valve and the pneumatic cylinder delayed the pressure rise as shown in Fig 6b. Pressure in the actuator chamber was estimated and compared to the test results in Figure 6b. The proposed model captured the transmission time delay and estimated the actuator pressure more accurately compared to the conventional pneumatic system model. The proposed model has a satisfactory accuracy at 1 Hz valve input as well. In addition, the representative pressure of the line matches well with the pressure measurements taken on the line towards the actuator side.

<u>*Facilitation Exercise using a Pneumatic Device*</u>

Ueda and Lacey developed an fMRI-compatible rehabilitation device with a pneumatic tendon hammer to study the neural mechanisms of Repetitive Facilitation Exercise (RFE), a rehabilitation method that is practiced to assist the patient's intended movements in conjunction with reflex-based facilitation. The developed system facilitates a myotatic reflex by applying a mechanical impact in synchronization with the patient's intention to move the hemiparetic limb. Accuracy in actuation timing is the crucial feature the rehabilitation device, shown in Figure 7, has to satisfy. Initial experimental results confirmed the feasibility of implementing an fMRI-compatible pneumatically driven actuator [8].

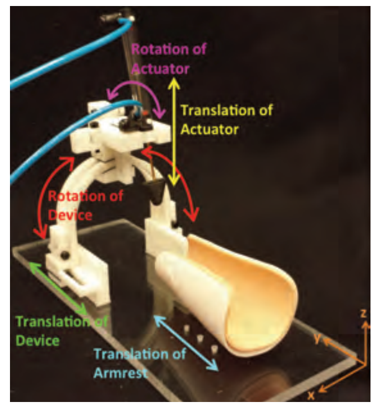

Figure 7: fMRI-compatible facilitation exercise device

<u>Plan for next 2 years</u>

The MRI scanners at Vanderbilt University Institute for Imaging Science (VUIIS) are available to all CCEFP investigators as Test Bed β, a zero maintenance, zero capital investment test bed. PIs Webster and Barth will continue collaboration with Dr. Joseph Neimat, a neurological surgeon at VU Medical Center, for clinical insight and guidance of the surgical robot project, and full integration of the surgical robot with Test Bed β. PI Ueda has been collaborating with Dr. Shinohara in Applied Physiology at GA Tech and Dr. Butler at Georgia State University so that project results can be seamlessly transitioned to clinical settings. Results may also be applicable to PI Ueda's stroke rehabilitation robot project in collaboration with Dr. Kawahira, M.D. at Kagoshima University, who invented a new therapeutic procedure for hemiplegic limbs. PI Ueda has submitted a NSF Smart and Connected Health (SCH) grant proposal with Drs. Shinohara, Butler, and King. 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, NetShape, Inc; Hoowaki, LLC, have agreed to support the project at VU. In addition, KYB Corporation, a NFPA member, and DTI Robotics USA Inc. have agreed to support the project at GT. PI Ueda and Dr. King of DTI Robotics have already worked to submit a NSF Partnerships for Innovation (PFI) grant proposal based on the optical sensor technology developed in Y5-Y6 of this project. During Y9-10, PIs Webster and Barth will collaborate with Enfield Technologies in the area of precision pneumatic controls research. This collaboration will include an annual working meeting for the team at Enfield's facilities in Shelton, CT.

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Project 3A.1: Operator Interface Design Principles for Hydraulics

Research Team

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Industrial Partners:	Caterpillar, CNH, Danfoss, HUSCO, Bobcat

1. Statement of Project Goals

This project will consolidate results on multi degree of freedom interfaces over the range of speeds, dimensions, numbers of interfaces, extent of automation and interface modalities found with hydraulic actuation. Experimentation via excavator simulation and simple displays has been the principle source of data up to this point. The excavator simulations were potentially compromised by lack of depth perception and will be verified with the recently completed stereo 3D display and with limited field tests by experienced operators. The intuitiveness of hand controllers, position versus velocity control, and the effectiveness of selected data presentation modes will be evaluated. Double digit percentage improvement in efficiency and economy are expected as have been illustrated in some instances. Interface designs that reduce fatigue while maintaining intuitiveness are proposed as improvements over previously tested designs.

2. Project Role in Support of Strategic Plan

The project supports the strategic plan's call to make fluid power effective, safe and easy to use. The Strategic Call for Proposals prioritizes high efficiency and effective system control, both of which are central to this project. Previous work has shown higher task efficiency as measured by soil moved per unit fuel consumed and soil removed per unit time when advanced, intuitive controls are used. Reasonable questions about the application of these advanced controls to the full range of fluid power applications still remain. It is known that dynamically slow machines favor human interfaces with velocity commands whereas dynamically faster machines favor interfaces with position commands, but the boundary condition between fast and slow is not well defined. When selecting a human interface for a task, the most intuitive controls are the most efficient, but the most intuitive controls can lack ergonomics and lead to rapid operator fatigue. The transition from one type of human interface to another depends on the task, and because fluid power is being applied to a huge range of tasks with different characteristics it is valuable to understand how to select an optimal interface. Excavators, patient transfer devices and high-speed robotic arms do not share an optimal interface or control strategy. This project will quantitatively justify interfaces and controllers based on task characteristics.

3. Project Description

A. Description and explanation of research approach

A large number of fluid power installations are operated directly by a human. In these systems, the effectiveness of the communication channels between human and machine have a high impact on system performance [1]. This research attempts to make excavator operation more efficient, safe and effective by optimizing the communication channels between the excavator and human operator.

Traditional excavator control is done at the kinematic joints. Using dual two degree of freedom joysticks, excavator operators control the pump flow to each piston on the four active excavator joints: boom, arm, bucket and swing; thereby applying a torque on the joint in either direction. All of these joints lie in the plane of the excavator arm except swing, which controls rotation of the arm at its base. This two-joystick interface was initially chosen because it was easy to implement from a hardware perspective, not because it was intuitive or easy to use. Since its inception, the interface has remained largely unchanged even though it is sub optimal. There is a steep learning curve associated with this interface because of the mental load it places on the operator. Humans break down tasks into Cartesian coordinate commands: emptying a bucket load requires moving the bucket up, then forward. The concept of Cartesian direction is lost on traditional excavator control. Operators are forced to do inverse kinematics, a process of translating

Cartesian commands to joint angles and angular velocities, to determine the necessary joystick positions. Skilled operators can do the required inverse kinematics in near real time, however it requires many hours of training to reach this skill level and even then operators are still prone to making mistakes. Due to the immense power and size of excavators, these mistakes can be both expensive and dangerous. The difficulty of performing the inverse kinematics suggests that the operator and excavator system would perform better if the command channel from the operator to the excavator were done in Cartesian space, because it would be more intuitive to the operator. This research has explored several non-traditional control interfaces that alleviate the need for the operator to mentally perform inverse kinematics.

When coordinated control is implemented in Cartesian space, commands can be given as positions, velocities, or accelerations. Prior studies [4, 5] are somewhat conflicting as to which input method is most effective. This research has sought to discern (1) an explanation for the preference for velocity control in hydraulic systems, (2) to determine if position control might improve performance and for which systems, (3) to see if augmented human-machine interfaces might facilitate this improved performance, and (4) to improve the design of the hand input mechanism itself to avoid operator fatigue. Discussion with industry partners explored the usefulness and feasibility of various alternatives for improving the interface.

Much of this research has been performed on the Georgia Tech excavator simulator. Early testing through teleoperation of TB1 in Purdue suggests that the simulator is a realistic substitute to a live excavator. However, verification of the simulator results on an outdoor excavator is envisioned. The Georgia Tech simulator is housed in an actual excavator that was donated by Bobcat. The excavator cab is powered to rotate as expected, but the excavator arm has since been removed and replaced by a large screen TV. The arm of the vehicle, the soil and the state of the excavator are displayed to the operator on the TV, and an audio signal mimics engine noise. Enhancements that provide a more realistic experience for the subject are continuously being proposed and considered, as a more realistic simulator will provide more accurate results. One enhancement that has been attempted several times is the addition of stereoscopic 3D, however this feature has proved elusive and difficult to implement.

B. Achievements

Achievements in previous years

This research has explored several ways of eliminating the need for the operator to perform inverse kinematics. One such implementation involved a position controller that was kinematically identical to the excavator arm. With this controller, the excavator would mimic any manipulation of the controller joint angles. By manipulating the end effector of the controller in Cartesian space, the operator could easily move the bucket up, down, forward, or backward with little to no cognitive load. This control method performed the inverse kinematics mechanically, as the desired excavator angles are identical to the controller joint angles because the two are kinematically identical. Another way to eliminate the need for the operator to perform inverse kinematics is through computation. Unlike humans, computers can perform the inverse kinematics required to move an end effector to a desired location or in a desired direction in real time, without error. Using a Phantom Omni 6 degree of freedom controller, several variations of coordinated control (commands sent in Cartesian space) were implemented.

This research has shown that both the kinematically similar position controller and the coordinated control implemented with the Omni Phantom perform better than the traditional dual joystick flow control, increasing operator effectiveness by as much as 81% and resulting fuel efficiency by 18% [2, 3]. While the alternative control strategies reduced operator errors and decreased task completion time, both the phantom and kinematically identical controller increased operator fatigue making them unfit for prolonged use. For the kinematically identical controller, the ergonomics were improved by rotating the mini excavator arm on its side, allowing the operator to rest their weight on an armrest.

This research has also provided a deeper insight to the differences, advantages, and disadvantages of the three control modes: position, velocity, and acceleration. Various ad hoc explanations have been given for the superiority of position or rate control in manually operated systems in previous studies. Dr. Elton proposed, in his PHD Thesis, the need for systems to match operator intent with feedback [6]. Elton's initial findings confirmed that rate control is more suited for dynamically slow systems than positional control. Elton then proposed that giving the operator feedback to match their intent while in position control could narrow the performance gap between rate and position control for slow systems. Elton confirmed this with several tracking based video games, and later on the excavator simulator. Elton matched operator intent with feedback by projecting a *ghost* in his games and on the excavator simulator. This *ghost* showed the operator the target position of the system, which alleviated the problem the operators were having not knowing what position they were commanding.

<u>Achievements in the past year</u>

3D Simulation Upgrade

On the Georgia Tech excavator simulator, the old HDTV has been replaced with a new passive 3D HDTV. When used with matching polarized glasses, this TV is capable of projecting images independently to each eye, providing the capability of displaying the simulation environment in virtual 3D. The simulator software has been modified to support the 3D hardware, as shown in Figure 1. When viewed without glasses, as these pictures were taken, the 3D TV appears blurry and the simulation seems poorly defined. This is because the TV is displaying two separate images in the same space, and only viewing the TV with appropriate glasses will separate those images.

The addition of 3D was in response to the complaints of several simulator operators seeking better depth perception. During testing, these operators frequently were unsure of the bucket's location in 3D space. Theoretically the 3D display will give the operators the depth perception they need to identify the bucket's location relative to other simulation objects and help them complete their desired task. Tests are scheduled to measure the effect that the addition of depth perception has on the operator and control system.

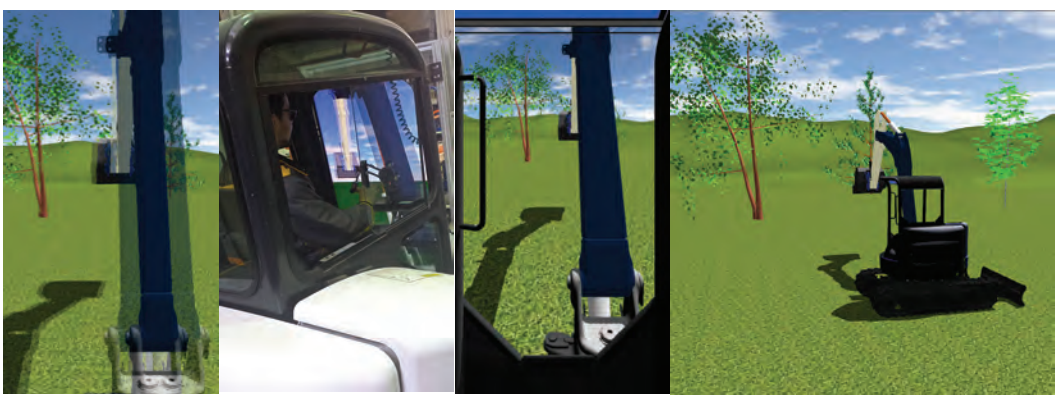

Figure 1: From left to right: (A) screenshot of 3D projection, (B) actual 3D projection, (C) distortion correction on excavator simulator, (D) environment.

Development of Distortion Correction Algorithm

While implementing the 3D display on the Georgia Tech excavator simulator, the distortion caused by the operator's proximity to the TV was preventing the 3D technology from functioning properly and creating a truly immersive 3D environment. One reason for this was due to the bottom edge of the TV being significantly farther from the operator than the closest point on the TV, causing simulation objects near the bottom of the screen to appear warped. Traditional setups don't need to account for this, as the TV is far enough away from the viewer that the distance to any point on the TV is roughly constant. However, in our condensed setup, it proved to be too inhibitive to ignore. In addition to being too close to the TV, the operator eyes were not centered on the TV (neither vertically or horizontally), and the TV has a slight (~ 6°) vertical offset as shown in Figure 2. All of these factors combined to make a traditionally rendered 3D scene unfit for use.

To combat these problems, an algorithm was developed to take into account all of the mentioned parameters and render a scene correctly as seen from the operators point of view. Figure 1 Image C illustrates the new rendering technique. In this picture, the boom is widest at the bottom of the image and narrows as it goes up. Compare this to Figure 1 Image A, where the boom has significantly less taper. This increased taper is due to the fact that the lower parts of the projection are farther from the operator and appear smaller. To account for this, objects at the bottom of the image need to be rendered larger in order to appear their actual size. While the benefits of such a projection technique are not apparent on a 2D representation, when viewed in 3D the new projection technique makes the simulation significantly more realistic and immersive.

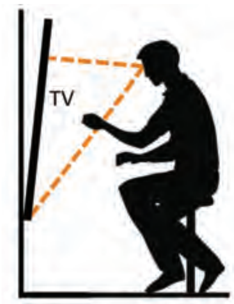

Figure 2: Condensed simulator layout creates undesirable distortion.

C. Plans

<u>Plans for the next year.</u>

While non-traditional control interfaces offer better economy long term, they would be expensive to implement on a traditionally operated vehicle. However, if applied to a teleoperated system these interfaces could be implemented with minimal additional cost. Industry has already acknowledged teleportation as a viable alternative on remote worksites or sites with increased operator risk; Caterpillar robotic trucks currently operate in some remote surface mines of Australia. A long-term goal of this project is to apply the lessons learned in this research to a teleoperated excavator. Implementing a *ghost* arm for a positional controller is significantly easier on a teleoperated excavator than it is on a traditionally operated one, and could justify the use of a non-traditional control interface.

In addition to the higher cost of implementing non-traditional control interfaces, equipment manufacturers are hesitant to change user interfaces for fear of alienating their existing user base. In effort to combat this conservative mentality, we have envisioned a Cartesian controller that can be implemented on the traditional dual joystick interface. This new controller will provide all the benefits of reduced cognitive load to the operator while using the same physical controllers of traditional setup. The control interface is currently being developed, and will be tested with the new 3D display. If proven effective, excavator manufacturers could insert a cheap toggle switch that would control which control interface the excavator responded to, allowing the operator to pick their preferred control strategy.

Lyons acknowledged that the effectiveness of the communication channels between human and machine have a high impact on system performance [1]. Much of the research on this project has focused on the channel from the human operator to the machine. This includes the user controller interface and the underlying control strategy of the system. The channel from excavator to operator has not been explored as extensively. This channel encompasses all the information that can be provided to the operator to help them do their job more efficiently, safely and effectively. One such information type is haptic feedback. Currently, the operators' only queue to system load is the volume of sound coming from the engine. Haptic feedback could provide additional information about the system that would prevent the user from 'pushing walls,' a technique that wastes time and drastically reduces fuel efficiency. A controller with haptic feedback will be implemented, and the effect that haptic feedback has on operator and excavator performance will be tested.

On a real excavator, the excavator arm or bucket can sometimes block the operator's view of critical work areas. Feedback through Google Glass or an alternative heads up display could alleviate this problem and provide additional, useful information to the operator. As seen in Figure 3, an orthographic projection of the dig site would give the operator clear information about the hole profile and the end effectors location relative to both the hole profile and the ground surface. Exploring what information can be given to the operator that is both useful and not cognitively overwhelming has been proposed as a future research area.

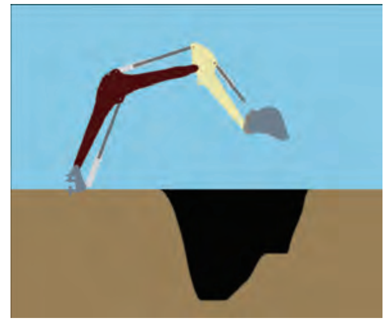

Figure 3: Orthographic projection of environment on a HUD could increase operator effectiveness.

The Georgia Tech excavator simulator has proven very useful and effective during the course of this research. We'd like to continue improving the simulation environment in an effort to make the user experience more realistic and immersive. The next planned improvement is the implementation of an IR head tracker. By tracking the location of the users head in the cab, and implementing the distortion correction algorithm discussed earlier, the simulation projection could dynamically match the operator's viewing location. This would grant the operator the ability to see around objects by moving side to side, or the ability to see farther into the digging trench by leaning forward. Other improvements are also under consideration.

Expected milestones and deliverables.

1. Paper on the importance of a 3D display in evaluating alternative operator interfaces
2. Complete the evaluation of selected coordinated control interfaces
3. Completion of experiments on actual hardware (dependent on coordination with industry and CCEFP test beds)
4. Generalization of results to other machines with similar characteristics

D. 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 Danfoss have donated equipment that has enabled the studies to be as realistic as possible. HUSCO has been invaluable in critiquing the progress and relating experience with excavator operations.

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

Research Team

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Industrial Partner:	Caterpillar

1. Statement of Project Goals

The goal of the project is to investigate human performance 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 will address the effectiveness and efficiency barrier by comprehensively assessing FP system operator performance, by developing a quantitative human-machine interaction model that will help excavator designers better understand the limits of cognitive and physical capabilities of human operators of fluid power systems. These quantitative models would be used to predict operator performance in an effort to develop a safe, intuitive, efficient and effective user interfaces for selected test beds. Further, this project will address the effectiveness barrier through the application of user centered design techniques/tools to improve the interfaces of emerging as well as existing fluid power systems by soliciting user needs and observing users interact with FP systems both in simulated laboratory environment and in real world scenarios.

3. Project Description

A. Description and explanation of research approach

Human factors play a very important role in fluid power systems ranging from interface design to operator performance and safety. In this project, we studied the impact of the auditory feedback on excavator operator performance and investigated the impact of various factors on nurses operating a patient transfer device. Traditionally, engineers have designed products centered from a technology perspective. Unfortunately, the technology driven approach has led to information overload and errors causing products to be ineffective [1]. Consequently, operators are usually blamed for 60% to 85% of all accidents [2, 3]. However, accidents/errors are not always the fault of the operator, rather, the design of the product itself [1]. Human factors research has shown that the users' perspective must be included in the design and development process to achieve effective and efficient results [4].

Most HMI stresses the visual perception, but auditory cues can improve the safety, efficiency and effectiveness of operator performance [5-8]. Therefore, it is important to investigate auditory feedback in haptic controlled excavator interfaces. Moreover, with the involvement of both the extremities (legs and hands) in operating levers/pedals, auditory cues are one of the only cognitive resources available beyond visual modality for the haptic-controlled excavator operators. To address these concerns, a preliminary study was conducted using a haptic-controlled excavator simulator in the laboratory to evaluate the effectiveness of various auditory cues on operator performance when operating a haptic-controlled excavator. The detailed approach is explained as follows:

<u>Participants:</u> Seven subjects between the ages of 18 and 60 were recruited to participate in the study. Experienced excavator operators were not required for the purpose of this study.

<u>Simulating Environment and Equipment:</u> The Phantom Premium 1.5 haptic device was used to simulate the excavator controls. The software used to design the simulated excavator environment

was coded in C++ and Mat Lab programming and developed by Georgia Institute of Technology. A schematic representation of the equipment setup is shown in Figure 1.

Experimental Design: A randomized design was used to minimize the effect of prior knowledge/ experience of the participants. The independent variable was the auditory cues with three levels (no auditory cue, alarm, and voice message). The dependent variable was operator performance measured by the task completion time, the number of scoops and the number of drops.

Tasks: The participants performed three typical tasks under three conditions: no auditory cues, an alarm and voice message. These tasks can be accomplished by using the stylus of Phantom Omni device to control and manipulate the boom/bucket assembly of the simulated excavator. When the bin is full, the content of the bin turns green. During the no auditory cue condition, participants were instructed to perform each task at their own pace. For the other conditions, the participants were instructed to dump the dirt into one of the bins only when the auditory cue was given.

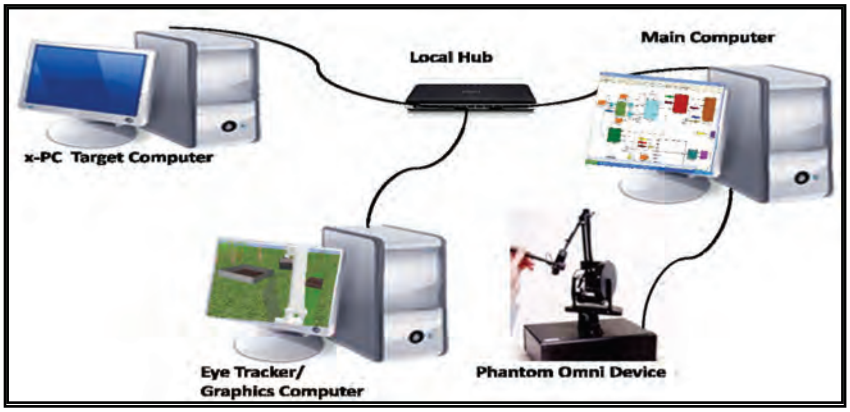

Figure 1: Schematic representation of the equipment setup.

Procedure: Participants were briefed about the experiment and asked to sign an informed consent form to participate in the study. A pre-study questionnaire was administered to each participant to collect demographic information and their experience with computers and the simulation software. To minimize the effect of prior knowledge/experience, all participants underwent a five minute training session to become familiar with the haptic device and simulation prior to testing. Next, a scenario about each task was given to the participants to complete. The order of the experimental conditions (no auditory cue, alarm, and voice) was randomized. Upon completion of the tasks, participants were asked to complete a post-questionnaire about the study. Finally, participants were debriefed and thanked for their participation. The entire experiment lasted about 45 minutes with 5 minute break given between experimental conditions. Participant performance data including task completion time, number of scoops and number of drops were automatically captured by the computer.

Descriptive statistics: Performance data of task completion time, number of scoops, and number of drops were used to assess participant performance. Mean and Standard deviation of the performance data were calculated and summarized in Table 1.

Table 1: Descriptive statistics of performance data

Experimental Condition	Completion Time (seconds)		Number of Scoops		Number of Drops	
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
No Auditory Cue	426.57	140.94	16.57	1.72	2.86	1.95
Alarm	360.86	96.83	13.43	0.79	1.14	0.90
Voice	377	121.74	13.29	1.89	0.71	0.95

Inferential statistics: To investigate the impact of auditory cue on operator performance, an analysis of variance was initially considered. Unfortunately, analysis on the residuals revealed violation of normality assumption. Shapiro-Wilk test was used to check the normality of the performance data. Results indicated that the performance data was not normally distributed (W=0.9101, p=0.0552 for Completion time; W=0.9425, p=0.2442 for the number of scoops; W=0.9417, p=0.2356 for the number of drops) and hence analysis of variance was not appropriate to use. Due to the small sample size, a nonparametric analysis of variance was used to test the hypothesis that the auditory cue has an impact on operator performance. Kruskal-Wallis test was conducted on the performance data. No statistical significance was found for the completion time ($F_{2,18}$=0.5589, p=0.5814). However, significant difference was found for the number of scoops ($F_{2,18}$=10.14, p<0.01) and number of drops ($F_{2,18}$=4.8879, p<0.05). For significant results, pairwise comparison was done using the Dwass, Steel, Critchlow-Fligner multiple comparison procedure. For the number of scoops, a significant difference was found between no auditory cue and alarm (Wilcoxon z=2.9471, p<0.01), no auditory cue and voice message (Wilcoxon z=2.5280, p<0.05). For the number of drops, a significant difference was found between no auditory cue and voice message (Wilcoxon z=2.5975, p<0.05).

Human performance plays a significant role in overall system performance. This can be evidenced by the patient transfer device. Work related musculoskeletal disorders (MSD) have become a challenge and financial burden for employers in the United States because of the negative impact on worker's compensation claims, absenteeism and productivity. In 2011, MSD accounted for 33% of all worker injury and illness cases reported [9]. Healthcare was the leading industry with the most reported cases [9]. Since 2006, nursing occupations have been reported as one of the top ten highest risks for work-related MSD in the United States [10]. MSD cases involving patient handling accounted for 98% of all reported cases [11].To help resolve these issues, a new patient transfer device using fluid power is under development. This study intends to identify significant factors and their impacts on nurses operating the patient transfer device and incorporate the findings in the design as part of the user centered design process. The American Nursing Association reported that the lower back followed by shoulders and knees are the most affected body parts when handling patients [12]. The Center for Disease Control reported that lower back injuries are also the most costly MSD [13]. The direct and indirect costs associated with only back injuries in the health care industry are estimated to be $20 billion annually, according to the U.S. Department of Labor [10]. Therefore, with nursing personnel currently leading the nation in work related back injuries, more research is needed to identify and provide safe guidelines for patient handling that will decrease the potential risk of MSDs. The objective of this study is to quantify the effect of weight, grip positions and height positions (sub-waist) on trunk kinematics (angular velocity and angular acceleration) measures to identify potential stresses on the lower back muscles and to provide recommendations on better patient handling/transferring guidelines to help prevent musculoskeletal disorders in the lower back. The following approach was used in this preliminary study:

Participants: Ten participants between the ages of 18-38 participated in the study. The participants consisted of three male and six female students. Anthropometric data was taken from each subject at the start of the study.

Apparatus: A workstation was built to simulate an exerted pulling force that takes place during patient handling tasks. During the pulling task, participants' trunk kinematics were collected using an Industrial Lumbar Motion Monitor (iLMM).

Experimental Design: A within subject design was used in this experiment. The independent variables in this study were the height of the workstation with two levels (knuckle height and waist height), exertion with three levels (0lbs, 5lbs, and 15lbs), and grip position with three levels (center, shoulder width, and wide). The dependent variables in this study included a measure of trunk kinematics during the loading phase of each task. The resulting dependent variables from the iLLM were angular velocities and angular acceleration in the sagittal plane. The 18 tasks had two trials (A and B), resulting in a total of 36 tasks per participant. The participants repeated each tasks 3 times. The trials were randomized with respect to weight, workstation height, grip location and randomly assigned to participants.

Experimental Procedure: All subjects reported to a biomechanics research laboratory for all test sessions. Upon arrival, each participant was greeted, informed on the purpose of the study, and were asked to sign an informed consent form to participate in the study. A pre-test questionnaire was administered via SurveyMonkey, an online survey tool, to collect demographic information, current health status, and their prior experience with patient handling. Next, the subject's weight, stature, standing knuckle and waist height and shoulder width were measured. Participants were asked to stretch before beginning the study. Each participants started in an upright standing position on the X marked in front of the workstation (X was marked for the center location). The participants were first given a demonstration on how to use the workstation pulley station and they were allowed to become familiar with the workstation. They performed eighteen tasks with two trials each. The task performed in the study involved the participant exerting a pulling force on the pulley workstation at the requested weight level and grip position at different heights. Figure 4 provides a visual representation of the task procedure. One to two minute rest periods were given after completing each task to prevent fatigue. Upon completion of the experiment, the participants were asked to complete a post-test questionnaire online and thanked for their participation.

Statistical Analysis Technique: MANOVA and subsequent univariate analysis of variance (ANOVA) techniques were used to analyze the lumbar kinematics data to investigate effects of workstation height, weight, and grip (and their interactions) on the angular acceleration (DV1) and angular velocity (DV2).

Results: No significant interaction effect among the weight, the workstation height, and grip location was found (Wilks' Lambda = 0.98967462, $p = 0.9927$). No interaction effect between the workstation height and grip location. (Wilks' Lambda = 0.98777870; $p = 0.7790$). None of the two way interaction effects -between the workstation height and weight (Wilks' Lambda = 0.98639404; $p = 0.7420$, between the grip location and weight (Wilks' Lambda = 0.97720408; $p = 0.9118$). No significant grip level effect was found (Wilks' Lambda = 0.99578244; $p = 0.9623$). However, a significant difference between the workstation levels (waist and knuckle height) (Wilks' Lambda = 0.72393358; $p < 0.0001$) and a significant difference between the weight levels (0lbs, 5lbs and 15lbs) (Wilks' Lambda = 0.89082705; $p = 0.0023$) were found. A post hoc analysis was performed to further explore any significant effect of the independent variables with two or more levels. SNK test revealed a significant difference between the knuckle and waist height are significantly different for both dependent variables; between 0 lbs and 15 lbs for both dependent variables; and no difference among the grip locations (center, wide and shoulder) for either dependent variable.

The results of this preliminary study confirmed that there is risk of lower back injury when transferring a patient. There is a significant concern of a greater risk when the patient is bariatric, immobile and/or has restricted limbs. Findings of this study will be incorporated in the design of the fluid powered patient transfer device that needs to require minimum bending and extension of the trunk and/or (2) an assistive device that the caregiver can easily use in positioning the patient onto the sling. Finally, more testing will be conducted in the future with the intention of providing patient handling guidelines for MSD prevention.

B. Achievements

Achievements prior to February 2013:

- Revised haptic-controlled excavator interface using user centered design approach – Spring 2012.
- Conducted literature review on quantification of human machine interaction – Spring 2012
- Developed a feedback control system representation of human-excavator model – Spring 2012
- Developed quantitative models for multimodal human excavator interface – Fall 2012
- Developed a forward and closed loop transfer functions for human-excavator model – Fall 2012
- Implemented models in MATLAB – Fall 2012
- Revised rescue crawler interface – Summer 2012

- Conducted usability testing on the revised interface – Fall 2012
- Conducted literature review on operator fatigue – Fall 2012
- Conducted literature review on auditory feedback – Fall 2012
- Designed games for PPAFO – Spring 2012
- Developed prototype GUI for PPAFO – Fall 2012

Achievements in this reporting period:

- Revised haptic-controlled excavator simulator in preparation for the auditory experiment – Spring 2013
- Conducted an empirical study on auditory feedback using the simulator – Summer 2013
- Conducted literature review on MSDs related to patient transfer – Summer 2013
- Conducted task analysis for patient transfer device – Fall 2013
- Developed apparatus for patient transfer experimentation – Fall 2013
- Conducted an empirical study on patient transfer – Fall 2013

Plans for the Next Five Years

- Identify usability goals for the patient transfer device
- Select alternative designs for joystick or haptic device placement
- Develop digital human models for the excavator operator
- Conduct experiments using the digital human models of excavator operators
- Conduct empirical study on excavator operator fatigue with human subjects
- Develop prototype interface for the patient transfer device
- Conduct usability study on the prototype interface of the patient transfer device
- Revise the interface design for the patient transfer device
- Develop human performance models for the patient transfer device
- Conduct empirical study on operator performance using human subjects for the patient transfer device

Expected Milestones and Deliverables

- Digital human model studying excavator operator fatigue
- Usability studies of the patient transfer device
- Empirical experiments studying excavator operator fatigue
- Development of prototype interface for the patient transfer device
- Human performance models for patient transfer device
- Empirical experiments studying operator performance for patient transfer device

C. Member company benefits

The human performance studies can be applied to investigate operator performance for any complex fluid power systems where operators interact with 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.3: Active Vibration Damping of Mobile Hydraulic Machines

Research Team

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Industrial Partners:	Parker Hannifin, CNH

1. Statement of Project Goals

The goal of the project is to develop a novel energy-efficient control methodology to reduce vibrations in hydraulic machines. The proposed control strategy has potential to replace or limit costly and energy dissipative methods currently utilized to achieve acceptable dynamical behavior in mobile fluid power (FP) applications. The novel solution would allow for a reduction of both amplitude and duration of actuators oscillation up to 70%. The solution offer also margin of energy consumption reduction. Based on an adaptive control method based on pressure feedback (using pressure sensors located in well protected locations of the machine), the proposed techniques is suitable to all mobile applications without introducing significant cost increase.

2. Project Role in Support of Strategic Plan

This project is related to the "control and controllability" topic, and addresses the major technical barriers of "control and energy management" and "efficient systems". In particular, the project proposes an innovative adaptive electro-hydraulic (EH) control methodology for general application to fluid power machines that permits to reduce machine vibrations according to a general and inexpensive technique that addresses the inherent nonlinearities of the hydraulic systems and the unpredictable operating conditions of the machine (e.g. varying inertia of the load, terrain roughness, variable geometrical configuration of the booms, etc.).

The proposed control method has positive implications as concerns safety, efficiency, controllability and productivity of current FP machines. Moreover, the novel EH method will allow: a) the simplification of current hydraulic circuits, through the removal of elements normally introduced to improve system dynamical behavior; b) to enlarge the area in which fluid power technology can be conveniently applied.

3. Project Description

A. Description and explanation of research approach

FP systems are routinely affected by *oscillatory dynamics* of moving parts which can lead to stability issues. Undesired vibrations not only worsen *controllability*, but also reduce *productivity* and impact *comfort* and *safety* of operation. Despite the research efforts in finding solutions to control such oscillations, a general solution has not been found yet. *Current damping methods* are designed for specific applications and they can damp oscillations only in a limited range of operating conditions. Additionally, they usually *introduce systems slowdown* (capacitive methods) or *energy dissipation* (resistive methods).

A first distinction among methods for vibration dampening is whether the hydraulic system is integrated with electronic control logic. According to this classification, there are pure hydraulic (PH) solutions and electro-hydraulic (EH) solutions.

Pure hydraulic technology: these methods are based on *capacitive* elements (e.g. accumulators) and/or *resistive* elements (e.g. orifices). Being based on fixed parameters these methods are suitable to damp the system only within a small range of operating conditions, and the tuning is typically based on extensive "trial and error" empirical processes made for each single application. The literature reports numerous methods that belong to the pure hydraulic technology category, including the use of accumulators or restrictors. Of particular interest for this research are the dissipative methods based on the applications of counterbalance valves [1-4].

Electro-Hydraulic (EH) technology: EH technology is based on an optimal management of the power source with respect to a feedback signal representative of the oscillation extent. EH technology has often

been combined with PH technology, to extend the range of stability of the hydraulic system and/or to limit the contribution of pure-hydraulic techniques drawbacks on the entire system. Examples are: active suspensions; earthquake simulators, vehicles braking systems; hydraulic robots; active damping seats.
This research particularly investigates the pressure feedback control methodology, in which the pressure signal is used to indirectly quantify the oscillation. In this case a control based on real-time identification of the relationship between pressure and oscillations is required. Some interesting results obtained in the past have not reached practical application because of the complexity of the proposed controllers and of its model-based nature, which makes it difficult to extend to other applications.

The solution of the drawbacks of the past proposed pressure-feedback techniques represent the main challenge of this project. In particular, the proposed control methodology will address the problem of oscillation damping of FP machines considering:

- The uncertainties typical of FP machines (unpredictable load mass, machine varying kinematics, terrain roughness, etc.) and inherent nonlinearities of the hydraulic actuation systems. For this reason the control methodology will be adaptive and not model based;
- The need for formulating a control method that ensures stability and performance over the entire range of operating conditions. This is the crucial limit of current adaptive solutions in FP applications. For this reason the adaptive control will be based on Extremum Seeking control methodology in an innovative way in the FP field;
- Functionality, reliability and cost requirements of FP applications. For this reason the proposed control methodology will be formulated for pressure feedback control (pressure sensors used as feedback signal), overcoming the limits of current position tracking control methods for harsh applications.

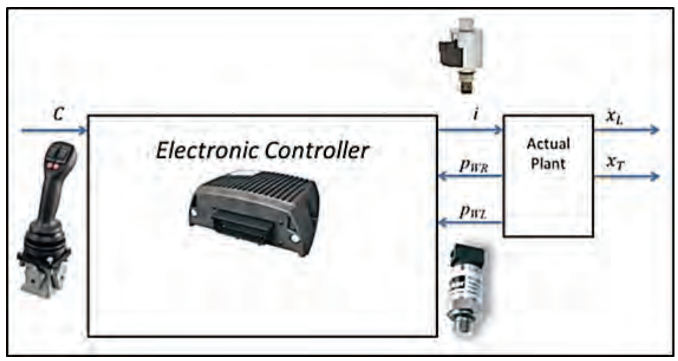

Figure 1: Basic schematic of the controller

The proposed control solution and its innovative contents

This research applies for the first time to FP applications the adaptation/optimization scheme using the Extremum Seeking (ES) theory. ES is an algorithm able to identify the set of parameters that can produce the maximum or minimum of a given function. Figure 1 and Figure 2 describe the idea under the proposed control approach. A controller is used to control the input signals of the control elements (flow control valves, for the case considered in this research), Figure 1. The input parameters of the controller are signals given by pressure sensors installed near the actuator for which the oscillations have to be minimized.

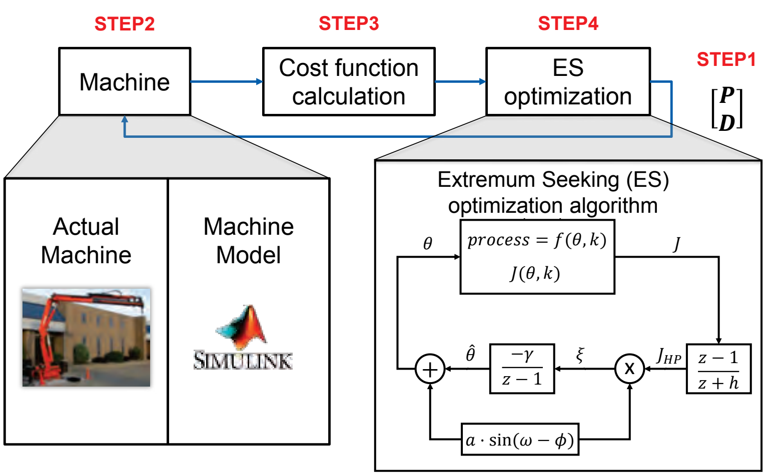

Figure 2: Controller tuning optimization process

The tuning of the control parameters is achieved through online or offline optimization methods. Figure 2 represents the idea for the optimization according to the offline scheme. A cost function associated to the oscillation is evaluated using real experiments or computer simulations. The ES algorithm is used to achieve minimum oscillation through a fast convergence loop.

B. Achievements

Achievements in previous years

Started in summer 2012, during the first year the following activities have been performed:

Control strategy achievements

A first off-line version of the control algorithm was implemented and tested on the reference machine (Figure 3). The optimization scheme is shown in the Figure 1 and Figure 2 and the controller was based on a proportional-derivative (PD) controller with gain scheduler based on the operator signal and on the pressure feedback. For the optimization, a simplified AMESim model for the entire system was implemented.

Figure 3: Reference machine instrumented at Maha Fluid Power Research Center.

The controller parameters obtained by this procedure were tested on the actual experimental crane equipped with accelerometers on the end of the mechanical arms. The measurements reported in Figure 4show a significant improvement in the machine dynamics (about 30% settling time and overshoot reduction). This is a remarkable result, considering that the crane was in its standard, energy inefficient configuration. Therefore the dynamic behavior was already acceptable. A more significant result will be obtained when the setting of the counterbalance valve would lead for less energy consumption, but providing more tendency for oscillation. The controller implementation and results were published in [5].

Energy consumption estimation

In order to perform an estimation of the energy consumption and its possible improvement, a study was conducted on the reference machine by changing the settings of the CBV. Two typical operating cycles were considered for the study, in order to investigate the overall operation of the machine (lifting/lowering, with/without load). A detailed AMESim model, created to model the behavior of the valve, supported this activity. Detailed discussion on the methods used and on the results achieved are given in the next section.

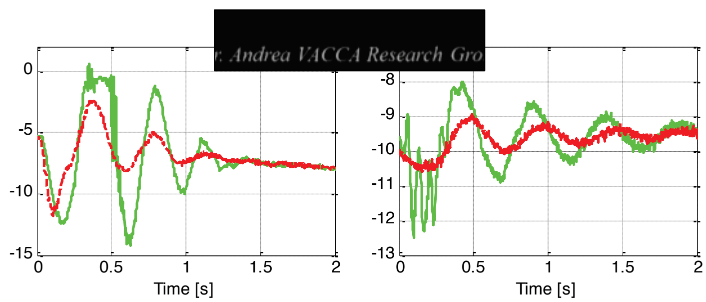

Figure 4: Tangential acceleration [m/s2]: Raise without load (Left); Raise with load (Right).

Achievements in the past year

During the last year (02/1/2013-01/31/2014), the following activities were completed.

Control strategy impact on the energy consumption and the dynamic response of the reference machine

The reference machine was equipped with adjustable counterbalance valves (CBV). The objective was to observe and to quantify the impact of the CBV settings on the energy efficiency and on the dynamic response of the machine.

First, an analytic study on CBV was performed with the goal of deriving a relation between the valve settings and the machine consumption/dynamics. The main results have been published in [6]. In this work a graphical method to study the operation of CBV was presented. Figure 5 summarizes the approach used to characterize the CBV.

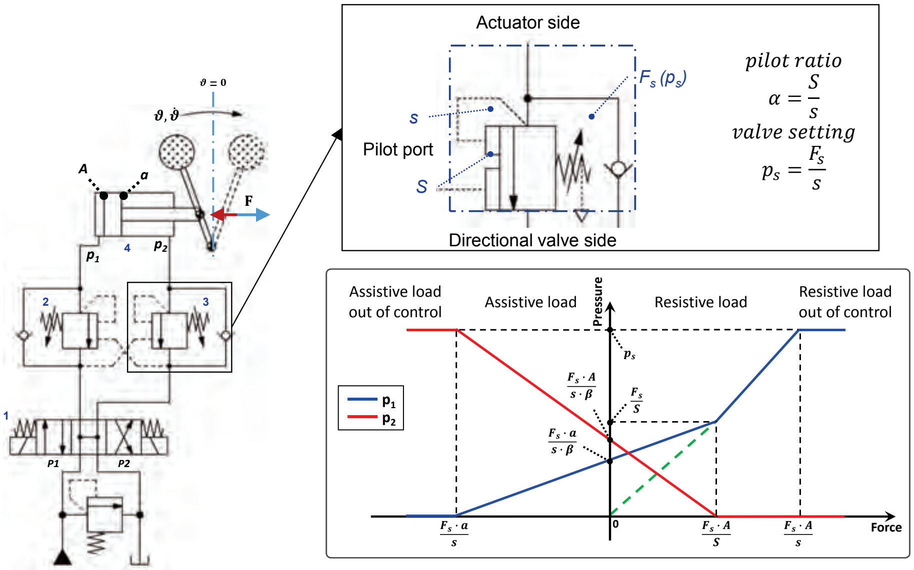

Figure 5: Graphical method to characterize CBV [6, 7]

An experimental activity showed the impact of different valve settings on the energy consumption of the reference machine. The results of Table 1 were obtained using two working cycles representative of the regular operation of the machine.

Table 1: Impact of CBV settings on the global energy efficiency of the reference machine. [7]

CBV settings		Cycle 1		Cycle 2	
p_s [bar]	α [-]	Energy consumption [kJ]	Biggest energy difference	Energy consumption [kJ]	Biggest energy difference
350	8	535.2	25.6%	697.2	24.5%
350	4	719.8	-	923	-
275	8	475	34%	636.8	31%
275	4	647.6	10%	814.5	11.7%

Figure 6 shows the dynamic response of the machine employing different valve settings. As it can be seen, the use of more energy efficient valve settings leads to a more unstable machine behavior. The successful application of the controller strategy is shown by the black line in Figure 6. The activation of the controller enables the use of better valve settings while keeping the dynamic response acceptable for a safe use of the machine.

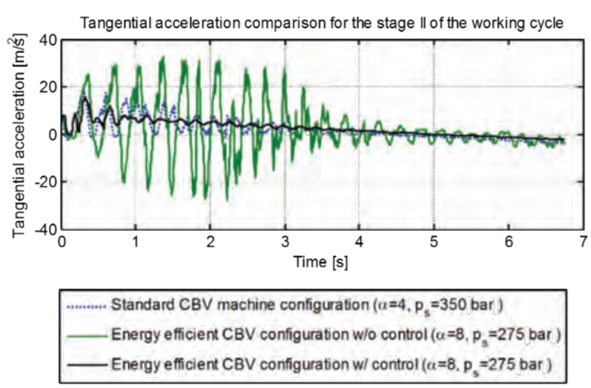

Figure 6: Dynamic response of the standard machine CBV settings and of the energy efficient machine CBV settings with and without control applied.

Control strategy achievements
Towards the on-line controller application, an observability study was performed. Specifically an analytic method for estimating mechanical arms acceleration was proposed in [8]. Solely utilizing pressure sensors it was demonstrated how it is possible to estimate arms acceleration in mobile hydraulic machines.

Figure 7 shows the experimental results obtained using the reference machine (a hydraulic crane). From the plot it is possible to observe a good agreement between the measurements and the acceleration estimation carried out using the method proposed in [8].

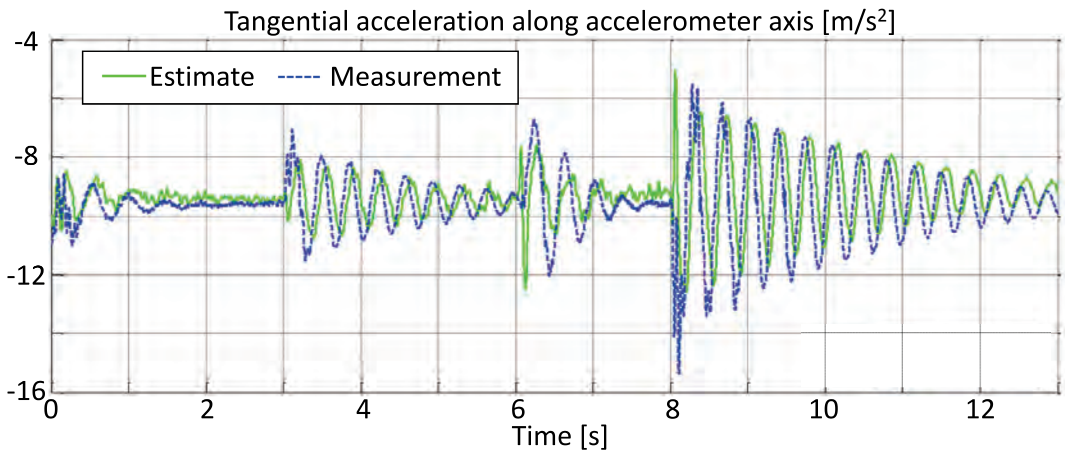

Figure 7: Comparison between measured and estimated tangential acceleration of the machine. [8]

C. Planned achievements following the report period – milestones and expected deliverables

- Experimental auto-tuning of the reference crane through off line application of the ES algorithm (April 2014)
- Definition of cost function for experimental offline tuning of the controller (April 2014)
- Real-time system control with ES:
  - Definition of cost function for online tuning of the controller (April 2014)
  - Simulation and comparison of performance between real time and offline ES control (May 2014)
  - Preliminary results on experimental application of online ES control

D. Member company benefits

- The member companies will gain knowledge on the EH techniques available to efficiently control flow control valves improving system dynamics
- General applicability. The technique can potentially be applied to completely different hydraulic machines (for example to reduce cabin oscillations of off road vehicles)
- No significant hardware requirements. Being the range of undesired oscillations at low frequency, traditional technology can be sufficient to obtain good oscillating damping features with the proposed technology
- Reduction of cost: the novel technology can be used in place of expensive devices of current state of the art (e.g. accumulators). Also the automatic controller tuning reduces the time required to tune up the system.

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Project 3D.1: Leakage and Friction Reduction in Fluid Power Systems

Research Team

Project Leader:	Richard F. Salant
Graduate Student:	Yuli Huang
Industrial Partners:	Trelleborg Sealing Solutions, Freudenberg NOK, Bosch-Rexroth, John Deere, Caterpillar, Concentric AB, 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 and friction 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. 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.

Past research on rod 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. The present project, in the CCEFP, builds on that work. At the same time, several other researchers have been making advances [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 and from the open literature.

B. Achievements

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

The transient models, both elastic and viscoelastic have 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 do indeed 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. The viscoelastic model has produced results similar to those from the elastic model for moderate to long cycle time applications. However, for short cycle time applications, the viscoelastic effects become important and produce cycle to cycle variations.

The seal models described above treat the seal surface as rough and the rod surface as perfectly smooth. To examine the effects of the rod surface finish, a seal model that includes the rod surface geometry has been developed. Two types of seals were analyzed, a polyurethane U-cup seal and a step seal with a PTFE sealing element. For the U-cup seal, over most of the velocity range, the fluid transport into the cylinder (during the instroke) with the plunge-ground rod is lower than that with a smooth rod, indicating that such a surface finish reduces the ability of the seal to prevent leakage, including that due to imperfections in the lip, non-axisymmetry, and other effects not accounted for in the model. Furthermore, during the instroke the friction force on the rod is higher for the plunge-ground rod than for the smooth rod. For the step seal, it was found that the plunge ground rod yielded the same performance as the smooth rod, in regard to both fluid transport and friction force. The reason for this difference in behavior compared to the U-cup seal has been determined to be due to the difference in seal roughness: the polyurethane U-cup seal has an rms roughness of 0.8 microns while the PTFE step seal has an rms roughness of 4.0 microns. It was also found that the plunge-ground rod finish increases the friction force on the rod over most of the velocity range with the U-cup seal, but not with the step seal. However, with both types of seal the plunge-ground finish produces large oscillations in the contact pressure, which are expected to increase the rate of fatigue induced wear.

The research generated by this project thus far has been published in 10 archival journal papers, presented in 3 plenary and 1 keynote lecture, [2 invited papers, 27 additional conference presentations and 5 seminars.

Progress During the Reporting Period

During the present reporting period the major effort has been directed toward developing a model to investigate engineered micro-patterned rod surfaces to reduce seal friction while maintaining zero net leakage. The past simulation work done on this project has 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 and mechanical seals. The present project takes a similar approach, applied to rod seals, initially considering a pattern of micron-scale triangular cavities in the surface of the rod.

During the present reporting period, two approaches have been taken to develop a model to study the effect of such a micro-patterned rod. In the first approach, the seal is treated as elastic and the model consists of a fluid mechanics analysis of the lubricating film, a contact mechanics analysis and a deformation analysis of the seal, similar to our previous models. For the fluid mechanics analysis, a two-dimensional Reynolds equation solver, which accounts for the two-dimensionality of the micro-pattern, has been constructed. This involves using the finite volume discretization technique. The two-dimensional discretized equations are 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 are then applied, allowing the use of the TDMA (tri-diagonal matrix algorithm) and cyclic TDMA algorithms.

Due to the two-dimensionality of the surface features, a three-dimensional finite element computation is required to determine the static contact pressure distribution in the seal-rod interface. This would normally introduce prohibitively large computation times into the iterative computations. However, a new unique approximate approach has been developed to reduce those computation times. It is based on the fact that the material in the seal lip above 100 microns from the sealing surface is unaffected by the rod surface features, like micro-cavities. This is seen from the figure below, which shows a comparison of the von Mises stress with and without the cavities, which look exactly the same outside the 100 micron layer segments. On the right is a magnified view, showing how the elastomer protrudes into the cavities. Therefore a 3D FEA is performed on a model of only the lower layer of lip material, divided into 6 axial segments. The 3D models of the 6 segments in the layer are then used to generate the static contact pressure distribution. This approach has wide application beyond the present seal analysis.

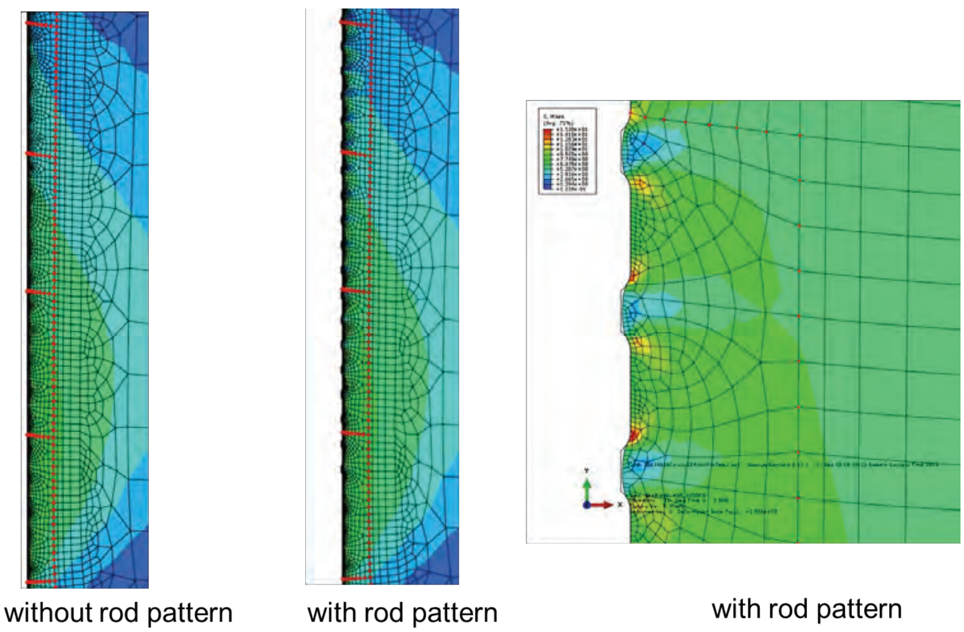

Figure 1. Von Mises Stress in Seal Lip near Rod-Seal Interface.

The simulations with this seal model will predict leakage and friction, as well as the detailed behavior in the sealing zone, as in the past. However, with this model the computation of the seal deformation is extremely time-consuming. Therefore, a second approximate approach has been taken.

In the second approach, it is noted that the deformation of the seal is very small compared to the interference during mounting, so the state of stress within the seal is relatively constant during operation. Therefore, the sum of the dynamic contact pressure and the fluid pressure in the sealing zone must equal the static contact pressure. Once the static contact pressure is computed and the fluid pressure is computed (from the Reynolds equation, as described above), the dynamic contact pressure is readily obtained. Using the Greenwood-Williamson model, the film thickness in the sealing zone is computed, without the need for a deformation computation. This film thickness distribution is then inserted into the Reynolds equation solver, and iteration proceeds to convergence. This approach also takes account of viscoelasticity by preventing the seal material from protruding into the cavities.

Planned Progress

While this project was planned to terminate at the end of year 8, work is expected to continue into year 9 under a Fund Carry-Forward. During the proposed Fund Carry-Forward period, the model described above will be used to analyze the behavior of a rod seal operating with a micro-patterned rod. Parametric studies will be performed in order to find the optimum pattern design and in order to obtain an understanding of the physical processes occurring. The following parameters will be varied: cavity dimensions, cavity geometry, pattern arrangement, operating conditions. The results will be documented in the form of refereed publications and a PhD thesis.

C. References

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Project 3D.2: New Directions in Elastohydrodynamic Lubrication

Research Team

Project Leader:	Scott Bair, School of Mechanical Engineering, Georgia Institute of Technology
Industrial Partners:	Lubrizol, Afton Chemical, John Deere, Shell

1. Statement of Project Goals

The goal of the project is to transform elastohydrodynamic lubrication into a quantitative field, able to provide solutions to problems in fluid power. This is a basic research program intended to support applied research in fluid power. There are five thrusts to this project. Much of the work will be done concurrently since progress depends upon collaborators in laboratories scattered around the world working on different schedules.

a. Rheology of degraded oil

Most efficiency testing is done on unused oil. Recent results from project 1G1 suggest that the improved mechanical efficiency of multigrade oils results from the reduced sheared viscosity. It is not known if this improvement stems from shear-thinning or shear degradation. Efficiency testing will be done by Paul Michael (1G1) on oils from Afton Chemical which have been degraded by severe shear. The viscosities of the new and degraded oils will be measured as a function of temperature, pressure and shear to investigate the origin of the improvement.

b. Accurate prediction of minimum film thickness in EHL

It is well-known that the classical film thickness formulas do not accurately predict the minimum film thickness even when the viscosity has been adjusted to explain the central thickness. This is an unfortunate situation since the minimum film thickness influences durability of the surfaces. During the previous five years of this project, many measurements of minimum film thickness have been collected at Brno University on rheologically well-characterized liquids. These data will be used in concert with the numerical simulations of Habchi at Lebanese-American University to arrive at an accurate minimum film thickness formula for engineering.

c. Solution of Navier-Stokes for piezoviscous liquids

The basic equation of lubrication, the Reynolds equation, a simplification of the Navier-Stokes equations, was derived under the assumption of constant viscosity. In EHL, the viscosity changes many orders of magnitude as the liquid is transported about 100 microns distance due to piezoviscosity. Incredibly, the field of EHL has been employing an equation which may be poorly suited to the task. Solving the Navier-Stokes equations for a piezoviscous liquid becomes problematic when the product of the principal shear stress and the pressure-viscosity coefficient goes to unity. Secondary flows develop as the product approaches one and the equations change character from elliptical to hyperbolic at one. A solution will be attempted for flow between parallel plates in collaboration with Michael Khonsari at LSU.

d. Thermal conductivity measurements at elevated pressure

Work over the last two years with Philippe Vergne at INSA has elucidated the importance of the thermal conductivity of the oil at the contact conditions to the friction at high sliding speeds. Low conductivity under pressure reduces friction for sliding speeds greater than 1 m/s, all other things being equal. Work has begun on a high pressure thermal conductivity cell using the transient hot-wire technique. Conductivity measurements will be conducted on several types of low-viscosity base oils with an eye to constructing a predictive model.

e. Targets of opportunity

A significant feature of this project has been that each new discovery has led to several other discoveries. We plan to continue to leverage what we learn to redirect efforts toward fruitful investigations.

2. Project Role in Support of Strategic Plan

The project addresses the Center's compactness and efficiency thrusts. 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 load and decrease in radius of curvature of the sliding/rolling elements will result in diminished film thickness. The

reduced film must impact the reliability. New insights into the effects of scale [2, 7], load [8] and lubricant degradation [16, 27] are being provided by this project.
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 [20, 23, 26] using the temperature/pressure correlation for viscosity devised by this project [4, 5, 6, 10, 17], the first experimentally validated EHL friction calculations were performed which included thermal-softening and shear-thinning. Fragility has been shown to be the principal property controlling friction at very high contact pressures. Thermal conductivity of the liquid becomes important at high sliding speeds. Discovering the nature and interactions of these relationships addresses the efficiency goal of the Center.

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 effects of scale [2,7], load [8], rheology [1,13,20,23,24,26], thermal properties [23,26,28] and shear degradation [16,17] has been predicted from EHL simulation using measured rheological properties and the predictions have subsequently been experimentally validated. Both film thickness and friction may now be predicted [23, 26, 28] 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. 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.

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. Fragility, a property strongly affecting EHL friction and transient EHL film response is now being intensely studied. 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.

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

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

Equation 1

where n is the power-law exponent which in the limit of high shear rate is $n = 1 + \partial \ln\eta / \partial \ln\dot{\gamma}$. 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 of the Einstein-Debye relation for the rotational relaxation time of a molecule in terms of the universal gas constant, R_g, is

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

Equation 2

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 often 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.

The identification of the importance of the thermal conductivity of the liquid to friction [20, 23, 28] at high sliding speed was an unexpected major development. The ability to measure thermal conductivity at EHL pressures will be addressed in the next two years.

An essential part of this program involves collaboration with partners around the world. 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. Roland Larson, Lulea University of Technology, traction measurements

A new collaboration with Paul Michael at MSOE and Mark Devlin at Afton will address the relative importance of shear-thinning versus shear degradation to mechanical efficiency in fluid power.

B. Achievements

This project has been providing discoveries at an astonishing rate. As a result of these discoveries the entire field of EHL has been transformed from one for which many explanations existed for the same phenomena to one in which precise predictions may be made from measurable properties of the liquid.

The achievements of this project may best be summarized by a list of resulting publications. Twenty-nine papers have resulted from the six years of work; eight have been written, submitted or published within the last year alone.

The high productivity of this program has been partly due to collaborations but also due to the unstructured plan. Each new discovery has opened the possibility of new opportunities. The same approach will be employed in future work. For example, work this year has emphasized the need for improved modelling of thermal properties, especially conductivity, at EHL pressure levels. Next year, a new thermal conductivity cell will be designed for 700 MPa.

C. Member company benefits

Member companies gain insight into the effects of liquid properties on the performance of concentrated contacts within equipment components. The property relations which are being generated in this program may be immediately used by industry members in modeling friction and film thickness.

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Project 3E.1: Pressure Ripple Energy Harvester

Research Team

Project Leader:	Kenneth A. Cunefare, Woodruff School of Mechanical Engineering, Georgia Institute of Technology
Graduate Student:	Ellen Skow
Undergraduate Students:	Nalin Verma, Aaron Kranc, Zachary Koontz, Brian Hults, Karthika Poonammalla Venkatasubramanian
Industrial Partners:	Parker-Hannifin, Danfoss Power Solutions

1. Statement of Project Goals

The goal of this project is to model, develop and prototype energy harvester devices capable of producing useful power from pressure ripple in high-pressure hydraulic systems. The application of the devices is for powering sensor nodes within a fluid hydraulic system, as may be used for health monitoring or data acquisition applications. Initial prototype devices sized for sensor-node power requirements will be available by Spring 2014. An initial power response model was available by Summer 2013; a refined model will be a major final deliverable in Summer 2014.

2. Project Role in Support of Strategic Plan

The research is predominately focused in the effectiveness thrust, in that it enhances the utility and efficiency of hydraulic systems. Further, it is enabling of compact and efficient implementation of self-powered sensors and control capabilities, relevant to the Efficiency thrust. Such capability, for example, is relevant to sensing systems considered for Test Bed 1. The technology could reduce the overall system complexity, improve reliability, and reduce maintenance contact.

3. Project Description

A. Description and explanation of research approach

Harvesting low levels of electrical energy from the pressure ripple in a hydraulic system is an enabling technology for integrated wireless health-monitoring sensors that eliminate the need for batteries or wires providing power to individual sensors. As with other such energy harvester developments, this would reduce maintenance contact and reduce the number of potential points of failure. Distributed sensors are common in hydraulic systems, and wireless health-monitoring systems are being deployed within the hydraulics industry, such that there are immediate applications for the technology.

The pressure ripple in a hydraulic system represents a relatively high energy density source such that the direct piezoelectric effect may be exploited to generate useful levels of power, as has been demonstrated in the work accomplished to date [1-5].

While there are numerous publications on energy harvesting from low density sources such as thermal, vibration, wind turbulence, flow turbulence, we have found no citations to work that directly exploits the pressure ripple directly as we consider here. There has been some work on energy harvesting from air borne noise by various means, but the low energy density of such fields has led to the use of techniques and devices that would not be appropriate in a pressurized hydraulic system [6-17]. A fundamental challenge of harvesting energy from typical acoustic noise is the very low energy density that is typically available; note that pressure ripple is just an industry-specific term to describe fluid-borne acoustic noise. For example, in air, a 60 dB plane wave has an intensity of approximately 1 $\mu W/m^2$, the intensity for a 100 dB plane wave is 10 mW/m^2, and the intensity of a 140 dB plane wave is approximately 100 W/m^2. These sound fields correspond to a conversational noise level, an uncomfortable loud noise level which would cause hearing damage from continuous exposure (and a temporary shift in hearing threshold for shorter exposures) and a noise level beyond the threshold of pain. If one seeks to harvest energy from a typical low level acoustic signal in the environment, either one must have a large device, or a means of achieving an efficient focusing of the available energy, or have a need for only very low power levels (microwatt or less). In pumped fluids, however, the situation is significantly different, as the use of positive displacement pumps can lead to high intensities within fluid systems, with intensities on the order of kW/m^2 being possible.

Project 3E.1 focuses on exploitation of pressure fluctuations in hydraulic systems for low power electricity generation through direct piezoelectric transduction. The devices developed in this project are termed Hydraulic Pressure Energy Harvesters (HPEH). A particular advantage of energy harvesting in fluid hydraulic system is that the pressure disturbance is often periodic in nature, such that the bulk of the energy is carried by one or a limited set of frequency components; this is in contrast to the majority of energy harvesting sources considered to date, where the energy distribution tends to be broadband and random. Another aspect unique to fluid hydraulic system is that they can be subject to high static pressures, e.g. 35 MPa, combined with acoustic pressures on the order of 5 to 10% of the static pressures. The fluid hydraulics community uses the terms “pressure ripple” and “dynamic” pressure for acoustic pressure. The high pressure and fluid nature of the system argue against the use of unbacked diaphragms, wafers, or films such as have been used in other energy harvesting applications.

B. Achievements

Achievements in previous year

From project inception in June, 2012, to the end of the previous year reporting period, January 31, 2013, significant progress was made in device modeling as well as device prototyping and testing. A model was developed to predict power output from HPEH devices into a resistive energy harvester load, accounting for volume and material properties of the piezoelectric element, applied dynamic pressure, frequency of excitation, and details of the harvester circuit. Three generations of HPEH devices, Figure 1, were designed, fabricated, and tested. Means were developed to test the HPEH prototypes. Performance of the devices closely conformed to the model.

Figure 1. Early HPEH prototypes

Achievements in past year

Significant advancement of the technology for HPEH devices was achieved over the course of the reporting period, including development and validation of a model for a higher-performing harvester circuit within an HPEH, development of multiple generations of HPEH devices for various objectives, and successful demonstration of the first ever HPEH-powered wireless temperature sensor. HPEH devices were developed that demonstrated power outputs ranging from 150 μW to over 3300 mW; given that low-data-rate wireless sensors may be expected to consume on the order of less than 100 μW, it is clear that HPEH devices have demonstrated the output power levels necessary to enable a wide variety of sensing applications.

Figure 1 depicts the key elements of an HPEH-powered wireless sensor mounted on a fluid hydraulic system. The housing of the HPEH retains a multilayer piezoelectric stack, and has a connection to the fluid system. The stack is exposed to pressure forces in the fluid system through an interface that serves to isolate the stack from the fluid, while permitting pressure forces to be coupled into the stack. The stack has a cross-sectional area A_{stack} while the interface has area $A_{interface}$; these areas need not be equal, and indeed, if $A_{interface}>A_{stack}$, greater force would be coupled into the stack than if the stack alone was exposed to the system pressure. The effective area of the HPEH may be represented as $A_{eff}=\gamma A_{stack}$, where γ is typically greater than unity.

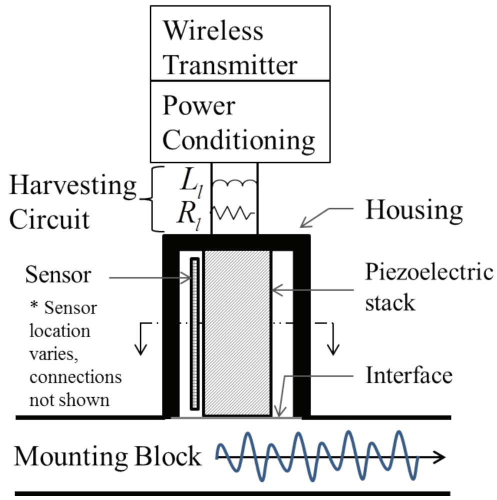


Figure 2: Simplified schematic of self-powered wireless hydraulic pressure energy harvester sensor, where the interface implements fluid-mechanical coupling between the piezoelectric stack and pressure ripple in a pressurized fluid.

Modeling

An advanced power production model has been developed that enables performance prediction of HPEH designs. Consider an HPEH using a multi-layer stack as its active element, terminated with a resistive and inductive load as depicted in Figure 3a. Note that the addition of the inductive element to the harvester circuit is a significant advancement in the past year. While inductive enhancement of piezoelectric energy harvesting devices has been known for some time, prior work has not been able to exploit it due to the very low capacitance of the piezoelectric elements used in those prior applications. Here, the piezoelectric stacks that we employ have a high enough capacitance such that the use of the inductive element is feasible. The use of such an element required modification of the circuit model used to design HPEH devices. The electrical equivalent model is depicted in Figure 3b, where the stack is represented as a current source in parallel with a capacitance.

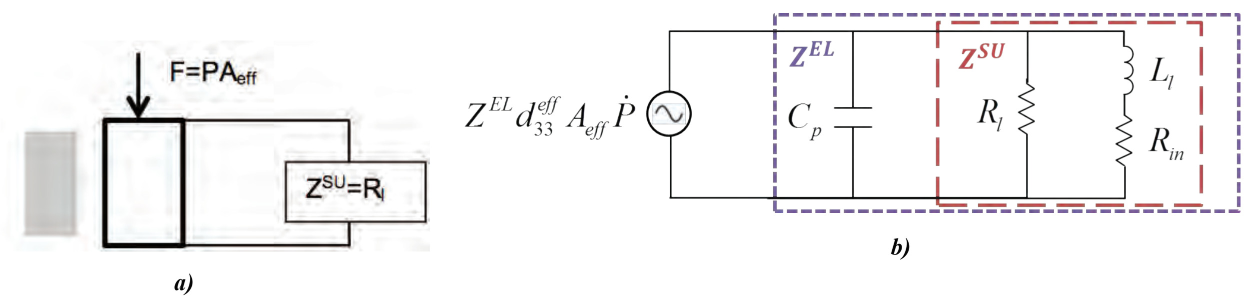


Figure 3: a) Multi-layer stack subject to an applied pressure force and terminated with an energy harvester resistive-inductive load impedance with internal resistance in the inductor, b) Equivalent electrical circuit with the stack modeled as a current source in parallel with a capacitance.

Consideration of the voltage response of the system leads to a predictive model for the power output of the device as

$$\Pi_{avg} = \frac{R_l\left(R_{in}^2 + R_l R_{in} + \omega^2 L^2\right)\left(\omega d_{33}^{eff} A_{eff} P_{rms}\right)^2}{\Psi^2 + \omega^2 \Lambda^2} \tag{1}$$

where

$$\Psi = -\omega^2 C_p^{eff} R_l L + R_l + R_{in} \tag{2}$$

and

$$\Lambda = L + C_p^{eff} R_l R_{in}. \tag{3}$$

The optimal load resistance and inductance to maximize the average power is found via

$$\frac{\partial \Pi_{avg,l}}{\partial R_l} = 0 \rightarrow R_{l,opt}, \frac{\partial \Pi_{avg,l}}{\partial L} = 0 \rightarrow L_{opt} \tag{4}$$

from which the optimal load resistance is

$$R_{l,opt} = \frac{\sqrt{\left(-2\omega^2 C_p^{eff} L + 1 + (\omega^2 C_p^{eff} L)^2 + (\omega C_p^{eff} R_{in})^2\right)\left(R_{in}^2 + \omega^2 L^2\right)}}{\left(-2\omega^2 C_p^{eff} L + 1 + (\omega^2 C_p^{eff} L)^2 + (\omega C_p^{eff} R_{in})^2\right)} \tag{5}$$

and the optimal load inductance is

$$L_{opt} = \frac{\left(R_l + 2R_{in}\right) + \sqrt{\left(R_l + 2R_{in}\right)^2 + 4(\omega C_p^{eff} R_l R_{in})^2}}{2\omega^2 C_p^{eff} R_l}. \tag{6}$$

The above analysis, developed in the reporting period, enables design analysis and optimization of HPEH devices for particular applications and available pressure ripple.

Prototypes

Six generations of HPEH prototypes, depicted in Figure 4, have been developed; three of the generations were developed in the current reporting period. The devices were designed to withstand a static pressure of 34.5 MPa (5000 psi). Of particular note, all of the devices were designed and fabricated by REU students. The REU students have also participated in the testing of the devices, and appear as co-authors on several of the project's publications.

Figure 4. HPEH prototypes with threaded connector for attachment to fluid hydraulic systems; successive generations, left to right to the center of the picture, designed for smaller piezoelectric element and more compact packaging. Later generations, from center of the picture to the right side of the picture, designed for specific piezoelectric performance assessment and alternative seal designs (center),and HPEH integration with existing commercial hydraulic sensor housings (right two prototypes).

Results

Testing of the HPEH prototype devices is performed on hydraulic flow rig where we can control, within limits, the static pressure, dynamic pressure ripple, and frequency of excitation. Measure the voltage response of HPEH devices when installed in the system and subjected to an input pressure ripple, and determine the power delivered into the energy harvester circuit. Example results for three generations of devices are presented in Figure 5; the devices had different target output power per volume, and as such span the range of device sizes and outputs targeted by the project. The HEH devices have met or exceeded all of the performance and schedule targets for the project.

One of the key accomplishments during the reporting period was an REU project demonstrating wireless sensing powered by an HPEH. The project employed commercially available electronics implementing energy harvester power conditioning and wireless communications. This system was combined with a thermistor integrated within the body of an HPEH, forming a wireless sensor node. The node successfully transmitted hydraulic fluid temperature to a remote receiver. This project was performed as part of the proof-of-concept development of HPEH devices, as a demonstrator of what HPEH devices might enable for the industry.

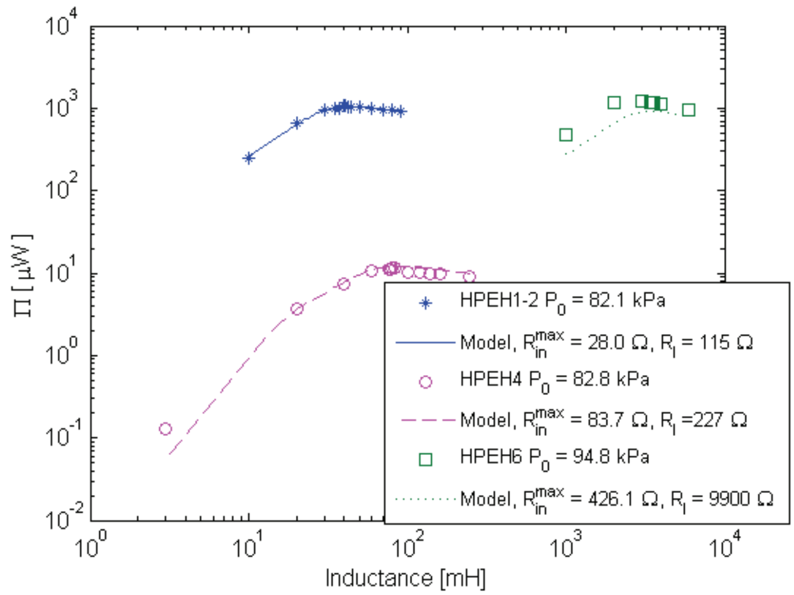
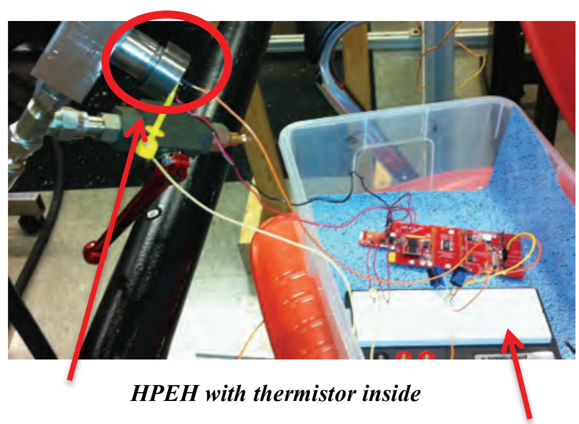


Figure 5. power output vs. inductance in the harvester circuit for three generations of HPEH prototypes.

a) Off-the shelf harvester power conditioning circuit and wireless transmitter/receiver



HPEH with thermistor inside

b) Harvesting circuit, processor, wireless transmitter

Figure 6. Wireless HPEH temperature sensor. a) Commercial electronics for prototyping energy harvester applications. b) HPEH with thermistor installed, powering wireless node.

C. Member company benefits

This project is yielding very positive results that are strongly rooted in practical application and the development of new technology. Beyond the immediate application to health monitoring systems, the technology is enabling of self-powered sensors at almost any type conceivable; it also enable self-powering of low-powered control valves, solenoids, etc. This concept has the potential for broad application far beyond its original inspiration. Interest in the technology seems to be quite high, including the project receiving editorial publicity in the November 2013 issue of *Hydraulics & Pneumatics*.

Two companies (Parker-Hannifin and Danfoss) have notified Georgia Tech that they will participate in the patenting and licensing of the technology through the Center's IP agreement. An affiliated program started up exploring the use of the technology to develop a HPEH-powered wireless pipeline leak detection system; this project is being funded through an STTR. A proposal for an affiliated project is still pending approval with a Center Industry sponsor.

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Test Bed 1: Heavy Mobile Equipment – Excavator

Research Team

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Test bed manager/staff:	Anthony Franklin
Industrial Partners:	Hydac, Bosch Rexroth, Danfoss, Sun Hydraulics, Parker Hannifin

1. Statement of Project Goals

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

Dramatic improvements on fuel economy have been predicted and demonstrated on the test bed, through use of displacement-controlled (DC) actuation. Lower waste heat was also predicted after transition to DC actuation, thus maintaining acceptable oil temperatures throughout the excavator hydraulic system. Also, a study for the feasibility utilizing a novel hydraulic hybrid architecture proved that a significant reduction in engine size is possible while equaling or exceeding the performance capability of a machine. Additional fuel savings were predicted for the DC hybrid architecture over the non-hybrid DC architecture.

In this reporting period, the primary question to be answered is what are the technological barriers, solutions and potential for DC actuation and hydraulic hybrid technologies to be successful in improving fuel consumption in multi-actuator mobile machines? Task definition and functional requirements:

– Reduce engine size by 50% of standard excavator
– Maintain standard machine performance
– Improve energy savings over non-hybrid DC excavator

2. Test Bed Role in Support of Strategic Plan

This test bed supports the Center's goal to achieve a drastic improvement in efficiency of existing fluid power applications and to reduce petroleum consumption and pollution. The test bed is used to demonstrate fuel saving technologies 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. Project Description

A. Description and explanation of research approach

Test bed 1, the excavator, has been used primarily to demonstrate potential energy savings of 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 and systems developed by projects throughout CCEFP.

The core of the test bed will be based upon the theoretical results from project 1A2 although technologies developed as part of other CCEFP projects will be integrated onto the test bed for demonstration. The contributions are as follows:

- Project 1A.2 (Ivantysynova, Purdue):
  - Controls for optimal power management of multi-actuator DC hydraulic system
  - Design and installation of novel 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
- Design and implementation of energy management strategies on hybrid hydraulic excavators
- Design of pump-switching architectures that enhance the capability of multi-actuator machines using DC actuation
- Investigation of advanced control strategies enabling pump-switching functionality in DC multi-actuator machines
- Investigation of system prognostic schemes for DC hybrid multi-actuator machine systems

- Project 1B.1 (Ivantysynova, Purdue): Development of next generation of highly efficient and smart variable displacement pumps
- Project 1G.1 (Michael, Milwaukee School of Engineering): Testing of energy efficient hydraulic fluids
- Project 3A.1 (Book, Georgia Tech): Tele-operation of the test bed using haptics controls and the Phantom controller
- Project 1E.2 (Cunefare, Georgia Tech): Novel energy-harvesting concept to provide power for pressure sensors
- Project 1E.2 (Lumkes, Purdue): Development of virtual variable displacement pump for the excavator low pressure hydraulic system using high speed on-off valves
- Project 1E.3 (Lumkes, Purdue): Development of a high efficiency, high bandwidth, actively controlled variable displacement pump/motor
- Project 1E.7 (Vacca, Purdue): New generation of variable displacement external gear pumps
- Project 3B.3 (Vacca, Purdue): Novel, adaptive control strategy based on extremum-seeking control for active vibration damping.

B. Achievements

Achievements prior to reporting period

- Four variable displacement pumps were installed on TB1 (mini-excavator) along with associated sensors and electronic control hardware. All eight functions were displacement controlled, and the test-bed was instrumented with required electronics (sensors and control hardware) for data acquisition and control. Working actuator and pump controls were implemented by Spring, 2010.
- Following system simulations, performance measurements made on the test bed demonstrated 50% energy savings, 40% fuel savings, 17% reduced cycle time and 69% productivity improvements over the standard, load sensing hydraulic system for an aggressive, digging cycle (August 2010) during independent, side-by-side testing done by Caterpillar.
- A simulation model predicted that installed cooling power in the system could be reduced by 50%, due to removal of control valves and subsequent elimination of heat generated due to throttling.
- A power management algorithm was evaluated for the non-hybrid DC excavator prototype, and fuel efficiency results showed a 56.4% improvement for a lighter duty cycle such as a pipe-laying cycle for an excavator.
- As part of 1A.2, a feasibility study in simulation predicted that a novel hybrid hydraulic architecture (called the DC series-parallel (S-P) hybrid excavator, Figure 1) allows meeting aggressive digging cycles with a 50% downsized engine. In this study, a conservative, rule-based power management approach was used (called 'single-point' strategy) and this showed 20.4% savings in fuel over the DC non-hybrid (51% over the standard) excavator [1].
- Another rule-based strategy (called the 'minimum-speed strategy') that attempted to exploit all available system degrees of freedom, showed higher fuel savings over the DC hybrid (25.4% fuel savings over the DC non-hybrid), and was closer to optimal power management results (26.8% more efficient than DC non-hybrid) from dynamic programming.

Achievements during the reporting period:

Integration of Series-Hybrid Swing Drive to Test-Bed 1

Figure 1 shows the novel DC S-P hybrid excavator architecture. Braking energy from the excavator's cabin rotation can be recovered and stored in a hydraulic accumulator through use of a variable displacement, over-center swing motor, and such a configuration does not need additional pumps on the engine shaft. The primary unit of the series-hybrid swing drive can charge or discharge accumulator and when appropriately controlled, is responsible for enabling up 50% engine downsizing in this architecture.

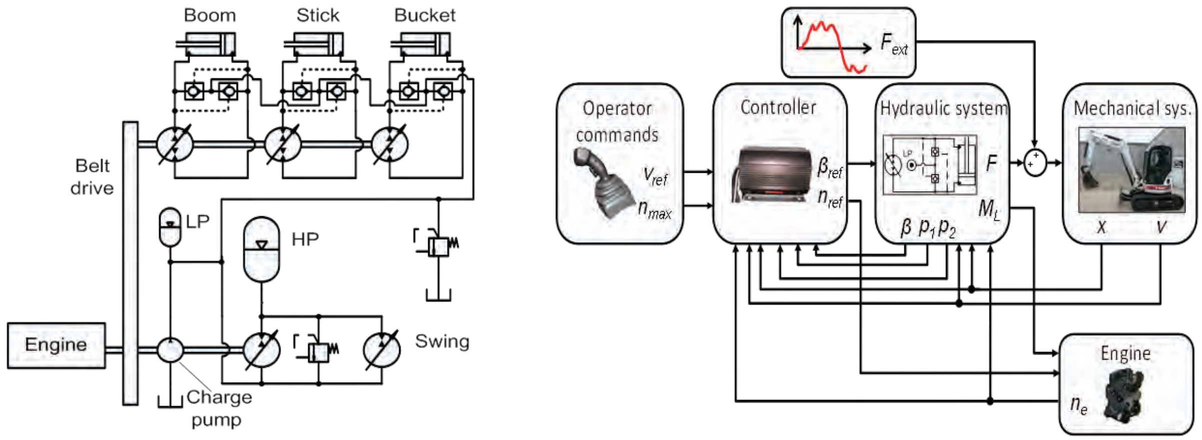

Figure 1: Series-Parallel Hybrid DC Excavator System (L) and Detailed System Model (R) used in Simulation

A detailed co-simulation model used to capture system dynamics (including all hydraulics, mechanics and engine dynamics), as well as evaluate power management strategies by predicting energy and fuel consumption. In Figure 2, are shown the key components integrated into the excavator to integrate the series-hybrid swing drive. Note that the engine was not actually downsized on the prototype excavator.

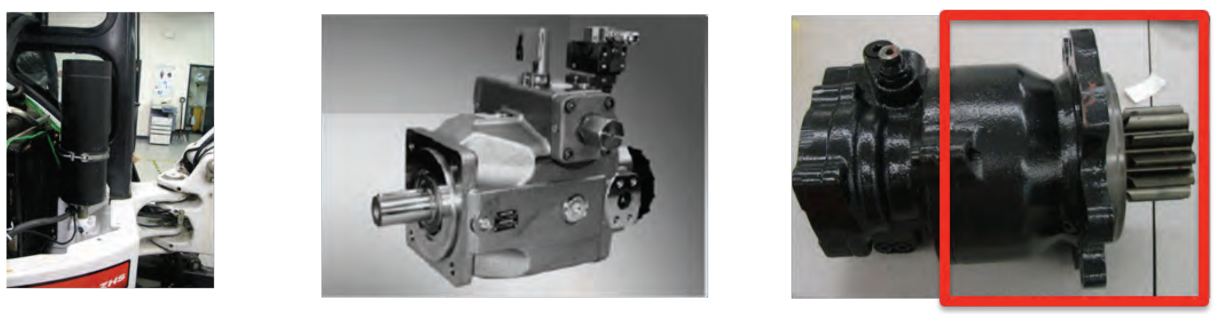

Figure 2 : Hybrid System Integration (L to R : accumulator, variable swing motor and new gearbox)

Closed-Loop Speed Control for Secondary-Controlled Swing Motor

In the left-half of Fig. 3, the control scheme is shown for the motion control of the swing motor. In essence, the swing drive is closed-loop speed controlled when the operator commands motion from the swing drive, whereas it is closed-loop position controlled when no motion is commanded. When motion is commanded, the speed-control strategy must account for varying accumulator pressures (needed for efficient system operation), and it does so through a feed-forward term. It also accounts for varying inertia of rotation, by using information from linear position sensors on the boom, stick and bucket.

Good tracking of speed commands was shown in measurements (top-right) in Figure 3, together with tracking of displacement commands for the swing motor (bottom-right).

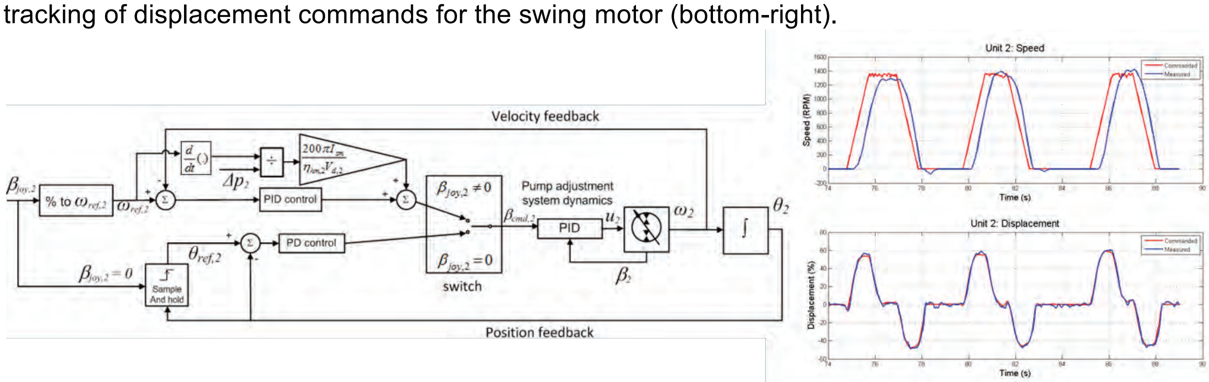

Figure 3 : Closed-Loop Speed Control for Secondary-Controlled Swing Drive

Single-Point Strategy for Power Management: Measurements

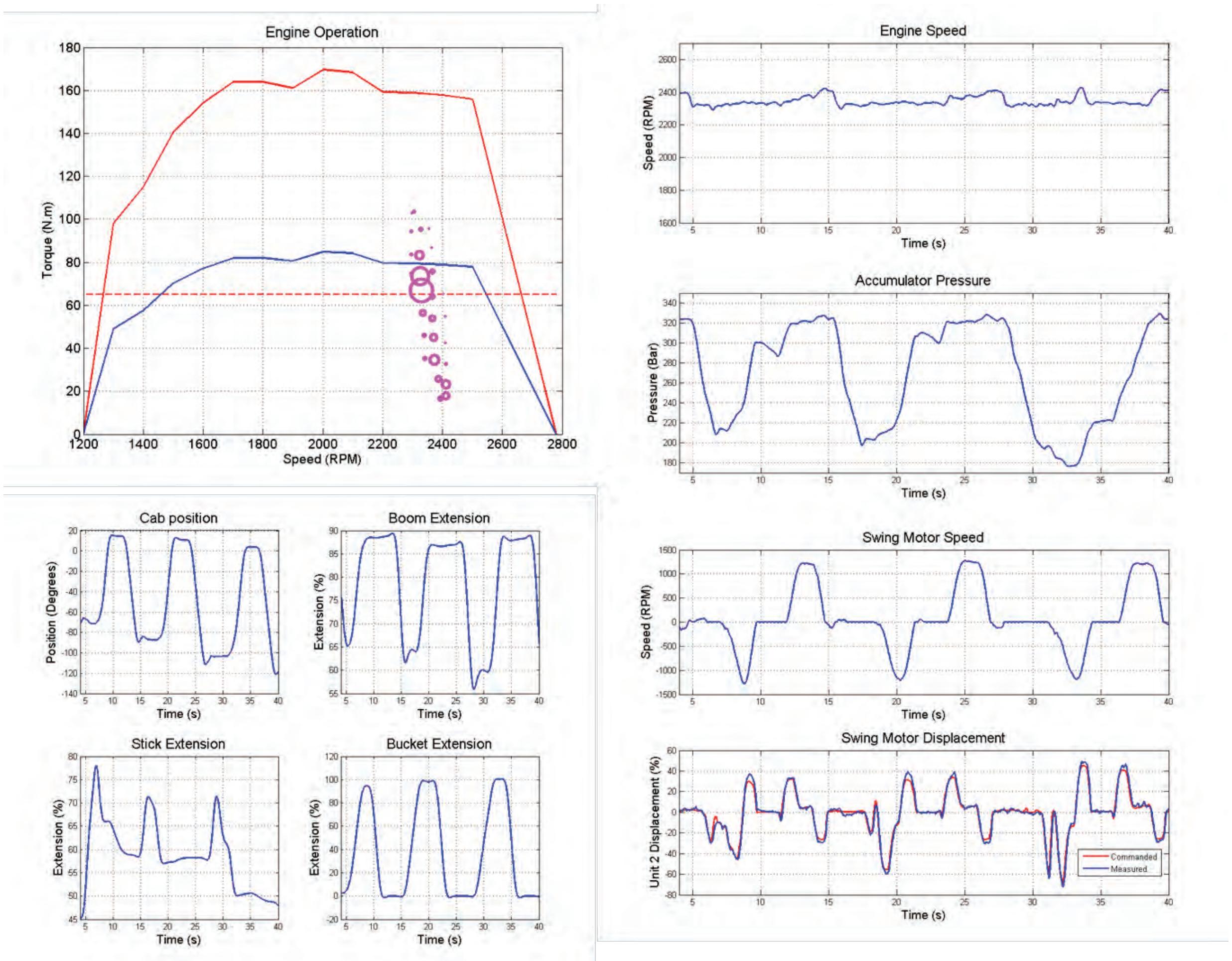

Figure 4 : Measurement Results – Single-Point Strategy

Figure 4 shows measurement results using the single-point strategy, from October, 2013. The full-sized engine is operated close to the sweet-spot of the downsized engine (by control of the primary unit through appropriate rules), and close to the maximum rated engine speed. The excavator was put through a 90-degree, novice digging cycle. The accumulator pressure is high for more than 50% of the time, because of the conservative nature of this strategy. More details on the strategy can be found in Hippalgaonkar and Ivantysynova [2].

Minimum-Speed Strategy for Power Management: Measurements

Figure 5 shows measurements made with the minimum-speed strategy (details of the rules used can be found in Hippalgaonkar, et al. [3], as the excavator was put through a 90-degree digging cycle. This strategy led to consistently lower accumulator pressures (bottom-right) than the single-point strategy. Good tracking of engine speed commands is also shown (top-right). For these experiments, it was desired to keep the engine below 25 kW (maximum power is 40 kW) the constant-power contour (due to the high inertia of the full-sized engine on the prototype, as compared to the inertia of a 50% down-sized engine (20-kW rated power)).

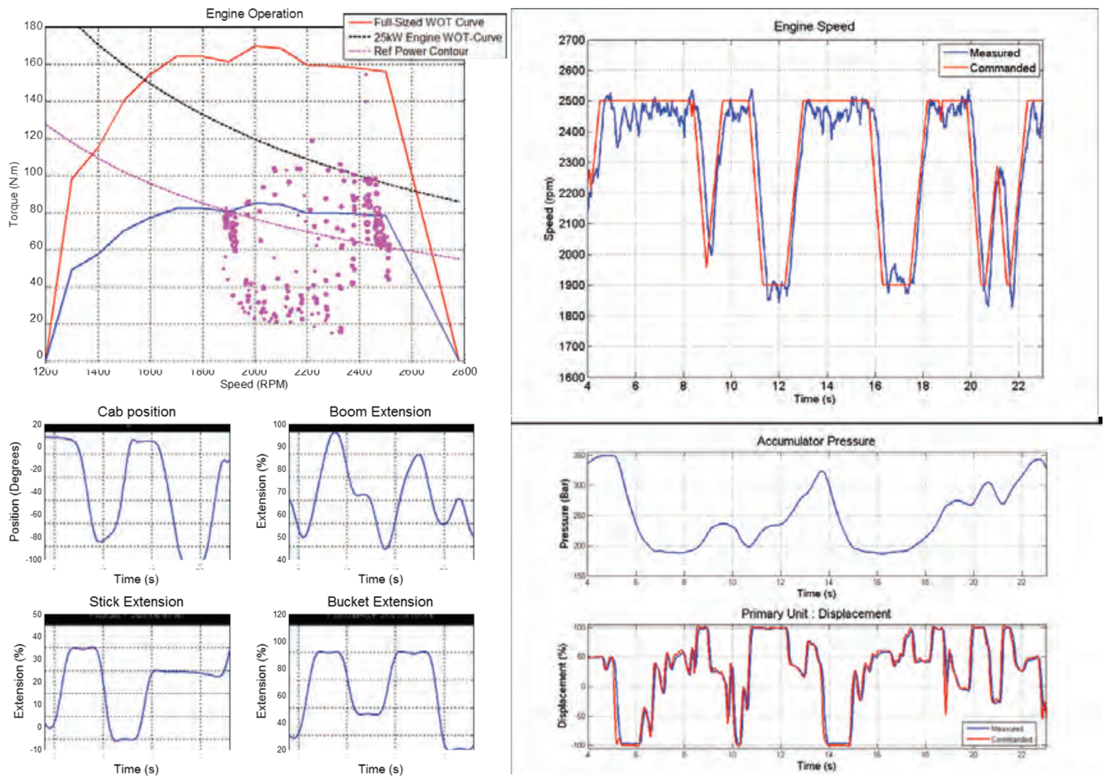

Figure 5: Measurement Results – Minimum-Speed Strategy

Planned Achievements following the reporting period:

- Conduct on-vehicle experiments. Deliverables include:
  - Demonstration of pump-switching technology on TB1 [Fall, 2014]
  - Implementation of enabling control strategies for pump-switching architectures [Spring, 2015]
  - Incorporation of system prognostics schemes [Fall, 2015]

- Demonstration of technologies from other CCEFP projects. Deliverables include:
  - Integration of high speed valves to create a virtual variable displacement pump for low pressure system and measurements of energy savings (1E.2) [Summer, 2015]
  - Comparison of energy consumption of TB1 using standard hydraulic oil and energy efficient fluids developed (1G1) [Summer, 2015]
  - Implementation of adaptive control strategies for active vibration control (3B.3) [Fall, 2015]
  - Integration of variable-displacement external gear pump (1F.1) [Fall, 2015]
  - Integration of next generation of efficient pumps for control of a single actuator (1B.1) [Spring, 2016]

C. Member company benefits

The results gained from 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 US emission regulations.

- From future work that is intended to implemented on TB1, the capabilities of DC hybrid multi-actuator machines will be enhanced through realization of novel pump-switching architectures.

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Test Bed 3: Hydraulic Hybrid Passenger Vehicle

Research Team

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1. Statement of Test Bed Goals

The overall goal of this project is to realize hydraulic hybrid powertrains for the passenger vehicle segment which demonstrate both excellent 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 meeting California standards; and (v) size, weight, noise, vibration and harshness comparable to similar passenger vehicles on the market. Power trains produced in the scope of this project 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 hydraulic assist to enable operating the engine at or near its “sweet spot” and regenerating brake energy. The power trains integrate high efficiency components, hydraulic fluids and energy management algorithms (thrust 1), compact energy storage (thrust 2) and methodologies for achieving quiet operation (thrust 3) from related CCEFP projects.

3. Test Bed Description

A. Description and explanation of research approach

The high power density of hydraulics makes them an attractive technology for hybrid vehicles, especially since the battery required for electric hybrids can be eliminated. 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.

TB3 focuses on power-split architectures, which are not as well studied as other hydraulic hybrid architectures. Power-splits combine the positive aspects of a 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” vehicle (Figure 1) was built in-house using the platform of a utility vehicle (a Polaris “Ranger”) connected to an in-house built hydrostatic dynamometer. 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.

The “Generation 2” vehicle is being developed in partnership with Folsom Technologies International (FTI). It is built on the platform of a F-150 pickup truck, which has refined vehicle dynamics capable of highway speeds. Its power-train utilizes a custom-built continuously variable power split hydraulic transmission developed by FTI which will be complemented with hydraulic accumulators to enable hybrid operation. The power train is built as a compact, integrated, self-contained package. However, the integrated package prevents changing out 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 “Generation 1” vehicle is being continued despite the pending availability of the roadworthy “Generation 2” vehicle.

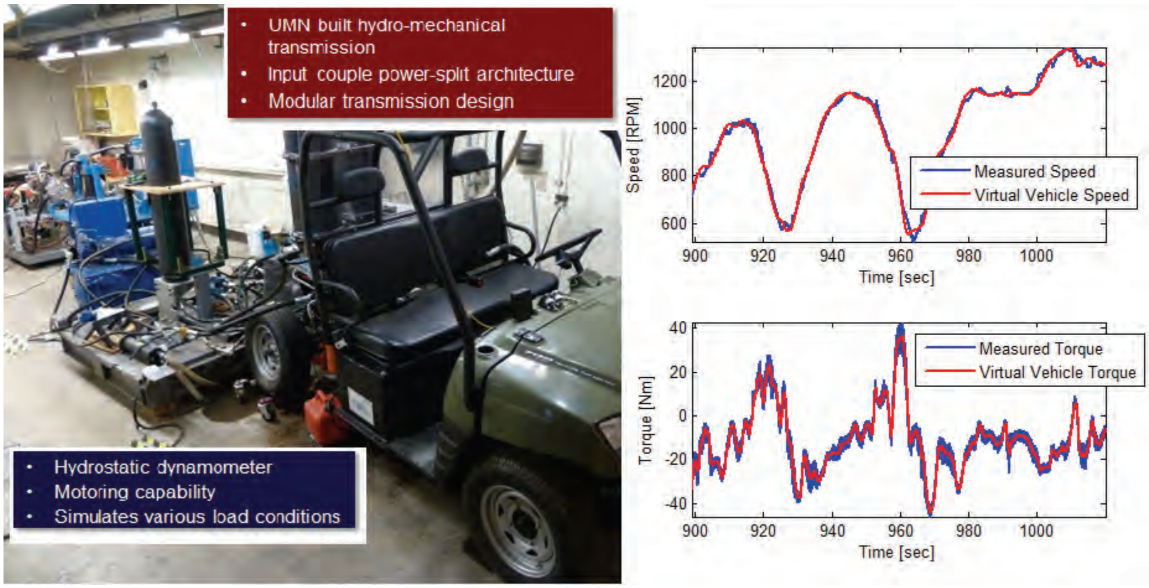

Figure 1: Overview of Test Bed 3 HHPV Generation 1 with hydro-static dynamometer. The graphs on the right illustrate the effectiveness of the dynamometer in fuel economy evaluation.

B. Achievements

Achievements Applicable to the Generation 1

Recent years' major achievements:

(i) *Drive train rebuild:* The first hydraulic hybrid transmission was completely rebuilt to use only gears to transmit power to and from the hydraulic pump/motors to improve its efficiency and reliability.

(ii) *Hydrostatic dynamometer system design and implementation:* An in-house hydrostatic dynamometer was designed and constructed in 2011-2012. The dynamometer enables repeatable fuel efficiency evaluation and eliminates the need to drive the vehicle on a test track. It also enables fine-tuning controllers rapidly. A novel controller was implemented to enable the dynamometer to exert the desired torque on the vehicle output shaft. It utilizes a "virtual vehicle" concept to account for the vehicle's inertia torque.

(iii) *New engine installation and characterization:* The vehicle's engine was discovered to be inadequate to take the vehicle through all planned drive cycles, so it was replaced with larger and more efficient engine. The new engine was characterized using the in-house hydrostatic dynamometer.

(iv) *General chassis improvements:* The charge flow system was rebuilt to substantially improve the system efficiency. A hydraulic circuit to facilitate start-up of the vehicle was developed. The vehicle chassis was entirely re-wired, resulting in better robustness and data acquisition quality.

Major achievements in year 2013:

Transmission CVT mode tests: With the hydrostatic dynamometer operational, the vehicle has undergone a series of performance and fuel economy evaluations. Two types of experimental efficiency evaluations were conducted: steady-state condition and drive cycle schedules. In this section, the hydraulic hybrid powertrain operated in Continuous Variable Transmission (CVT) mode, which will be used to set baseline performance. In CVT operating mode, the accumulator is maintained at a constant pressure, so it is essentially not utilized. Figure 2 depicts the steady-state efficiency of the power-split transmission operated in CVT mode as a function of output power. The highest overall powertrain efficiency recorded is approximately 23% at 10kW output load. The transmission was operating at 80% efficiency at this point. The general trend shows increasing efficiency with increasing output power. While the engine was operated at relatively steady efficiency, the transmission efficiency is reduced drastically at low load (below 4kW) due to power recirculation.

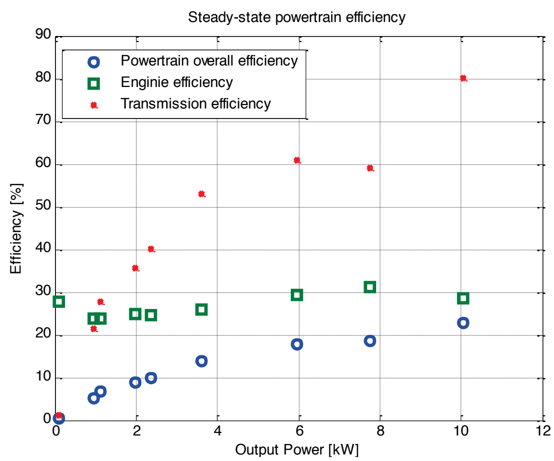

Figure 2: UMN-built power-split transmission steady-state efficiency in CVT mode

The powertrain is driven through EPA specified UDDS and highway drive cycles, using the hydrostatic dynamometer, to evaluate the fuel economy. Figure 3 shows the tracking performance and repeatability of the vehicle-dynamometer system, with approximately 1mph standard deviation tracking error. The tests yield 50 mpg for the UDDS cycle and 62 mpg for the highway cycle.

Energy management strategy implementation: Various algorithms developed in Project 1A.1 are being incorporated into the high level control for the hydraulic hybrid vehicle and evaluated with dynamometer testing. The first strategy, rule-based, has been successfully implemented for the highway drive cycle, with fuel efficiency of 3% improvement compared to CVT strategy. The hybrid powertrain behaved as predicted in simulation as shown in Figure 4 Testing of other algorithms are in progress.

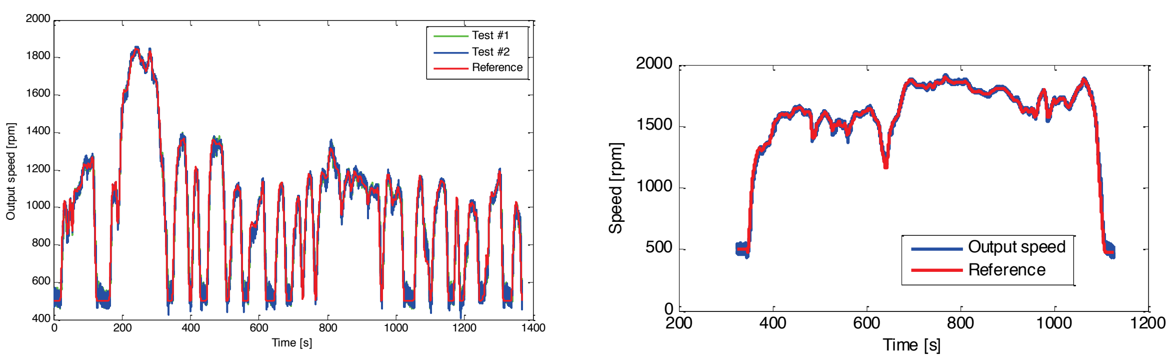

Figure 3: UDDS (left) and highway (right) drive cycle tracking

Powertrain and dynamometer control systems: Three core controllers have been designed and successfully implemented on the vehicle-dynamometer system to obtain consistent and reliable drive cycle test results [14]. Firstly, the hybrid powertrain controller utilizes the three-level hierarchical strategy developed in previous years [5]. Secondly, the dynamometer controller, completed this year, applies a novel “virtual vehicle” concept to exert correct load on the vehicle based upon the torque applied by the power-train. Lastly, the “virtual driver” controller is designed to eliminate the need of an actual driver during drive cycle tests.

Improving efficiency: During early test runs, output torque was found to be lower than anticipated. The cause was identified to be lubrication oil being pumped within the gearbox. By lowering the oil level, the gearbox viscous friction has been reduced by 44%. Several internal hydraulic leakages have also been identified and corrected. Pressure and temperature sensors were added while the transmission was torn down to enable improved testing of energy efficient fluids.

Dynamometer Hardware and Electrical Upgrades: A flywheel has been installed to modestly increase the inertia. This reduces the sensitivity of the system to high frequency disturbances and as a result, leads to significant improvement in the vehicle load tracking performance. High dynamic bandwidth can still be achieved. A portion of the electrical system has also been re-wired to improve the actuation of the pump/motors and reliability.

Achievements Applicable to the Generation 2

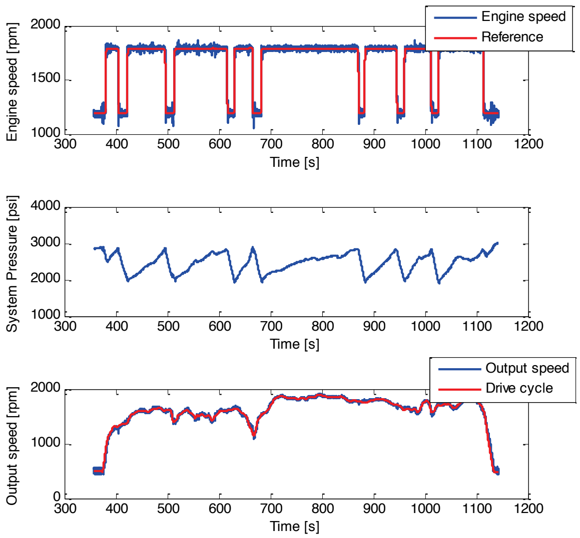

Figure 4: Hybrid powertrain operated with rule-based strategy in highway drive cycle

Recent years' achievements:

Transmission Characterization: A method has been developed to determine the FTI transmission efficiency map under various hybrid operating conditions given limited data. This map is necessary for proper design of the vehicle operating strategy. Preliminary transmission characterization tests revealed significant leakage which was attributed to broken seals. The seals were subsequently replaced.

Effect of hydraulic oil: The transmission efficiency depends on the hydraulic oil used. It has been demonstrated that replacing the low viscosity (5 cSt) Automatic Transmission Fluid (ATF) with a higher viscosity (15 cSt) fluid results in improved efficiency especially at low transmission ratios.

Current year achievements (2013): The FTI transmission has recently been re-installed on the F-150 at Folsom. With help from Ford, a signal conditioning and data acquisition system for interfacing with the vehicle and transmission has been constructed. Hardware-in-the-loop testing is near completion at UMN and will soon be installed on the vehicle.

C. Plans

Plans for Generation 1 Vehicle

Plans for the Generation 1 vehicle will focus on core project integration and are described in order below.

Hybrid operation will be tested with various energy management strategies. Both the modified Lagrange multiplier strategy and Project 1A.1's Rule-based control strategy are currently in progress. 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 2014

For Project 1G.1 (Energy Efficient Fluids), a synthetic biodegradable ester will be utilized as the hydraulic fluid, which is expected to exhibit higher efficiency at low speeds [10]. The new oil will be compared with a baseline shear stable high viscosity index hydraulic fluid on the vehicle in Fall 2014.

A pulse width modulated virtually variable displacement pump/motor (VVDPM) designed in Project 1E.1 will be evaluated using torque and speed data provided by the Gen I vehicle. Simulations have been performed to optimize the gear ratios for the pulse width modulated pump/motor [8]. The VVDPM will be evaluated on a test bench using the torque-speed data in a hardware-in-the-loop configuration. Performance will be compared with the baseline bent-axis unit (Fall 2014)

Strain energy accumulators are designed to provide the advantage of constant pressure operation, thereby improving its energy density. We are planning to replace the low pressure accumulator with a prototype provided by Project 2C.2, and we will measure the change in efficiency associated with this replacement (Spring/Summer 2015)

Plans for Generation 2 Vehicle

Much of the controller development that has been completed for the Generation 1 vehicle will be adapted to the Generation 2 transmission, and fine-tuned for the differences in architecture. After the Generation 2 vehicle is fully functional, a continuous variable transmission (CVT) strategy and hybrid strategy will be tested. The current plan is to house it at FTI in New York where they will take the role of maintaining, housing the vehicle and for providing hardware support. The TB3 team will then visit FTI 5 times and Ford for 1 time, each time for several days for implementations. As schedule for the visits is as follows:

- Visit #1: Implement computer interface with vehicle, gain access to engine and transmission control inputs, gain access to vehicle and transmission measurements. [3/14]
- Visit #2: Perform system identification (for vehicle control). [4/14]
- Visit #3: Low level vehicle control implementation and tuning. [8/14]
- Visit #4: Implementation of two high level control strategies: CVT and mild hybrid (regenerative braking, launch assist, CVT). [10/14]
- Visit #5: Implementation of full hybrid operation and prepare vehicle for dynamometer testing. [12/14]
- Visit #6 (Ford, Dearborn): Dynamometer testing of CVT, mild hybrid and full hybrid operations. [5/15]

Plans for Generation 3 Vehicle

Generation 3 powertrain will target a mid-sized sedan (Toyota Corolla or Honda Civic). The goal is to apply the knowledge gained from Gen 1 and Gen 2 development and design a power train that fits the need for a passenger vehicle. In addition to efficiency, there will be focus on driving performance and compactness. Designing a new platform, however, requires substantial amount of resources and support from industry. Hence collaboration with OEMs plays a vital role to the success of Generation 3. By the end of Y9/Y10, partnership with a transmission manufacturer, a hydraulic company, a fluid specialty manufacturer and a kit-car manufacturer is expected. Before the hardware development stage, the conceptualization and design stage can be separated into three stages:

- Phase 1: In search of partnership with industrial OEMs. [6/1/15]
- Phase 2: Identify and determine the powertrain requirements and components. [12/1/15]
- Phase 3: Simulation and design of transmission and components integration to achieve all thrusts. [5/31/16]

Milestones and Deliverables

Generation I:

- Task 1: Compare the effectiveness of various energy management strategies. Candidates include algorithms developed in Project 1A.1 (Model Predictive Control, and Stochastic Dynamic Programming), and the modified Lagrange multiplier method developed by the TB3 team. [11/14]
- Task 2: Baseline Generation I vehicle performance by running it through the EPA urban drive cycle in continuously variable transmission (CVT) mode using mineral oil based hydraulic fluid. Evaluate performance of biodegradable synthetic hydraulic oil using identical drive cycle and mode. [8/14]
- Task 2a: Design and install a fluid conditioning system to improve transmission efficiency. Necessity of this stage will be determined by fluid condition measured during Task 2, and initiated if deemed essential. [9/14]
- Task 3: Performance evaluation of the 4 quadrant Virtually Variable Displacement Pump/Motor (VVDPM) under HIL test (1E.1) [3/15]
- Task 4: Testing of strain energy accumulator (2C.2) [6/15]
- Task 5: Passive noise control implementation [6/15]

Generation II:

- CVT and Mild Hybrid Control strategy demonstrated in Generation 2 vehicle [10/14]
- Hybrid Control strategy demonstrated in Generation 2 vehicle [12/14]
- EPA cycle fuel economy evaluated [5/15]

Generation III:

- Initiation of Generation 3 powertrain conceptualization and design [6/15]

D. Member company benefits

Development of practical hydraulic hybrid passenger vehicles creates a new and lucrative market for hydraulic products. In addition, development of the HHPV enables member companies to gain experience in a potential market segment where they have not traditionally worked which requires very high efficiency at relatively low power.

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Test Bed 4: Patient Transfer Device – Hydraulics at Human Scale

Research Team

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Industrial Partners:	Parker Hannifin, Eaton

1. Statement of Test Bed Goals

The high level goal of Test Bed 4 is to explore ways to expand and improve the use of fluid power to needs at the human scale and associated new application areas. Many applications in this power range interact with humans; the patient transfer assist device provides an opportunity for us to explore how fluid power can be utilized with humans in the workspace. We have identified a significant market need for an improved assist device for transferring mobility limited patients, especially heavier patients. This device is designed to meet this growing need by providing a way for caregivers to move patients without injury to the patient or themselves. It also provides a human scale system for testing integrations of various CCEFP subsystem projects/components.

To benefit from the power and force density of fluid power, effective human interfaces and control algorithms are very important. It must be safe for humans in its workspace, allow for simple and intuitive operation of multiple degrees of freedom (DOFs) by a single caregiver, have smooth motion without vibration or oscillation, and be highly maneuverable. Related and client CCEFP projects include passivity based control (3A.2), control of vibration/swing (3B.3), multi-modal human machine interfaces (3A.1), user-centered design (3A.3), the hydraulic transformer (1E.5), and potentially others.

2. Test Bed Role in Support of Strategic Plan

The CCEFP seeks to make fluid power ubiquitous. As such the power of hydraulics must be adapted to uses in the delicate situations which are epitomized by patient care. Affordable, quality care of mobility limited individuals is currently hampered by the need for multiple caregivers to perform transfers of patients that may occur a dozen times in a day. Obese, even moderately heavy patients are especially difficult to transfer. The needs for the patient transfer assist device application exemplify some primary CCEFP goals, such as the need for a safe and effective operator interface, a very compact and mobile design, and minimal noise and leakage, all in a multi-DOF system. This test bed provides an opportunity to explore how fluid power can be used in non-traditional environments such as homes and clinical institutions, with humans in the workspace. It also provides a system in which to test features needed for these fluid power applications.

3. Project/Test Bed Description

A. Description and explanation of research

Overview

A significant market need has been identified for an improved mobile assist device to aid in transferring mobility limited people, particularly bariatric patients [1, 2]. With the increasing aging population and the increasing number of bariatric patients, the number of mobility limited patients is significantly increasing. Institutions have recognized the risks of injury to caregivers and most are implementing "no lift policies" which require the use of an assist device to lift the weight of a patient. However, current market lift devices are antiquated and insufficient for many patient and caretaker needs; transfers often require multiple personnel and as much as 10-20 minutes. Only a few projects have addressed the problem of patient transfers, and most do not consider bariatric patients. One example of a prototype patient transfer and rehabilitation device was developed by NIST [3]. This test bed concept stemmed from a related project with our collaborators at the Quality of Life Technology NSF ERC, which developed a wheelchair-mounted device for transferring patients. However, using electrical actuation, they were unable to achieve the desired lifting power [4]. Hydraulic actuation has the advantage of providing large force capability in a compact package, with the power source located at the base of the device. This is an ongoing test bed; currently it has two degrees of freedom fully functional. The next stage of the research focuses on various control techniques, operator interface design, and modeling and dynamic simulation.

Challenges & Technology Advancement Barriers

One challenge is to develop a multi-DOF device that is compact, untethered and highly maneuverable, while also powerful enough to maneuver up to 1000lb payload. Another primary challenge is the development of a control strategy to allow a single caregiver to control all degrees of freedom of this powerful lift device in an intuitive, safe, simple manner, while simultaneously maneuvering and fine-tuning the complex patient payload. The machine itself needs to be untethered, mobile, and capable of maneuvering a heavy payload through complex motions; hydraulic actuation provides the needed compact power source, and it allows for the power source to be located at the base of the device. These requirements directed us to an onboard battery power supply and electric motors driving hydraulic pumps, in an efficient pump controlled architecture to eliminate valve losses.

The control and caretaker interface design objectives are unique and challenging aspects and primary areas for continued work. In this operator interface, the caretaker and machine collaborate to maneuver the patient; the caretaker interacts directly with the patient, fine-tuning position and orientation, placing limbs, etc., while simultaneously controlling the lift device. In order for a single caregiver to perform transfers quickly and safely, the caretaker needs to remain near the patient and within reach of the input device. Key components of this control and interface research include (a) safe operation of a powerful hydraulic machine with humans in the workspace, (b) lower level electro-hydraulic pump control in multiple degrees of freedom, and (c) intuitive collaborative manipulation using an assistive device. Additional challenges involve management of the slow and nonlinear plant dynamics.

B. Achievements

Achievements in previous years

In previous years, much of the needs assessment was conducted, including interviews with a range of stakeholders, including mobility limited patients, clinicians in various settings, and industry representatives. From this information, a first set of design requirements was developed, and a subsequent high level device design concept was developed. A hydraulically actuated exploratory pre-prototype device was used to obtain additional design requirements, to gain experience with transfer operations, and to test control strategies using a force sensing handle.

Achievements in the past year

Needs Assessment

A substantial needs assessment and involvement of collaborators with expertise in a range of areas was performed. In the area of assistive device research, our advisors include Dr. Stephen Sprigle, of Georgia Tech’s Center for Assistive Technology and Environmental Access, Dr. Rory Cooper, of the Quality of Life Technology Engineering Research Center (QoLT ERC). We obtained two IRB approvals, one for a focus group and individual interviews, and one for benchmark operator testing using current market lift devices. Our focus group and individual interviews included a range of outside stakeholders, including (1) engineers and salespeople with current market lift manufacturers, (2) clinicians and physical therapists in nursing homes and the Shepherd Center, (3) home caregivers of spinal cord injury patients including one bariatric, and (4) spinal cord injury patients. We have also worked with our collaborators in the human factors area Dr. Park, Dr. Jiang and Brittney Jimerson, with North Carolina A&T (NCAT) on the evaluation of current market lifts, task analysis, and operator experiment design. Brittney from NCAT provided a very detailed task analysis, helped to develop a subsequent benchmark operator testing protocol, and helped run those operator experiments with current market lifts, which involved performing a variety of mannequin transfers within a simulated home environment. The results of this needs assessment were combined and transformed into functional design requirements, such as necessary motions, lifting capabilities, and battery life.

Machine Design and Design Review Meeting

Based on the functional requirements and experiments with an exploratory pre-prototype lift device, we developed a set of lower level design requirements, and we analyzed a variety of options for mechanisms, actuation, hydraulic and electric power. We computed the necessary power, force/torque and speed for each mechanism option, then determined associated flow and pressure needs. We opted for a form of electro-hydraulic pump control, using a separate hydraulic power unit for each DOF. We also investigated options for onboard electric power, controllers, sensing, as well as other analyses such as weight, stowable size, and battery life.

A design review meeting was held at Georgia Tech in May 2013, in which we discussed the design options, analyses, and proposed device. A range of interests and expertise were represented in the meeting, including assistive device design experts Dr. Stephen Sprigle from Georgia Tech and Dr. Rory Cooper from the QoLT ERC, systems design specialist Dr. James Van de Ven from UMN, design engineer for a leading lift manufacturer Mr. Scott Gregory, NCAT human factors PhD student Brittney Jimerson, and research engineer and hydraulics and fabrication specialist James Huggins from Georgia Tech.

The current design has two degrees of freedom currently functional, a main lifting mechanism and a boom extension. The lifting utilizes a scissor lift actuated by a hydraulic cylinder and the boom uses a timing belt and sprockets actuated by a hydraulic motor. Each DOF is powered by a Parker OilDyne hydraulic power unit, which includes a reversible DC motor, a bidirectional gear pump, and a reservoir. Onboard power is from two 12V deep cycle batteries in series. Sensor data acquisition, processing and control algorithms are implemented using a National Instruments Compact Rio (cRio). The cRio provides a control signal to an Advanced Motion Control servo drive for the electric motor, operated in current control mode.

Figure 1: Power and Actuation for Each Degree of Freedom Using Electro-Hydraulic Pump Control.

Fabrication and Testing of First Prototoype

Two primary DOFs of the prototype patient transfer assist device have been fabricated and are fully functional and untethered, the main lifting and boom extension; the device is currently on an unpowered mobile base with casters, and a pair of differential drive wheels are being added. The patient rests in a sling suspended from a hanger bar, similar to the patient interface of a current market lift. Operator control from a force sensing handle mounted near the patient has been implemented, as well as software control. All electrical and hydraulic power components, controllers, sensors, and signal processing are onboard. The current prototype is shown in Figure 2. While the current prototype is bulkier than desired, this is only for providing modularity and simplicity in the prototype design; it can easily be optimized to fit in a much more compact package.

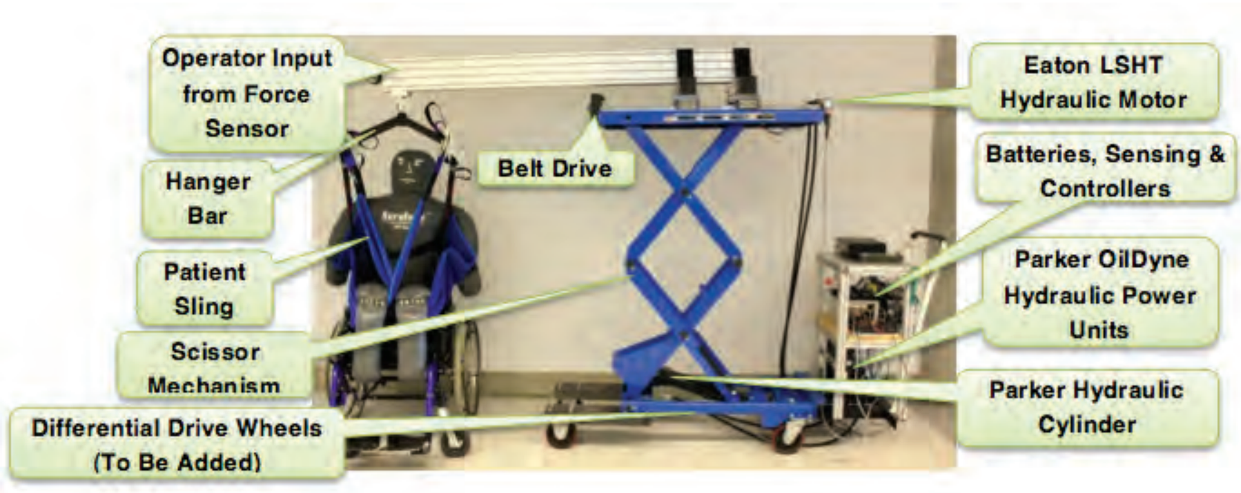

Figure 2: Current Prototype Patient Transfer Device

Control and Caretaker Interface Design

A first step toward an advanced operator interface strategy was implemented on one DOF of a valve-controlled exploratory pre-prototype device, a passivity based human power amplifier control algorithm, an extension of the algorithm developed in graduated CCEFP project 3A.2 [5]. Advantages of this strategy are that it provides a balance of tradeoffs between rate control and force control, way to manage environmental interaction forces, and provides safety and stability. It utilizes a virtual mass and the compressibility of the fluid to provide some compliance and achieve force- and velocity- coordination with the operator input, and it provides a form of haptic information on external and load forces. This form of control was implemented on one DOF of the exploratory pre-prototype device [5, 6].

As a first step on the new prototype device, basic rate control using the NI Compact Rio, servo drives, and position sensor feedback was implemented in two degrees of freedom. The device can be controlled from a force sensing operator input handle mounted at the end of the arm, near the patient, which includes a multi-axis force/torque sensor. As for the low level control, the electric motor and hydraulic pump lead to a highly nonlinear plant; one challenge is to obtain desired dynamic response while managing overall slow plant dynamics, nonlinearities such as pump “stiction”, and switching required for the series wound motor.

C. Plans

Plans for the next year

Control and Caretaker Interface Design

Control algorithms to be tested include collaborative manipulation strategies that allow for management of interaction forces, low level electro-hydraulic pump control, and other features to make the operation more intuitive. Approaches to achieve force/rate control, add compliance and manage interaction forces include further development of the passivity-based human power amplifier control [5] to work with the electro-hydraulic pump control system, as well as impedance/admittance control [7]. The intuitiveness features include methods to mitigate undesirable effects and allow the caretaker to focus more on the patient, such as preventing tipping, managing base/arm kinematic redundancy, managing environment interaction forces, compensating for patient swing/oscillation, and mitigating any effects of the machine dynamics interacting with the operator biodynamics [8]. Further testing will be required to determine which features are most needed. For preventing tipping, several approaches have been investigated, including a model predictive control method implemented on the previous version of Test Bed 4, the Compact Rescue Crawler [9], as well as an online moment computation method used on mobile cranes [10]. A wide array of approaches have also been used to manage swinging/oscillation, including the vibration control approach used by Dr. Vacca in project 3B.3 [11]. Versions of passivity based control, tip-over stability control, and oscillation compensation are all graduated or current CCEFP projects to be implemented on Test Bed 4. Additionally, a new, more accessible and ergonomic force sensing operator input device will be designed and implemented.

Machine Design and Modeling

Several features will be added to this prototype. First, a dynamic simulation including the mechanical system with patient payload, hydraulic and electrical systems will be completed. Also, a set of differential drive wheels will be added to the base, utilizing the same electro-hydraulic pump controlled system as the other degrees of freedom, actuated by hydraulic wheel motors. Additional sensors such as pressure and force are needed for various control strategies. Also, an improved, more ergonomic and easily accessible force sensing operator input device will be designed and implemented. We are making the machine and software designs as modular as possible, to enable integration of CCEFP subsystem projects. An actuated variable base width or shape modification may also prove to be a useful additional degree of freedom.

Human Operator Studies

Once the first control system design is complete, a set of human operator experiments with a mannequin will be performed, along with statistical analyses of the results. Experiments will include full transfer operations, using a protocol similar to the benchmark testing that NCAT helped to develop, as well as subtask experiments aimed at testing individual controller and device features.

Longer Term Vision

In future years, this test bed can provide a system in which to test additional subsystem and component technologies, as they further develop. Alternative operator interface designs developed by collaborators at NCAT can be tested. Alternative hydraulic system architectures may also be tested. The needs assessment indicated that several additional actuated degrees of freedom would be helpful, but they are beyond the scope in the next year. These include a patient sling rotation, swing/rotation with respect to the mobile base, and base geometry adjustments.

Expected milestones and deliverables.

Milestones:

- Differential drive wheels tested [Month 3]
- Dynamic simulation model validated [Month 4]
- Preliminary testing with control strategies implemented in simulation and hardware completed [Month 10]
- First round of human operator studies [Month 12]

D. Member company benefits

This project provides several potential benefits to member companies. It responds to a significant market need where fluid power technology can be utilized, thus providing an opportunity to expand the use of fluid power in home and healthcare applications. This has potential to combat any negative perceptions of fluid power in these areas (e.g. noisy, leaky, unsafe, etc.), paving a way for further expansion into these domains. It also provides an opportunity to develop more effective operator interface concepts for multiple degrees of freedom that work well with humans in the workspace. Furthermore, it is expected to demonstrate methods for effective small scale closed loop electro-hydraulic pump control from electric motors.

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

Research Team

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Industrial Partner:	Parker Hannifin

1. Statement of Test Bed Goals

The goal of test bed 6 (TB6) 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. Test Bed Role in Support of Strategic Plan

The test bed addresses the Center's compactness goal through the creation of miniature fluid power systems that push the practical limits of weight, power and duration for compact, untethered, wearable fluid power systems. The test bed also addresses the goal of making fluid power ubiquitous by creating human-scaled fluid power devices to assist people with daily activities and creating new market opportunities for fluid power, including 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 lower limb orthoses [1]. For individuals with impaired ankle function, current solutions are passive braces that provide only motion control and joint stability and lack the ability to actively modulate motion control during gait and cannot produce propulsion torque and power.

Challenges: 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, 7]. 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.

B. Achievements

Portable Pneumatic AFO (PPAFO) UIUC

In 2010, the first generation portable powered ankle-foot orthosis (PPAFO) was constructed to demonstrate device feasibility [8-10]. The Gen1.0 PPAFO is an improvement over state-of-the-art passive and active systems [4, 5, 11] because it provides subject-specific motion control and torque assistance without tethered power supply or electronics. The device can provide modest dorsiflexion (toes-up) and plantarflexion (toes-down) torque actuation at the ankle. Two U.S. patents on the technology embodied by the PPAFO have been filed; co-inventors are CCEFP students and faculty from the U Illinois, U Minnesota, Georgia Tech, and MSOE [12, 13].

Figure 1: pneumatic elastomeric accumulator

We have improved the efficiency, compactness, control, usability, and possible applications of the PPAFO. Using a commercial pneumatic rotary actuator located lateral to the ankle joint (originally from SMC, currently from Parker Hannifin) and a canister of compressed CO_2 at the waist to serve as a placeholder for a more compact actuation systems and power source, the Gen 1.0 PPAFO can generate up to 12 Nm at 100 psig with run times less than 30 minutes with a 20 oz. bottle. Theoretical and experimental component and system efficiencies of the PPAFO system suggested an overall efficiency of 19% based on calculations from the product of component (50%) and system (39%) efficiencies [14, 15]. That analysis also suggested that the exhaust gas from the higher pressure plantarflexion actuation (100 psig) could be captured into an accumulator and then recycled to power the lower pressure dorsiflexion actuation (30 psig). Working with students at Vanderbilt on Project 2C.2 (strain energy accumulator), a pneumatic elastomeric accumulator was constructed for use with the regenerative pneumatic circuit that was tested during walking tests (Figure 1). In 2013, the effect of two control algorithms on fuel efficiency was investigated. It was found that, by increasing the net work output, a more intelligent, state estimation controller improved the fuel efficiency by 72% as compared to a basic, direct event controller with the regenerative circuit [15]. With the use of the state estimation controller and the regenerative pneumatic circuit, the run time of a 9 oz bottle was expanded to 19 minutes from an original 15 minutes.

To address compactness, we have focused on the development of pneumatic ankle actuation systems with higher torque output (target: 50Nm @ 120 psig) than commercially available. It was realized that the compact integrated rotary actuator developed by MSOE in 2010 would not be a viable design (max capable 50psig for 6 Nm). In 2011, work began with CCEFP industry partner Parker Hannifin to utilize their expertise in pneumatic rotary actuators to design a custom product. This work stopped in fall of 2012 due to Parker work priorities. We have sponsored ME capstone design teams at Bradley University. The current team is optimizing a new pneumatic linear actuator and gear train design. In 2012, a lighter and less complex structural shell design for the Gen 2.0 PPAFO was developed, which will allow for swapping of modular system components (Figure 2). The weight of the PPAFO went from 1.86 kg to 1.60 kg. In 2013, multiple sized (S, M, L) foot and shank bilateral shells to support testing on a variety of sized test subjects were received. These designs allowed us to start testing on a variety of test subject sizes and begin clinical trials on various patient populations.

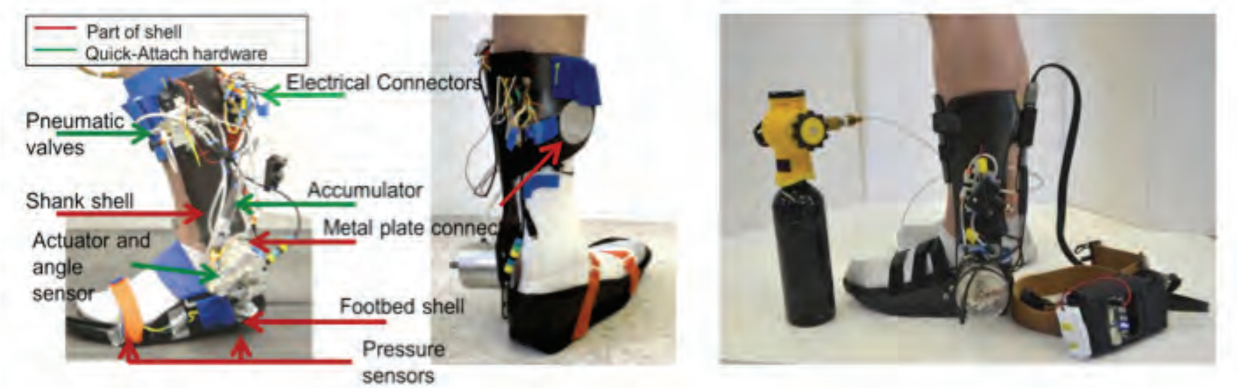

Figure 2 Gen 2.0 PPAFO. Left, Middle: Includes elastomeric accumulator, revised valving, and new shell without metal struts or medial side. Modular hardware can be swapped between different sized shells. Right: PPAFO with belt-worn controller box and CO2 power supply.

To address control of the PPAFO across a variety of walking environments (level ground, stairs, ramps), different actuation-timing control strategies, solenoid vs. proportional control, and recognition and control for different gait modes were examined. The initial controller for level ground walking was a simple direct event threshold-based control using just the heel and toe sensors [9]. To better accommodate impaired gait, a model-based state estimator controller was developed that also added the angle sensor [8]. We examined how work and fuel use were affected by these two controllers and inclusion of a regenerative circuit using the elastomeric accumulator [15]. A simulation and bench-top study highlighted that proportional valve control has better tracking and efficiency performance compared to solenoid valves [10]; however due to the large size of OTS proportional valving systems, inclusion of proportional control on the PPAFO has not yet been implemented. These results highlight technological barriers to compact fluid-powered orthoses due to low torque actuation and large valves. In 2011, work began in recognition and control for different gait modes using a 6DOF inertial measurement unit (IMU) [16, 17]. Progress in 2012 and 2013 resulted in success rates of identifying level ground, stairs, or ramps of 97-99% on average. It was determined that only stair or ramp descent require a different control scheme than level ground or stair/ramp ascent, and differential gait mode control has been implemented [18]. Although having a high identification success rate, the use of a single IMU still resulted in a one-step delay in control actuation of the PPAFO. Further work is ongoing to eliminate this delay.

In 2011, CCEFP faculty and students at NCAT began development of two user interfaces: (1) a clinician user interface for tracking patient medical history and therapy progression, and (2) an interactive game interface (using a serious gaming approach) to be used by the patient while using the PPAFO as a joy stick as part of a seated rehab therapy. In collaboration with researchers at the Rehabilitation Institute of Chicago, we have begun testing the advantages of the PPAFO compared to a range of other assistive devices (tibial stimulators, and commercially-available passive AFOs) in post-stroke and multiple sclerosis subject populations. In an associated project with collaborators at the Parkinson’s disease and Movement Disorders Center at the University of Minnesota, we are investigating the use of the PPAFO as a gait initiation device for people with Parkinson's disease. A pilot study on healthy young adults provided insight into the feasibility of this application [19], and preliminary data collection with people with Parkinson's began in 2013 [20].

Hydraulic AFO (HAFO) UMN

The research objective of the HAFO project within TB6 has been to understand the capabilities and limits of small-scale hydraulics. The research motivation of the project has been the need for small, light, untethered, wearable robots. The development objective of the project was to create an untethered HAFO that meets demanding specifications. The results of the project have been a better understanding of hydraulic systems at small scale from a theoretical perspective and the creation of a physical prototype that is the highest power, untethered AFO.

A key part of our work has been system and component level modeling to predict the efficiency and weight of hydraulic systems [21]. Simple physics was used to model components and the models were validated with experimental data when needed. For example, a simple model was used to determine the leakage and friction of an o-ring seal, important because o-rings are the most logical choice to seal pistons and rods at tiny scales. The models showed conclusively that the practical limit on component size is efficiency. For example, the efficiency of a cylinder with bore of the cylinder. Below about 4 mm bore, practical systems become highly inefficient. Additional models showed that at small sizes, it can be more efficient to use gap rather than o-ring seals. Modeling the efficiency and weight of components for a motor plus transmission compared to a conduit plus cylinder system led to a useful result about system design. For a 100 W system, if the hydaulic solution is to be lighter than the electromechanical solution, the hydraulics must be run at high pressure so all of our prototypes are designed to run at 2000 psi.

With the computational models informing the design, we determined that the best system architecture is a power transmission chain that is battery > motor controller > DC electric motor > tiny hydraulic pump > hose > cylinder > linear-to-rotary transmission > ankle torque. We also determined that the best configuration is to place the power supply at the waist and the cylinder at the ankle with thin hoses as the interconnect (Figure 3). The power supply is complete while the powered ankle component is being fabricated. The HAFO runs at 2,000 psi, provides 90 Nm at 100 deg/s, weighs less than 1 kg at the ankle and fits under a pair of loose-fitting pants. The University of Minnesota will file a provisional patent application for the HAFO in February, 2014 and an NIH R21 application has been submitted to use the HAFO as an AFO emulator in a project to optimize fitting of AFOs to children with cerebral palsy.

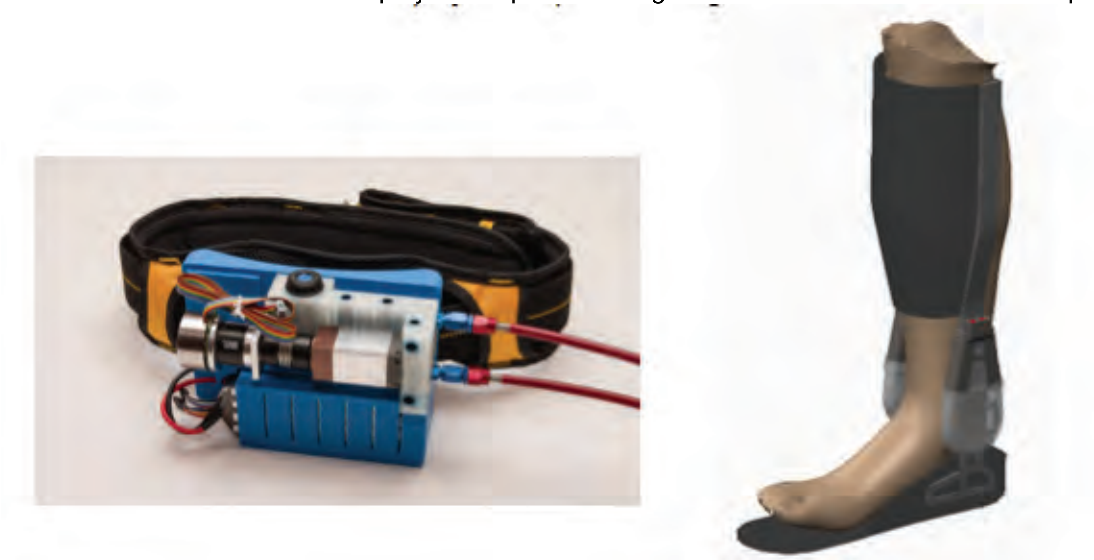

Figure 3: HAFO prototype with waist-worn power supply (left) and ankle component (right).

Simulation of the complete system showed that position control is possible while providing joint torques that mimic walking. The system simulation also showed the importance of the oil as mineral oil, our preferred choice for this application, can trigger control instabilities at transition points of the gait cycle because of its viscosity and bulk modulus properties.

Plans, Milestones and Deliverables for Next Year

PPAFO: Complete longevity assessment of PPAFO with additional healthy test subjects to verify robust operation. Continue to work with Bradley University to develop new actuation system. Perform clinical trials on use of PPAFO on post-stroke, multiple sclerosis, and Parkinson’s populations. Investigate new control schemes. (Spring 2014). Implement new higher torque output pneumatic actuation system on

PPAFO. Demonstration of HCCI engine with PPAFO (Summer 2014). Initial evaluation of MEMS proportional valve on PPAFO (Fall 2014)

HAFO: Complete version 0 of prototype AFO, validating operation to 2,000 psi (Spring 2014). Complete first controller for HAFO: position-based walking controller (Summer 2014). Evaluate alternative fluid power circuits. Preliminary design of custom pump (Fall 2014).

Plans, Milestones and Deliverables for Next Two-Five Years
PPAFO: We will demonstrate the PPAFO on two different applications and will seek external funding to support extended clinical research. To achieve these goals, we will conduct the following tasks:

- Task 1: Technology improvements: Increase the efficiency of power consumption, improve torque to weight and torque to size performance, and integrate a compact power source and a proportional MEMS valve. Integrate MEMS valve and Stirling engine. Milestones: Integrate custom actuator into PPAFO [May 2014]; Integrate HCCI engine into PPAFO [Summer 2014]; Integrate MEMS proportional valve into PPAFO [October 2014]; Integrate Stirling engine [January 2015].
- Task 2: For a walking assistance application, design and implement control, including neural network state estimation and gait mode recognition. We will also explore energy harvesting from the biomechanics of walking to aid with improving system efficiency. Milestones: ANN integration (computer driven) completed [May 2014]; Gait mode recognition and actuation without one-step delay completed [May 2015]; Concepts for energy harvesting completed [December 2014].
- Task 3: For a seated rehabilitation therapy application, we will work with clinical stroke collaborators to identify testing protocols. Pressure and air flow control for torque and rotational velocity control will be examined to allow proper operation of the PPAFO. A post-stroke therapy system will be demonstrated. Milestones: Identify therapy requirements [June 2014]; Initial integration of clinician and patient user interfaces with PPAFO [September 2014]; Torque and rotational velocity control completed [March 2015]; Demonstration of post-stroke therapy [May 2015]

HAFO:

- Task 1 --Fluid Power Circuits, Control Algorithms and Fluids: Examine alternative circuits in simulation and experiments and will assess for size, weight and efficiency. Deliverables: Simulations and experimental data from several circuit, control algorithm and fluid realizations. Publication reporting findings. (Sept 2014 – May 2015).
- Task 2 --Tiny Pumps: Fully understand the pump requirements for the HAFO, and then examine system level trade-offs using simulation. Design and fabricate a custom pump that matches the application.. Designing our own pump means we can explore component integration in the power supply to further reduce size and weight. Deliverables: Multiple prototype pumps. Simulation and experiment testing for performance. Publication reporting findings. (January 2015 – December 2015).
- Task 3 -- Using an Accumulator to Handle Power Burst: Determine through simulation and experimentation how to optimize energy storage in an accumulator to handle the power burst that occurs at toe-off. Adapt the strain energy accumulator developed in CCEFP project 2C.2 for use in our application. Consider super-capacitors to store energy on the electrical side instead of the fluid side. Deliverables: HAFO with energy storage. Simulations and experimental data with results. Publication reporting findings. (January 2015 – December 2015).
- Task 4 --Two DOF Upper-Extremity Assistance Machine: Extend our findings to a system of greater complexity. A two degree of freedom upper extremity wearable assist machine is an appropriate configuration for beginning to examine issues where fluid power actuation needs to be coordinated. The machine will be targeted for repetitive tasks where human judgment is required, for example package handling or fruit harvesting. This extension to the test bed will also enable pilot data to be collected that can be used for submitting research proposals to NSF and NIH. Deliverables: Simulations of configurations. Working prototype that has been evaluated for task use by a human operator. Publication reporting findings. (June 2015 – May 2016).

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.

D. References (references after [5] are from work supported by this testbed)

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

Thrusts, Projects and Program Objectives	Promote STEM Learning	Promote Awareness of Fluid Power	Fluid Power Curriculum	Culture of Research and Education Integration
Thrust A: Public Outreach **Bringing the message of fluid power to the general public**				
A.1 Interactive Exhibits Fluid Power	x	x		x
Thrust B: Pre-College Outreach **Bringing fluid power education to K-12 students, with a focus on middle and high school outreach**				
B.1 Research Experiences for Teachers (RET)	x	x	x	x
B.3 Hands-on Fluid Power Workshops	x	x		
B.4 gidaa STEM Programs	x	x		
B.5 BRIDGE Program	x	x		
B.7 NFPA Fluid Power Challenge Competition	x	x		
Thrust C: College Education **Bringing fluid power education to undergraduate and graduate students**				
C.1 Research Experiences for Undergraduates (REU)	x	x		x
C.2 Fluid Power College Level Curriculum	x	x	x	x
C.3 Fluid Power Projects in Capstone Design Courses	x	x	x	x
C.4 Fluid Power in Engineering Courses	x	x	x	x
C.5 giiwed'anang North Star Alliance	x	x		x
C.6 Fluid Power Simulator	x	x	x	
C.8 Student Leadership Council (SLC)	x	x		x

C.9/10 Research Diversity Supplement (RDS)	x	x		x
C.11 Innovative Engineers (IE)	x	x		x
Thrust D: Industry Engagement Making connections between CCEFP and industry				
D.1 Fluid Power Scholars/Interns	x	x		x
D.2 Industry Student Networking	x	x		x
D.5 CCEFP Webcasts Series	x	x		x
Thrust E: Evaluation Measuring CCEFP program effectiveness	x	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.

The objectives of the Education and Outreach Program are to:

1. Motivate diverse citizens to travel the STEM pathway in order to expand and promote a talented STEM workforce.
2. Promote awareness of fluid power and its applications through positive, authentic experiences in informal, K-12, undergraduate, graduate, and industrial contexts.
3. Infuse new fluid-power research and innovative, evaluated, fluid power curricula and programs into informal, K-12, and college level course offerings.
4. Creating a culture that integrates research and education for undergraduate and graduate students across all partner institutions.

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 AGEP institutions; 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]

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. 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.3 Hands-On Fluid Power Workshops Fluid power is most easily understood by students of all ages when accompanied by hands-on experiments. 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.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 LRC LacCore Facility 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 (science, technology, engineering, and math) subjects. The gidaa K-12 STEM Camps are offered 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. The gidaa K-12 Robotics Program is offered day and after-school for interested students at South Ridge (K12 school within the Fond du Lac reservation) and Cloquet Middle and High School, Cloquet, MN. South Ridge hosts the only regional RoboFest Competition in the state. [Project Leaders: 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]

Project B.7 NFPA Fluid Power Challenge Competition The Fluid Power Challenge is a design competition for eighth grade students to learn how to solve an engineering problem using fluid power. The event comprises of two days. On the first day - Workshop Day - students are introduced to the basics of fluid power, get hands-on experience by building kits that use fluid power, and are introduced to the challenge they must solve. The students return to their schools to work in teams to design and build their fluid power device, along with keeping a portfolio to document their work. About a month later, the students return for the second day of the event - Challenge Day - to build their device they designed at their own schools and compete against the other teams in a timed competition. The goals of the Fluid Power Challenge are to: 1) Actively engage students in learning the basics about fluid power; 2) Give support and resources to teachers for science and technology curriculum; 3) Create a fun learning environment for math and science; 4) Encourage students to acquire a diversity of teamwork, communication, engineering, and problem-solving skills; 5) Introduce eighth grade students to the fluid power industry; 6) Help build a strong workforce for tomorrow. [Project Leaders: Cherie Bandy, CCEFP, Alyssa Burger, CCEFP]

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, CCEFP]

Project C.2 Fluid Power College Level Curriculum The purpose of the Fluid Power College Level Curriculum 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. 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. Initiatives include a fluid power MOOC and several mini-book modules. [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. CCEFP also provides supplemental funding to research faculty to incentivize fluid power projects across the Center. [Project Leader: Jim Van De Ven, UMN, Alyssa Burger, CCEFP]

C.3a Capstone Senior Design Project: A Third-Generation Pneumatic Rotary Actuator Driven by Planetary Gear Train The primary educational impact of this project is to expose a team of undergraduate engineering students to concepts of fluid power design, specifically rotary torque generation using a pneumatic power source. All of the students participating in the capstone design course will be exposed to fluid power issues as they participate in the gated review process which includes four oral progress report presentations by the design team. The project has exposed the student teams to first-hand experiences with fluid power through pneumatic design issues such as torque generation, leakage and seals, fluid dynamics, and also thermodynamic analysis of dealing with expansion of compressed gas (CO_2). [Project Leader: Elizabeth Hsiao-Wecksler, UIUC]

C.3b Parker Hannifin Chainless Challenge Four of the seven CCEFP institutions have participated in the Parker Hannifin Chainless Challenge - an engineering design competition for undergraduates to design and create the most efficient and effective human-assisted green energy vehicle. The students are required to design and build the drive system for their vehicles, as well as participate in the final demonstration competition. They can utilize either off-the-shelf components provided by Parker Hannifin or design their own. The demonstration event includes a judging criterion, a straight sprint race, and distance/performance race. This final event is conducted over a two day period. Cash awards were given to the winning team in each specified category. The CCEFP provides supplemental funding to team who apply for the Center's Capstone Project Grant. [Project Leader: Brad Bohlmann, CCEFP]

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 The CCEFP launched the giiwed'anang North Star Alliance. Primary goals include student support of local AISES chapters. The project also strives to grow and nurture the student and professional regional chapters of the American Indian Science and Engineering Society (AISES). As the CCEFP winds down, the sustainability plan calls for the AISES North Star professional chapter to assume the student support responsibilities as the CCEFP redirects focus. [Project Leader: Alyssa Burger, UMN]

Project C.6 Fluid Power Simulator For undergraduate mechanical, aerospace and agricultural 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: Will Durfee, UMN]

Project C.8 Student Leadership Council (SLC) The Student Leadership Council is an independent board of the CCEFP. 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.9/10 Research Diversity Supplements (RDS) The Center's Education and Outreach program is committed to providing opportunities to broaden the participation of underrepresented students in undergraduate and graduate engineering programs through this Research Diversity Supplement to current CCEFP research projects. [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. Fluid Power Scholars/Interns receive a scholarship to an intensive three and one half-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. [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.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: Cherie Bandy, CCEFP, Alyssa Burger, CCEFP, Student Leadership Council]

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. Quality Evaluation Designs (QED) is the contracted external evaluator of CCEFP Education and Outreach. The overall goal of the QED external evaluation is to collect data that have the potential to promote sustainability of E&O beyond NSF funding of CCEFP. To do this, QED will pursue the following objectives: to anticipate in the evaluation design a new administrative/organizational CCEFP structure that supports and integrates E&O goals and objectives, to identify current and potential stakeholders who could sustain E&O goals and/or programs during and after the current funding cycle, to collect data and draft reports that address the value-added of E&O to CCEFP goals and programs.

E&O Programs and Projects, On Hold

Project B.6 High School Research Opportunity Program *(on hold)* CCEFP works with local high schools to recruit talented rising high school juniors and seniors to engage in Center's research labs. Students who participate are expected to volunteer for six-week summer research experiences at the Center. With the help of their high school teachers, the high school students work either during the summer months with faculty, graduate students and REUs to conduct research projects. The program will be designed to help capable young people develop an interest in careers related to fluid power. Participants will be encouraged to attend universities affiliated with CCEFP, and be given priority for REU opportunities.

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 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 D.6 Graduate Internships in Fluid Power (on hold) 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. The CCEFP collaborates with corporate members of the fluid power industry to provide learning and training opportunities for CCEFP graduate students. The CCEFP helps to facilitate the placement of graduate engineering students as engineering interns—in openings provided by the Center's corporate members. We invite CCEFP corporate members to post graduate level fluid power internship positions to our website. We will display them publicly and advertise the opportunities to CCEFP graduate students and those with expertise outside the Center. Students will apply for internships positions through the company's established application procedures. We invite graduate students of the CCEFP, as well as graduate students outside the CCEFP who are currently and actively engaged in fluid power research to consider applying for graduate level internships. [Project Leader: Alyssa Burger, CCEFP]

Graduated E&O Programs and Projects

Project A.2 Youth Science Team Fluid Power Youth Science Team at the Science Museum of Minnesota. Funded by the CCEFP, the Youth Science Team teaches others about fluid power through museum exhibits, student-created learning activities and outreach.

Project A.3 Multimedia Educational Materials The CCEFP leverages the use of multimedial to inform, train, educate and interest the general public in fluid power technology. Utilizing audio visual technology to promote hydraulics and pneumatics and how these systems are part of societies everyday operation. In 2008, the CCEFP and NFPA produced two videos: *Discovering Fluid Power* and *Fluid Power: The Force for Change* for both public and private use. Both organizations regularly disseminate the video, it is offered on public television outlets and has been broadcast across the world. Secondly, a sponsored CCEFP project includes the Fluid Power Educational Smart-App for Mobile Devices - a gaming mechanism for interactive fluid power learning. [Project Leaders: Alyssa Burger, UMN]

Project A.3 Discovering Fluid Power Video 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.

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]

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]

C.3c Hydraulic Fluid Power for Fuel-Efficient School Buses A project to develop a hydraulic hybrid retrofit of a school bus at the Georgia Institute of Technology is yielding impressive results. Not only is the work of a team of graduate and undergraduate students realizing the potential of new fuel efficiencies for school buses everywhere, but it also provides a model for effectively engaging college and pre-college students in hands-on learning about eco-friendly fluid power. [Project Leader: Michael Leamy, GT]

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, and formally assisted by Education Outreach Coordinator, Cherie Bandy. The Directors report to CCEFP Director Kim Stelson. Additionally, Principal Investigators of specific projects contribute to program direction and implementation.

The Education and Outreach Task Force is a core strategic working group including CCEFP faculty and staff.

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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EO Project A.1: Interactive Exhibits

Project Team	Science Museum of Minnesota
Project Leader:	Director of Physical Sciences, Engineering, & Math, J. Newlin
Other Personnel:	Master Prototyper, Forrest Price Master Prototyper, Peder Thomson Head of Exhibit Production, Cliff Athorn Senior Exhibit Developer, Chris Burda Director of Learning Technologies, Keith Braafladt Learning Technologies Specialist, Peter Kirschmann

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.

<u>Capstone Projects</u> In 2007, 2008, 2011, and 2012, 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 sixth (2012) was an exhibit that demonstrates the use of an open accumulator to capture energy from a wind turbine (Figures 6 – 7). 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 improved by museum staff in 2012. The sixth exhibit has been on display at the museum since July, 2012. Plans for this coming year include rebuilding the hydraulic assist exhibit so it can be placed on the museum floor.

<u>High School Project</u> 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. It was on exhibit floor from 2008 until summer, 2012.

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. This exhibit was on display from 2008 until summer 2012. The second is a working cut-away variable-displacement axial piston pump arranged to pump tall streams of clear hydraulic fluid (Figure 2). This exhibit has been on display since 2008.

SMM built a Hydraulics Lab (Figures 3 – 5) 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. In 2012, SMM relocated and redesigned the exhibit to improve both visitor interaction and daily maintenance. SMM added two attractive hydraulic devices and challenged visitors to make them work. One is an imaginative carousel operated by a Pelton wheel. The second is a large bell that can be rung by operating a double-acting hydraulic cylinder. To make using the lab easier for visitors, SMM installed a touch-screen video display that shows how to make hydraulic tube and device connections and how to build hydraulic circuits that incorporate pumps, check valves, flow meters, spool valves, and accumulators. The Hydraulics Lab includes three exhibits that define simple hydraulic circuits (Figure 5):

a. At Pumped Water Storage, visitors use a cylinder pump with two transparent check valves to pump water from a lower reservoir into a high reservoir. They then open a valve to release the water to operate a Pelton wheel that drives a small generator, which lights several LEDs.
b. At Variable Force Pump, 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.
c. 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.

In 2012, SMM built Pneumatic Ball Run (Figure 8), an exhibit that challenges visitors to design a system of channels and lifts that will move a ball from one side of a vertical panel to the other side, ending at the same height. The lifts are all operated by pneumatic pumps and cylinders.

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.

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, Hydraulics Lab, Pneumatic Ball Run, and Compressed Air Wind Energy Storage.

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

Summer 2013. SMM will reconstruct the Hydraulic Assist exhibit developed by the Capstone Team of mechanical engineering students in 2011. This needs substantial redesign to harden the device for the exhibit floor.

Fall of 2013. SMM will work with a team of senior mechanical engineering students to develop an exhibit that demonstrates the achievements of one of the CCEFP test beds. Since SMM now has exhibits that relate to the Hybrid Hydraulic Passenger Vehicle and the Fluid Power Assisted Orthosis, the team will focus on an exhibit that demonstrates a High Efficiency Excavator.

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.

Fall of 2014. SMM will SMM will work with a team of senior mechanical engineering students to develop an exhibit that demonstrates the achievements CCEFP research of one of the CCEFP test beds. To complement other CCEFP-related exhibits, the team will focus on an exhibit that demonstrates a Fluid Power Rescue Robot.

Fall of 2015. If funds allow, SMM will continue working with a Capstone Design team to add to its collection of exhibits about applications of fluid power and the accomplishments of the CCEFP.

Figure 1: Hydraulic Hybrid Car

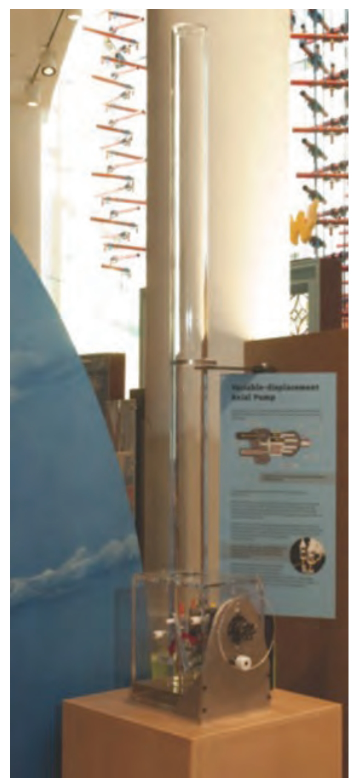
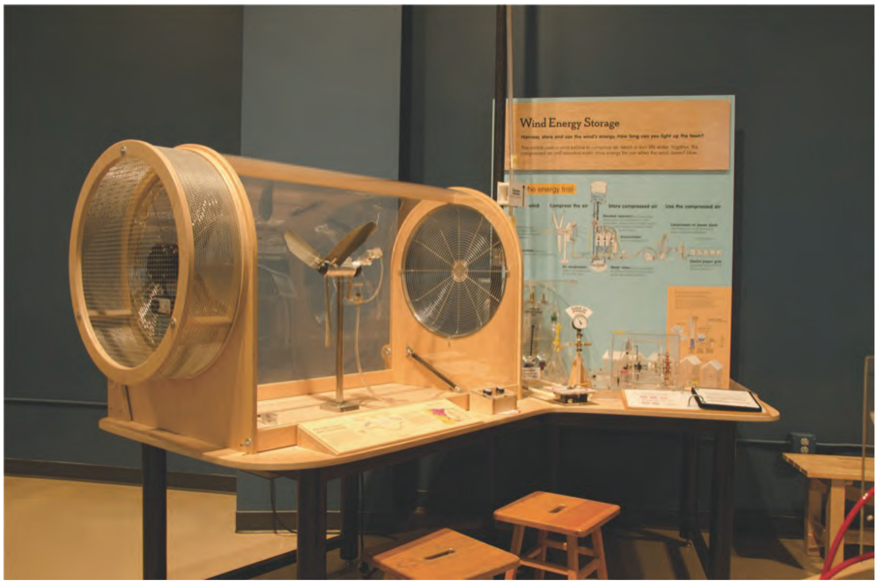


Figure 2: Axial Piston Pump

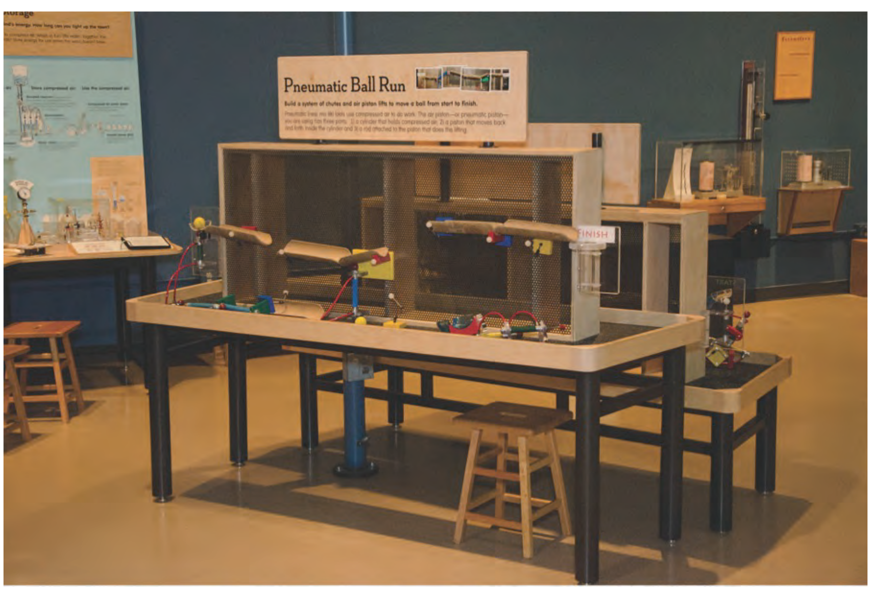
Figure 3: Hydraulics Lab (Left)

Figure 4: Hydraulics Lab Touch Screen Instructions (Above)

Figure 5: Simple Hydraulic Circuits



Figures 6 - 7: Compressed Air Wind Energy Storage



Figures 8: Pneumatic Ball Run

Project B.1: Research Experiences for Teachers (RET)

Project Team

Project Leader: Alyssa Burger, Education Outreach Director, CCEFP

Other Personnel: Prof. John Lumkes, Purdue University
Dr. Eui Park, North Carolina A&T State University

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.

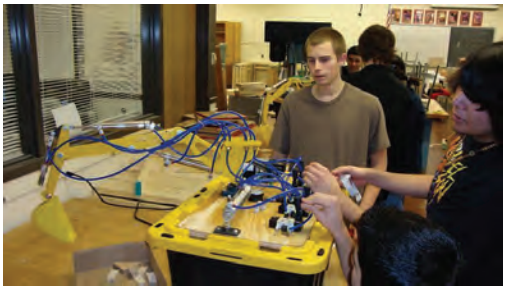
3. Achievements

- Four teachers participated as RETs in summer 2013, the seventh year of the CCEFP RET program: two at Purdue (returning RET teachers) and two at North Carolina A&T State University.
- Six teachers participated as RETs in summer 2012, the sixth year of the CCEFP RET program: four at Purdue University and two at North Carolina A&T State University.
- Purdue RETs (2013) conduct outreach in Tanzania (second year) with high school students.
- Purdue RETs (2013) conduct elementary school outreach with small wooden hydraulic excavator and earth-moving machine kits.
- NCAT RETs (2013) created several modules: *Fluid Power and Excavator Testing, the Human Factor* and *Using Geometric Methods to Deign an Efficient Excavator* and *Water as Fluid Power Resource.*
- NCAT RETs (2013) participated in a Summer Institute hosted by NCAT
    - 56 public school teachers attended for a week-long public school teachers training.
    - The teachers were from 6 rural counties in the state of NC
    - Applications of fluid power and CCEFP were introduced
- A great collaboration between local schools and teachers has been established both at Purdue and NCAT.
- Over 44 teachers have participated in the CCEFP RET program since it's inception, and several have been repeat participants, especially the established collaboration at Purdue and it's outreach program involving local teachers.
- 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 2012 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, visited 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 chaperoned a group of four 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. The students designed a PVC water pump that worked in local village schools. Students worked on two additional projects: A Hydraulic Clay Brick Press and a PTO shaft water pump. Student successfully raised their own travel funds. A YouTube video captures the result of the activity, from the students' perspective:
     https://www.youtube.com/watch?feature=player_embedded&v=gYlxvnX969g#!
   - Mr. Gary Werner and two McCutheon high school students will visit the NSF Site Team at the 2013 CCEFP Site Visit at Purdue.

- 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:
    - **2011:** Six teachers participated 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.
    - **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.
    - **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.
    - **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.

4. Plans, Milestones and Deliverables

- In 2014, the CCEFP commits to hosting four teachers within its university network, two at Purdue, two at NCAT.
- The Center will promote any newly developed fluid power curriculum modules at its website, on TeachEngineering.com, on YouTube and TeacherTube, as well as on other appropriate channels.
- This program will be phased down beginning in Y9 as it will not be part of the future CCEFP sustainability plan under Workforce 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.

EO 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 University
CCEFP Faculty
CCEFP Student Leadership Council
CCEFP Graduate Students

Industry Partners: Donaldson
Bimba Manufacturing Company

1. Project Goals

Through this project portable demonstration kits and curricular materials have been developed for use in hands-on workshops about hydraulics and pneumatics. All 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. Additionally, the CCEFP considers "outreach" any engagement to an external audience.

2. How Project Supports the EO Program Strategy

This project supports the EO program strategy in several ways. Workshops based on pneumatics and hydraulics serve to broaden an awareness of fluid power among pre-college students and their teachers, undergraduate students and the general public.

3. Achievements

- **HIGHLIGHT**. In Y8, CCEFP was invited by NSF ERC leadership to present the PFPD's at the "CHANGE THE WORLD: Science and Engineering Careers Fair" in Washington DC. It's estimated over 400 people stopped by during the 2-day event. Five CCEFP personnel attended the event, including Purdue faculty, graduate students, RET and high school students.
- In a single reporting year, over **36** unique fluid power outreach events have occurred across the CCEFP. Outreach events include laboratory and demonstration tours, fluid power activities and engineering workshops, mentoring, retreats, special group presentations (Women in Engineering, Juniors Exploring Engineering, Innovative Engineers), challenges and competitions (NFPA Fluid Power Challenge, Hydraulic Bicycle Competition), 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. (See list below).
- In Y8, including the Science Museum of Minnesota, over **22,000 K12 students, college, community and the general public** participated in CCEFP outreach and engagement events.
- In Y8, over **1,300 volunteer hours** (and likely, significantly more) clocked by ERC students, faculty and staff at these various outreach events.
- In Y7, **1,135** student and community members participated in CCEFP outreach events; more than **614** volunteer hours clocked by ERC staff and ERC students at these events.
- In Y7, the original PFPD are still being utilized at Purdue (and other CCEFP institutions) during various K-12 outreach programs, museums, high schools, conferences, and distributed to CCEFP member universities. The previous demonstrators have been successful in classrooms, science museums, on campus programs and other engagement activities. However, their size, weight

and large loose components make long-range travel, shipping, and transporting as baggage on airlines unnecessarily difficult.

- In Y8, the Student Leadership Council continues its Project Grant program in which the SLC distributed funds to students at CCEFP institutions to host outreach events, often utilizing the Portable Fluid Power Demonstrator. Total, over 10 project grant proposals were awarded to students at various institutions by the SLC. Two of those grants were utilized to build the portable fluid power demonstration excavator kits for their institution.

4. Plans

- The near term goals for the Nano PFPD project (Project B.3b) include the development and subsequent assessment of the smaller and more portable, fluid power educational platform.
- Outreach is encouraged to all CCEFP personnel.

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 2014. Sponsored, in part, by the SLC Project Grant program.

6. Member Company Benefits

These workshops contribute to an increased awareness of fluid power by a growing number of pre-college students.

CCEFP Fluid Power Outreach Events – 2012-2014

Date	Event type
02.01.12	Undergrad outreach in Greensboro, NC
02.17.12	Workshop and Purdue Maha Lab tour
02.17.12	Outreach to White Earth Indian Reservation - Circle of Life School
02.29.12	Collaboration with Bradley University
03.09.12	Engineering Open House; UIUC
03.09.12	Demonstrate fluid power using mini excavator kits at Engineering Open House; UIUC
03.13.12	Research Experience for Teachers Program; Vanderbilt U
04.12.12	Hydraulic bicycle competition; Irvine, CA
04.13.12	Outreach; White Earth Indian Reservation - Circle of Life School
04.16.12	Women in Engineering Event; Purdue U
04.16.12	Women in Engineering Event; Purdue U
05.16.12	Outreach and Implementation; Jinotega, Nicaragua
06.03.12	REU Orientation and Welcome; Purdue U
06.03.12	Engineering Workshop; Purdue
06.04.12	Annual Summer Enrichment Program on Robotics; Roswel, Georgia
06.26.12	Outreach; White Earth Indian Reservation - Circle of Life School
07.11.12	Introduction to Engineering; Purdue ABE Fluid Power Lab
08.22.12	Outreach to students to promote interest in STEM fields; Vanderbilt U
08.22.12	Lab Tour; Vanderbilt U STORM Lab
09.26.12	Lab Tour in conjunction with the National Fluid Power Association Educator's Summit; UIUC
10.17.12	Outreach; White Earth Indian Reservation - Circle of Life School
11.09.12	Innovative Engineers / BRIDGE Wind Demonstration; White Earth Indian Reservation - Circle of Life School
11.27.12	Outreach to White Earth Indian Reservation - Circle of Life School

11.28.12	Outreach Tutorial; Vanderbilt U
01.07.13	Education and Outreach to wide public audience; fluid power workforce
01.10.13	Ongoing mentorship for year-long project
1.7.13	Fluid Power Challenge - Competition Day
1.10.13	Mentorship high school student in research activities
1.25.13	Mast Lab Tour
2.19.13	Research Roundtable Fluid Power Recruitment
2.23.13	Women in Engineering Program - Introduce a Girl to Engineering Day
3.8.13	Miniature hydraulic excavators: hands-on exhibit
3.22.13	RoboFest Competition
4.10.13	National Robotics Week
5.10.13	Robotics Teacher Training
5.20.13	Fluid Power Demonstration
5.27.13	ERC Bootcamp
5.28.13	CCEFP 2013 Bootcamp
5.28.13	Fluid Power Scholars Fluid Power Training Workshop
6.10.13	Summer robot enrichment class
6.10.13	White Earth Science and Math Academy
6.10.13	K12 teacher professional development
6.15.13	Fluid Power for Energy Harvesting and Medical Robotics
7.5.13	2013 Institute of Summer Teachers
7.16.13	Robotic Competition
7.31.13	CCEFP SLC Student Retreat
8.19.13	IAB Dinner Hosted by Science Museum of Minnesota
8.20.13	Wind power development in Nicaragua
8.21.13	Fluid Power Challenge
9.7.13	Robox Sumo
9.28.13	CHANGE THE WORLD: Science & Engineering Careers Fair
10.14.13	Women in Engineering Program Fluid Power
10.17.13	Role of FEA In Design & Development
11.1.13	Examples of The Finite Element Method
12.12.13	White Earth Indian Reservation Outreach
12.13.13	White Earth Circle of Life Science Fair
1.1.14	Science Museum of Minnesota - Year-Round
1.14.14	Fluid Power Challenge Competition
1.17.14	White Earth Indian Reservation Outreach
1.31.14	Mentoring Fabrication of Fluid Power Exhibit for Science Museum
1.31.14	Guest Lecture on Precision Pneumatic Nonlinear Controls

Project B3.b: Portable Fluid Power Demonstrator and Curriculum

Project Team

Project Leader: Professor, John Lumkes, Purdue University

Other Personnel: Jordan Garrity, Purdue University
Gary Werner, McCutcheon High School
Tyler Helmus, Purdue University

Industrial Partner: Clippard Instrument Laboratory, Inc., Vex Robotics

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.

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".

Achievements

Undergraduate level students from Purdue were recruited to help design a new 'nano' PFPD kit and curriculum. REU students have also participated in the design phase.

The 2013 efforts have focused on a new multi-actuator smaller educational tool that can be easily transported, doesn't require any setup or water, can be plugged into any 110/220V outlet, and introduces students to fluid power and the interaction of electronics, microcontrollers, and actuators in fluid power systems. The original PFPDs are still being utilized at Purdue various K-12 outreach programs, museums, high schools, conferences, and distributed to CCEFP member universities. The previous demonstrators have been successful in classrooms, science museums, on campus programs and other engagement activities. However, their size, weight and large loose components make long-range travel, shipping, and transporting as baggage on airlines unnecessarily difficult.

The new demonstrator is much more compact and designed to meet the requirements for carry-on luggage in size, weight, and content. This design still features all parts of a pneumatic circuit clearly showing the flow source, control valves, reservoir, and actuators. Rapid setup, simple circuitry, and easy transport makes this device ideal for conferences, teach training visits, and other such pre-existing opportunities that the current trainers do not work well for.

A careful analysis of learning objectives and other goal related limitations along with the mechanical design of the system resulted in the design of a pneumatic cantilevered gantry crane with position feedback and an electro magnet gripper at the end of a small, guided electric winch. The position feedback comes from an ultrasonic distance sensor and variable resistance position sensor. Additionally, a camera was mounted below the winch to allow for contrast recognition. The device is controlled by an Arduino micro-controller allowing students to interact with the code to change controls or develop their own functions. There are several games which could be developed either for or by students to enhance their education of fluid power and mechatronics. Currently, 3 different modes have been programmed for the demonstrator, a user controlled manual mode, a shape tracking mode, and a shape identification mode.

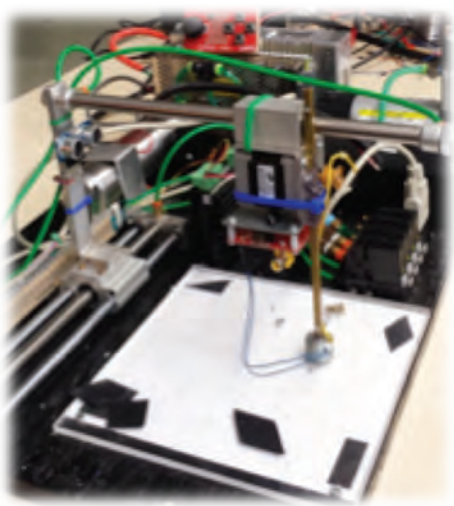
The small portable device demonstrates pneumatics, robotics, and programming in environments where these topics were previously only discussed.

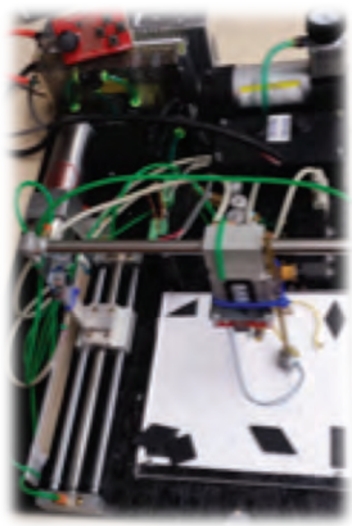
Summary of PFPD outreach activities to date

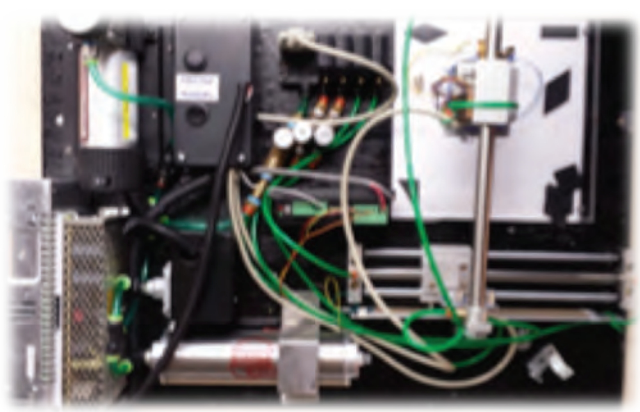
Between Feb. 1, 2013 – Jan. 31, 2014, Purdue offered three pre-college outreach programs at Purdue. There were 84 participants, of whom 68 were female (81%), 16 were male, and 11 were from under-represented ethnic groups. In total, Purdue has offered over 30 programs, reaching over 800 students with over 50% of the participants being female and/or from under-represented groups.

In September, 2013, this project was nominated by the CCEFP and NSF to participate in the "CHANGE THE WORLD: Science & Engineering Careers Fair" in Washington D.C. The PFPDs were always busy and an estimated over 400 people stopped by during the 2-day event.

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 used at various high schools, state fairs, outreach events, tours, and workshops.







Plans, Milestones and Deliverables

The near term goals for the project include the development and subsequent assessment of the smaller and more portable, fluid power educational platform.

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

EO Project B.4: *gidaa* STEM Programs

Project Team

Project Leader: Alyssa A. Burger, Education Outreach Director, CCEFP

Other Personnel: Holly Pellerin, *gidaa* Coordinator
Lowana Greensky, Director of American Indian Education in St. Louis County Schools
Cameron Lindner, Robotics Program teacher
TJ Ray, Robotics Program teacher
Richard Rhoades, Robotics Program teacher

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. Various activities for K-12 Native American students have been held on a regular seasonal basis since 2003. gidaa is a hands-on STEM outreach program - science, technology, engineering, arts and math, which are taught all together.

gidakiimanaaniwigamig ("Our Earth Lodge" in Anishinabe) 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 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.

A highlight of the gidaa program, initiated and launched by CCEFP, is the gidaa Robotics Program that exists 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. 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 gidaa 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 Robotics Program will continue their education at a community college or a four-year university. This program currently engages students at the elementary, middle and high school levels.

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.

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* robotics is in its fifth year and has expanded to include Cloquet Middle and High School, in addition to South Ridge.
- CCEFP sponsored five new classroom kits for Southridge School and 10 new classroom kits and software upgrades for Cloquet Middle and High School day and after-school robotics programs.
- South Ridge will be hosting its 5th Annual Regional Robofest competition in March with more local schools participating. CCEFP will sponsor winners from the regional competition to attend the International Competition at Lawrence Technical University in Michigan.
- Robotics Teacher Training was hosted at South Ridge and sponsored by CCEFP in May 2013 with three local teachers attending 10 hours worth of training learning how to implement a robotics program at their schools.
- 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* camp 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.

4. Plans

Placing emphasis on the gidaa robotics program, the CCEFP will continue to foster the growth of the activities that have been initiated through gidaa.

- 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 Culver and Fond du Lac Indian Reservation geographic area.
- Expanding Lawrence Technological University's Robofest Competition across Minnesota.

5. Milestones and Deliverables

- 200 students per year participating in program camps, day and after-school robotics programming and competitions.
- 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.
- 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.

EO 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 has evolved into a multi-institution program. It is now referred to as the Bridges Program and includes active partners at the University of Minnesota, Villanova University, the National Engineering University of Nicaragua, and LaSalle University in Leon, Nicaragua.

The Bridges Program is a collaboration between the Universidad Nacional de Ingenieria (UNI), the Universidad Tecnologica LaSalle (ULSA), Villanova University (VU), and the University of Minnesota (UMN) dedicated to building relationships and empowering people, communities, and the nation of Nicaragua. This is done through the initiation, support, and coordination of community-based projects. That is,

- Initiation based on community need and community involvement,
- Support from each of the program partners, and
- Coordination of human, institutional, and community resources.

The greatest value to be gained through these efforts will be the formation and nurturing of strong, supportive relationships. These relationships are at the core of the program.

The mission of the Bridges Program is to enable relationships to thrive between UNI, ULSA, VU, UMN, and the communities and people of Nicaragua, through the initiation and support of community-based projects, and through the advancement of practical research,

- To create a technical and societal ecosystem in which students can build their skills and grow in their passions,
- To have a positive impact on the people and communities with which we work, and
- To share equally in this mission with all who join us.

The vision of the Bridges Program is empowered communities supported by a dedicated network of active partners.

The value of the program is unique to each partner. For Nicaragua, the program will create capabilities in communities and in institutions of higher education. The program will strive to elevate and empower girls and women.

The value of the program for students, in Nicaragua and in the United States, will be to bridge cultures and provide hands-on authentic pedagogy enabling them to reach their full potential as citizens of the world.

The value of the program for communities will be empowerment. As partners in the very work that is meant to help them, they will have responsibilities, ownership, and ultimately, empowerment.

The value of the program for UNI and ULSA will be to expand instructional capabilities, elevate educational levels, and expand research capabilities that are pertinent to Nicaragua. The program will increase the visibility of UNI on a national and international stage.

The program is aligned with the mission of Villanova University to be in service. Furthermore, the program will empower Villanova students, giving them the opportunity to use their engineering skills in a program of authentic pedagogy. The program will enhance the reputation of Villanova enabling them to further promote their mission.

The program will empower University of Minnesota students, giving them the opportunity to use their engineering skills in a program of authentic pedagogy. The program will enhance the reputation of the University of Minnesota enabling them to further promote their mission.

This started as the BRIDGE (Building Resources and Innovative Designs for Global Energy) Project, which was a shared endeavor of 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 and thrived and evolved through major support from the CCEFP (Center for Compact and Efficient Fluid Power).

The program is now strengthened through firm commitment across institutions, but the major goals are unchanged

- Outreach to pre-college students in the United States and abroad.
- Technical and personal development of university engineering students.
- Implementation of renewable energy systems in communities, which are currently not served by modern energy services.

The work is focused in the area of renewable energy, and specifically in renewable energy systems that can be constructed from locally sourced and inexpensive materials using local talents and accessible technologies. University of Minnesota student members of Innovative Engineers, and soon student members on Innovative Engineers at UNI and ULSA, coordinate outreach programs with pre-college students in Minnesota and Nicaragua in which they produce and refine renewable energy systems (specifically wind turbine electrical systems at this time) with the goal of implementing these systems in developing nations where modern energy systems are not available. Everyone involved is a shoulder to shoulder partner.

The BRIDGE Project (now Bridges Program) has impacted students and communities across the state of Minnesota and in Nicaragua. 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.

Design work in the 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. How Project Supports the EO Program Strategy

Beginning in Y6, the CCEFP 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. Following CCEFP association with the BRIDGE project, the project now has a fluid power component, which includes the incorporation of fluid power educational activities in the BRIDGE outreach and development of novel fluid power methods in hybrid hydraulic/electric wind systems.

3. Accomplishments

Highlights over the past year reflect its wide range of influence.

- BRIDGE has sought out ways to engage at-risk high school students by hosting weekly engagement with students at North Community High School (a minority high school in Minneapolis) and by sponsoring visits for these students to university laboratories.
- The project has developed usable designs to use in implementing wind energy systems in remote communities.
- Continued and expanded work with students at the Circle of Life High School (COL) on the White Earth Indian Reservation in Northern Minnesota. This work started with weeklong summer outreach in 2009 and now included bimonthly outreach at the school.
- 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.
- In total, BRIDGE members have made eleven trips to rural Nicaragua to build long-term relationships.

Work has accelerated over the last year with the support from CCEFP.

- Commissioned a1kW wind turbine in the community of La Hermita, Nicaragua.
- Visited several sites in remote areas of Nicaragua to assess their potential for community buy-in to partnerships that would result in implementation of renewable energy systems.
- Involved with a weeklong education program on the White Earth Indian Reservation.
- Activities and trips continue to involve exchange students from Norway.
- Over 20 university students have taken lead roles including travel and work in remote areas.

4. Plans

The BRIDGE Project (now Bridges Program) has formed strong ties with people and organizations of a diverse nature around the world. Plans include a concerted effort to leverage our connections. To this end, future plans include:

- Hold annual Summits in Nicaragua each August to bring together partners for support, sharing, and planning.

- Form two international branches of Innovative Engineers in Nicaragua to support the work of Bridges.

- Travel to Nicaragua 2-3 times per year for implementation and active engagement with communities and schools.

- Active engagement with Esc. Luis Valencia Albarado, a technical school in Jinotega, Nicaragua.

- Continued work with Prof Jeronimo Zeas of the National Engineering University in Managua, Nicaragua. Prof Zeas' work includes small to large scale wind projects in Nicaragua.

- Identify and connect with 3 additional communities in the Jinotega Department of Nicaragua. Work to be done in connection with AVODEC and Esc. Luis Valencia Albarado. The Program 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.

- Bimonthly visits to the Circle of Life School on the White Earth Indian Reservation to continue work in wind turbine design and development.

- Facilitate direct collaboration between students at the Circle of Life School on the White Earth Indian Reservation, universities in Nicaragua, AVODEC, and Esc. Luis Valencia Albarado.

Related Projects

The Program is supported and is a supporter of 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. Of these, the Innovative Engineers is also sponsored by the CCEFP and its cross connection has been very useful.

5. Milestones and Deliverables

- Formulating final working agreements between the University of Minnesota, Villanova University, the National Engineering University of Nicaragua, and LaSalle University in Leon, Nicaragua.

- Hold inaugural Bridges Summit in August 2014 in Nicaragua.

- Install wind turbine at the Circle of Life School on the White Earth Indian Reservation.

- Formulate working agreement with 3 additional communities in Nicaragua.

- Install wind turbine on a farm on Lake Managua.

- Continues support of hybrid hydraulic/electric wind turbine currently being developed by a CCEFP supported project through the Innovative Engineers student group.

6. Member Company Benefits

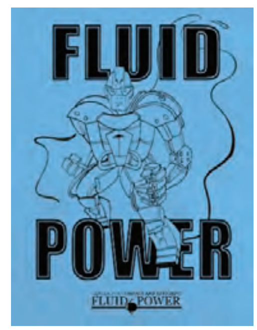
All of industry, and certainly the CCEFP's member companies, appreciate programs that are socially and educationally relevant. Bridges is such a program, building STEM skills among pre-college and university students; contributing to the quality of life within communities in need; and, given its new 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.

EO Project B.7 Fluid Power Challenge Competition

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	Cherie Bandy, Education Program Coordinator Don Haney, Communications Director Ben Adams and Alejandro Ojeda Saint-Martin, Volunteers
Industrial Partner:	FORCE America MICO, Inc. Pro Laser National Fluid Power Association (NFPA) University of Minnesota's College of Science and Engineering

1. Project Goals and Description



The Fluid Power Challenge is an event where eighth grade students learn how to solve an engineering problem using fluid power. The event comprises of two days. On the first day - Workshop Day - students are introduced to the basics of fluid power, get hands-on experience by building kits that use fluid power, and are introduced to the challenge they must solve. The students return to their schools to work in teams to design and build their fluid power device, along with keeping a portfolio to document their work. About a month later, the students return for the second day of the event - Challenge Day - to build their device they designed at their own schools and compete against the other teams in a timed competition. The goals of the Fluid Power Challenge are to:

- Actively engage students in learning the basics about fluid power
- Give support and resources to teachers for science and technology curriculum
- Create a fun learning environment for math and science
- Encourage students to acquire a diversity of teamwork, communication, engineering, and problem-solving skills
- Introduce eighth grade students to the fluid power industry
- Help build a strong workforce for tomorrow

2. How Project Supports the EO Program Strategy

This project supports the EO Program Strategy in several ways. Our work with strong partners, such as the National Fluid Power Association and Project Lead the Way, optimize both exposure and promotion of K12 fluid power education. The ease with which this project can be replicated maximizes opportunities for use by many workshop leaders in many settings. An essential part of the CCEFP strategic plan is to promote diversity in science, technology, engineering, and math (STEM) fields. The Fluid Power Challenge Competition enables students in and around Minnesota to use concrete learning experiences with hydraulics and pneumatics to better understand design concepts, physics concepts, develop mathematical thinking, problem solving; and participate in team-building through hands-on construction engineering.

3. Accomplishments

Press Release

Minneapolis, Monday, January 6, 2014 — The University of Minnesota will host the NFPA Fluid Power Challenge, a competition that gets middle school students excited about fluid power. A Workshop Day for the event was held on December 3, 2013, followed by a Competition Day on January 14, 2014.
During the Fluid Power Challenge, middle school students learn about fluid power technology (hydraulics and pneumatics) and gain hands-on experience while building a fluid power mechanism with real world applicability. The program is designed to introduce the students, and their teachers, to the world of engineering and fluid power careers.

During the Challenge Day at the University of Minnesota, 21 8th-grade teams (four students per team) will design and build fluid power mechanisms that pick an object from one platform, rotate and place it on another. In addition to the number of pick-and-place cycles a school's machine completes, a review of each team's design approach, teamwork and portfolio will be used in the final evaluation.

A student from a past competition said "This opens up more opportunities for engineering and careers kids aren't aware of. It's fun...you get to work with other kids and learn more math and science."

Through the Challenges, the Center for Compact and Efficient Fluid Power (CCEFP) at the U of MN and the National Fluid Power Association (NFPA) hopes to encourage students to select more mathematics and science courses in their high school curricula to keep their options open for technology-based post-secondary studies.

Highlights

- 2013/2014 Fluid Power Challenge Competition recruited 20 teams, over 80 students and teachers, from Minnesota, the majority coming from outside the Twin Cities. Only one veteran teacher returning with a new team of students. A school from Northern Minnesota brought five teams of girls, which won three of the five awards.

- 2012 / 2013 Fluid Power Challenge Competition recruited 18 teams from Minnesota, the majority from the Twin Cities of Minneapolis and St. Paul. Three teams joined the event from outstate western Minnesota.

- Typically, over half of the 8th grade student participants are female. Secondly, by observation, a highly diverse student body.

- Several of the teachers recruited were Project Lead the Way teachers, who have a fluid power module in their PLTW Principles of Engineering curriculum.

- Each sponsoring company provided one or two engineers to judge the competition.

- In early 2013, a local news station, NBC's KARE 11 highlighted the Fluid Power Challenge on their 5 pm newscast. It can be viewed at YouTube: http://www.youtube.com/watch?v=_IdvGyWxnTo.

- One of the 2013 corporate sponsors, Tolomatic, wrote a blog about the competition: http://info.tolomatic.com/linear-actuator-blog/.

4. Plans
Given the successful efforts by CCEFP to coordinate the Fluid Power Challenge, and the strong interest in industry sponsors and teachers alike, the CCEFP will plan to host a competition each Fall. Goals include gaining more industry sponsorship, to reduce the cost to the Center, including direct funding from NFPA. The sustainability of the project includes identifying external funding sources and continued support from NFPA.

- Host **two** competitions in the Fall of 2014

- Recruit more industry sponsors
- Identify additional funding sources for additional support

Related Projects

This project aligns well with the Center's former relationship with Project Lead The Way (PLTW), where CCEFP and NFPA provided content experts to design a fluid power curriculum module in PLTW's Principles of Engineering course. This competition provides the means and the applicability for PLTW teachers to teach hands-on hydraulics and pneumatics in a design environment.

5. Milestones and Deliverables?

- Host a Fluid Power Competition each Fall at one or two CCEFP location(s)
- Recruit a minimum of 15 teams to participate in any Fluid Power Challenge Competition
- Recruit a minimum of five industry sponsors
- Keep costs low by finding additional sources of sponsorship and funding support
- Generate interest in fluid power at the K12 level and through teachers
- Market this program and create an investing group of teachers who anticipate participating in this program.
- Get University of Minnesota to buy-in for additional sustainability.
- This program has been identified as part of the CCEFP's future program portfolio.

6. Member Company Benefits

The 2013-14 Fluid Power Challenge corporate sponsors include MICO, Inc., FORCE America, National Fluid Power Association (NFPA), University of Minnesota's College of Science and Engineering. 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.

2013-2014 Fluid Power Challenge Competition at UMN

2012-2013 Fluid Power Challenge at UMN

EO Project C.1: Research Experiences for Undergraduates (REU)

Project Team

Project Leader: Alyssa A Burger, Education Outreach Director, CCEFP

Other Personnel: CCEFP REU faculty advisors
CCEFP REU 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

- The CCEFP is pleased to announce it being the recipient of an NSF REU Site Award. Three years, a $390,000 grant.
- To date, the CCEFP has hosted over 150 undergraduate students in the highly successful REU program.
- Since revising the CCEFP REU program structure in 2008, the CCEFP REU Program has recruited, on average, over 35% women, and over 33% racially or ethnically underrepresented students into the program on a yearly basis. The CCEFP's recruiting strategy includes identifying institutions, programs and people with whom to develop relationships that, in turn, open pathways to CCEFP summer programs and beyond for underrepresented students.
- The CCEFP completed a longitudinal study of our past participants in early 2014. At the time of the report, 57% of all former CCEFP undergraduate researchers enter graduate school, and 25% of those are PhD candidates. Extremely positive statistics!

2013 REU Program:

- Eighteen REU students participated in summer 2013, the seventh year of the program. Six of the students were recruited from outside the CCEFP seven institutions.
- All REUs participated in the Fluid Power Bootcamp at Purdue University, lead by over 10 faculty and graduate student lecturers and laboratory leaders. Given the experience from the previous two years, Professor Andrea Vacca, Purdue University, continues to improve upon the instruction.

2013 REU at Purdue Fluid Power Bootcamp

2012 REU Program:

- Twenty-three REU students participated in summer 2012, the sixth year of the program: three at the University of Minnesota, one at the University of Illinois, nine at Purdue, two at MSOE, three at North Carolina A&T, two at Georgia Tech and three at Vanderbilt University. None of these REU students had previous experience with CCEFP. 10 of the 23 were recruited from outside the CCEFP's core institutions.
- Following a highly successful Fluid Power Bootcamp at the University of Minnesota in 2011, the CCEFP hosted the 2012 REU Fluid Power Bootcamp at Purdue University. Professor Andrea Vacca of Purdue orchestrated the bootcamp curriculum, which included three separate fluid power lab sessions led by CCEFP PU graduate students. Those lab sections are: Lab 1: Pump/system Characterization on Water Hydraulic Test Rig; Lab 2: Circuit Construction and Debugging; Lab 3: Displacement Control System. Students had an opportunity to socialize with each other as well as find themselves completely immersed in fluid power technology. The program at PU was so well received, the Center will host the 2013 REU Bootcamp at PU as well.
- Two REUs from North Carolina A&T State University received travel grants from NFPA to attend and present a poster at the Fall 2012 NFPA Workforce Summit and CCEFP Annual Meeting held at the University of Illinois, Urbana-Champaign.

4. Plans, Milestones and Deliverables

- The CCEFP's first and second 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 2012 and awaits word.
- The Center is committed 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 2013 Fluid Power Bootcamp at Purdue University.
- The University of Minnesota will host two Hispanic REU students from the Rochester Institute of Technology, as an exchange program with Professor Larry Villasmil, who will work on a joint project on wind power with Professor and Director Kim Stelson. The students will be co-supported by RIT's NSF LSAMP Program and CCEFP.
- As in 2011 and 2012 REU program, the students will participate in a research blog, launched and contributed to by the students involved.

- 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.
- 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 2013 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.

EO Project C.2: Fluid Power College Level Curriculum

Project Team

Project Co-Leaders: Prof. Will Durfee, University of Minnesota
Prof. Jim Van de Ven, University of Minnesota

Other personnel: Prof. Andrea Vacca, Purdue University

1. Project Goals

The purpose of the college level curriculum project is to create and disseminate high-quality teaching and learning material on fluid power. The target audience is undergraduate and graduate engineering students and professionals in fluid power companies.

One component of the project is the Fluid Power OpenCourseWare (FPOCW) activity, which 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. FPOCW content is archived 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.

The current FPOCW content includes lecture notes from fluid power courses at Minnesota, Purdue and Vanderbilt; videotaped lectures from the fluid power lab course at Minnesota, and two open-source textbooks.

Another component is a fluid power MOOC (massive online open course) targeted at undergraduate and graduate students working in fluid power research labs, and at entry level engineers in fluid power companies.

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. Further the projects enables online education of engineers in the fluid power industry who are new to fluid power.

3. Achievements

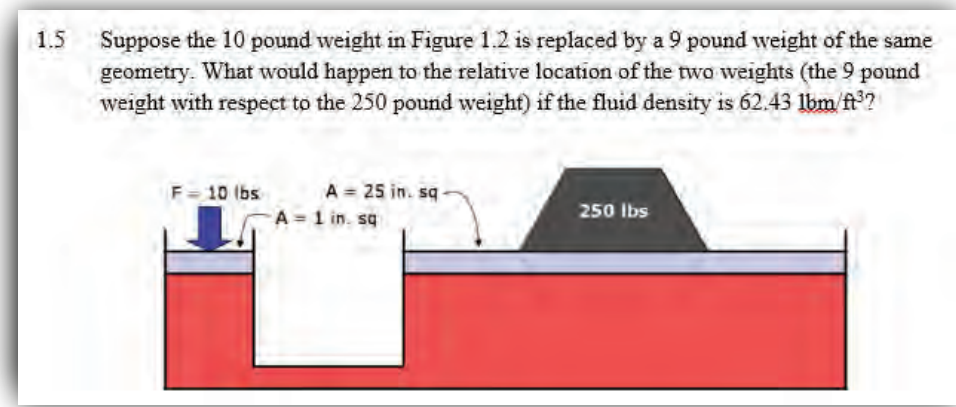
Content for fluid mechanics

Fluid power course material for introductory fluid mechanics courses continues to be developed by Vacca at Purdue.

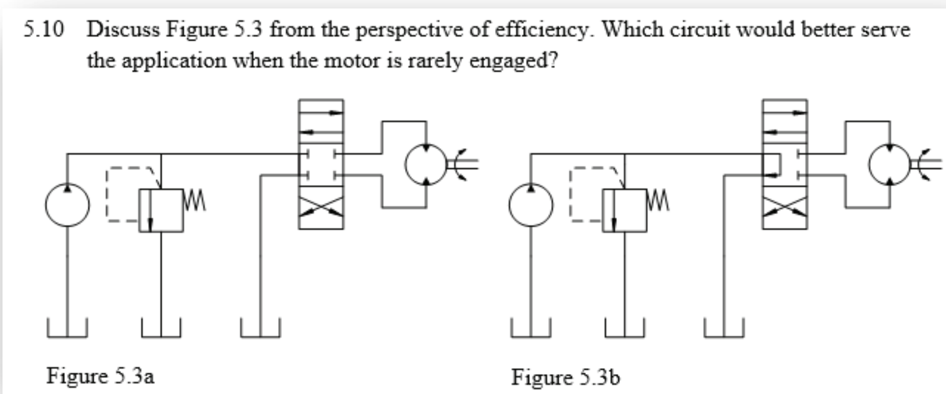
Fluid power problem set bank

A question bank was developed to support insertion of fluid power content into courses. This project was undertaken after we realized that a barrier to teaching fluid power is a lack of problems for use as in-class examples and on problem sets. In Summer 2013 "Problems in Fluid Power" was developed to fit this need. It is a 33 page document containing hundreds of fluid power problems. Problems are cataloged into six categories: fluid fundamentals; power, energy and work; internal flow and orifices, actuators; flow and pressure control valves; dynamic circuits. A companion solutions manual for the instructor was also developed.

One simple and one advanced problem from the bank are reproduced below.



1.5 Suppose the 10 pound weight in Figure 1.2 is replaced by a 9 pound weight of the same geometry. What would happen to the relative location of the two weights (the 9 pound weight with respect to the 250 pound weight) if the fluid density is 62.43 lbm/ft^3?



5.10 Discuss Figure 5.3 from the perspective of efficiency. Which circuit would better serve the application when the motor is rarely engaged?

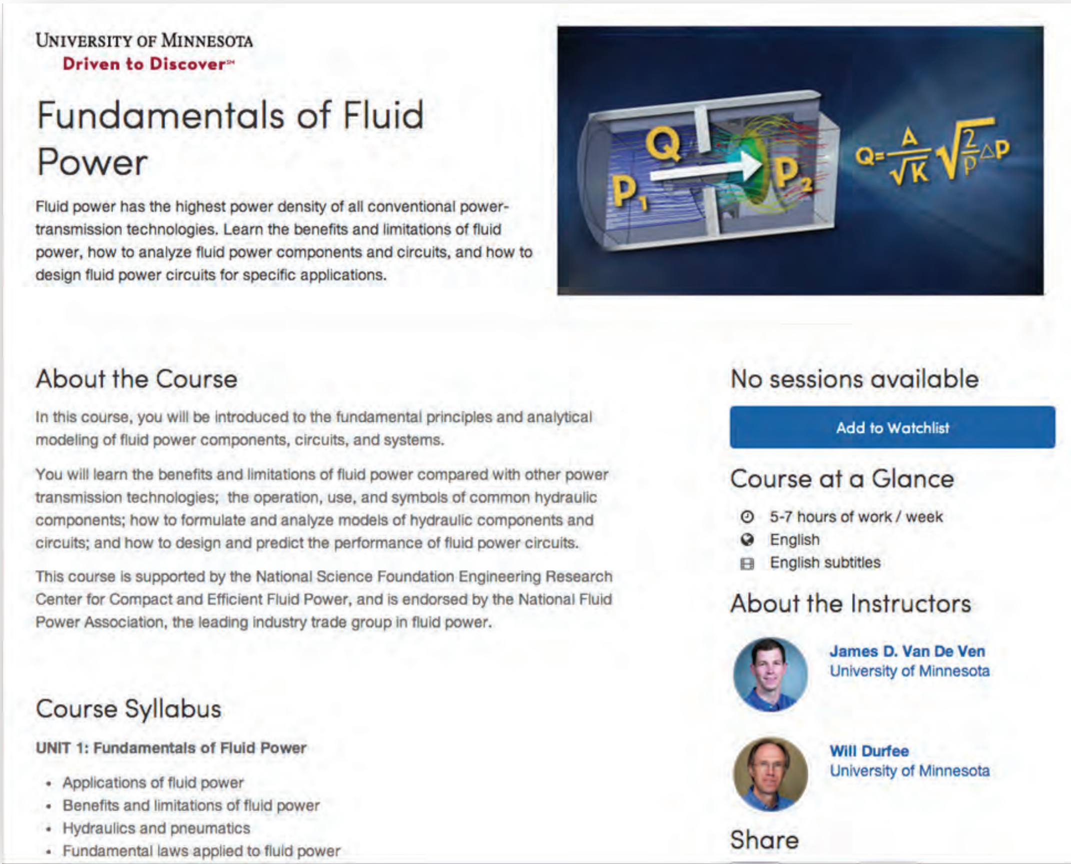
Figure 5.3a

Figure 5.3b

The problem solutions were created and vetted by Minnesota CCEFP graduate students.

Fluid Power MOOC

Minnesota professors Van de Ven and Durfee will be offering a Massive Online Open Course (MOOC) titled “Fundamentals of Fluid Power.” The course was competitively selected by the University of Minnesota to be offered on Coursera, the leading world-wide provider of MOOCs. The course will introduce students to the fundamental principles of fluid power systems, circuits, and components. Students will learn: 1) the benefits and limitations of fluid power compared with other power transmission technologies, 2) the function of common hydraulic components, 3) how to formulate and analyze models of hydraulic components and circuits, and 4) how to design hydraulic circuits for specific system requirements. The course will be delivered through short, focused video presentations that will include lectures, laboratory demonstrations, large system demonstrations, and interviews with industry experts. The target audience for the course includes entry-level engineers, senior-level undergraduate students, and entry-level graduate students. The six week course will be first offered in Fall 2014. As far as we know, this will be the first fluid power course in the world to be offered in MOOC format.



4. Plans
(1) Revise intro to fluid power mini-book. (2) Develop a MOOC for release in Fall 2014. (3) Continue work on new mini-books.

5. Member Company Benefits
Member companies can use the course materials and curriculum internal training, or sales forces can use to educate customers. Member companies also benefit as more engineering students receive training in fluid power.

EO Project C.3: Fluid Power Projects in Capstone Design Courses

Project Team

Project Leader: Jim Van de Ven, University of Minnesota

Other personnel: Alyssa Burger, Education Outreach Director, CCEFP
All CCEFP faculty

Industry partners: NFPA and CCEFP 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. Long-term, this project is to be 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
The CCEFP Education and Outreach program initiated a supplemental funding program for faculty across the CCEFP who wish to advise and mentor a capstone project in fluid power. In this reporting year, four projects have been granted supplemental awards resulting in over 25 undergraduate engineering students gaining direct experience in fluid power. Secondly, the EO Program provided a $6,000 grant ($2^{nd}$ year of funding, EO Project C.3a) to Elizabeth Hsiao-Wecksler at UIUC to host a joint fluid power capstone project with a Bradley University.

CCEFP EO Supplemental Funding Awards:

University	Year	EO Funding	Project Title
Milwaukee School of Engineering	Fall 2013 / Sp. 2014	CCEFP Supp Award	"Fluid Power Legged Robot" MS Capstone Project by Jonathon Slightam, Advisor: William Farrow, MSOE
Bradley University	Sp. 2014	CCEFP Supp Award	"A Third-Generation Pneumatic Rotary Actuator Driven by Plantery Gear Train" CCEFP Advisor: Elizabeth Hsiao-Wecksler, UIUC
Bradley University	Sp. 2013	CCEFP Supp Award	"A Second-Generation Pneumatic Rotary Actuator Driven by Plantery Gear Train" CCEFP Advisor: Elizabeth Hsiao-Wecksler, UIUC
GeorgiaTech	Sp. 2013	CCEFP Supp Award	"Noise Control Device for Plumbing" CCEFP Advisor: Kenneth Cunefare, GT
Purdue University	Fall 2012 / Sp. 2013	CCEFP Supp Award	"Green, Human-Assisted Hydraulic Vehicle Design" *part of the Parker Hannifin Chainless Challenge Capstone Team* CCEFP Advisor: Andrea Vacca, PU
University of Minnesota	Fall 2012 / Sp. 2013	CCEFP Supp Award	UMN Parker Hannifin Chainless Challenge Capstone Team CCEFP Advisor: Brad Bohlmann, UMN
University of Illinois, Urbana-Champaign	Fall 2012 / Sp. 2013	CCEFP Supp Award	UIUC Parker Hannifin Chainless Challenge Capstone Team CCEFP Advisor: Elizabeth Hsiao-Wecksler, UIUC

A compilation of recent fluid power capstone projects at Center schools is shown in Figure 1 below.

University	Year	Sponsor	Project Title
UMN	Sp 2014	CCEFP & SMM	"Adiabatic and Isothermal Compression Exhibit." Exhibit design for the Science Museum of Minnesota on heat transfer in a compressed air energy storage system. (James Van de Ven and J. Newlin)
MSOE	AY13-14	CCEFP	"Fluid Power Legged Robot" MS Capstone Project by Jonathon Slightam (William Farrow)
UIUC	AY13-14	CCEFP	"A Third-Generation Pneumatic Rotary Actuator Driven by Plantery Gear Train" at Bradley University (Elizabeth Hsiao-Wecksler)
VU	AY12-13	CCEFP	This capstone design course for Mechanical Engineers at Vanderbilt, frequently features some projects involving fluid systems. Indirectly, CCEFP faculty shares lessons learned through ERC research on a case by case basis with student teams doing related projects. (Robert Webster)
UIUC	AY12-13	CCEFP	"A Second-Generation Pneumatic Rotary Actuator Driven by Plantery Gear Train" at Bradley University (Elizabeth Hsiao-Wecksler)
GT	Sp. 2013	CCEFP	"Noise Control Device for Plumbing" (Kenneth Cunefare, GT)
PU	AY12-13	Parker Hannifin and CCEFP	"Green, Human-Assisted Hydraulic Vehicle Design" *part of the Parker Hannifin Chainless Challenge Capstone Team* (Andrea Vacca, PU)
UMN	AY12-13	Parker Hannifin and CCEFP	UMN Parker Hannifin Chainless Challenge Capstone Team (Brad Bohlmann, UMN)
UIUC	AY12-13	Parker Hannifin and CCEFP	UIUC Parker Hannifin Chainless Challenge Capstone Team (Elizabeth Hsiao-Wecksler, UIUC)
UMN	Sp. 2012	CCEFP	Hydraulic Fuel Pump Drive (Brad Bohlmann)
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)
MSOE	Sp. 2010	CCEFP	An Investigation of the Tribological Conditions and Lubrication Mechanisms Within a Hydraulic Geroler Motor
MSOE	Sp. 2010	CCEFP	Fluid Power Actuator for use in Active Ankle Foot Orthotics
PU	Sp. 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

In the future, CCEFP expects to work with NFPA to promote capstone design projects in fluid power to its member companies. In recent years, NFPA board members committed to sponsoring fluid power capstone projects, likely CCEFP industry members may be interested in the same. A process is to be developed where CCEFP faculty or staff would facilitate matching CCEFP and NFPA companies with an interest in sponsoring a project to the appropriate engineering program, either within or outside the CCEFP network.

Regardless of the anticipated cooperation with NFPA, the CCEFP will continue to launch and support new fluid power capstone design projects every year within the local engineering capstone course. The CCEFP will continue to 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.3a Capstone Senior Design Project:
A second-generation, compact, light-weight, pneumatic actuation system for an ankle AFO

Project Team

Project Leader: Prof. Elizabeth Hsiao-Wecksler, MechSE UIUC

Other Personnel: Prof. Martin Morris, MechE, Bradley University
UIUC Graduate Students: David (Yifan) Li, Morgan Boes, Matt Petrucci, Mazhar Islam, Ziming Wang, Gavin Kwon

1. Project Goals and Description

Statement of functional objectives (what problem will be solved; or what will be developed; include metric for success if possible)

This project is a continued collaboration between researchers and students at the UIUC and Bradley University on a project to develop prototype pneumatic actuators that can be useful in Test bed 6 on the portable pneumatic ankle-foot orthosis (PPAFO). Limitations of the current pneumatic actuator on the PPAFO are torque output and size of commercially available small pneumatic rotary actuators (example: 15 Nm @ 150 psi, dual vane, 2.5" dia, casing height 2.4"; model PRNA30D, Parker Hannifin Corp). (Figure 1)

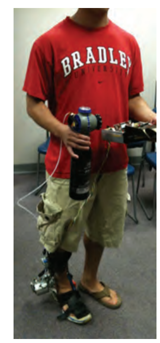


Figure 1. PPAFO with current commercial rotary actuator.

This E&O project has supported three capstone senior design project teams in the Mechanical Engineering Department at Bradley University in Peoria, IL. Bradley is a small, private university with undergraduate and graduate programs, and is located 90 miles from the UIUC campus. Their capstone design course covers two semesters. Prof. Martin Morris has an expertise in fluids and design, and runs the capstone design course in the ME department. CCEFP E&O funds have been used to support three different design teams, AY11-12, AY12-13, and currently AY13-14.

The objectives for the first team (AY11-12) were to: (1) increase torque output of pneumatic rotary actuators in a compact housing, (2) explore the possibility of using a planetary gear train constructed from plastic designed to increase the output torque, (3) examine the use of labyrinth sealing in the pneumatic actuator to minimize frictional losses, and (4) perform a thermodynamic analysis to determine if energy consumption of pneumatic fuel (compressed CO_2) could be improved with different design modifications to power source. (Due to the vaporization process of CO_2 from liquid to vapor, cooling of the CO_2 canister is observed. Temperature of a gas is negatively correlated with gas density, which could affect fuel efficiency.)

The original objectives for the second team (AY12-13) were to: (1) retain, as a minimum, the torque output generated by the compact, first-generation pneumatic rotary actuator while increasing the number of activation cycles, (2) explore the possibility of increasing the efficiency of the plastic planetary gear train, (3) improve the effectiveness of the labyrinth seal in the pneumatic actuator to maintaining low frictional losses, and (4) improve the utilization of the driving gas energy (the available energy). However, as the school year progressed and the students brainstormed alternate actuator designs, these original objects were not addressed since the team decided not to continue to focus on just modifying last year's design mainly due to leaking issues that were encountered with trying to develop their own pneumatic actuator. The team decided to use a single off-the-shelf linear pneumatic cylinder and convert the translational force to a rotary torque via a gear train.

The objectives of the third team (AY13-14) are similar to the previous year but modified for the linear system: (1) retain, as a minimum, the torque output generated by the compact, first-generation pneumatic linear actuation system, (2) explore the possibility of increasing the efficiency of the gear train, (3) maintain low frictional losses in the pneumatic cylinder, and (4) improve the utilization of the driving gas energy (the available energy). This team has chosen to use a dual linear cylinder design to increase torque capability and to decrease the depth of the actuation system relative to side of the leg.

For all teams, a working prototype actuator is the primary deliverable from the 9 month capstone senior design project experience.

2. How Project Supports the EO Program Strategy

How does the project support the E&O program?

The primary educational impact of this project is to expose a team of undergraduate engineering students to concepts of fluid power design, specifically rotary torque generation using a pneumatic power source. All of the students participating in the capstone design course will be exposed to fluid power issues as they participate in the gated review process which includes four oral progress report presentations by the design team. The results from the project will be revealed to the entire campus community on both campuses during two campus-wide expositions. The project has exposed the student teams to first-hand experiences with fluid power through pneumatic design issues such as torque generation, leakage and seals, fluid dynamics, and also thermodynamic analysis of dealing with expansion of compressed gas (CO_2).

3. Accomplishments

Provide a list of achievements in previous years with more detail on accomplishments in the past year.

The first-generation prototype (Figure 2) was delivered at the end of AY11-12. It had a diameter of about 3.5” with a casing height of about 1.5”, and utilized labyrinth sealing. The torque output for the prototype actuator was designed to deliver 40 Nm of torque with a relative motion of 55° between the components using a supply pressure of 100 psig. The planetary drive train was designed to deliver a torque amplification of about 3. Actual testing of the design by the end of the 9 month period was not possible due to leakage in the system. The thermodynamic analysis found that if the power source (compressed CO_2 canister) was allowed to remain at an isothermal as opposed to isentropic condition, then the system could have a ~10% improvement in actuation duration.

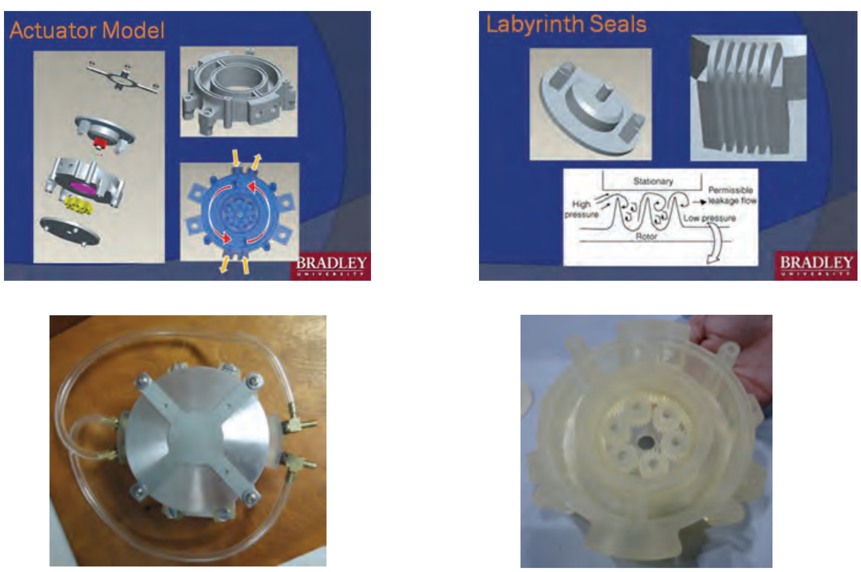


Figure 2: CAD and physical models of first-generation pancake pneumatic rotary actuator driven by planetary gear train that were completed by AY11-12 team.

The second team used a commercially-available pneumatic actuator in order to avoid the leakage problem that can be encountered by designing one's own actuator. Further, instead of designing a pancake rotary actuator, they decided to use a linear actuator combined with a limited range sector gear in order to convert translational motion to the linear actuator into rotation motion at the ankle (Figure 3). The final prototype was able to produce 23 Nm at 90 psi, range of motion of 55°, and mass of 588 g.

Figure 3. CAD and physical models of design which used an off-the-shelf linear actuator with sector gear to create torque about the ankle axis by AY12-13 team. Right panel: comparison of linear design with commercially available pneumatic rotary actuator.

The third year team is still working on the project. After examining multiple design concepts, they have recently decided to select a dual cylinder design. The proposed design is anticipated to generate 44 Nm at 110 psi, have overall length of 8.8", width of 3.25", and depth of 2.2", and weigh 664 g.

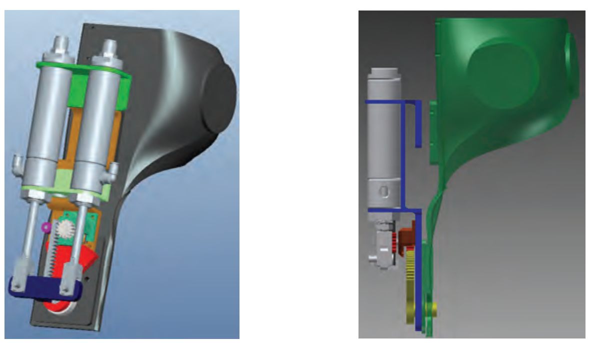


Figure 4. CAD models of proposed design attached to orthosis lower leg shell. The design uses dual off-the-shelf linear actuators with yoke and sector gear by AY13-14 team.

The Bradley design teams for all years have consisted of four Mechanical Engineering students. For AY11-12 and AY112-13, both teams had two women for each year. The AY13-14 team has one woman.

Bi-weekly/weekly teleconference meetings have been held between UIUC and Bradley team members throughout this project. UIUC faculty and students also virtually attended staged gateway review presentations, which are used to evaluate team progress and deliver concurrent feedback by clients, Bradley faculty, and other design teams.

AY11-12 Bradley students presented their design during the University of Illinois' College of Engineering Open House in March 2012 (Figure 5). Engineering Open House weekend attracts thousands of students (K-college), teachers, and the general public from across Illinois and the Midwest. The Bradley students also presented their results as part of the annual Bradley University Student Exposition during Parents Weekend in May 2012.
AY12-13 Bradley students also presented a poster on the first generation design and thermodynamic analysis at the CCEFP Annual Conference in September 2012 (Figure 5). The AY13-14 team is anticipated to present their design at the 2014 University of Illinois' College of Engineering Open House event again.

Figure 5: (left) Bradley student presenting team's work during the 2012 University of Illinois' Engineering Open House weekend. (right) Bradley students at 2013 CCEFP Annual Meeting student poster show.

4. **Plans**

What are the plans for the next 3 years, if applicable?   What is the sustainability plan of the project, if any?

If funding for this project were to continue over the next 3 years, future student teams would work on refined versions of the previous actuator prototypes with focused efforts to continue to improve system efficiency in terms of fuel consumption while continuing to address the need for higher output torques generated from smaller packages.

Related Projects

Is there any integration of this project elsewhere?

Should a successful prototype be constructed, it would be tested in Testbed 6 on the portable pneumatic ankle-foot orthosis test platform.

5. **Milestones and Deliverables?**

What are the expected milestones and deliverables for the project.

The milestones for the project align with the milestones defined by the Bradley ME department's senior design curriculum:

1) 1st Oral Presentation (Gateway 1)	Before September 31, senior year
2) Proposals to the Client	Before October 31, senior year
3) 2nd Oral Presentation (Gateway 2)	Before October 31, senior year
4) Written Progress Report	Due end of Fall semester
5) 3rd Oral Presentation (Gateway 3)	Before February 28, senior year
6) 4th Oral Presentation (Gateway 4)	Before April 31, senior year
7) Written Final Report & Deliverables	Due end of Spring semester

For all teams, a working prototype actuator is the expected primary deliverable at the end of the course. Additional deliverables were interim and final reports. These reports include performance characterization of the actuator at a range of pneumatic pressures, engineering drawings of the components, and details about the actuator construction.

6. **Member Company Benefits**

Who are your corporate sponsors, how have they contributed, how do you expect them to contribute in the future?

This project does not have corporate sponsors, although the students on both teams have worked with Winzler Gear, a plastic gear engineering and manufacturing firm in Chicago, which has worked with the students to design appropriate gear trains. The AY12-13 team worked with engineers at Bimba Manufacturing on the linear pneumatic actuator. Should future designs be successful, we would be happy to share with CCEFP or NFPA industry members.

EO Project C.3b: Parker Hannifin Chainless Challenge

Project Team

Project Leader:	Brad Bohlmann, University of Minnesota
Other personnel:	Elizabeth Hsiao-Wecksler, University of Illinois, Urbana-Champaign
	Andrea Vacca, Purdue University
Industry partners:	Parker Hannifin

1. Project Goals

The Parker Hannifin Chainless Challenge is a design competition for undergraduate college and university students. The focus is creating a human powered vehicle (typically bicycles or recumbent or upright tricycles) in which the conventional mechanical chain drive is replaced with a hydraulic transmission. Elements of the competition include the design (creativity/novelty, functionality, presence of renewable energy systems), fabrication (quality, aesthetics), design process (design report, cost analysis) and a three event competition (efficiency, acceleration and distance events).

The goal of this project is to provide students with an opportunity to learn about fluid power, apply their knowledge to a real world open-ended design project and compete in a national competition to demonstrate their work.

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. It also increases the number of mechanical engineers graduating from Center schools with training and experience in fluid power (about 20 students from Center schools per year).

3. Achievements

The Chainless Challenge is a two semester commitment for students and faculty. In Fall semester, the students generally work on the project in their capstone design projects course. A team of 5-6 undergraduate students learn about fluid power, develop design specifications for the modifications to their bike, complete the design and install the modifications on the bike. In Spring semester, the students test and optimize the bike's operation in preparation for the national competition in April.

There are typically about a dozen teams in the Chainless Challenge competition. In 2011-12, CCEFP was represented by Illinois, Illinois Tech (advised by Prof. Jose Garcia, a recent CCEFP PhD from Purdue), Minnesota and Purdue. Minnesota took second place overall in the competition. In the 2012-2013 competition, CCEFP was represented by teams from Illinois, Minnesota and Purdue. Illinois took first place overall in the event (photo at right).

One student from the University of Minnesota team participating in both the 2011-12 and 2012-13 Chainless Challenges is currently pursuing a Masters degree in a fluid power-related area at UMN. Prof. Perry Li is advising both students.

Most schools have a one semester capstone design course which doesn't align well with the two semesters required for Chainless Challenge participants. The supplemental funding from CCEFP Education and Outreach helps to provide resources that ease this challenge.

4. Plans

The Chainless Challenge is a fun and educational experience for the students and advisors. It provides a unique opportunity for students to learn about fluid power. All of the schools currently participating have found it to be a meaningful experience for their students and they plan to continue fielding teams for the competition. We hope to expand CCEFP's participation in Chainless Challenge ideally having teams from each of our seven schools in future competitions.

5. Member Company Benefits

Capstone design projects are a way to connect the Center to the engineering program at a local university. The Chainless Challenge provides an in depth exposure of students to fluid power. Even if their career path doesn't take them into the fluid power industry upon graduation, their knowledge of fluid power makes it a possible solution for the engineering challenges they will face during their career.

Parker Hannifin benefits directly by meeting and working with the students on the project team. They have an opportunity to observe students in a job-like situation which can help find potential employees. It also provides a way to get bright minds on an engineering problem of interest to the company.

EO 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

- ME 3017: System Dynamics taught by Jun Ueda at Georgia Institute of Technology. Incorporates modeling of fluid power systems. New 2014.
- ME 4452: Control of Dynamic Systems taught by Jun Ueda at Georgia Institute of Technology. Incorporates modeling of pneumatic systems as an example for formulating differential equations. New 2014.
- Problem Set for Fluid Power System Dynamics Mini-Book developed by the students at the student leadership retreat in August, 2012. The problem set will be integrated into the next edition of the mini-book, making it easier for instructors to utilize the book in existing courses by being able to assign the problems as homework.
- Developed a Video Lecture Archive from Fluid Power Controls Laboratory taught by Professor James Van de Ven at the University of Minnesota. The videos, available in multiple formats, and the handouts from in-class activities are available on the Fluid Power OpenCourseWare site. New 2012.
- INEN 371: Human Factors Engineering taught by Professor Eui Park & Steven Jiang at NC A&T University, uses outcomes of CCEFP funded projects
- INEN 665: Human Machine Systems taught by Professor Eui Park at NC A&T University uses outcomes of CCEFP funded projects. New 2011.
- ME 271: Introduction to Robotics taught by Robert Webster at Vanderbilt University covers forward and inverse kinetics, dynamics and control of manipulators. Includes a hands-on final project. Some examples are drawn from ERC funded project 2G. New Fall 2012.
- ABE 435: Hydraulic Control Systems taught by Professor Andrea Vacca at Purdue University was prepared using material from his CCEFP research and educational program. New Fall 2012.
- ME 310: Fundamentals of Fluid Dynamics taught by Professor Randy Ewoldt and some material contributed by Andrea Vacca (Purdue U) is the traditional undergraduate fluid mechanics course. Fluid power examples are included in homework to emphasize basic principles. A single lecture is dedicated to fluid power. New Spring 2013.
- ME 236/336: Linear Control Theory taught by Eric Barth at Vanderbilt University includes homework and examination questions related to the control of fluid power systems. Fall 2010.
- ME 351: Nonlinear Control Theory taught by Eric Barth at Vanderbilt University includes great examples of pneumatic systems are included in the course. New Spring 2013.

- ME 340: Dynamics of Mechanical Systems taught by Andrew Alleyne at University of Illinois at Urbana-Champaign, includes a lab that uses fluid power.
- ME 360: Signal Processing taught by Andrew Alleyne at University of Illinois at Urbana-Champaign, includes a lab that uses fluid power.
- ME 236/336: Linear Control Theory taught by Eric Barth at Vanderbilt University includes homework and examination questions related to the control of fluid power systems. Fall 2010.
- 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

- Minnesota professors Van de Ven and Durfee will be offering a Massive Online Open Course (MOOC) titled "Fundamentals of Fluid Power." The course was competitively selected by the University of Minnesota to be offered on Coursera, the leading world-wide provider of MOOCs. The course will introduce students to the fundamental principles of fluid power systems, circuits, and components. Students will learn: 1) the benefits and limitations of fluid power compared with other power transmission technologies, 2) the function of common hydraulic components, 3) how to formulate and analyze models of hydraulic components and circuits, and 4) how to design hydraulic circuits for specific system requirements. The course will be delivered through short, focused video presentations that will include lectures, laboratory demonstrations, large system demonstrations, and interviews with industry experts. The target audience for the course includes entry-level engineers, senior-level undergraduate students, and entry-level graduate students. The six week course will be first offered in Fall 2014. As far as we know, this will be the first fluid power course in the world to be offered in MOOC format.
- 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 completion of ongoing projects to develop mini-books.
    - Andrea Vacca, Purdue – Fluid Mechanics module
    - Robert Cloutier, Stevens Institute of Technology – Systems Engineering
    - 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.

EO Project C.5: giiwed'anang North Star Alliance

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	Simone Gbolo, North Star STEM LSAMP Anne Hornickle, North Star STEM LSAMP
Participating Colleges / Universities	University of Minnesota, University of Minnesota-Morris

1. Project Goals
The American Indian Science and Engineering Society (AISES) is a national organizations with a goal: to increase the number of Native American college students in STEM fields. In 2007, the CCEFP launched the giiwed'anang North Star Alliance which helped to form partnerships between the AISES student chapters in Minnesota. It exists to provide tools and resources to assist students of AISES Chapters. Since inception, the alliance has found its niche – to continue to be a resource, a small centralized organization-bridging people together. Now its primary function is student travel support to attend AISES related events.

2. How Project Supports the EO Program Strategy
This program is designed to build interest in and prepare underrepresented students for STEM careers.

3. Achievements

- **2013**
  - The CCEFP helped to co-sponsor 8 AISES students to attend the AISES National Conference in Boulder, CO, Fall 2013 and sponsored a group dinner.
- **2012**
  - The giiwed'anang Northstar STEM Alliance continues to provide student support to chapter members in Minnesota, primarily at the University of Minnesota Twin Cities and Morris campuses. Student support includes travel grants, open house grants, sponsored meetings and gatherings.
  - giiwed'anang along with the Northstar STEM LSAMP Alliance (UMN), Northstar AISES Professional Chapter and the University of Minnesota's College of Science and Engineering sponsored over 14 students to attend the AISES National Conference in Anchorage, Alaska, November 1-3, 2012. giiwed'anang hosted a dinner for over 40 student participants in Anchorage, during the AISES National Conferences.
  - giiwed'anang sponsored the travel expenses for four University of Minnesota AISES Chapter students to attend the All-National Rocket Launch workshop in Green Bay, WI, December 2012. Co-sponsorship includes the Minnesota NASA Space Grant Consortium. The past two years, the UMN-TC AISES Chapter has participated in this rocket competition, to score in first and second places.
  - The University of Minnesota AISES Chapter now has over 20 members, 10 highly active members, the highest enrollment the Chapter has ever had on the Twin Cities campus.
  - giiwed'anang will sponsor the attendance of several students at the AISES Leadership Conference in Albuquerque, New Mexico in February 2013.
  - giiwed'anang, along with the Northstar LSAMP (UMN) will sponsor the attendance of the entire UMN-TC AISES Chapter to attend the AISES Regional Meeting in Morris, Minnesota, February 2013.

4. Plans, Milestones and Deliverables

- Every effort will be made to find a viable organization within the University of Minnesota to continue the work of the giiwed'anang North Star Alliance.
- This program has not been selected to be part of the future CCEFP program portfolio.

5. Member Company Benefits

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 Project Lead The Way (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

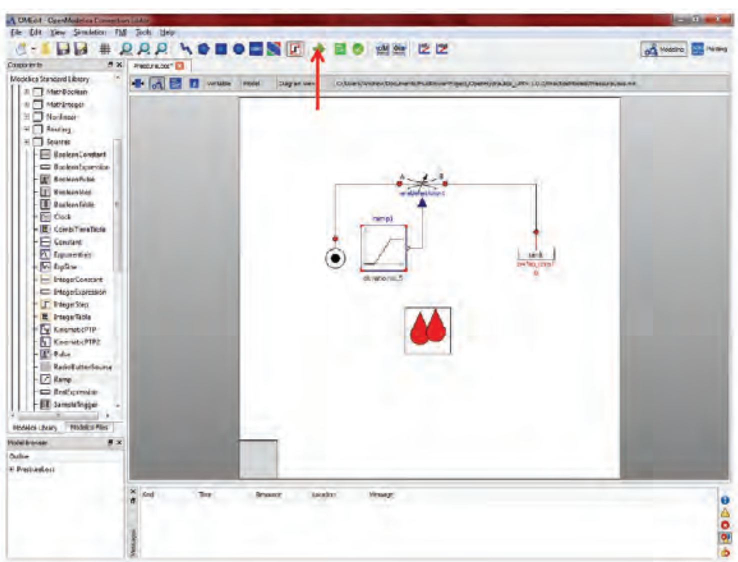
Not all students have access to fluid power hardware through teaching labs or to professional-grade fluid power simulation applications. Exposing more undergraduate and pre-college students to fluid power engineering can be achieved by providing a high quality simulation package that can be used by anyone 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.

The simulator uses the OpenHydraulics Modelica library from Georgia Tech and runs on the OpenModelica simulation environment. The front-end GUI is based on the Open Modelica Connection Editor.

The front-end is drag-drop-and-connect style that has the user pulling components from a parts library and connecting components with lines that represent conduits. The component library is small, but includes, for example, essential orifice drops, line length drop, cylinder volumetric and force efficiency models.

3. Achievements

Bugs in some of the component models have been worked out, and the basic interface to the Modelica Connection Editor has been built. A prototype user's manual has been started. The image below is a screen shot of a circuit containing a pressure source connected to a variable orifice.



4. Plans

- Continue development of simulator with goal of first use for students in the fluid power MOOC

5. Milestones and Deliverables

- First release of simulator in September 2014.

6. Member Company Benefits

Increased awareness of fluid power. Increased knowledge of fluid power by engineering students. Use of simulator by entry-level engineers in the company to simulate rudimentary hydraulic circuits.

EO Project C.8: Student Leadership Council

Project Team

Project Leader:	Alyssa Burger, Education Outreach Director, CCEFP
Other Personnel:	Cherie Bandy, Education Program Coordinator, CCEFP 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 within 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. In addition to university representatives from each CCEFP partner institution. The SLC serves as a liaison between the student body and the senior CCEFP leadership providing guidance, 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. Although a wide platform of methods exists to educate young students about science, technology and specifically fluid power, the importance of a human connection cannot be overstated. In this aspect, the student body of the CCEFP is potentially the greatest asset to inspire pre-college students of all ages. Presently the SLC itself sponsors project grants which allow individuals at member universities to pursue projects that allow them to connect with and educate the youth within their communities.

3. Achievements

To fulfill the mission of the Student Leadership Council, a number of distinct efforts are undertaken by the SLC membership supported by this EO project:

Travel Grants

The SLC Travel Grant Program aims to provide funds for students to travel to another project or industry location, making collaboration more accessible. Twice a year the SLC solicits proposals for travel by contacting all CCEFP students and faculty. Member students are invited to submit short written proposals and the SLC discusses and votes on which travel grants to approve based of funding resources and proposal strength. The maximum grant for any trip is $1,000, and preference is given to collaboration between projects over collaboration with industry. In addition to providing an outstanding collaborative opportunity for CCEFP graduate students, it also provides an experience for members of the SLC who must review and vote on a variety of differing proposals.

This program has proven to be very popular among students and faculty. During year 8, 7 travel grants were awarded. In February 2013, David Comber traveled from Vanderbilt to MSOE to collaborate with Jonathon Slightam on a MRI compatible pneumatic linear stepper motor.

"*During my trip to MSOE, Jonathon and I brainstormed several conceptual designs for an MRI-compatible linear stepper motor, to be powered by hydraulic or pneumatic fluid. Each concept was evaluated using key performance criteria and the best idea was selected for us to take to the detailed design and prototyping stage. We began the detailed design during my visit and completed it after I had returned to Nashville"* - David Comber

The power of face to face interaction, especially early in a collaborative effort, cannot be stressed. This particular collaboration spurred a prototype design, illustrated below, which has been submitted for a provisional patent. Although a second follow-up travel grant was awarded for the summer of 2013, virtual collaboration efforts proved sufficient to continue project development and the award was unneeded.

Project 2G, Linear Stepper Motor Prototype

Travel sponsored through a SLC project grant during the summer of 2013 fostered collaboration between a specialist gear manufacturer and project 1F.1, providing necessary expertise and insight. "*Travel to the Concentric AB® facility in Rockford, IL was to discuss the benefits of introducing asymmetric gears in external gear machines. In the course of project 1F.1, a new design of gear machines was developed with asymmetric teeth [to] significantly reduce the fluid borne noise emissions. In this visit, simulation results were discussed with the specialists of the company, and to understand the manufacturing processes to be used for asymmetric gears in mass production, since they have never been used in a hydraulic gear machines previously. Several constructive suggestions were provided by the engineers at Concentric, which proved to be beneficial in improving/refining the results towards a final machinable product.*" - Ram Sudarsan Devendran

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 lunch 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, four project grant proposals were awarded to students at various institutions by the SLC. Three of those grants were utilized, to provide lunch during center webcasts at CCEFP member institutions. The efficacy of food to encourage attendance is clear – previously often only SLC membership were in attendance whereas now often 5-6 students at institutions with food provided is not uncommon. The graph below shows student attendance from one member institution for 11 webcasts during 2013. Note the markedly decreased attendance for webcast number 10 which lacked provided food. This bi-weekly event also provides a social networking opportunity for center students within an institution. Nevertheless, there remains a segment of the center student population who do not attend the bi-weekly webcasts due to scheduling conflicts or differing priorities.

Student attendance during the bi-weekly webcast from one institution when food is provided.

CCEFP Bi-Weekly Webcasts

The Center estimates between 45 - 60 participants view each webcast on a regular basis. Participants include industry, faculty, staff and students. 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 special topics, education outreach presentations and "State of the CCEFP" discussions presented by Center Leadership.

As mentioned in the previous section, project grant food monies have been shown to clearly improve student webcast attendance. Thus, the center has decided that starting in 2014, a blanket provision will be made to fund food for the bi-weekly webcasts. Although this now relieves individual institutions from submitting project grant proposals for webcast food, SLC representatives at each member institution must still reserve meetings rooms, setup teleconference equipment, remind colleagues, and order delivery food for every webcast.

SLC Social Activities and Student Retreat

In addition to organizing the previously mentioned resources, the SLC also aims 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 2013 CCEFP student retreat was held in central Illinois by Caterpillar, a CCEFP member company. The two day event featured team building activities between students and an opportunity to present our research in an elevator pitch and poster session style to Caterpillar engineers who are normally unable to attend center meetings. A local baseball game the first evening and dinners provided opportunities for students to casually network with Caterpillar engineers and other center students. Two production facility tours and a visit to the flagship Caterpillar visitor center gave students insight to the product side of fluid power components and systems – an aspect often not given significant consideration in most center research due to the more fundamental work that comprises student's research. Above all, the event reestablishes personal connections between center students – a critical component to ensure strong inter-university collaboration. The SLC is grateful for the donation of time and resources by our member companies, without which engaging events like this would not be possible.

SLC Student Retreat in Peoria, Illinois – 2013

In addition to organizing the special student retreat where center students meet face to face, a special student lunch was held during the 2013 fall annual meeting. Taking advantage of the center event which most students already attended, the luncheon featured an ice-breaker activity, and a group wide student introduction to help foster names to faces and projects. The student leadership council membership were introduced as well as providing a "CCEFP Student Handbook" to new center students. The SLC flagship project and travel grant program were heavily promoted. Forcing interaction between unfamiliar individuals can be a challenge, but the luncheon was very well received by both old and new students alike.

SLC Student Luncheon in Sarasota, Florida – 2013

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 5 Infrastructure, sub-section 5.1 Configuration and Leadership Effort.

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, travel and project grants were awarded and processed, 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 colleagues at other institutions. The SLC will work to continue to ensure that a student lunch or dinner is scheduled for CCEFP meetings where students will already be present to take advantage of the opportunity.

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 conferences or retreats.
- The SLC is looking to promote and foster internships between CCEFP graduate students and member companies.
- The SLC hosted Webcasts 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.

EO 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 providing 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, nine supplemental requests have been proposed and/or granted.

- **Fall and Winter 2013**: (Two Awards). Mark Abotossaway, University of Minnesota, Native American undergraduate student supported on CCEFP affiliated project: Hydrostatic Transmission for Wind Power Generation.
    - **Advisor**: Professor Kim Stelson, University of Minnesota
    - **Post Doc**: Feng Wang, University of Minnesota
    - Wind power is becoming increasingly important as a source of renewable electric power that can greatly reduce the effects of global warming. The gearbox is heavy, costly and the least reliable component of the wind power generator. The purpose of the proposed research is the critically evaluate each possible advantage of a hydrostatic transmission over a mechanical gear box. Mark assisted in completing the layout of the wind turbine test platform; designed the foot mounts for the high-speed rotating group; quote the foot mounts from BSF and placed the order; get connection with Bosch team on the Hagglund motor installation; manufactured the base plate to align the electric motor to Bosch pump and Linde motor; ordered the installation tools and the tool box; ordered the bolts and nuts required on the platform; checked and installed the foot mounts from BSF, identified the issues. Mark was an essential asset to the project advancement.

- **Fall 2013**: Reginald White, North Carolina A&T State University, African-American undergraduate student supported on CCEFP project:
    - **Advisor**: Zongliang Jiang, North Carolina A&T State University
    - Mr. Reginald White was recruited through the CCEFP E&O program as an undergraduate research assistant to assist CCEFP graduate research assistants and faculty at NCAT to conduct human subject experiments. Throughout this experience,

Reginald acquired the fundamental knowledge and skills in using a multi-joint dynamometer system to conduct strength and mobility-related measurements on human subjects. He assisted with fitting the dynamometer system with a portable A/D data acquisition interface to allow the testing of custom serious games using the dynamometer system. Reginald also assisted with conducting the pilot tests.

- **Fall 2013:** Jose Gomez, Purdue University, Hispanic undergraduate student supported on CCEFP project: Investigation and Implementation of New Control Concepts for Active Vibration Damping
    - **Advisor**: Professor Monika Ivantysynova, Purdue University
    - **Graduate Student**: Enrique Busquets, Purdue University
    - The aim of this project was to investigate various methods of active vibration damping via DC on a skid-steer loader and look for ways to improve performance. The project focused on the development and implementation of different control methods to reduce the whole body vibration induced on the operator using the existing working cylinders. During his stay at Purdue, Edgar investigated these control concepts. Previous work in the Maha lab has confirmed that active damping shows improvements in comfort rating compared not only to the base machine but also to other available damping strategies. The existent simulation and machine prototype were utilized for the formulation and implementation of new control concepts; however, the prototype machine was not functional. In order to implement controller strategies, Edgar assisted on the reconstruction of the prototype's electronic system. Edgar was able to deliver a fully functional prototype for the implementation of active vibration damping and the corroboration of his active vibration damping strategy functionality with Displacement Controlled Actuation

- **Spring 2013**: Lashawn Nevins, North Carolina A&T State University. African-American undergraduate student supported on CCEFP affiliated project: Ankle-Foot Orthosis.
    - **Advisor:** Professor Zongliang Jiang, North Carolina A&T State University
    - **Project description:** Within the CCEFP, Test bed 6 is developing a portable and pneumatically powered ankle-foot orthosis (PPAFO) prototype. The human factors research team at NCAT supports this effort by developing a clinician-centered graphical user interface for the PPAFO. Such a user interface is designed around the clinician needs to facilitate their information processing and decision-making. More specifically, the design of the rehabilitation function of the PPAFO centers on the design of serious games (built into the user interface) as the main approach to therapies. With the built-in serious games, clinicians assemble therapy routines using game modules, and patients interact with the game-based routines independently from clinician supervision using the PPAFO as the main controller. The student will assist the research team to conduct experiments on human subjects recruited from the NCAT community. The student will measure user performance using the visual analog scale; analyzing and reporting the data. Student will implement the research findings in the development of the user interface.

- **Spring 2013**: Kali Johnson, University of Minnesota. Caucasian Female undergraduate student supported on CCEFP Testbed 6.
    - **Advisor**: Professor William Durfee, University of Minnesota
    - **Project description**: Develop and test hydraulic ankle foot orthosis system. Specifically will be responsible for developing and conducting performance tests to characterize miniature hydraulic components and to characterize the assembled system.

- **Summer 2012**: Jessica Tello, University of Minnesota. Hispanic Female undergraduate student supported on CCEFP-Affiliated Wind Turbine project.
    - **Advisor**: Brad Bohlmann, Mechanical Engineering, University of Minnesota
    - **Project description**: CCEFP Alternative Test Bed β is a 2.5 MW Clipper Liberty wind turbine owned by the University of Minnesota. It is located on a 5,000 acre site owned by the University in Rosemount, MN and was constructed as a research wind turbine with

funding from the Department of Energy. The research on the wind turbine is administered by the University's Eolos Wind Energy Research Consortium of which CCEFP is a partner (http://eolos.umn.edu/).

- **Spring 2012**: Lee Ann Monaghan, University of Illinois, Urbana-Champaign. Caucasian Female undergraduate student 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).

- **Spring 2012**: Brianna Benedict, North Carolina A&T State University. African-American Female undergraduate student 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 candidate 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, 2014.

4. Plans, Milestones and Deliverables

- As usual, a start-up program requires time to gain footing.
- 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, continuing into year 9. 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.

5. Member Company Benefits

The URDS program contributes to the building of an informed and motivated student group—future leaders for industry and academia.

EO Project C.10: NSF and CCEFP Graduate Research Diversity Supplement (GRDS)

Project Team

Project Leader:	Alyssa Burger, Education Outreach Director, CCEFP
Other Personnel:	Marcus Huggans, External Relations Director, GEM Kim Stelson, Center Director, CCEFP Paul Imbertson, Education Director, CCEFP CCEFP Faculty advisors
Industrial Partners:	National GEM Consortium Caterpillar, Inc. Parker Hannifin

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 complimented by the CCEFP's own Graduate and Undergraduate Research Diversity Supplement (GRDS, URDS, respectively). (See E&O Project C.9.) Ideally, the CCEFP's URDS would positively influence a student to enter graduate school within the Center.

3. Achievements

In years three through seven, CCEFP had been awarded five years of funding under the NSF GRDS supplement and has supported four female graduate students. The NSF GRDS program has since been put on hold, as of January 2013. Due to this challenge, the CCEFP created it's own diversity supplement program for graduate students to continue to support the existing students, originally funded under the NSF GRDS, as well as new and incoming diverse graduate researchers.

NSF Graduate Research Diversity Supplement (NSF GRDS)

Funded: 2012 - 2013:	**Ms. Charreau Bell**, Vanderbilt, GRDS and CCEFP Funding **Ms. Morgan Boes,** UIUC, GRDS and CCEFP Funding
Funded: 2011 - 2012:	**Ms. Katherine (Braun) Houle**, UMN, NSF and CCEFP GRDS Funding **Ms. Emily Morris**, UIUC, NSF and CCEFP GRDS Funding **Ms. Morgan Boes**, UIUC, NSF and CCEFP GRDS Funding
Funded 2010 - 2011:	**Ms. Katherine Braun**, UMN, NSF GRDS Funding **Ms. Emily Morris**, UIUC, NSF GRDS Funding
Funded 2009 – 2010:	**Ms. Emily Morris**, UIUC, NSF GRDS Funding

In Year 8 and planned in subsequent years, the CCEFP contributes over $60,000 in matching funds to support two underrepresented graduate students, half-time, while the faculty advisor is responsible for providing the remaining support. Finally, the CCEFP has launched a new program under the auspice of the CCEFP GRDS initiatives, which includes a joint graduate student fellowship between CCEFP, the National GEM Consortium and Industry.

CCEFP Graduate Research Diversity Supplement (CCEFP GRDS)

Project Summary from Pre-Proposal (November 2013)

The Center for Compact and Efficient Fluid Power (CCEFP) is collaborating with the National GEM Consortium (GEM) to devise a novel interface between National Science Foundation's (NSF) Engineering Research Centers (ERC), the GEM and the companies of the manufacturing, biotechnology, energy and electronics industries, to recruit and retain underrepresented students pursuing graduate study in science, technology, engineering, and mathematics (STEM). The proposed interface is a ***GEM-ERC Fellow***, sponsored by the collaborating organizations of the NSF ERC, GEM and a joint corporate member of the ERC and GEM. The GEM-ERC Fellow would conduct traditional ERC research, engage in an industry internship and would be supported in full through a variety of sponsorship through the ERC, GEM, and the GEM Member University.

The proposed GEM-ERC Fellow leverages the existing and established infrastructures of the NSF Engineering Research Centers, the corporate members of the NSF ERCs and the National GEM Consortium to design a novel fellowship program for masters and doctoral students pursuing engineering within an ERC. The GEM-ERC Fellow 1) would participate in traditional research and engagement activities of the ERC/GEM Member University, 2) would be an intern with a GEM Employer Member as well as of the ERC, and 3) would be a formal student matriculating through the GEM Consortium's professional development programming.

The proposed GEM-ERC Fellow interface directly answers NSF's goal to expand efforts to increase the participation of underrepresented groups at the most challenging level for ERCs -- the graduate level. The CCEFP and GEM have successfully piloted a program, which proved the feasibility of the ERC-GEM Fellow interface. Using the established GEM Fellowship model, the CCEFP and GEM have negotiated an innovative and advantageous way in which ERCs can recruit an underrepresented graduate student into the ERC research program. A student, the GEM-ERC Fellow, will conduct ERC research aligned with the goals of the ERC and the interests of the corporate member. The corporate member, in turn, provides the GEM-ERC Fellow a hands-on internship. Unique to this new model, the ERC, alongside the corporate member, serves as the GEM Co-Employer to fully support the GEM-ERC Fellow as s/he matriculates through the graduate program and the ERC.

The proposed GEM-ERC Fellow is a program that could be duplicated and replicated across all NSF Engineering Research Centers for a relatively low one-time investment. A $55,000 yearly commitment from an ERC would support two underrepresented graduate students each year. The impact of this proposed program is compelling. The initial investment to sponsor a GEM-ERC Fellow would allow NSF ERCs to recruit and retain a significant number of underrepresented graduate students each year. It is recommended that all NSF ERCs participate in this program, supporting at a minimum of two GEM-ERC Fellows each year. For the proposed program, the funding necessary to support 40 new GEM-ERC Fellows at each of the 20 NSF ERCs for one year is $1,100,000.

The CCEFP will utilize core EO funds to offer a GEM Fellowship, which is worth over $150,000 for the GEM Fellow, while leveraging the support of the corporate member and the available GEM grants at GeorgiaTech.

Accomplishments:

Year 8 accomplishments include:

- Creating a program between an NSF ERC, Industry and the National GEM Consortium that could be sustainable.
- Attempting a pilot program, which proved moderately successfully while proving some roadblocks to overcome. The first GEM-ERC Fellow is Oscar Pena at Georgia Institute of Technology.
- Presented the concept in talks with NSF personnel.
- Drafted a pre-proposal (a snapshot of the project summary is noted above).
- Held a face-to-face meeting with NSF ERC Leadership to discuss the opportunities. It was well received.
- Invited to submit a final proposal to receive supplemental funding to sponsor up to two GEM-ERC Fellows within the CCEFP.
- Final program proposal to be submitted to NSF March 2014.
- Additionally, Parker Hannifin confirmed their interest in supporting several GEM-ERC Fellows in the upcoming academic year.

Funded 2013 – 2014: **Mr. Oscar Pena**, GT, CCEFP GEM-ERC Fellow

4. Plans, Milestones and Deliverables

- The CCEFP E&O and Research program will look for ways to support underrepresented graduate students, utilizing NSF supplemental opportunities, as long as research within the Center can sustain it.
- The CCEFP will continue to work with the National GEM Consortium on supporting a GEM Fellow in years 9, 10 and beyond.
- The supplement will require advisors to issue a mentoring plan for each student and invite awardees to present at one or more of the following events: CCEFP Annual Meeting, CCEFP Site Visit, or CCEFP IAB Summit or CCEFP Research Webcast.
- Efforts will be made to encourage GRDS awardees to achieve their Masters and PhDs through the CCEFP.

5. Member Company Benefits

Member companies can participate in graduate research projects as mentors. Member companies can also take advantage of the new relationship with the National GEM Consortium. 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 Education and Outreach Director
Student Members of the Innovative Engineers (IE) Student Organization

1. Project Goals and Description

The Innovative Engineers (IE) student group, with support from the Center for Compact and Efficient Fluid Power (CCEFP), is dedicated to providing authentic pedagogical experiences for engineering students, primarily in the area of renewable energy solutions for developing nations. They do this by actively engaging students in the design and implementation aspects of real-world problems in the United States and abroad. The group was formed by engineering students at the University of Minnesota who were inspired to actively pursue renewable energy solutions for people in remote and developing areas. They now have branches at the University of Minnesota and at Universidad Ibero-Americano in Mexico City, Mexico. 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 through work on real projects.

2. Project Role in Support of 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

The Innovative Engineers have positively impacted communities, university students, and pre-university students through an assortment of implementation projects and outreach programs in the United States and Nicaragua, involving inner-city schools, American Indian Reservations, technical schools in Nicaragua and remote communities in Nicaragua.

Sustainia100: The Innovative Engineers were honored in 2012 to be listed as one of the top 100 examples of sustainable solutions that show a path to a viable future for our planet. They were included on the Sustainia100 list along with projects from 56 countries and were the only university students group so honored.

Press: 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.

- "International honor for wind energy work in Nicaragua", Revista Eolica y del Vehiculo Electrico (REVE), June 2012
- "U of M Innovative Engineers receives international honor for wind energy work in Nicaragua", Physics.org, June 2012
- "U of M student group honored for wind turbine in Nicaragua", KSTP News, Summer 2012
- "Winds of Change", Inventing Tomorrow, a publication for alumni of the College of Science and Engineering, Winter 2012
- "Wind-Wind Situation", University of Minnesota Foundation, Summer 2011

- “Promueven energia eolica en Jinotega (Promoting Energy in Jinotega)”, La Prensa, May 2011
- “Building turbines and relationships”, College of Science and Engineering”, April 2011
- “U Engineers Aid Nicaraguan Village”, Minnesota Daily, November 2010
- “Innovative Engineers Power Third World”, Minnesota Daily, March 2010

Activities: Work during the past year includes the following.

- IE continues to support and maintain a wind turbine that they designed, built, and installed in the community of La Hermita in Nicaragua for the BRIDGE Project. The CCEFP supported the final installation efforts, and the continuing support efforts.
- IE finished design and construction of a hydro turbine and generator for a hydroelectric facility in Bocay, Nicaragua. IE delivered the turbine to partners at the National Engineering University in Managua, Nicaragua. Collaborative testing is planned. With our partners in Nicaragua we plan to use these designs for multiple installations in the Bocay region of Nicaragua.
- A second hydro turbine and generator is being built in Minnesota to aid collaborative design and testing with the National Engineering University in Managua.
- Work is ongoing on the design and development of a hybrid electric/hydraulic wind turbine. This work is directly supported by the CCEFP. With new student leadership, testing is planned for the first half of 2014.
- DC (Developing Nations) Wind Turbine. The goal of this project is to simplify generator designs with the aim to create designs that can be easily constructed by local residents in developing nations. Major accomplishments include characterization of the existing generator design, evaluation of winding shapes, and completion of a cut-in speed study. New this year are plans to test the generator design at a farm on Lake Managua in Nicaragua.
- IE continues active collaboration with the National Society of Black Engineers (NSBE) and American Indian Science and Engineering Society (AISES) on outreach efforts to the White Earth Indian Reservation in northern Minnesota. White Earth is located in the poorest county of Minnesota and is often overlooked because of its remote location. Students travel overnight twice each month to work with the native students.

4. Plans

Innovative Engineers is positioned for growth and more efficient project development with its partnership with the CCEFP. Future plans include:

- Talks are underway to form two new international branches of IE. One would be at the National Engineering University (UNI) in Managua, Nicaragua. The other would be at LaSalle University (ULSA) in Leon, Nicaragua. The other international branch is at IberAmericana Universidad in Mexico City.
- Identify and begin work with additional communities in Jinotega Department in Nicaragua for collaborative development of wind and hydroelectric energy production systems.
- Expand work with Universidad Ibero Americana in Mexico City.
- Expand outreach efforts by partnering with The St. Paul Public Schools. IE is in active discussions with the school district on ways to create opportunities for long term impact.

- Continue and expand BRIDGE activities on the White Earth Indian Reservation.
- Testing and verification of hybrid hydraulic/electric wind turbine.
- Test and install new generator designs for developing nations (DC Wind Turbine).
- Install hydroelectric energy system in Bocay, Nicaragua with the support of the National Engineering University of Nicaragua.
- Coordinate with electrical system officials in Bocay, Nicaragua to discuss further hydroelectric development in the remote Bocay region.

5. Related Projects

The Innovative Engineers work with the National Society of Black Engineers (NSBE), the American Indian Science and Engineering Society (AISES), and the BRIDGE project, which is in turn supported by the CCEFP. The Innovative Engineers also work with the CCEFP on the hybrid hydraulic electric wind turbine.

6. Milestones and Deliverables

7. Member Company Benefits

Benefits to member companies include access to students and projects. Further, member companies may benefit from the public visibility that can come from an association with IE.

EO Project D.1: Fluid Power Scholars/Interns Program

Project Team:

Project Leader:	Alyssa Burger, CCEFP Education Outreach Director
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

Drawing upon three years of an established program, yet still convinced there was a more efficient way to reach the same objective, the CCEFP has modified the Fluid Power Scholar's Program yet again.

The History: As interns, students learn about hydraulics and pneumatics through hands-on experiences while companies with whom they work 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.

- The history of the Fluid Power Scholars Program demonstrates that 68% of former participants stay in the fluid power industry; 52% of former participants are hired directly into their host company; others are either still in school or are pursuing graduate education.
- All company sponsors have expressed their satisfaction with the program. Seven of the nine corporate sponsors in 2012 were repeat participants; two companies were new to the program. Those who have elected not to participate are 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.
- The CCEFP will expand the method and modes of this program to launch, in Y7, a similar effort for graduate-level internships in CCEFP member companies.

The Change: Over the years, several companies asked if they could name their "Fluid Power Scholar" from existing leadership intern programs within their company, or otherwise utilize their own hiring infrastructure and systems to recruit and employ the intern they would name as the "Fluid Power Scholar". Eventually, it was becoming clear the procedures we established (posting a position electronically, recruitment, application process, etc.) was laborious for all parties involved (Center staff, company staff, company human resources, student applicants). It was also clear the original procedures were not the element of the program that industry needed our help. What we could provide, in which the companies may not, was a short fluid power training program. In fact, the "rigmarole" was actually a deterrent for some companies, as they had to create a "special" process to work with us. Thus, the Center has eliminated the efforts of providing the recruitment of students and asked companies to utilize their own infrastructure to recruit, identify and hire their intern, which will be named the CCEFP Fluid Power Scholar. Instead, the CCEFP recruits the companies to commit to hiring one or two interns to be named Fluid Power Scholars and provide the sponsorship to the MSOE fluid power training workshop.

Essentially, the Fluid Power Scholars program is a sponsorship of an industry intern to fluid power training program at the outset of the internship experience.

2013 Fluid Power Scholars Program

- Scholar/Intern positions: six companies offered to support Fluid Power Scholars in the summer of 2013: Case New Holland, Sauer-Danfoss, Parker Hannifin, Deltrol Fluid Products, HUSCO International and Sun Hydraulics. HUSCO was unable to identify a candidate.

2012 Fluid Power Scholars Program

- Scholar/Intern positions: nine companies offered to support nine scholars in the summer of 2012: Caterpillar, John Deere, Case New Holland, Sauer-Danfoss, Parker Hannifin, Deltrol Fluid Products, Eaton Corporation, HUSCO International and Sun Hydraulics.
- Fluid Power Scholars were from the following institutions: University of Missouri-Columbia (2), Iowa State University (2), Kansas State University, Illinois Institute of Technology, University of Minnesota, University of Minnesota-Duluth, Purdue University
- Since the summer experience, five Fluid Power Scholars were hired by their host company, one student was hired into the fluid power industry, two continue their undergraduate studies and two have pursued graduate study.

2012 Fluid Power Scholars

4. Plans, Milestones and Deliverables

- As of this writing, company and student recruitment for the 2014 Fluid Power Scholars/Interns Program is still in process under the new procedures. Parker Hannifin, Sauer, Deltrol, Sun Hydraulics, and HUSCO International. CNH and Bosch Rexroth have expressed interest.

- The CCEFP has expanded it's offer to host more than one Scholar, up to 16, at the MSOE Fluid Power Training Workshop.

- The orientation to fluid power offered by MSOE to scholars/interns was lengthened by a day in 2012 and the existing program will follow this trend. The change follows recommendations by students and industry.

- A thorough evaluation of the Scholars/Interns Program will be conducted at the launch and at the end of summer 2013 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.

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: 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.

3. Achievements

- Student Retreats: 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.
    - Caterpillar, Inc. hosted the SLC's annual Student Retreat in August 2013 at its hydraulics facility in Joliet, IL. 22 CCEFP students and staff attended the event which included a manufacturing plant tour, a Caterpillar museum visit, an assembly plant tour and a Joliet Slammers baseball game. Student attendees also gave short research presentations to the Cat engineering audience.
    - In 2012, the Student Leadership Council held it's annual Student Retreat in August at Sauer-Danfoss in Ames, Iowa. The students were given a facility plant tour, had lunch with a number of hydraulic engineers and had various social arrangements around the Ames geographic area.
    - The experience was mutually benefitting for students and for industry members at both companies.

- CCEFP Annual Meetings: Since 2006, the CCEFP has held an annual meeting at each Center's partner institutions. Representatives of the Center's industry members attended each of these meetings. The next Annual Meeting will be at Vanderbilt University in Nashville.
    - At the Fall 2013 Annual Meeting in Sarasota, FL, in conjunction with the BATH/ASME Fluid Power Symposium, students and industry members were invited to participate in a "resume exchange" where individuals were able to meet one-on-one with each other to either learn more about the company or to inquire about internship or employment opportunities. Companies received the resume booklet in advance of the meeting.

    - In the Fall of 2012, the CCEFP partnered with NFPA in hosting the first NFPA Workforce Summit and CCEFP Annual Meeting at the University of Illinois, Urbana-Champaign. The event was a synergistic combination of networking among industry and students with a student poster session and competition followed by an industry networking kiosk session where all attendees were able to mingle over appetizers and beverages. Over 17 companies hosted a kiosk during the reception. The event hosted a resume exchange for students and industry as well as panel presentations and discussions by fluid power leaders. Immediately after the "Workforce Summit", CCEFP launched into the traditional Annual Meeting where students presented on CCEFP research, had UIUC laboratory tours as well as closed-door meetings between the Industry Advisory Board and the Scientific Advisory Board regarding the sustainability of the Center. Overall, a powerful meeting achieved by NFPA and CCEFP.

- IAB Summits: Added to the Center's agenda in 2012, the CCEFP hosts IAB Summits at one of Center's partner institutions approximately three times each year (pending conflicts with other meetings and events). The Summits exist to provide a more intimate knowledge transfer between CCEFP research and IAB representatives. This is an excellent opportunity for industry to engage with students on a more one-to-one level. The atmosphere gives the student a chance to demonstrate their research and area of expertise.
- Resume Exchanges: At the CCEFP Annual Meeting in 2011, 2012, and 2013, a resume exchange session was held between Center students and representatives of its member companies. Each company had its own designated table, and students rotated throughout the room to speak to the company representatives.
- Research Poster Sessions: 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, 2012 and 2013 CCEFP Annual Meetings.
- The Fluid Power Scholars Program was launched in 2010. The goal is to introduce and interest undergraduate engineering students to the possibility of working in the fluid power industry. Prior to beginning an internship in a member company, each scholar attends an intensive Fluid Power Bootcamp program at MSOE. To date, 30+ Fluid Power Scholars have been supported through the program.
- The CCEFP supports the Parker Chainless Challenge Competition for undergraduate engineering students interested in fluid power.
    - In 2012 and 2013, teams participated from University of Minnesota, advised by Brad Bohlmann; University of Illinois, Urbana-Champaign, advised by Elizabeth Hsiao-Wecksler; Purdue University, advised by Andrea Vacca; and Milwaukee School of Engineering, advised by Vincent Prantil. Over 20 students had direct exposure to fluid power through their capstone design course via the Parker Hannifin Chainless Challenge.
    - 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.

- The CCEFP supports the NFPA Fluid Power Challenge Competition for 8th grade students, a competition in which students had to design a device to accomplish a task using fluid power (see EO Project B.7). Competition judges included representatives from local industries who invited students to ask them questions about their careers. CCEFP has hosted the Challenge at the University of Minnesota in 2009, 2012, and 2013. Over 300 students have participated between each competition.
- The Student Leadership Council (SLC) hosts a Research Webcast every other Wednesday afternoon. Students and faculty from CCEFP institutions participate, along with representatives from affiliated industrial member companies. These webcasts are intended to keep everyone in

the Center informed about research progress, give and receive suggestions, and generally promote inter-university collaboration as well as cooperation between academia and industry. These webcasts are typically very well attended with approximately 180 members from CCEFP's 52 member companies requesting invites.

4. Plans, Milestones and Deliverables

- 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.
- Resume exchange and Industry Kiosks will continue at future CCEFP Annual Meetings. Students will have a chance to visit the booths and see which companies are of particular interest.
- Industry sponsorships will be encouraged as a way of getting middle and high school students interested in fluid power.
- 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 students 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. See EO Project C.8.

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.

EO Project D.5: CCEFP Webcasts

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	Cherie Bandy, Education Program Coordinator SLC President and Vice President CCEFP graduate students 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, faculty, and CCEFP member companies. The webcasts are presentation based, with audio and visual capabilities. A brief question and answer session after each presentation allows the audience to ask for clarifications and give feedback to the presenter. 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 CCEFP welcomed two new guest speakers to its 2013 agenda:

  Mr. Don Leonard, Chief Marketing Officer, Netshape Technologies, Inc.
  "Using Powered Metal for Fluid Power Components".

  Mr. Philip Dybing, Program Manager / Systems Engineer, Eaton Corporation.
  "Hydraulic System Trends for the Refuse Industry"

- The guest speakers were well received. The CCEFP will host three to four guest presenters from industry each year.
- Each research project funded through the CCEFP presents once per year. The CCEFP hosts "State of the Center" addresses by the Center Director each year.
- The Center estimates between 75-100 participants join the webcast on a regular basis. Participants include industry, faculty, staff, and students including special invitations to the Scientific Advisory Board.
- The Center continues to find ways to improve 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 CCEFP has awarded the Student Leadership Council funding to host lunch at each partner site to encourage participation and attendance.
- 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.

- Students who were awarded SLC Travel or Project grants are invited to present to give a brief description of where they went and what was achieved.

4. Plans, Milestones and Deliverables

- The CCEFP has experienced some technical challenges related to recording and archiving the webcasts. The Center will be reviewing other available technologies to improve the experience for the users, presenters and the audience.
- 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.

5. Member Company Benefits

All Center participants—faculty, SAB, 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.

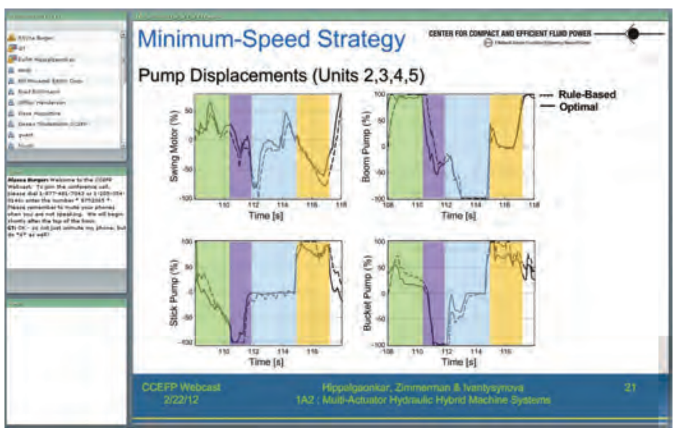


Figure 1: Screenshot of a webcast presentation

Project E.1: External Evaluation of Education and Outreach Program

Project Team

Project Leader:	Quality Evaluation Designs (QED)
Other Personnel:	Gary Lichtenstein, Principal, Quality Evaluation Designs Jenifer Helms, Senior Research Associate, Quality Evaluation Designs Aran Glancy, Research Associate, Quality Evaluation Designs Paul Imbertson, Education Director, CCEFP Alyssa Burger, Education & Outreach Director, CCEFP

1. Project Goals

Quality Evaluation Designs (QED) has been the external evaluator of CCEFP Education and Outreach since FY7, 2012-2013. The E&O evaluation has three objectives.

1) Identify objectives that cross-cut all E&O programs, create metrics for assessing them, and report E&O progress on each.
2) Anticipate post-ERC graduation CCEFP organizational and business plan and collect data relevant to stakeholder value propositions.
3) Related to #2, above, QED is focused on identifying the many pathways that lead students to and through CCEFP. CCEFP currently has no means by which to remain in contact with students who have participated in CCEFP projects, programs and curricula. By tracking students who have engaged CCEFP activities, greater continuity can be achieved in students' experiences overall, the opportunities to attract these students into the fluid power industry increase, and industry partners a talent pool of potential, desirable, motivated and trained employees is created for industry partners.

2. How Project Supports the EO Program Strategy

Partnership with QED is an application of a key E&O strategy--identifying and working with a strong partner in order to maximize results. Specifically, QED has helped the E&O taskforce clarify program objectives, quantify results, and chart a course towards post-ERC graduation sustainability.

3. Achievements

In the first year of the QED evaluation (FY7), QED, working with NSF and CCEFP leadership, formulated four cross-cutting objectives that reflect overall goals of CCEFP projects and programs. In FY8, QED has operationalized those in order to assess E&O overall success in meeting them. Interviews with E&O program project directors as well as faculty have generated data that reflect how cross-cutting objectives have been addressed with each E&O activity. Deeper dives into two specific programs (the Webcasts and the Fluid Scholars Program) give texture and shading to students' experiences and how they relate to the cross-cutting objectives. These data will be reported at the end of Year 8.

In FY7, QED conducted a Sponsor Study in which we interviewed representatives from 19 fluid power companies to specify their E&O-related activities and their companies' motivation for supporting these activities. The data showed that companies' primary motivation for supporting Education and Outreach is to attract potential employees to the fluid power workforce and, as those potential employees become college age, to their companies specifically. Companies are most interested in supporting E&O in order to gain access to talented students who are interested in jobs and careers in fluid power.

Based on these data, QED has begun identifying the pathways taken by students who intersect CCEFP activities, in order to devise ways to keep track of those who have participated in CCEFP projects and programs. Subsequently, E&O can create a database to track these students, which can motivate students towards the industry, enhance their fluid power training, and, ultimately provide a talent pool for industry partners.

Goals for the 2013-14 evaluation include:

- Interviewing all E&O project and program directors, as well as faculty who create fluid power curricula, and assessing the extent to which these activities meet the four cross-cutting objectives.
- Collecting data that reflects students' experiences related to the cross-cutting objectives as they have participated in E&O programs (i.e., Webcasts, Fluid Power Scholars).
- Identifying the pathways that lead students to and through CCEFP and beginning to strategize the creation of a data base to track these students and communicate with them about fluid power related activities and opportunities.

Dr. Lichtenstein presented the evaluation overview at the NSF site visit in Purdue in April, 2012. In August, the QED team (Dr. Lichtenstein, Dr. Helms, and Mr. Glancy) met with the newly created, E&O taskforce to give background to the evaluation and learn the taskforce's goals and priorities. Cross-cutting objectives were discussed and evaluation objectives and strategies were adjusted to align with a post-ERC graduation focus of the taskforce. QED developed instruments and conducted interviews with E&O project and program leaders, created a Webcast survey that was first deployed in December, and conducted interviews with former Fluid Scholars Program participants. Data collection will continue through February, with data analysis and reporting taking place from February through April.

4. 2013-14 Implementation and Deliverables

Month	**Activities**
Aug 2013	QED met with E&O taskforce
Sept 2013	E&O taskforce responded to QED request for post-ERC graduation objectives
Nov 2013	The QED subaward was finalized.
Nov 2013	Y8 QED evaluation design confirmed
Dec-Feb 2013	Webinar survey deployed
Jan-Feb 2014	Interviews with E&O program and project directors, and faculty who create fluid power curricula
Jan-Feb 2014	Interviews with Fluid Power Scholars
Feb-Apr 2014	Data analysis
Apr 2014	QED presents at NSF Site Visit (UMN)
May 2014	QED submits annual report

Associated Project Abstracts: Research

Thrust 1 – Efficiency

A Characterization of the Pressure-Viscosity and Compressibility Response of Five Oils for a Wide Range of Temperatures
Project Leader: Scott Bair
Sponsors: Deere and Company

A Characterization of the Pressure-Viscosity Response of Four lubricating Oils
Project Leader: Scott Bair
Sponsors: Shell Global Solutions
Abstract: Time-temperature-pressure superposition is applied to the modeling of the shear-thinning of motor oils.

Advances in Modeling External Spur Gear Machines and Development of Innovative Solutions
Project Leader: Andrea Vacca
Sponsors: Casappa S.p.A.
Abstract: Development of proprietary solutions and related models for new designs of gear pumps

Design of Low Noise Emission Internal Gear Machines
Project Leader: Andrea Vacca
Sponsors: Confidential
Abstract: *Unavailable due to confidentiality of project.*

Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump*
Project Leader: Andrea Vacca
Sponsors: Dae Jin Hydraulics – TECPOS
Abstract: A radial piston pump for high pressure application is investigated

Dynamic model development for hydraulic pumps
Project Leader: Monika Ivantysynova
Sponsors: confidential
Abstract: *Unavailable due to confidentiality of project.*

EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage
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.

Energy Saving Hydraulic System Architecture Utilizing Displacement Control
Project Leader: Monika Ivantysynova
Sponsors: Confidential
Abstract: *Unavailable due to confidentiality of project.*

Evaluation and Design Improvements for a Hydraulic Pump
Project Leader: Monika Ivantysynova
Sponsors: Confidential
Abstract: *Unavailable due to confidentiality of project.*

Evaluation of a Proprietary Gear Pump
Project Leader: Andrea Vacca
Sponsors: Triumph Aerospace Systems
Abstract: A proprietary aerospace solution for a gear pump is investigated

Generating of FSTI gap design input parameters
Project Leader: Monika Ivantysynova
Sponsors: confidential
Abstract: *Unavailable due to confidentiality of project.*

Modeling and Analysis of Swash Plate Type Piston Motor
Project Leader: Monika Ivantysynova
Sponsors: confidential
Abstract: *Unavailable due to confidentiality of project.*

Modeling of Lubricating Features of External Gear Machines and Development of Quieter Solutions
Project Leader: Andrea Vacca
Sponsors: Casappa S.p.A.
Abstract: This project explores new solutions for improved axial balance of pressure compensated external gear machines for reduced power losses. Novel modeling technique is developed in aid to the design of the pressure compensation areas in the lateral bushes. The lateral bushes are also modified to permit lower pressure pulsation, thus reduced noise emissions.

New system concept for Electrical Hydraulic Actuation system
Project Leader: Andrea Vacca
Sponsors: Midwest Precision
Abstract: A novel concept for an electro-hydraulic actuator for aerospace application was designed, with particular reference to the flow generation unit, which is based on a miniature gear pump.

Optimal Design of a Hydro-Mechanical Transmission Power Split Hybrid Hydraulic Bus
Project Leader: Muhammad Ramdan (Kim Stelson)
Sponsors: Malaysian Ministry of Higher Education (MOHE) and University of Science, Malaysia (USM)
Abstract: This research finds the optimal power-split drive train for hybrid hydraulic city bus. The research approaches the optimization problem by studying the characteristics of possible configurations offered by the power-split architecture.

Pump Dynamic Model Development
Project Leader: Monika Ivantysynova
Sponsors: confidential
Abstract: *Unavailable due to confidentiality of project.*

Thrust 3: Effectiveness

Adaptive ride control for construction machines
Project Leader: Andrea Vacca
Sponsors: CNH America, Inc.
Abstract: Novel riding control techniques are explored in this project for application to construction machines.

Determining Water Content at Saturation for Three Common Wind Turbine Gearbox Oils: Mobilgear SHC XMP 320, AMSOIL EP Gear Lube ISO-320 and Castrol Optigear A320
Project Leader: Matthew Whitten and Kim Stelson
Sponsors: Donaldson Company
Abstract: To meet America's growing energy demand, wind turbines will need to become larger and more cost effective [1]. However, estimates show that the average wind farm energy output is 10 percent less than predicted and that half of this short fall is due to gearbox downtime [2]. Increasing service life of the gearbox begins with monitoring the oil and controlling contamination by both particles and water. When online relative humidity monitoring is not available, oil samples from the gearbox need to be analyzed for quality and remaining service life. Field samples sent to a lab for testing often report water content as parts per million (ppm). Because the gearbox oil should be dried or replaced before the relative humidity reaches 100 percent (saturation limit), a relationship between ppm and the oil's saturation limit needs to be established. The present research characterizes this relationship using an environmental chamber to simulate operating conditions and Karl Fischer titration to measure the water content. The resulting plots are of water content (ppm) at saturation versus temperature for three common wind turbine gearbox oils: Mobilgear SHC XMP 320, AMSOIL EP Gear Lube ISO-320 and Castrol Optigear A320.

High Pressure Compliant Material Development
Project Leader: Kenneth Cunefare
Sponsors: Danfoss
Abstract: Develop material(s) with significant compliance throughout 40-400 Bar system pressure range. An existing material has been shown to be effective at removing high frequency pressure ripple between 0 and 40 Bar system pressure where the material bulk modulus is below 500 Bar. We expect the material development will result in the identification of several materials which can be appropriately combined in order to achieve ~500 Bar compliance from 40-400 Bar system pressure.

High Pressure Viscosity and Density Measurements on Diesel Fuels
Project Leader: Scott Bair
Sponsors: Cummins Engine
Abstract: Transport properties of Diesel fuels are investigated and modeled for use in software.

High Pressure Viscosity and Density Measurements on Krytox Fluids
Project Leader: Scott Bair
Sponsors: DuPont
Abstract: The dynamic properties of branched perfluoropolyethers are characterized to very high pressure.

Model Predictive Control of Pneumatic Actuators
Project Leader: Wayne Book
Sponsors: National Defense Science and Engineering Graduate Fellowship (NDSEG);
Abstract: Pneumatic actuators possess a number of qualities that make them potentially versatile actuators: they have high power and force density, are clean, safe, and low cost, and possess inherent

compliance and potentially adaptable stiffness that make them useful for contact and interaction tasks. However, control of pneumatic actuators has proven difficult, limited by the inherent compliance of the actuator, friction in the cylinder, and third order dynamics that are both nonlinear and discontinuous. In general, past controls solutions have had limited application, applied where position tracking is not critical, or using high-gain PD controllers to transform the system into a stiffer one that succeeds in precision tracking but possesses high output impedance and lacks compliance. Of the variety of advanced controllers that have been tested, the most successful have been sliding mode controllers, which add robustness criteria to simpler feedback controllers. Input shaping has shown that the tracking problem can be solved in the open-loop case without sacrificing compliance and impedance goals. Model predictive control offers the potential to extend this concept to the pseudo-closed-loop case, by effectively iteratively solving a feedforward problem to achieve good tracking performance of a system with high compliance and low output impedance that interacts safely and securely with its surroundings. A predictive observer can then be used to compensate for friction, and especially stiction, proactively, rather than using an additive compensation term at each instant. This may improve performance for a pneumatic system, which has generally slow dynamics. Finally, the predictive control enables the user to place constraints on the optimization, thereby enabling the controller solution to operate closer to the optimal capability of the system, which is subject to dynamic and mechanical limits. The resultant system resembles the increasingly common series elastic and variable stiffness actuators, coupled with a new method to achieve control of compliant actuators for use in robots that require both good tracking and environmental interaction.

New Generation Of Green, Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology

Project Leader: Monika Ivantysynova

Sponsors: confidential

Abstract: The proposed research effort aims to formulate a green, viable, energy-efficient and economical solution to the current dependency of hydraulic powered machines on oil-based lubricants.

Optimization of Valve Plate to Reduce Noise and Maintain Low Control Effort

Project Leader: Monika Ivantysynova

Sponsors: confidential

Abstract: *Unavailable due to confidentiality of project.*

Rheology Modeling for Mechanical Face Seals

Project Leader: Scott Bair

Sponsors: John Crane

Abstract: Rheological models are developed for the very high shear conditions of a mechanical face seal.

Self-powered Leak Detection System for Pipeline Monitoring

Project Leader: Kenneth Cunefare

Sponsors: Veraphotonics, Mistras

Abstract: In collaboration with the Georgia Institute of Technology and Mistras Inc., Veraphotonics proposes to harvest the energy of hydraulic pressure ripple in pipeline systems by piezoelectric transduction to enable self-powered wireless leak and damage detection systems toward sustainable energy transmission and monitoring. The pressure ripple present within most hydraulic systems, or within any fluid system subject to pumping action, is commonly viewed as an annoyance or a detriment to system performance; however, the pressure ripple may also represent a high-intensity power source for energy harvesting. In a pipeline system, an energy harvesting technology might be further integrated with health-monitoring sensors and eliminate the need for batteries or wires providing power to individual sensors; this would reduce maintenance contact and eliminate potential points of failure. Distributed sensors are common in hydraulic systems, and health-monitoring systems are being deployed within the hydraulics industry, and remote sensing and monitoring is common in processing industries, such that there are immediate applications for the technology. Whereas the commonly explored energy harvester technologies developed to date have been applied to energy sources of relatively low power intensity, the pressure ripple in a hydraulic system represents a relatively high power intensity by comparison. In this STTR Phase I project, the hydraulic pressure harvesting mechanism will be combined with four-channel acoustic emission (AE) based leak and damage detection hardware along with power management electronics to enable self-powered wireless health monitoring in pipeline systems. By combining our theoretical simulation and experimental testing, hydraulic pressure energy harvester systems will be designed and optimized for characteristics of typical oil pipeline systems. Wireless AE-based leak detection and energy harvester systems will be integrated with impedance matching and optimal power management to achieve the maximum efficiency.

Testbed Related

CPS: Synergy: Integrated Modeling, Analysis and Synthesis of Miniature Medical Devices
Project Leader: Pietro Valdastri
Sponsors: confidential
Abstract: The objective of this project is to create a focused cyber-physical design environment to accelerate the development of miniature medical devices in general and swallowable systems in particular. The project develops new models and tools including a web-based integrated simulation environment, capturing the interacting dynamics of the computational and physical components of devices designed to work inside the human body, to enable wider design space exploration, and, ultimately, to lower the barriers which have thus far impeded system engineering of miniature medical devices. Currently, a few select individuals with deep domain expertise create these systems. The goal is to open this field to a wider community and at the same time create better designs through advanced tool support. The project defines a component model and corresponding domain-specific modeling language to provide a common framework for design capture, design space exploration, analysis and automated synthesis of all hardware and software artifacts. The project also develops a rich and extensible component and design template library that designers can reuse. The online design environment will provide early feedback and hence, it will lower the cost of experimentation with alternatives. The potential benefit is not just incremental (in time and cost), but can lead to novel ideas by mitigating the risk of trying unconventional solutions.

I-Corps: CO2 Insufflator for Minimally Invasive Procedures
Project Leader: Pietro Valdastri
Sponsors: EndoInSight LLC
Abstract: The estimated Colorectal Cancer (CRC) economic burden to the Medicare program and its beneficiaries was $7.49B in Year 2000. Under current trends, this number is expected to increase to over $14B by Year 2020. One way to decrease this burden is by increasing CRC screening compliance prior to enrollment in Medicare in an effort to reduce the number of individuals that will require treatment for this preventable disease. As a leading deterrent to screening compliance, the perceived pain associated with colonoscopy-based CRC screening represents an area for technological improvement that has the potential to dramatically increase CRC screening compliance. Researchers have shown that a simple method for reducing the pain associated with colonoscopy is the use of CO2 insufflation in lieu of room-air. However, currently only a small minority of gastroenterologists offers CO2 insufflation during colonoscopy, suggesting that the available commercial CO2 insufflation systems are not well suited to meet the needs of patients and clinicians. Hence, there is a need to develop new methods for providing clinicians with the ability to administer CO2 insufflation during traditional colonoscopy. Effervescent

chemical reactions are one of the few physical phenomena capable of safely generating biocompatible gases in a rapid manner. This ability enables an entirely new paradigm for providing surgical insufflation, where cumbersome and expensive compressed-gas CO2 insufflation systems are replaced by small, light-weight and disposable devices that can be used safely in standard clinical settings, remote locations and frontline triage units. While there are many applications for such a device throughout the field of minimally invasive surgery, this technology will have the most immediate impact in the area of colonoscopy-based CRC screening, where it will save lives by helping increasing compliance with suggested screening guidelines and will offer clinicians a cost-effective alternative to pain-inducing room-air insufflation. In order to realize this impact, commercial interest will need to be met with a viable and compelling business plan for delivering a well-vetted value proposition to a well-defined customer. The objective of this proposal is to leverage the resources offered by participation in the I-Corps Program to support our efforts in vetting the commercial potential represented by effervescence-based CO2 insufflation.

Modulation of Anticipatory Postural Adjustments in Parkinson's disease Using a Portable Powered Ankle-Foot Orthosis

Project Leader: Elizabeth Hsiao-Wecksler

Sponsors: NSF IGERT Student Fellowship

Abstract: Two of the most debilitating symptoms in Parkinson's disease are freezing of gait (FOG) and start hesitation. Previous research has shown that presenting an extra sensory cue can alleviate FOG symptoms, however the results have been inconsistent. To date, mechanical assistance given as a cue (or during another cue) has been under explored. We are testing the efficacy of providing mechanical assistance at the ankle through the portable powered ankle-foot orthosis to alleviate FOG symptoms in Parkinson's disease.

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.

NSF REU Site Award
REU Site: Research Experiences for Undergraduates in Fluid Power
Source: National Science Foundation
Location: University of Minnesota
PI: Kim A Stelson
Funding: $390,000. 6/1/13 - 5/31/16

The Center received the competitive NSF Research Experiences for Undergraduates (REU) Site Award for Years 8 – 10. The goal of NSF REU programs are to kindle the interest of diverse participants in attending graduate school. Additionally, CCEFP's goal also includes increasing the number of undergraduate students knowledgeable in fluid power, a positive outcome from industry's point of view as well. To date, more than 145 REU students have participated in the CCEFP program -- more than in many REU site programs. Based on responses by 54 undergraduates to a 2012 longitudinal study, 55% of all former CCEFP REU students enter graduate school and 33% eventually become PhD candidates. Since revising the CCEFP REU program structure in 2008, the CCEFP REU Program has recruited, on average, over 35% women, and over 33% racially or ethnically underrepresented students into the program on a yearly basis. The CCEFP's recruiting strategy includes identifying institutions, programs, and people with whom to develop relationships that, in turn, open pathways to CCEFP summer programs and beyond for underrepresented students.

EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Bases Targeted Mathematics-Science Partnership
Lead Personnel: Tamara Moore, Paul Imbertson (CCEFP), Gil Roehrig, Martin Davis, Siddika Guzey
Grant: National Science Foundation - Math and Science Partnership (NSF-MSP)
Funding: $8,000,000 over 5 years

The EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Based Targeted Mathematics-Science Partnership vision is to increase grade 4-8 student learning of science concepts, as well as the mathematics concepts related to data analysis and measurement, by using an engineering design-based approach to teacher professional development and curricular development. The partnership involves the University of Minnesota's Science, Technology, Engineering, and Mathematics (STEMEdCtr) Education Center (Lead Partner) and the Center for Compact and Efficient Fluid Power (CCEFP) (Core Partner), the Saint Paul Public Schools (Core Partner), the North Saint Paul-Maplewood-Oakdale School District (Supporting Partner), and the South Washington County Schools (Supporting Partner). A sixth partner is the ECSU/GRO Leadership Council (Supporting Partner) who is uniquely qualified to provide research-based professional development. Together these six partners will explore the overarching research question: What are the effects of engineering design pedagogies and curricula combined with a coaching model on student learning in science, data analysis, measurement, and critical thinking?

This project is designed to help 200 teachers develop engineering design curricular units for each of the major science topic areas within the Minnesota State Academic Science Standards for grades 4-8 with a focus on vertical alignment and transition from upper elementary to middle-level. This will impact 15,000 students over the life of the grant. The alignment will be in both the scaffolding of the concepts and the pedagogy used in these grades. The partnership is using summer professional development and curriculum writing workshops paired with a cognitive coaching model to allow teachers to design engineering design-based curricular units focused on science concepts, meaningful data analysis, and measurement. These curricular units will go through an extensive design research cycle to ensure a quality product and then will be submitted to an online peer-reviewed NSF-funded digital library TeachEngineering (teachengineering.org) for use across the United States and beyond. An external advisory board consisting of recognized experts in engineering, science education, engineering education, mathematics education, science assessment, and cognitive coaching will meet annually to provide guidance to the project.

The research findings will provide directions for designing effective curriculum and learning of STEM. The dissemination of the curriculum modules on the peer-reviewed NSF websites and the findings of the dissemination of the curriculum modules on the peer-reviewed NSF websites and the findings of the research studies will inform practitioners, administrators, researchers, and policy makers who aim to improve student achievement and interest in STEM careers.

CCEFP role: The CCEFP serves as a partner to this project providing technical content experts and direction in engineering pedagogy. Paul Imbertson (CCEFP) serves as the Content Director for the project.

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.

NC A&T State University Regional Collaborations for Excellence in STEM

Lead Personnel: Eui Park

Funding: $500,000 over 2 years

Abstract: The North Carolina A&T State University Regional Collaborative for Excellence in STEM is a comprehensive and inclusive project that targets the enhancement of STEM education and learning outcomes for middle school aged children in five counties in Eastern North Carolina: Bertie, Edgecombe, Gates, Pitt, Wilson. In particular, this project focuses on cohorts of 6th grade students 2012. The project will follow these students with programming until high school graduation. In each year following the first cohort, an additional 6th Grade cohort will be added to the project creating a pipeline into high school and post-secondary education.

The approach to this project is to collaboratively assess design and implement programs focused on STEM education tailored to the needs and capacities of the identified rural areas. The needs and the capacities of these localities will differ; however, given the array of partners, the resources in this collaborative, coupled with its comprehensive approach, each locality will be able to improve the educational experience and outcomes in STEM areas, particularly in math and science.

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.

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.

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.

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Thrust 1 – Efficiency

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Skelton, D.; Xiong, S.; Breidi, F.; Lumkes, J. "Improving actuation speed and controllability" SAE Off-Highway Engineering Magazine (2013)

Skow, E.; Cunefare, K.; Erturk, A. "Transduction as energy conversion; harvesting of acoustic energy in hydraulic systems" Proceedings of the Joint 21st meeting of the International Congress of Acoustics and 165th Meeting of the Acoustical Society of America (2013)

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Bair, S.; Krupka, I.; Sperka, P.; Hartl, M. "Quantitative Elastohydrodynamic Film Thickness of Mechanically Degraded Oil" Tribology International Volume 64, Pages 33-38, August (2013)

Davis, D.; Franca, P.; Delpish, R.; Jiang, S. "Usability testing of rescue robot interface using eye tracking" Proceedings of the 2003 Industrial and Systems Engineering Research Conference, May 18-22, (2013)

deMattos, P.; Park, E.; Miller, D. "Decision Making In Trauma Centers from the Standpoint of Complex Adaptive Systems Management" Decision

Guo, F.; Jia, X.; Huang, L.; Salant, R.; Wang, Y. "The Effect of Aging During Storage on the Performance of a Radial Lip Seal" Polymer Degradation and Stability, Vol. 98, pp. 2193-2200, (2013)

Huang, Y. and Salant, R. "Simulation of the Effects of a Plunge-Ground Rod on Hydraulic Rod Seal Behavior" Tribology Transactions, Vol. 56, pp. 986-996, (2013)

Humphreys, H.; Book, W.; Feigh, K. "Development of Controller-Based Compensation for Biodynamic Feedthrough in a Backhoe" Journal of Systems and Control Engineering (2013)

Humphreys, H.; Book, W.; Huggans, J. "Hydraulically Actuated Patient Transfer Device with Passivity Based Control" Proc. of the ASME/BATH Symposium on Fluid Power and Motion Control (2013)

Jia, X.; Guo, F.; Huang, L.; Salant, R.; Wang, Y. "Parameter Analysis of the Radial Lip Seal by Orthogonal Array Method" Tribology International Vol. 64, pp. 96-102, (2013)

Opperwall, T. and Vacca, A. "A Combined FEM/BEM Model and Experimental Investigation into the Effects of Fluid-borne Noise Sources on the Air-borne Noise Generated by Hydraulic Pumps and Motors" Proceedings of the Institution of Mechanical Engineers, Part C, Journal of Mechanical Engineering Science (2013)

Opperwall, T. and Vacca, A. "Performing and Interpreting Experiments Towards Understanding Noise Generation in Displacement Machines" The 13th Scandinavian International Conference on Fluid Power, SICFP (2013)

Osafo-Yeboah, B.; Frota, E.; Jiang, S.; Ntuen, C. "Quantitative Modeling of Human Interaction with Haptic-controlled Excavators" Proceedings of the 2003 Industrial and Systems Engineering Research Conference, May 18-22, (2013)

Osafo-Yeboah, B.; Jiang, S.; Delpish, R.; Jiang, Z.; Ntuen, C. "Empirical Study to Investigate the Range of Force Feedback Necessary for Best Operator Performance in a Haptic Controlled Excavator Interface" International Journal of Industrial Ergonomics, 43(3), pp.197-202 (2013)

Park, E. and Bagley, K. "Development of Graphic Unser Interface as data Collection Tool for Cognitive Performance" Proceedings of 2014 International Conference on Industrial Engineering and Operations Management (2014)

Ritelli, G. and Vacca, A. "Energy Saving Potentials of a Novel Electro-Hydraulic Method to Reduce Oscillations in Fluid Power Machines: The Case of a Hydraulic Crane" SAE Int. J. Commer. Veh., Vol.6(2), (2013)

Ritelli, G. and Vacca, A. "Energetic and dynamic impact of counterbalance valves in fluid power machines" Energy Conversion and Management 2013. Vol.76: p. 701-711 (2013)

Salant, R. "Friction in Seals" 41487 Encyclopedia of Tribology. (J. Wang & Y-W Chung, Eds.), Springer, New York (2013)

Salant, R. "Reciprocating Seal Analysis" Encyclopedia of Tribology(J. Wang & Y-W Chung, Eds.), Springer, New York (2013)

Salant, R. "Rotary Lip Seal Analysis" Encyclopedia of Tribology(J. Wang & Y-W Chung, Eds.), Springer, New York, (2013)

Skow, E.; Cunefare, K.; Erturk, A. "Design and Performance Enhancement of Hydraulic-pressure Energy Harvesting Systems" Part of Proceedings of SPIE Vol. 8688 Active and Passive Smart Structures and Integrated Systems (2013)

Zhou, J. and Vacca, A. "A Methodology to Model Oil Flow Through Orifices Considering Dynamic Air Release" The 8th Int. Conference on Fluid Power Transmission and Control, ICFP (2013)

Zhou, J.; Vacca, A.; Manhartsgruber, B. "A Novel Approach for the Prediction of Dynamic Features of Air Release and Adsorption in Hydraulic Oils" ASME Journal of Fluid Engineering 135(9), 091305 (8 pages), Jul 11 (2013)

Testbeds and General

Bell, C.; Obstein, K.; Valdastri, P. "Image Partitioning and Illumination in Image-based Pose Detection for Teleoperated Flexible Endoscopes" Artificial Intelligence in Medicine, Vol. 59, N. 3, pp. 185-196 (2013)

Gorlewicz, J.; Battaglia, S.; Smith, B.; Ciuti, G.; Gerding, J.; Menciassi, A.; Obstein, K.; Valdastri, P.; Webster III, R. "Wireless Insufflation of the Gastrointestinal Tract" IEEE Trans Biomed Eng., 60(5):1225-33, May (2013)

Obstein, K.; Battaglia, S.; Smith, B.; Gerding, J.; Valdastri, P. "Novel Approach for Colonic Insufflation Via an Untethered Capsule (with video)" Gastrointestinal Endoscopy, Vol. 77, N. 3, pp. 516-517 (2013)

Boes, M.K.; Islam, M.; Li, Y.; Hsiao-Wecksler, E. "Functional Efficiency of a Portable Powered Ankle-Foot Orthosis" IEEE 13th International Conference on Rehabilitation Robotics, ICORR (2013)

Di Natali, C.; Beccani, M.; Valdastri, P. "Real-Time Pose Detection for Magnetic Medical Devices" IEEE Transactions on Magnetics IEEE Transactions on Magnetics, Vol. 49, N. 7, pp. 3524-3527 (2013)

Du, Z.; Cheong, K.; Li, P.; Chase, T. "Fuel Economy Comparisons of Series, Parallel and HMT Hydraulic Hybrid Architectures" American Control Conference (2013)

Li, Y. and Hsiao-Wecksler, E. "Gait Mode Recognition and Control for a Portable-Powered Ankle-Foot Orthosis" IEEE 13th International Conference on Rehabilitation Robotics, ICORR (2013)

Obstein, K. and Valdastri, P. "Advanced Endoscopic Technologies for Colorectal Cancer Screening" World J Gastroenterol; 19(4): 431-439 (2013)

Petrucci, M.; MacKinnon, C.; Hsiao-Wecksler, E. "Mechanical Modulation of Anticipatory Postural Adjustments of Gait Using a Portable Powered Ankle-Foot Orthosis" IEEE 13th International Conference on Rehabilitation Robotics, ICORR (2013)

Shorter, K.A.; Xia, J.; Hsiao-Wecksler, E.; Durfee, W.; Kogler, G. "Technologies for Powered Ankle Foot Orthotic Systems: Possibilities and Challenges" IEEE/ASME Transactions on Mechatronics, 18(1): 377-347, (2013)

Opdenbosch, P. "Intelligent Controls for Electro-Hydraulic Poppet Valves" Control Engineering Practice, accepted, Feb. (2013)

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 by-laws. 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.

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.

Douglas E. Adams
Department of Civil and Environmental Engineering
School of Mechanical Engineering
Vanderbilt University

Professional Preparation

University of Cincinnati	Mechanical Engineering	B.S.	1994
Massachusetts Institute of Technology	Mechanical Engineering	M.S.	1997
University of Cincinnati	Mechanical Engineering	Ph.D.	2000

Appointments

2013-present	Distinguished Professor and Chair, Civil and Environmental Engineering and Professor of Mechanical Engineering, Vanderbilt University
2010-2013	Kenninger Professor, School of Mechanical Engineering, Purdue University
2009-2013	Professor, School of Mechanical Engineering, Purdue University
2005-2009	Associate Professor, School of Mechanical Engineering, Purdue University
2000-2005	Assistant Professor, School of Mechanical Engineering, Purdue University

Closely Related Products

1. Kusnick, J., and Adams, D. E., "Wind Turbine Rotor Imbalance Detection using Nacelle and Blade Measurements", *Wind Energy*, accepted for publication.
2. Meyer, A., and Adams, D. E., "Damage identification of ground vehicle through passive probing of suspension damping", 2013, *Experimental Mechanics*, Vol. 53(4), p. 557.
3. Gupta, L., Brouwer, M., Sadeghi, F., Peroulis, D., and Adams, D., "High Temperature Dynamic Viscosity Sensor for Engine Oil Applications," 2012, *Sensors & Actuators: A. Physical*, Vol. 173(1), pp. 102-107.
4. Mahulkar, V., and Adams, D. E., "Derivative Free Filtering in Hydraulic Systems for Fault Identification", 2011, *Control Engineering Practice*, Vol. 19, Issue 7, pp. 649-657
5. Mahulkar, V. and Adams, D. E., "Minimization of Degradation through Prognosis Based Control for a Damaged Aircraft Actuator," 2009, *Proceedings of the Dynamic Systems and Control Conference*, Hollywood, CA, Paper No. DSCC2009-2787, pp. 669-676.

Significant Products

6. Myrent, J., Kusnick, J., Barrett, N., Adams, D., and Griffith, D., "Structural Health And Prognostics Management For Offshore Wind Turbines: Case Studies Of Rotor Fault And Blade Damage With Initial O&M Cost Modeling," April 2013, Sandia Report SAND2013-2735, unlimited release.
7. Pham, H., Sharp, N., Adams, D. E., and Dietz, J. E., "Lithium-Ion Battery Cell Health Monitoring using Vibration Diagnostic Test," 2013, *Proceedings of the International Mechanical Engineering Congress and Exposition*, San Diego, CA, IMECE-63962.
8. Adams, D. E., "Health Monitoring of Structural Materials and Components," 2007, John Wiley & Sons, Chichester, U.K.
9. Adams, D. E., "Chapter 18: Prognosis Applications and Examples," 2005, John Wiley & Sons, (Editors) Professor Daniel Inman, Dr. Charles Farrar and Dr. Daniel Inman, "Damage Prognosis."
10. Adams, D. E., and Jata, K., "Part 17: Damage Prognosis in Metallic and Composite Structures," *Encyclopedia of Aerospace Engineering*, John Wiley & Sons, 2010.

Synergistic Activities

Recent Patent Activities:
(a) Peroulis, D., Kovacs, A., Koester. D., Sadeghi, F., Scott, S., and Adams, D. E., "Highly-Reliable Micro-Electromechanical System Temperature Sensor," August 2013, US 2013/0202012 A1.
(b) Calhoun, K., Kiser, R., Adams, D., Gul, K., Yoder, N., Bruns, C., and Yutzy, J., "System and Method for Detecting Fault Conditions in a Drivetrain Using Torque Oscillation Data," May 2013, US 2013/0116937 A1.
(c) Adams, D. E., Yutzy, J., and Dana, S., "Load Shape Control of Wind Turbines," December 2012, US 2012/029254.

(d) Bond, R. and Adams, D. E., "Entropy-Based Impact Load Identification," November 2013, US 2013/0298690 A1.
(e) Adams, D. E., Caruthers, J., Sadeghi, F., Suchomel, M., Sharp, N., and David, A., "Vibratory Analysis of Batteries," January 2013, US 2012/026351.
(f) Adams, D. E., Di Petta, T., and Koester, D., "Extended Smart Diagnostic Cleat," January 2013, US 2012/029954.

Dissemination: Delivered over 150 invited seminars and keynote addresses worldwide including keynote lecture at upcoming NSF-sponsored International Conference on Next Generation Wind Energy in Spain (2014), and invited lectures at 2013 Dresden Airport Seminar, 2009 Marie Curie Action on Stability, Identification and Control of Structural Dynamics in Belgium, 2008 National Academy of Engineering Workshop on Material State Awareness, and 2003 NSF-sponsored Pan American Studies Institute on Prognosis in Brazil.

Education initiatives: Launched NSF DUE-supported inquiry-based laboratory course in 2002 in experimental structural dynamics and offered course for seven semesters, sponsored 30 undergraduate research students on special projects, and delivered 30 short courses for continuing education in nonlinear system identification and diagnostics & prognostics to NASA Glenn/Kennedy, Center for Monitoring of Structures (Germany), Air Force Research Laboratory, Palmdale Aerospace Institute, and at other venues.

Managing Editor of Structural Health Monitoring: An International Journal, Sage Publications. Former Associate Editor of ASME Journal of Dynamic Systems, Measurement and Control.

Conference Organization activities: Organized and chaired many sessions on nonlinear system identification and structural health monitoring at ASME IMECE, SEM IMAC, and other meetings. Served on many conference organizing committees such as IEEE International Conf on PHM, USNCTAM, Intl. Conf. on Advances in Experimental Mechanics, etc.

Collaborators & Other Affiliations

Collaborators within the last 48 months (other than students listed):

Daniel Griffith (Sandia National Lab), Charles Farrar (Los Alamos National Lab), Fu-Kuo Chang (Stanford Univ.), R. Byron Pipes, Farshid Sadeghi, CT Sun, James Caruthers, Kartik Ariyur, Edward Delp, Steven Son, Jeffrey Rhoads, Stuart Bolton, Patricia Davies, Anil Bajaj, Alok Chaturvedi, Jan Vitek, and Ananth Grama (Purdue University), Michael Steer and Mohammed Zikry (North Carolina State Univ.), John Scales (Colorado School of Mines), Michael Todd (University of California San Diego), Eric Barth, Florence Sanchez, Sandra Rosenthal, Ronald Schrimpf, Janos Sztipanovits, Caglar Oskay, and Sankaran Mahadevan (Vanderbilt University).

Ph.D. Students Supervised:

Chulho Yang (Oklahoma State), Timothy Johnson (Dow Corning), Muhammad Haroon (University of Braunschweig), Shankar Sundararaman, Hao Jiang (Oakridge National Laboratory), Shawn McKay (RAND Corporation), Kamran Gul (ExxonMobile), Jonathan White (Sandia National Lab), Vishal Mahulkar (Eaton Corp), Nathanael Yoder (ATA), Janette Meyer (Purdue), Nasir Bilal (Purdue), Sara Underwood (General Electric), Janene Silvers (Purdue), and Major Eric Dittman (United States Air Force).

Ph.D. and M.S. Advisors:

Ph.D.: Randall Allemang, Dept. of Mechanical Engineering, University of Cincinnati.
M.S.: Kamal Youcef-Toumi, Dept. of Mechanical Engineering, Massachusetts Institute of Technology

Research Visitors:

Prof. Hoon Sohn, KAIST, Korea; Professor Ioannis Georgiou, National Technical University of Athens, Greece; Dr. Jose Machorro Lopez, Instituto Politecnico NAcional, Mexico; Dr. Darryll Hickey, University of Sheffield.

Andrew Alleyne
Department of Mechanical and Science Engineering
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

Closely Related Products

- 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.

Significant Products

- 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
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

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

Closely Related Products
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.

Significant Products
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

Closely Related Products

1. D. B. Comber, D. Cardona, R. J. Webster III, and E. J. Barth, "Precision Pneumatic Robot for MRI-Guided Neurosurgery," Journal of Medical Devices, March, vol. 6, p. 017587-1, 2012.
2. D. B. Comber, D. Cardona, R. J. Webster III, and E. J. Barth, "Precision Pneumatic Robot for MRI-Guided Neurosurgery," DMD2012-6929, ASME Design of Medical Devices Conference, 2012, Minneapolis, MN. Note: **Winner of the 3-in-5 competition**.
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.

Significant Products

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. Associate Editor of ASME Journal of Dynamic Systems, Measurement and Control (2012-current)
2. Chair of the ASME Fluid Power Systems and Technology (FPST) Division (2010-2012)
3. Management Committee Member, NSF Center for Compact and Efficient Fluid Power (CCEFP)
4. Member of the Faculty Advisory Committee for the Vanderbilt Center for Technology Transfer and Commercialization (CTTC) (2012-current)
5. Member of the ASME Dynamic Systems and Control Division (DSC) Conference Editorial Board (2009-2011)
6. ASME Fluid Power Systems and Technology Division (FPST): Executive Committee Member.
7. ASME Division of Dynamic Systems and Control (DSCD): Member of Mechatronics Technical Committee.
8. ASME Division of Dynamic Systems and Control (DSCD): Member of the Robotics Technical Committee.
9. Member of the National Fluid Power Association (NFPA) by invitation
10. Program Committee Member of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), October 9-14, 2006, Beijing, China.
11. Program Committee Member of the 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2005), July 24-28, 2005, Monterey, California, USA
12. Track Representative of Fluid Power Systems Technology Division (FPST) for IMECE 2005.
13. 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 (all in Dept. of Mechanical Engineering, Vanderbilt University): John Tucker, M.S. (2012), Chao Yong, Ph.D. (2011), Alexander Pedchenko, M.S. (2011), Andy Willhite, Ph.D. (2010), Jose Riofrio, Ph.D. (2008), M.S. (2005), Taib Tariq Mohamad, M.Engineering. (2007), Yong Zhu, Ph.D. (2006), Navneet Gulati, Ph.D. (2005), Mark Adams, M.S. (2004). *Current*: Mark Hofacker, Ph.D. Student, Alexander Pedchenko, Vanderbilt University, Dave Comber, Ph.D. Student, Dan Cramer, M. S. Student.

Bradley F. Bohlmann
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

University of Minnesota	Mechanical Engineering	B.S., 1985
University of Michigan, Dearborn	Mechanical Engineering	M.S., 1988
University of Saint Thomas	Business	M.B.A., 2000

Academic/Professional Appointments

12/10-5/11 & 10/12-1/13	Acting Industrial Liaison Officer, National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power, University of Minnesota
2012-present	Teaching Specialist, Mechanical Engineering, University of Minnesota
2010	Adjunct Professor, Mechanical Engineering, University of Minnesota
2009-present	Sustainability Director, National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power, University of Minnesota
1997-2009	Business Development Manager, Advanced Technology, Eaton Fluid Power Group
1990-1997	Manager, Technical Services, Cummins Power Generation
1986-1989	Project Engineer, Lead Engine Engineering, Chrysler Motors

Closely Related Products

Rahul Dutta, Feng Wang, Bradley Bohlmann, Kim Stelson, “Analysis of Short-term Energy Storage for Mid-size Hydrostatic Wind Turbine”, in Proceeding of the 2012 ASME Dynamic Systems and Control Conference, DSCC-2012-8815, Fort Lauderdale, FL, USA, 2012 (selected as a top 20 outstanding paper).

Synergistic Activities

REU Advisor, 2012

Advisor, ME 4054W Capstone Design Projects course, University of Minnesota

- Fall 2011-Spring 2012: Advised a team of 5 undergraduate students working on a fluid power capstone design project. The project focused on a national competition funded by Parker Hannifin called the Chainless Challenge. The competition required that the mechanical link between the pedals and the drive wheel(s) of a bike be replaced with a hydraulic transmission. Twelve universities participated in the competition and the UMN team took second place overall. One of the 5 students is a graduate student at the University of Minnesota working with Prof Perry Li. Another is at the University of California, Santa Barbara pursuing a PhD in biomedical engineering.
- Fall 2012-Spring 2013: Advised a team of 5 undergraduate students working on a fluid power capstone design project focused on improving the previous year’s bike in the Chainless Challenge. The 2012-13 competition will be held in April 2013. Two of the five students have expressed an interest in studying fluid power in graduate school.

Collaborators And Other Affiliations

Kim Stelson, University of Minnesota, Feng Wang, PostDoc, University of Minnesota

Member, Technical Advisory Group, CALSTART (2005-2011)

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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

Closely Related Products

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.

Significant Products

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.

Synergistic Activities

Editorial Activities: Senior Technical Editor, ASME J Dynamic Systems, Measurement and Control, 1994-99; Associate Editor 1984-1987. Associate Editor, IEEE Trans Automatic Controls. Also Int J of Fluid Power, 2004-present Management Committee, Joint ASME-IEEE Trans Mechatronics, 1995-2008. Chair, 1999, Ed. Board and Associate Editor, J. of Systems and Control Eng. 2011-present.

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, Mark Elton.

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

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

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

Closely Related Products

1. Tu, H. C., Rannow, M. B., Wang, M., Li, P. Y., Chase, T. R. and Van de Ven, James D., 2012, "Design, Modeling and Validation of a High-Speed Rotary Pulse-Width-Modulation On/Off Hydraulic Valve", *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 134, No. 6, Paper #061002.
2. Li, Perry Y., and Chase, Thomas R., 2012, "Pulse Width Modulated Fluidic Valve", US Patent #8286939 B2.
3. 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.
4. 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.
5. 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.

Significant Products

6. 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.
7. 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.
8. Adamson, P., et al. (including T. R. Chase), 2006, "First Observations of Separated Atmospheric ν_μ and $\bar{\nu}_\mu$ events in the MINOS Detector", *Physical Review D (Particles and Fields)*, Vol. 73, No. 7, article #072002.
9. 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.
10. 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, 9/1/04-12/31/12.
2. Level 3 Manager for Scintillator Module Design, NuMI Off-Axis υ_e Appearance (NOν A) 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 & Other Affiliations

Collaborators Over The Last 48 Months:
J. Davidson, W. Lipinski & G. Venkatesan (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) – NOν A 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
S. Trolier-McKinstry (PSU Dept of Materials Science & Engineering) – 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

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
1. Gopinath Venkatesan, Post-Doctoral Research Associate, 2013-14
2. Edward Sandberg, MSME, 2013
3. Henry Kohring, MSME (John Deere), 2012
4. Stephen Sedler, MSME, 2012
5. Ross Makulec, MSME, 2011
6. Tyler Kuhlmann, MSME (MTS Systems Inc.), 2010
7. Anne Fundakowski, MSME, 2010
8. David Grandall, MSME (Stefan Maier Organbuilding), 2010
9. John Robelia, MSME, 2009
10. Benjamin Nitti, MSME, 2008

Total Number of Graduate Students advised: 37 (completed)

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

Douglas L. Cook
Research Engineer, Rapid-Prototyping Research
Milwaukee School of Engineering

Professional Preparation

Milwaukee School of Engineering	Mechanical Engineering	B.S., 1998
	Electrical Engineering	B.S., 1998
Fachhochschule Luebeck	Elektrotechnik	Dipl.-Ing., 1998
Milwaukee School of Engineering	Engineering	M.S., 2007

Academic/Professional Appointments

Research Engineer	MSOE, RP Research	June, 2006 – Present
Principal Investigator	MSOE, ATC	June, 2005 – May, 2006
Graduate Research Asst.	MSOE, RPC	Dec. 1998 – July, 2003
Undergrad Research Asst.	MSOE, RPC	Nov. 1996 – Nov. 1998

Closely Related Products

1. **Douglas Cook**, Samuel Newbauer, Adam Leslie, Vito Gervasi and Subha Kumpaty, Ph.D., P.E. "Unit-Cell-Based Custom Thermal Management through Additive Manufacturing." Proceedings of the 23rd Annual International Solid Freeform Fabrication (SFF) Symposium, Austin, Texas (2012). http://utwired.engr.utexas.edu/lff/symposium/proceedingsArchive/pubs/Manuscripts/2012/2012-09-Cook.pdf
2. **Douglas Cook**, 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).
3. **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). http://utwired.engr.utexas.edu/lff/symposium/proceedingsArchive/pubs/Manuscripts/2011/2011-54-Cook.pdf
4. **Douglas Cook**, Bradley Knier, Vito Gervasi, 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). http://utwired.engr.utexas.edu/lff/symposium/proceedingsArchive/pubs/Manuscripts/2010/2010-55-Cook.pdf
5. Gunnar Vikberg, **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).

Significant Products

1. Hsiao-wecksler, Elizabeth T., Alex K. Shorter, Vito Gervasi, **Douglas L. Cook**, Richard Remmers, Geza F. Kogler, and William K. Durfee. "Portable Active Pneumatically Powered Ankle-Foot Orthosis." ***U.S. Patent 20,120,289,870 A1***, published November 15, 2012.
2. **Douglas Cook**, Vito Gervasi, Robert Rizza Ph.D., Sheku Kamara, Xue-Cheng Liu, Ph.D., M.D. "Additive Fabrication of Custom Pedorthoses for Clubfoot Correction," Rapid Prototyping Journal, vol. 16, issue: 3, pp. 189-193, 2010, http://dx.doi.org/10.1108/13552541011034852
3. **Cook, Douglas Lee**, and Thomas E. Bray. "Flux Concentrator for Biomagnetic Particle Transfer Device." ***U.S. Patent 7,799,281***, issued September 21, 2010.
4. 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, pp. 3483-3487, August 2007, http://ieeexplore.ieee.org

Synergistic Activities

1. REU advisor for the summers of 2010, 2011 and 2012, and co-advisor for the summers of 2007 and 2008. RET advisor for the summers of 2008 & 2009. Funded by NSF's Center for Compact and Efficient Fluid Power. http://www.msoe.edu/reu/
2. Voting member of ASTM's Technical Committee F42 on Additive Manufacturing, contributor on the Design subcommittee.
3. Led the development of foam inserts for custom orthoses for children with club feet in a collaborative project between the Medical College of Wisconsin and MSOE (U.S. Dept. of Education, Grant No. H133G060142).
4. Outreach presentations: Altair-Northwestern University Symposium for Design Optimization 2008, SIAM Mathematics in Industry 2009, SME-RAPID 2011.

Collaborators & Other Affiliations

Collaborators:

Barth, Eric J., Ph.D. Vanderbilt University, Chase, Tom, Ph.D. University of Minnesota, Durfee, William K., Ph.D. University of Minnesota, Gervasi, Vito Milwaukee School of Engineering, Hsiao-Wecksler, Elizabeth T., Ph.D. University of Illinois, Urbana-Champaign, Kamara, Sheku Milwaukee School of Engineering, Knier, Bradley University of Wisconsin, Madison, Kogler, Geza, Ph.D., C.O., L.O. (IL), L.Ped. (IL), B.C.O. Georgia Institute of Technology, Kumpaty, Subha, Ph.D., P.E. Milwaukee School of Engineering, Leslie, Adam (unknown), Liu, Xue-Cheng, Ph.D., M.D. Children's Research Institute and Medical College of Wisconsin, Mallmann, A. James, Ph.D. Milwaukee School of Engineering, Newbauer, Samuel (unknown), Pettis, Devin (unknown), Remmers, Richard Bucyrus International, Inc./Caterpillar Inc., Rizza, Robert, Ph.D. Milwaukee School of Engineering, Rocholl, Josh Orbital Technologies Corporation, Stahl, Douglas, Ph.D. Milwaukee School of Engineering, Vikberg, Gunnar (unknown)

Graduate Advisors:

A. James Mallmann, Ph.D. (Milwaukee School of Engineering)
Steven E. Reyer, Ph.D. (Retired)
Thomas E. Bray (Milwaukee School of Engineering)

Thesis Advisor:

Graduate Students: Richard Remmers (Bucyrus International, Inc./Caterpillar Inc.)

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

Closely Related Products

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.

Significant Products

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.

Closely Related Products

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.

Significant Products

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

Randy H. Ewoldt
Department of Mechanical Science & Engineering
University of Illinois at Urbana-Champaign

Professional Preparation

Iowa State University	Mechanical Engineering	B.S., 2004
Massachusetts Institute of Technology	Mechanical Engineering	S.M., 2006
Massachusetts Institute of Technology	Mechanical Engineering	Ph.D., 2009
University of Minnesota – Twin Cities	Institute for Math. and its Apps. & Dept. Chem. Engr. and Matl. Sci.	Post-Doc, 2009-2011

Appointments

Assistant Professor, University of Illinois at Urbana-Champaign	Aug 2011 – Present
Postdoctoral Fellow, University of Minnesota – Twin Cities	Sept. 2009 – Aug. 2011

Products (selected)

[1] Ewoldt, R.H., "Extremely soft: Design with rheologically-complex fluids," *Soft Robotics*, 1(1) (2013) (**invited review for inaugural issue**)

[2] Johnston, M.T. and R.H. Ewoldt, "Precision rheometry: Surface tension effects on low-torque measurements in rotational rheometers," Journal of Rheology, 57(6), 1515-1532 (2013)

[3] Ewoldt, R.H., N.A. Bharadwaj, "Low-dimensional intrinsic material functions for nonlinear viscoelasticity", *Rheologica Acta*, 52(3) 201-219 (2013)

[4] Ewoldt, R.H., "Defining nonlinear rheological material functions for oscillatory shear," *Journal of Rheology*, 57(1) 177–195 (2013)

[5] Felts, J., S. Somnath, R.H. Ewoldt, W.P. King, "Nanometer-scale flow of molten polyethylene from a heated atomic force microscope tip," *Nanotechnology*, 23 (21) 215301 (2012)

[6] Hyun, K., M. Wilhelm, C.O. Klein, K.S. Cho, J.G. Nam, K.H. Ahn, S.L. Lee, R.H. Ewoldt, and G.H. McKinley "A review of nonlinear oscillatory shear tests: Analysis and application of Large Amplitude Oscillatory Shear (LAOS)," *Progress in Polymer Science*, 36(12), 1697-1753 (2011)

[7] Ewoldt, R.H., P. Tourkine, G.H. McKinley, and A.E. Hosoi, "Controllable adhesion using field-activated fluids," *Physics of Fluids*, 23, 073104 (2011)

[8] Celli, J.P., B.S. Turner, N.H. Afdahl, S. Keates, I. Ghiran, C. Kelly, R.H. Ewoldt, G.H. McKinley, P. So, S. Erramilli, and R. Bansil, "Helicobacter pylori moves through mucus by reducing mucin viscoelasticity," *Proceedings of the National Academy of Sciences*, 106 (34) 14321-14326 (2009)

[9] Ewoldt, R.H., A.E. Hosoi and G.H. McKinley, "New measures for characterizing nonlinear viscoelasticity in large amplitude oscillatory shear," *Journal of Rheology* 52(6), 1427-1458 (2008); **highest number of citations among all articles published in Journal of Rheology 2004-present**

[10] Ewoldt, R.H., C. Clasen, A.E. Hosoi, and G.H. McKinley, "Rheological fingerprinting of gastropod pedal mucus and synthetic complex fluids for biomimicking adhesive locomotion," *Soft Matter* 3(5), 634-643 (2007)

Synergistic Activities

[1] *Industrially-relevant short courses on rheology*: Lecturer for seven rheology short courses for practicing users of rheology (Minneapolis, San Francisco, Boston, Belgium, Montreal).

[2] *The Rheology Zoo:* Outreach and educational effort to encourage diversity and broad participation of underrepresented groups in engineering (funding from NSF-BRIGE Award #1342408 and NSF-CAREER Award #1351342). The Zoo is a hands-on curated library of rheologically interesting

materials that will serve as a platform for outreach, engagement, and undergraduate research opportunities.

[3] *School of Art+Design Collaborative teaching:* For three semesters, collaborative teaching to use rheology as a disruptive technology in industrial design studio projects, and integrate design and creativity into a graduate-level course on non-Newtonian fluids and rheology.

[4] *Software Development:* **MITlaos**, a fully-documented and free software to calculate rheological properties from data, based on Ewoldt et al. J. Rheol. 2008. Requested by over 145 corporate and academic groups across the world.

[5] *Manuscript reviewer* for 49 journal articles 2009-present

<u>Collaborators & Other Affiliations</u>

1. Collaborators and Co-Editors (last 48 months)

Kyung Hyun Ahn (Seoul National University, Korea), James Allison (UIUC), Jonathan Bailey (UIUC, Carle Hospital), Frank Bates (Minnesota), Rafael Bras (Wrigley), Kwang Soo Cho (Kyungpook National University, Korea), C. Clasen (KU-Leuven), Karin Dahmen (UIUC), C. J. Dimitriou (MIT), J. Felts (UIUC), Douglas Fudge (U. Guelph, Canada), Francisco Galindo-Rosales (University of Porto, Portugal), A. Kate Gurnon (U. Delaware), Sascha Hilgenfeldt (UIUC), Anette "Peko" Hosoi (MIT), Gavin Horn (UIUC), W. Hu (Minnesota), Kyu Hyun (Pusan National University, Korea), Iwona Jasiuk (UIUC), William King (UIUC), Seung Jong Lee (Seoul National University, Korea), Carlos Lopez-Barron (ExxonMobil), Chris Macosko (Minnesota), Luca Martinetti (U. Minnesota), Gareth McKinley (MIT), Leslie D. Morgret (Wrigley), Eric Morrison (EarthClean), Florian Nettesheim (DuPont), T.S.K. Ng (MIT), Martin Ostoja-Starzewski (UIUC), F.J. Rubio-Hernandez (University of Málaga, Spain), A. Sevilla (Universidad Carlos III de Madrid, Spain), Cliff (S.S.) Shin (UIUC), H. Craig Silvis (Dow Chemical), S. Somnath (UIUC), J. Song (Dow Chemical), Johannes Soulages (ExxonMobil), James W. Swan (MIT), P. Tourkine (Ecole Normale Superieure), Norman J. Wagner (U. Delaware), Manfred Wilhelm (Karlsruhe Institute of Technology), T. M. Winegard (U. Guelph, Canada)

2. Graduate and Postdoctoral Advisors

Post-Doctoral: Christopher Macosko (Minnesota)

Ph.D. Gareth McKinley and Anette “Peko” Hosoi (MIT);

S.M. Anette “Peko” Hosoi and Gareth McKinley (MIT)

3. Thesis Advisor and Post-Scholar Sponsor (last five years)

N. Ashwin Bharadwaj, Brendan Blackwell, Rebecca Corman, Michael Johnston (now Boeing, CA), Jeremy Koch, Arif Nelson, Jonathon Schuh, Piyush Singh (all UIUC)

Total Graduate Students Advised: 8 **Total Postdoctoral Scholars Sponsored: 0**

Vito R. Gervasi
Research and Development
Milwaukee School of Engineering

PROFESSIONAL PREPARATION

Milwaukee School of Engineering Manufacturing Engineering Technology B.S, 1996 Milwaukee School of Engineering Mechanical Engineering M.S., 2003

APPOINTMENTS

1993-present Director, Research & Development, Rapid Prototyping Research, Milwaukee School of Engineering
1985-1990 United States Air Force, honorable discharge

Closely Related Products

1. Gervasi, Vito R., Josh Rocholl, Adam J. Schneider, Doug C. Stahl. "Casting Process." U.S. Patent 8,312,913, issued November 20, 2012. (CMP-Hybrid Casting Process, licensed).

2. Gervasi, Vito R. "Three dimensional object." U.S. Patent 6,641,897, issued Nov 4, 2003. (TetraLattice structure).

3. Douglas Cook, Bradley Knier, Vito Gervasi, 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).

4. Gervasi, Vito R. "Method of making three dimensional object." U.S. Patent 6,309,581, issued Oct 30, 2001. (Method of producing lattice structure, licensed).

5. 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.

Significant Products

6. 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.

7. 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- (1st place poster for entire symposium)

8. Gervasi, Vito R., Robert S. Crockett, "Process of making three dimensional object." U.S. Patent 6,623,687, issued Sep 23, 2003 (Intertwined three dimensional lattice structure, licensed).

9. Hsiao-wecksler, Elizabeth T., Alex K. Shorter, Vito Gervasi, Douglas L. Cook, Richard Remmers, Geza F. Kogler, and William K. Durfee. "Portable Active Pneumatically Powered Ankle-Foot Orthosis." U.S. Patent 20,120,289,870 A1, published November 15, 2012.

10. 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 (SFF Symposium Outstanding Paper).

SYNERGISTIC ACTIVITIES

MSOE's executive committee representative for the NSF Center for Compact and Efficient Fluid Power, started June 2006. Primarily involved in research related to thrust area II, "compactness." Former 2D Project leader. Now 2G Co-project leader (ranked #1 among Center projects) and member of the CCEFP Executive Committee. Led hosting of several CCEFP events at Milwaukee School of Engineering. Supports center projects related to additive manufacturing.

Through collaborative efforts between industry and MSOE aimed at bringing innovations to market a number of novel processes, designs and methods invented or co-invented by Gervasi (as well as many trade secrets) are commercially available in the form of many products through three companies, including: DSM-Somos (US patents 6,309,581, 6,641,897, 6,623,687), Orbital Technologies Corporation (Orbitec, US patent 8,312,913), 3DMolecular Designs (US patents 6,793,497, US6,471,520). Products include education molecular models, AM-based patterns for investment casting, reduced-mass components, FGM's, harsh environment components and DoD components.

Promotes activities and education of the Rapid Prototyping Consortium (RPC) industrial membership in areas of additive manufacturing. 1) Educated and trained industrial members and MSOE community on RP related topics at consortium meetings as well as at member locations. 2) Suggested and arranged numerous RPC guest speakers for monthly meetings. 3) Conducted applied research with consortium membership on numerous RP related projects

Contributor to the NIST Measurement Science for Metal-Based Additive Manufacturing Roadmap and participant in ASTM F42 (AM Technologies). 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." Currently contributing to the "NAMII/SME additive manufacturing body of knowledge project." Currently involved in the RTAM Masters Exam Committee.
Contributes to several sections of Wohler's Additive Manufacturing and 3D Printing State of the Industry Annual Worldwide Progress Report.

COLLABORATORS & OTHER AFFILIATIONS

Thomas Bray, Doug Cook, Shajan John, Sheku Kamara , A. James Mallmann Ph.D., Subha Kumpaty Ph.D. PE, Eric Durant Ph.D., Paul Michael, Matey Kalchev Ph.D., Robert Rizza Ph.D., Douglas Stahl, Tim Herman Ph.D.(3DMD), Josh Rocholl (Orbital Technologies Corporation), Liu Xue-Cheng Ph.D. M.D. (Medical College of Wisconsin), T. Wohler (Wohler's & Associates, Mark Abshire (DSM), Eric Barth Ph.D. (Vanderbilt University), Tom Chase Ph.D. (University of Minnesota), William Durfee Ph.D. (University of Minnesota), Elisabeth Hsiao-Wecksler Ph.D. (University of Illinois Urbana-Champaign), Geza Kogler Ph.D., C.O., L.O. (IL), L.Ped. (IL), B.C.O. (University of Illinois Urbana-Champaign), Richard Remmers (Bucyrus International, Inc./Caterpillar Inc.), Arthur Sauer (Orbital Technologies Corporation), Dan Maas (X-One), Robert Webster Ph.D.(Vanderbilt University), Kim Stelson Ph.D. (University of Minnesota)

GRADUATE ADVISORS

G. Hoffmann (Retired), Matthew Panhans Ph.D. (Milwaukee School of Engineering), William Howard Ph.D. (East Carolina University)

THESIS ADVISOR

Graduate Students: Richard Remmers (Bucyrus International, Inc. /Caterpillar Inc.)

Elizabeth T. Hsiao-Wecksler
Dept of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

PROFESSIONAL PREPARATION

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

APPOINTMENTS

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 05/10 – 05/12

Closely Related Products

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*, 16(5):835-844, 2011.*
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*, in press.*

Significant Products

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)

Paul Imbertson
University of Minnesota
Department of Electrical and Computer Engineering
200 Union Street S.E.,
Keller Hall 4-146
Minneapolis, MN 55455
Phone: (612) 625-6529 Fax: (612) 625-4583
Email: imbertson@umn.edu

Professional Preparation
PhD, 1997, University of Minnesota, Electrical Engineering,
MS, 1994, University of Minnesota, Electrical Engineering,
BS, 1983, University of Minnesota, Electrical Engineering,

Positions

Teaching Professor (current title), Electrical and Computer Engineering, University of Minnesota,	1997-Present
Education Director, Center for Compact and Efficient Fluid Power (CCEFP)	2011-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 (NSBE), Student Branch
Faculty Advisor, Innovative Engineers (IE), University of Minnesota
Faculty Advisor, Solar Vehicle Project
Faculty Advisor, Kappa Eta Kappa, Electrical Engineering Fraternity
Faculty Advisor, Mad Scientists Club

Awards
Award for Global Engagement; University of Minnesota, 2013
Senator Amy Klobuchar's Carbon Buster Award, December 2008
Ten times awarded "Best Professor Award" from IT/CSE 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. Noted for activity with communities throughout Minnesota on issues related to sources of renewable energy and hydroelectric power, June 2002

Patents
U.S. Patent #5,245,520: Asymmetrical Duty Cycle Power Converter

Activities
Developing novel active-learning classroom models and methods in engineering curriculum in collaboration with researchers at the University of Minnesota STEM Education Center.

EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Targeted Mathematics-Science Partnership, NSF-MSP.
Co-PI and Content Director working in the area of K-12 STEM education.

Initiated “Bridges Project” who’s mission is to build local empowerment here and abroad through collaborations with the Universidad Nacional de Ingenieria (UNI) in Managua, Nicaragua, Universidad La Salle (ULSA) in Leon, Nicaragua, Villanova University, and communities in Nicaragua.

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.

Consultant to the nonprofit Bright New Ideas and the for-profit ValuLamp. Both entities founded by UMN engineering graduate, Patrick Delany, which has developed, produced, and distributed several thousand solar lanterns for citizens of developing nations. Worked with Patrick from the inception of the project.

Member of working group to develop a graduate engineering program in Tanzania.

Dusome Foundation: Board Member. The Dusome Foundation is working to build libraries in Tanzania.

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, Nicaragua, and Tanzania featured in articles in “Inventing Tomorrow” the magazine of the Institute of Technology, University of Minnesota.

Founding advisor to Applied Environmental Solutions (AES) student group.

Founding advisor to Innovative Engineers student group.

Founded an international branch of the Innovative Engineers at Universidad Ibero Americano in Mexico City, Mexico.

Education and curriculum development:

1. Developed new undergraduate course “Alternative Energy in Scandinavia”, three week May-term study abroad course to Iceland Norway and Denmark. Course has been executed six times 2004 to 2013 with plans to continue with yearly offerings. Informal survey of 145 past participants suggests that 75% of those who took the course are currently working in the energy field.
2. Curriculum Integration -- Study Abroad Participant, visiting Scotland and England to further study-abroad opportunities.
3. Developed new undergraduate course “Energy, Environment, and Society”.
4. Developed new senior/graduate level course in electrical and computer engineering “Energy Conversion and Storage Technologies: Theory and Applications”.

Regional Sustainable Development Partnership UMN (RSDP): Active engagement with Minnesota communities to develop and plan for local energy needs and to heighten energy awareness. This involved numerous speaking engagements, panel discussions, and one-on-one discourse at community meetings throughout Minnesota, and over 4000 travel miles.

Regional Sustainable Development Project - Distributed Energy Project: A site study to determine the financial feasibility of reactivating the hydro-electric power facility located on the Fish Hook Dam, Park Rapids, MN.

Presentation – “Power to the People: Building Citizen Leadership for a Sustainable Energy Future” Joint International Summit on Community and Rural Development, July 2001.

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 Electric Power Curriculum including Power Electronics and Electric Drives, 2003 to present.

Presentation – “Sharing the Load: Local Electric Energy Generation and Distribution” A Citizens’ Action Congress, March 2001.

Invited Speaker, IEEE-USA Annual Meeting in STEM track, 2010.

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 at North High School, an inner city, minority high school in Minneapolis, MN, involving university members of the National Society of Black Engineers (NSBE).

Technical consultant to Bakken Museum’s Green Energy Art Garden; 2013, 2012, Renewable Energy Sculpture Garden; 2010, and “Electrifying Minnesota” exhibit; 2007.

Panelist, ASEE Annual Meetings; 2010, 2013.

Planning committee, Minnesota Power Systems Conference, MIPSYCON 2009, 2010.

Tutorial: “Motors 101”, MIPSYCON 2009.

Eagle Bluff Environmental Learning Center (ELC).
Concept and specifications for Zero-Energy-House demonstration/experimental project.

Prairie Woods Environmental Learning Center (ELC)
Concept, specifications, and construction of solar powered yurt classroom.

Publications

1. J. Ling, P. Imbertson, T. Moore, “Introducing an Instructional Model in Undergraduate Electric Power Energy Systems Curriculum-Part (II): Authoritative vs. Dialogic Discourse in Problem-Centered Learning,” ASEE 2014 Annual Conference (accepted).

2. J. Ling, P. Imbertson, T. Moore, “Introducing an Instructional Model in Undergraduate Electric Power Energy Systems Curriculum-Part (I): Authoritative vs. Dialogic Discourse in Problem-Centered Learning,” ASEE 2013 Annual Conference.

3. Jia-Ling Lin, Paul Imbertson, and Tamara Moore, “Applying design-based research to investigate instructional strategies for problem-centered learning in undergraduate electric energy systems curriculum,” TRUES Conference, June 3, 2012.

4. 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.

5. P. Imbertson, M. Masoud, and A.Sonnenberg, “Energy: Bridging Developing Nations and Inner-City Youth,” Minnesota Power Systems Conference (MIPSYCON), 2009.

6. 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.

7. 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.

8. Ned Mohan, William P. Robbins, Paul Imbertson, Tore M. Undeland, Razvan C. Panaitescu, Amit Kumar Jain, Philip Jose, and Todd 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.

9. P. Imbertson, “Local/Community Aspects of Generation,” Minnesota Power Systems Conference (MIPSYCON), 2002.

10. Rohit Tirumala, Paul Imbertson, Ned Mohan, Chris Henze and Russ Bonn, “An Efficient, Low Cost DC-AC Inverter for Photovoltaic Systems with Increased Reliability,” IECON 2002.

11. N. Mohan, M. Riaz, P. Imbertson, and T. Brekken, “A Strategy for the Revival of Electric Machines and Drives Courses,” IEEE PELS web resources, 2001.

12. 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.

13. P. Imbertson and N. Mohan, “A Novel Asymmetrical Duty-Cycle Soft-Switching DC-DC Converter with Lower Conduction Losses Than in Hard-Switched PWM Converters,” PEDES 1996.

14. N. Mohan, P. Imbertson, and G. Kamath, “Panel Discussion on Future Trends in Power Electronics: Power Converters,” International Power Electronics Conference (IPEC), 1995.

15. 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.

16. P. Imbertson and N. Mohan, “New PWM Circuits Combining Zero Switching Loss with Low Conduction Loss,” International Telecommunications Energy Conference (INTELEC), 1990.

17. P. Imbertson and N. Mohan, “Square-wave Resonant Power Converter,” International Power Electronics Conference (IPEC), Tokyo, Japan, 1990.

18. P. Imbertson and N. Mohan, “A Method for Estimating Switch-Mode Power Supply Size,” Applied Power Electronics Conference (APEC), 1989.

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

Closely Related Products

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. 2012. Heat Transfer and Thermal Elastic Deformation Analysis on the Piston/Cylinder Interface of Axial Piston Machines"; ASME Journal of Tribology. Vol. 134, October 2012, pp. 1- 15.
3. Zecchi, M. and Ivantysynova, M. 2012. A novel approach to predict the cylinder block / valve plate interface performance in swash plate type axial piston machines. ASME/Bath Symposium on Fluid Power and Motion Control (FPMC 2012), Bath, UK, pp. 13-28.
4. 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. **Best paper award**
5. 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.**

Significant Products

1. Sprengel, M. and Ivantysynova, M. 2012. Coupling Displacement Controlled Actuation with Power Split Transmissions in Hydraulic Hybrid Systems for Off-Highway Vehicles. ASME/Bath Symposium on Fluid Power and Motion Control (FPMC 2012), Bath, UK, pp. 505-517.
2. Hippalgaonkar, R., Zimmerman, J. and Ivantysynova, M. 2011. Investigation Of Power Management Strategies For A Multi-Actuator Hydraulic Hybrid Machine System. SAE 2011 Commercial Vehicle Engineering Congress, , Sep 13-14 2011, Rosemont, IL, USA. SAE Technical Paper 2011-01-2273

3. Hughes, E.C., Williamson, C.A., Zimmerman, J.D. Ivantysynova, M.M. 2012. Displacement – controlled hydraulic system for multi-function machines. US Patent No: US 8,191,290 B2 issue June 5, 2012.
4. 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.
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 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

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)), 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), 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:
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, Matteo Pelosi, Micheal Cross, Brent Warr, Jess Rose, Matt Kronlage, Domgjune Albert Kim

Total number of graduate students supervised: 87 Postdoctoral scholars: 6 Undergraduate Research Students: 25

Steven X. Jiang
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

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

Closely Related Products
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.

Synergistic Activities
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.

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

Closely Related Products

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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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

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

Closely Related Products

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.

Significant Products

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

2009 Spring	Bye Fellow, Churchill College, Cambridge University
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

Closely Related Products

1. Tian, L., Kittelson, D.B., Durfee, W.K., 2011. "Model based design of a miniature free-piston engine compressor". Proceeding of the IFPE conference, Las Vegas, U.S., 2011.
2. Tian, Lei, David B. Kittelson, William K. Durfee, 2009. Miniature HCCI Free-Piston Engine Compressor for Orthosis Application, JSAE paper number 20097176.
3. 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.
4. 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.
5. 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.

Significant Products

6. Lucachick, Glenn, Aaron Avenido, David Kittelson, and William Northrop, 2014." Exploration of Semi-Volatile Particulate Matter Emissions from Low Temperature Combustion in a Light-Duty Diesel Engine," SAE paper number 2014-01-1306.
7. Fang, Wei, David B. Kittelson, William F. Northrop, and Junhua Fang, 2013. "An Experimental Investigation of Reactivity-Controlled Compression Ignition Combustion in a Single-Cylinder Diesel Engine Using Hydrous Ethanol," Proceedings of the ASME Internal Combustion Engine Division 2013 Fall Technical Conference, ICEF2013.
8. Bika, Anil Singh, Luke Franklin, and David B. Kittelson, 2012. "Homogeneous charge compression ignition engine operating on synthesis gas," International Journal of Hydrogen Energy, v 37, n 11, p 9402-9411, June 2012
9. Bika, Anil Singh; Luke Franklin, David B. Kittelson, 2011. Engine Knock and Combustion Characteristics of a Spark Ignition Engine Operating with Varying Hydrogen and Carbon Monoxide Proportions, International Journal of Hydrogen Energy, v 36, n 8, p 5143-5152, April 2011
10. Bika, Anil Singh, Luke Franklin, Helmer Acevedo, and David Kittelson, 2011. Hydrogen Fueled Homogeneous Charge Compression Ignition Engine, SAE paper number 2011-01-0672.

Synergistic Activities

- Directs Center for Diesel Research
- Highly recognized for developing key understanding about engine-generated nanoparticles
- PI or Co-PI on a variety of projects aimed at understanding combustion and emissions of alternative fuels

Collaborators and Other Affiliations

Collaborators and Co-Editors:
Aichlmayr, H. T., Sandia National Labs; Andrews, Gordon, Leeds University; Collings, Nick, Cambridge University; Durbin, Tom, UCR: Durfee, William K., U of Mn: Fang, Junhua, U of MN; Fang, Wei, U of MN; Goersmann, C., Johnson-Matthey; Kraft, Markus, Cambridge U.; Johnson, Kent, UCR; Johnson, Tim, TSI, Inc.; Johnson, Tim, Corning; Jung, Heejung, UC Riverside; Liu, Z. Gerald, Fleetguard; Lucachick, Glenn, U of MN; McMurry, P. H., University of Minnesota; Miller, Arthur, NIOSH ; Northrop, William, U of MN; Twigg, Martyn, Johnson-Matthey, plc.; Walker, A. P., Johnson-Matthey; Warrens, C. P., British Petroleum; Watts, W., Univ. of Minnesota; Zachariah, Michael R.. University of Maryland; Zarling, Darrick D., University of Minnesota; Zheng, Zhongqing, UCR; Ziemann, Paul J., UCR.

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)
Avenido, Aaron, TSI Inc.; Bennett, David, self-employed; Thul, Dain, Donaldson; Tian, Lei, Polaris; Patwardhan, Udayan, Schlumberger; Hathaway, Brandon, post-doc, Univ. of Minn.; Sweeney, Joe, ACS; Kirk Johnson, Polaris; Ryan Becker, Honeywell; Aaron Collins, MSP; Andre Olson, Scania; Ragatz, Adam, NREL; Mathew Kenitzer, Deere; David Gladis, Cummins; Franklin, Luke, Dow; Anil Bika, GMR; Jason Johnson, TSI Inc.; Jeffrey Campbell, US State Department; Jacob Swanson, MSU; Andy Tan, Cummins; David Hall, Phillips Temro; Brad Dana, MTS; John Dixon, Cummins

Thomas R. Kurfess, P.E.
HUSCO Ramirez Distinguished Chair in Fluid Power and Motion Control
and
Professor
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia USA

Professional Preparation:

M.I.T., Cambridge, MA	Mechanical Engineering	**S.B.** (1986)
M.I.T., Cambridge, MA	Mechanical Engineering	**S.M.** (1987)
M.I.T., Cambridge, MA	Electrical Engineering and Computer Science	**S.M.** (1988)
M.I.T., Cambridge, MA	Mechanical Engineering	**Ph.D.** (1989)

Appointments:

2012-Present, HUSCO Ramirez Distinguished Chair in Fluid Power and Motion Control and Professor, Woodruff School of Mechanical Engineering, GA Tech, Atlanta, GA.

2012-2013, Assistant Director for Advanced Manufacturing, Office of Science and Technology Policy, Executive Office of the President of the United States of America, Washington, DC.

2005-2012, Professor and BMW Chair of Manufacturing Integration, Department of Mechanical Engineering, Clemson University, Clemson, SC.

2000-2005, Professor, Woodruff School of Mechanical Engineering, GA Tech, Atlanta, GA.

1993-2000, Associate Professor, Woodruff School of Mechanical Eng., GA Tech, Atlanta, GA.

1993, Associate Professor of Mech. Eng. and Engineering and Public Policy, Carnegie Mellon University (CMU), Pittsburgh, PA.

1989-93, Assistant Professor of Mech. Eng. and Engineering and Public Policy, CMU, Pittsburgh, PA.

1992-present, participating guest in the Precision Engineering Program at the Lawrence Livermore National Laboratory (LLNL), Livermore, CA.

1992-93, Summer Faculty LLNL, in the Precision Engineering Program, Livermore, CA.

Products

1. Carter J. A., Tucker, T. M., Kurfess, T. R., “3-Axis CNC Path Planning Using Depth Buffer and Fragment Shader,” Computer-Aided Design & Applications, Vol. 5, No. 5, pp. 612-621, 2008.
2. Panyam, M., Tucker, T. M., Kurfess, T. R., “Least-Squares Fitting of Analytic Primitives on a GPU,” Journal of Manufacturing Systems, Vol. 27, No. 3, pp. 130-135, July 2008.
3. Tarbutton, J. A., Kurfess, T. R., Tucker, T. M., “Graphics Based Path Planning for Multi-Axis Machine Tools,” Computer-Aided Design & Applications, Vol. 7, No. 6, pp. 612-621, 2010.
4. Tarbutton, J. A., Kurfess, T. R., Tucker, T. M., “Machining by Ray-Casting into Voxel Models, Proceedings of 2010 International Symposium on Flexible Automation,” Tokyo, Japan, July 12-14, 2010 UPL-2503.

Products (other)

1. Kurfess, T. R., “CMMs Are Key to Auto Quality” Manufacturing Engineering, Vol. 137, No. 3, pp. 131-140, September 2006.
2. Roth, J.T., Mears, L., Djurdjanovic, D., Yang, X. and Kurfess, T. R., “Quality and Inspection of Machining Operations: CMM Integration to the Machine Tool,” ASME Journal of Manufacturing Science and Engineering, Vol. 131, No. 5, October 2009.
3. Kurfess, T. R. (Editor), Robotics and Automation Handbook, 2005, CRC Press, Inc., Boca Raton, FL.
4. A. J. Henderson, C. Bunget, and T. R. Kurfess, "On-machine monitoring of tool wear with touch probes," *Proceedings of NAMRI/SME,* vol. 39, p. 8, 2011.
5. M. Estrems, H. T. Sanchez, T. R. Kurfess, C. Bunget, A. J. Henderson, and B. J. Richardson, “Influence of size effect and radial runouts on the end milling of a nickel-based superalloy," *Proceedings of NAMRI/SME,* vol. 39, p. 8, 2011.

Synergistic Activities

1. Board of Director MT Connect Institute.
2. Co-Chair National Network for Manufacturing Innovation Working Group, Advanced Manufacturing Partnership 2.0.
3. Board of Directors, Society of Manufacturing Engineers.
4. Board of Directors, National Center for Manufacturing Sciences.
5. Board of Directors, National Center for Defense Manufacturing and Machining.
6. Board of Editors, International Journal of Engineering Education.
7. Member National Academies Panel on Manufacturing Engineering.

Collaborators & Other Affiliations

Collaborators and Co-Editors:

Douglass Chinn (Sandia National Laboratories), R. Cowan* (Georgia Tech), Steven Danyluk (Georgia Tech), Levent Degertekin (Georgia Tech), Craig Henderson (Sandia National Laboratories), Steven Liang* (Georgia Tech), Shreyes Melkote* (Georgia Tech), Mark L. Nagurka* (Marquette University)

Graduate Advisors:

C. L. Searle (M.I.T.), D.E. Whitney (M.I.T)

Thesis Advisor:

M.S: R. Anderson, K. Aravalli, P. Aussaguel, S. Billington, S. Bittle, V. Bobba, J. Bradon, Z. Brooks*, S. Burns, A. Caccialupi, J. Ceremuga, A. Chen, W. Choi, I. Chuckpaiwong, A. Claudet, R. Coulter, R. Cowan, M. Crudele, M. Cummings, T. Dawson, C. Gallagher, S. Gamble, M. Greene, O. Karhade, B. Kim, H. Kohli, K. Laughlin, M. Leclerc, T. Lloyd, D. Longanbach, R. Lopez, J. Miller, C. Moore, J. Morrisette, J. Nichols, P. Padmanabhan, M. Panyam, J. Rayner, J. Reyer, B.J. Richardson, U. Sadiq, M. Schmittdiel, M. Shilling, M. Shilling, J. Shiroishi, J. Sills, W. Stone, J. Stuhlfire, J. Tarbutton, G. Toledo, T. Tucker*, J. Tucker, B. Ulmer, J. Whidby, T. Williams, A. Wilson, M. Yang, S. Yim.

Ph.D.: M. Aminzadeh*, P. Amy, M. Arant, M. Bowler*, Aoyu Chen*, Austin Chen, W. Choi, I. Chuckpaiwong, A. Claudet, T. Dawson, D. Delorenzis, A. Henderson, Hodge Jenkins, O. Karhade, B. Kim, D. Konobrytskyi, K. Kreuger, J. Limroth, D. Longanbach, L. Mears, P. Murray, J. Nichols, H. Razavi, M. Shilling, W. Stone, J. Tarbutton, T. Tucker*, H. Vasseur, S. K. Wang

Post-Graduate Scholars: A. Bryan, C. Bunget, G. Bunget, S. De Rosa (University of Naples "Federico II"), Manuel Estrems (Universidad Politécnica de Cartagena, Spain), P. Gutheil (Fachhochschule Trier, Germany), Y. Jung (Pusan National University, Korea), J. Karandikar* (Georgia Tech), D. Kim (Kumoh National University of Technology), P. Kerstiens (Fachhochschule Gelsenkirchen, Bocholt, Germany), J. Marquez (ETSII. Polytechnic University of Madrid), H. Razavi (Georgia Tech)

Number of MS students: 55, Number of Ph.D. students: 25, Post-doctoral scholars sponsored: 11
* Indicates current

Michael J. Leamy
G. W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology

PROFESSIONAL PREPARATION

Clarkson University, Potsdam, NY	Mechanical Engineering	B.S. 1993
University of Michigan, Ann Arbor, MI	Mechanical Engineering	M.S. 1995
University of Michigan, Ann Arbor, MI	Mechanical Engineering	Ph.D. 1998
Technion, Haifa, Israel	Nonlinear Mechanics	1998-1999
NASA Langley Research Center	Computational Mechanics	1999-2000

APPOINTMENTS

Jul. 2012 – Present	Georgia Institute of Technology, Associate Professor
Aug. 2007 – Jul. 2012	Georgia Institute of Technology, Assistant Professor
Sep. 2004 – Aug. 2007	MITRE Corporation, Research Scientist
Sep. 2003 – Aug. 2004	University of Maine, Assistant Professor
Jun. 2000 – Aug. 2003	United States Military Academy, West Point, Assistant Professor

CLOSELY RELATED PROJECTS

1. Leamy, M.J., 2012, “Exact Wave-Based Bloch Analysis Procedure for Investigating Wave Propagation in Two-Dimensional Periodic Lattices,” *Journal of Sound and Vibration*, **331**: 1580-1596.
2. Narisetti, R.K., Ruzzene, M., Leamy, M.J., 2011, “A Perturbation Approach for Analyzing Dispersion and Group Velocities in Two-Dimensional Nonlinear Periodic Lattices,” *Journal of Vibration and Acoustics*, **133** (6): 061020, pp. 1-12.
3. Farzbod, F., Leamy, M.J., 2011, “Analysis of Bloch's Method in Structures with Energy Dissipation,” *Journal of Vibration and Acoustics*, **133** (5): 051010, pp. 1-8.
4. Manktelow, K., Leamy, M., Ruzzene, M., 2011, “Multiple Scales Analysis of Wave-Wave Interactions in a Cubically Nonlinear Monoatomic Chain,” *Journal of Nonlinear Dynamics,* **63**: 193-203.
5. Narisetti, R.K., Leamy, M.J., Ruzzene, M., 2010, “A Perturbation Approach for Predicting Wave Propagation in One-Dimensional Nonlinear Periodic Structures,” *Journal of Vibration and Acoustics*, **132** (3): 031001, pp. 1-11.

SIGNIFICANT PRODUCTS

1. Kulpe, J.A., Lee, C.-Y., Leamy, M.J., 2011, “Computation of Acoustic Absorption in Media Composed of Packed Microtubes,” *Journal of the Acoustical Society of America*, **130** (2): 826-834.
2. Lee, C.-Y., Leamy, M.J., Nadler, J.H., 2010, "Frequency Band Structure and Absorption Predictions for Multi-Periodic Acoustic Composites," *Journal of Sound and Vibration*, **329**: 1809-1822.
3. Farzbod, F., Leamy, M.J., 2009, "The Treatment of Forces in Bloch Analysis," *Journal of Sound and Vibration*, **325**: 545-551.
4. Leamy, M.J., DiCarlo, A., 2009, "Phonon Spectra Prediction in Carbon Nanotubes Using a Manifold-Based Continuum Finite Element Approach," *Computer Methods in Applied Mechanics and Engineering*, **198** (17-20): 1572-1584.
5. Leamy, M.J., Lee, C.-Y., 2009, “Dynamic Response of Intrinsic Continua for Use in Biological and Molecular Modeling: Explicit Finite Element Formulation,” *International Journal for Numerical Methods in Engineering*, **80** (9): 1171-1195.

SYNERGISTICS ACTIVITIES

Associate Editor, *Journal of Vibration and Acoustics* (2012-Present)
Elected Member of the Technical Committee on Vibration and Sound, ASME (2011-present)
Member of ASME, SAE

SESSION/SYMPOSIA ORGANIZER (MOST RECENT)

- Technical Track Co-Chair, 'Multiscale Mechanics of Materials,' *49th Annual Society of Engineering (SES) Technical Meeting*, 2012, Atlanta, GA.
- Symposium Co-Organizer, 'Emerging Applications in Dynamic Systems,' *24th Conference on Vibration and Noise*, 2012 ASME IDETC Conference, Chicago, IL.
- Member of Scientific Advisory Board, *Phononics 2011 – International Conference on Phononic Crystals, Metamaterials & Optomechanics*, 2011, Santa Fe, NM.
- Topic Chair, 'Structural Dynamics,' *ASME IDETC Conference*, 2011, Washington, DC.
- Minisymposium Organizer, 'Computational Mechanics of Phononic Metamaterials and Phononic Crystals,' *11th U.S. National Congress on Computational Mechanics*, 2011, Minneapolis, MN.

COLLABORATORS & OTHER AFFILIATIONS

Collaborators: Prof. Thomas Bradley, Dr. Gary Caille (Colorado State University), Prof. Ken Cunefare, Prof. Aldo Ferri, Prof. Peter Hesketh, Prof. David Hu, Prof. Massimo Ruzzene, Prof. Karim Sabra, Prof. David Taylor (Georgia Institute of Technology), Dr. Mahmoud Hussein (University of Colorado), Prof. Mario Encinosa, Prof. Mark Jack (Florida A&M University), Prof. Chiara Daraio (Cal Tech).

Post Graduate Advisors: Prof. Ahmed Noor (NASA Langley Research Center, University of Virginia), Prof. Oded Gottlieb (The Technion, Israel).

Thesis Advisor and Postgraduate-Scholar Sponsor (Previous 5 Years)

Graduate Students (11): Dr. Farhad Farzbod, 01/2008 – 11/2010, Dr. Raj Narisetti, 06/2008 – 11/2010, Mr. John Arata, 01/2010 – 11/2011, Mr. Kevin Manktelow, 08/2009 – Present
Mr. Kyle Karlson, 08/2009 – Present, Mr. Jason Kulpe, 08/2010 – Present, Mr. Kamil Kocak, 08/2011 – Present, Mr. Dekun Pei, 08/2011 – 12/2012, Mr. Ryan Hopman, 01/2008 – 08/2009, Ms. Dooroo Kim, 09/2007 – 08/2009, Mr. Thibaut Autrusson, 09/2007 – 05/2009

Postdoctoral Scholars (1): Dr. Chang-Yong Lee (01/2008-01/2010).

Perry Y. Li
Department of Mechanical Engineering
University of Minnesota

Professional Preparation
Cambridge University, England, Electrical and Information Sci., B.A.(Hons.), Jun 1987
Boston University, Boston, Biomedical Engineering, M.S., Jan 1990
University of California, Berkeley, Mechanical Engineering, PhD, May 1995
Major: Control systems; **Minors**: Signal processing and bioengineering

Appointments
Zhejiang University, Hangzhou, China
2011-2012 High Level Expert in Mechatronics (Visiting Professor)
University of Minnesota, Minneapolis MN
2008 - present, Professor of Mechanical Engineering
2006 - present, Deputy Director, NSF-ERC for Compact and Efficient Fluid Power.
2003 - 2008, Associate Professor of Mechanical Engineering
1999 - present, Graduate faculty in Control and Dynamic Systems (CDyS) Program
1997 - 2003, Nelson Assistant Professor of Mechanical Engineering
Xerox Corporation, Webster, NY
1995 - 97, Research Staff II, Xerox Wilson Center for Research & Technology

Honors
-Visiting Faculty, Department of Mechanical Engineering, University of Bath (Spring 2001)
-Young Investigator Award, Japan/USA Symposium on Flexible Automation (2000-2002)
-Special Recognition Award, Corporate Research & Technology, Xerox Corp. 1997
-Achievement Award, Corporate Research & Technology, Xerox Corp. 1996

Closely Related Products

1. M. Saadat and P. Y. Li, "Modeling and Control of a Novel Compressed Air Energy Storage System for Offshore Wind Turbine", 2012 American Control Conference, Montreal, Canada, June 2012
2. A. T. Rice and P. Y. Li, "Optimal Efficiency-Power Tradeoff for an Air Motor/Compressor with Volume Varying Heat Transfer Capability", ASME DSC Conf 2011, October, 2011
3. P. Y. Li and V. Durbha, "Passive control of fluid powered human power amplifiers", Proc. of the 7th JFPS International Symposium on Fluid Power, Toyama, Japan, September, 2008
4. D. J. Lee and P. Y. Li, “Passive Decomposition of Multiple Mechanical Systems under Coordination Requirements”, IEEE Trans on Automatic Control, Vol 58:1, pp230-235, 2012.
5. M. Wang and P. Y. Li, "Passivity based adaptive control of a two chamber hydraulic actuator", 2012 American Control Conference, Montreal, Quebec, Canada, June 2012.

Significant Products

6. H. Tu, M. B. Rannow, M. Wang, P. Y. Li, and T. R. Chase, “Design, Modeling and Validation of a High-Speed Rotary PWM On/Off Valve for Use in Virtually Variable Displacement Pumps”, ASME J. of Dyn. Sys, Meas. & Control, Vol. 134:6, #061002, 2012
7. K. L. Cheong, P. Y. Li and T. R. Chase, "Optimal Design of Power-Split Transmission for Hydraulic Hybrid Passenger Vehicles", 2011 American Control Conference, pp.3295-3300
8. D. Berg and P. Y. Li, "Achieving Dexterous Manipulation for Minimally Invasive Surgical Robots Through the Use of Hydraulics", ASME DSC Conference, [DSCC2012-MOVIC2012-8685], Ft. Lauderdale, Nov. 2012
9. “Pulse Width Modulated Fluid Valve”, (with Tom Chase) US Patent. US 2010/0212743 A1

10. “Open Accumulator for Compact Fluid Power Energy Storage”, US Patent (approved) US 2010/0018196 A1.

Synergistic Activities

Hydraulic hybrid vehicles; Compressed air wind energy storage; Efficient control using hydraulic transformers; Fluid powered robotic surgical tools; Throttle-less control of hydraulic systems; passivity based human interactive robotics, control of underwater ROVs.

Collaborators:
T. Chase, W. Durfee, T. Simon, J. Van de Ven (Minnesota), E. Loth (U. of Virginia)

Graduate advisors: R. Horowitz (PhD, Berkeley), Z. Ladin (MS, Boston)

Post-doctoral advisor to: Dr. J. Van de Ven, Dr. T. P. Sim, Dr. Farzad Shirazi

PhD Thesis advisor to: (all at U. of Minnesota):

- S. Saimek (King Munkut U, Thailand), D. J. Lee (Seoul National U.), K. Krishnaswamy (Honeywell Labs), Q. Yuan (Eaton Corp), Z. Liu (United Technologies), T. P. Sim (E-Ink), Rachel Wang (Eaton)

Gary Lichtenstein, Ed.D.
Evaluation and Assessment
Quality Evaluation Designs

Professional Preparation

B.A. Honors in Rhetoric, University of California, Berkeley, 1983
M.A. Education, Curriculum & Teacher Education, Stanford University, 1989
Ed.D. Administration and Policy Analysis, School of Education, Stanford University, 1997

Appointments

1996-present	**Sole Proprietor, Quality Evaluation Designs (QED)** QED is a successful evaluation and research firm that has conducted research and evaluation throughout the United States for over a decade.
Jan 2011- Dec 2014	**Project Director, University of Colorado, Denver, CO**, *Rocky Mountain Prevention Research Center*. Implementation and evaluation of a 3-year grant to reduce obesity among school children in southern and eastern Colorado
2005-present	**Consulting Associate Professor, Stanford University, Stanford, CA** Consulting professor of research methods in the School of Engineering. From 2005-2008, responsible for analyzing and reporting qualitative and quantitative data in the Center for the Advancement of Engineering Education (CAEE), part of a national, NSF-funded study looking at factors that correlate with academic persistence and professional intention among undergraduate engineers.
1996-2007	**Adjunct Professor, University of Denver, Denver, CO** Professor of research, evaluation, and community-based research in the College of Education.
2002-2004	**Director of Research & Evaluation, Colorado Small Schools Initiative, Denver, CO.** Provided program direction and evaluation to high schools engaged in small school reform.
2000-2002	**Research Associate, Carnegie Foundation for the Advancement of Learning** Responsible for data collection and analysis for nationwide study of undergraduate engineering majors. PI: Dr. Sheri Sheppard

Closely Related Products

1. Retention and Persistence of Women and Minorities Along the Engineering Pathway in the U.S., Gary Lichtenstein, Helen Chen, Karl Smith, & Theresa Maldonado, in *Cambridge Handbook of Engineering Education Research*, Eds. Aditya Johri & Barbara Olds (forthcoming, 2013).
2. Final Evaluation Report of Research Experiences for Teachers (RET):*What factors influence high school seniors to pursue STEM majors in college?* Unpublished Technical Report by G. Lichtenstein & Martin L. Tombari (Dec 2012). Colorado: Quality Evaluation Designs.
3. Cost of an Engineering Major, by Gary Lichtenstein, Alex McCormick, Sheri Sheppard & Jini Puma, JEE Selects Column in *PRISM*, a magazine for engineers and engineering educators, December, 2010, p.47.
4. An Engineering Major Does Not (Necessarily) an Engineer Make: Career Decision-making Among Undergraduate Engineers. Gary Lichtenstein, Heidi Loshbaugh, Brittany Claar, Helen Chen, Sheri Sheppard, Kristyn Jackson. *Journal of Engineering Education*, July 2009, pp.227-234.
5. Persistence, Engagement, and Migration in Engineering Programs. Matt Ohland, Sheri Sheppard, Gary Lichtenstein, Ozgur Eris, Debbie Chachra, Richard Layton. *Journal of Engineering Education (JEE). Special edition: How People Learn Engineering*, v97, n3, pp. 259-278. July 2008.

Significant Products

Development of a National Survey to Assess Student Outcomes of Community-Based Research, by Gary Lichtenstein, Trisha Thorme, Nick Cutforth and Martin L. Tombari. Journal of Higher Education Outreach & Engagement, v15,n2, pp.7-33, 2011.

Is the Supply of Engineering Majors a Problem of Many Losses or Few Gains? Persistence and Migration of Engineering Majors Compared to Other Fields. Alex McCormick, Gary Lichtenstein, Sheri Sheppard, Jini Puma (in preparation).

Comparing the Undergraduate Experience of Engineers to All Other Majors: Significant Differences are Programmatic, by Gary Lichtenstein, Alex McCormick, Sheri Sheppard & Jini Puma. Journal of Engineering Education, v99, n4, pp.305-317, October 2010.

"Graduation and Dropout Statistics: Time to Tell Hard Truths." Gary Lichtenstein. The Term Paper (formerly HeadFirst Colorado), The Piton Foundation, v4, #2, April/May 2005.

A Call for High School Reform. Gary Lichtenstein (technical research report). CO: Colorado Children's Campaign, April 2003.

Synergistic Activities

1. Quality Evaluation Designs (QED), the firm conducting the external evaluation, is a sole-proprietorship with a single owner. For over 20 years, Gary Lichtenstein has designed and conducted educational research and evaluation nationwide. Lichtenstein collected data for the Carnegie Foundation's book, *Educating Engineers* (Sheppard et al., 2009), conducted the evaluation of the National Academy of Engineering, *Frontiers of Engineering Education* and *"A Forum on Characterizing the Impact and Diffusion of Engineering Education Innovations"* grants, as well as Stanford's NSF-funded EESP grant, and has had several articles on engineering education published in the *Journal of Engineering Education*. Clients have included: The National Academy of Engineering, SRI International, EDC (Boston), Princeton University, the Carnegie Foundation for the Advancement of Learning, the Colorado Department of Education and others. Selected to write the chapter, *Persistence, Retention, and Motivation* in the Cambridge Handbook on Engineering Education (forthcoming, 2013).
2. Two-time recipient of the William Elgin Wickenden Award from the American Society for Engineering Education (ASEE) for the research articles, "Persistence, Engagement, and Migration in Engineering Programs," (July 2008) and "Comparing the Undergraduate Experience of Engineers to All Other Majors: Significant Differences are Programmatic," (October 2010) in the Journal of Engineering Education (JEE). The annual award recognizes authors whose article reflects the highest standards of scholarly research in engineering education among those articles published in JEE each year.
3. National Science Foundation panel reviewer (CAREERS grant 2011, and reverse site visit, 2012). ASEE member (division member: Evaluation and Research Methods, Minorities in Engineering, Women in Engineering.

Collaborators and Other Affiliations

Collaborators: Sheri Sheppard (Stanford U.); Helen Chen (Stanford Univesity); Karl Smith (University of Minnesota); Theresa Maldonado (National Science Foundation); Alex McCormick (Indiana University); Matt Ohland (Purdue).

Graduate Advisors: L. Cuban (Stanford University)

John H. Lumkes Jr.
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

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

Closely Related Products

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.

Significant Products

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.

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.

<u>Collaborators And Other Affiliations</u>
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)

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

Closely Related Products

Khalid, H. and Michael, P. "An Investigation of Hydraulic Motor Efficiency through Stribeck Analysis," TLT,70:1, 20-23 (2014)

Michael, P. Garcia, JM. Bair, S. Devlin, MT, Martini, A. "Lubricant Chemistry and Rheology Effects on Hydraulic Motor Starting Efficiency," Tribology Transactions, 55: 549-557, (2012)

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)

Significant Products

Michael, P. and Wanke, T. "Hydraulic Fluid and System Standards," <u>Handbook of Hydraulic Fluid Technology</u>, 2nd Edition, G.E. Totten and V.J. De Negri Ed., CRC Press, Boca Raton, (2012)

Michael, P. Khalid, H. and Wanke, T. "An Investigation of External Gear Pump Efficiency and Stribeck Numbers," SAE Commercial Vehicle Conference, Paper 2012-01-2041, Chicago, IL (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)

Synergistic Activities

Chairman, Hydraulic Fluid Compatibility Section D02.N0.09, ASTM International
Chairman, Fluids Committee, National Fluid Power Association
REU Advisor in 2013, 2012, 2011, 2010, 2009, 2008 & 2007 (5 of the 6 students were from underrepresented groups)
RET Advisor in 2009 & 2008
Member 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
Patrick Henning, Spectro Inc – Oil Analysis Instrumentation
Scott Bair, Georgia Tech – High Pressure Rheology
Steve Herzog, Rohmax USA – Hydraulic Fluid Research
David Holt, Exxon-Mobil – Hydraulic Fluid Research

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
Graduate Students:

Kelly Heathcote, General Dynamics
Hassan Khalid, Pentair
Aaron Kimball, Cobham Mission Systems
Meghan Miller, ExxonMobil
Corey Reynolds, Poclain Hydraulics
Total Number of Graduate Students advised: 5

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

J. Shipley Newlin, Jr
Science Museum of Minnesota
St Paul, MN

Professional Preparation

1963 - 1966 1970 - 1971	St. John's College, Annapolis, Maryland – Liberal Arts and Sciences (Great Books Program)
1973 - 1974	Drexel University, Philadelphia, Pennsylvania – courses in Physics, Chemistry, and Mathematics
1975 - 1976	Temple University, Philadelphia, Pennsylvania – Graduate courses in Communications

Appointments

1986 – present	Science Program Director, Physical Sciences, Engineering, & Mathematics
2000 - 2006	Minneapolis College of Art & Design, Minneapolis, Minnesota Adjunct Professor
1984 - 1986	New York Hall of Science, Corona, Queens, New York Exhibits Director
1973 - 1983	The Franklin Institute, Philadelphia, Pennsylvania Director of Exhibits; Senior Instructor; Lecturer & Technician
1966 - 1969	U.S. Peace Corps Volunteer, Somalia School Construction Program Secondary School Teacher (English & Mathematics)

Closely Related Projects

1. 1994 "Experiment Gallery" (project director)
A permanent, developing hall devoted to visitor experiment in physics, chemistry, and engineering.

2. 1993 Experiment Bench Project (project director)

NSF-supported project to develop ten multiple-outcome exhibits to promote experimenting in a museum setting.

3. 2012 “Engineering Studio” (project director)

Permanent exhibits that involve visitors in engineering design, problem-solving, prototyping, and testing.

4. 1976 "Benjamin Franklin: Scientist and Inventor" (project director)
The Franklin Institute's special lecture-demonstration for the US Bicentennial

5. 1980 "Physics: Movement, Matter, and Energy" (project director)
An exhibition on mechanics that contains more than 40 interactive devices and computer activities at three levels of sophistication.

Significant Products

6. 1982 "Shipbuilding on the Delaware" (project director)
A major, permanent exhibition on the history, science, technology, and economics of the shipbuilding industry that flourished along the Delaware River from 1700 to 1960.

7. 1997 “Atmospheric Explorations” (co-principal investigator)
NSF-supported project (with Atmospheric Sciences Group at Augsburg College) to develop three computerized exhibit models of atmospheric phenomena.

8. 2002 “Playing with Time” (principal investigator)
A major traveling exhibition about change over a range of time scales from billions of years to femtoseconds

9. 2002 “Investigations in Cell Biology” (co-principle investigator)
A set of six wet-biology exhibits at which visitors can pursue computer-guided experiments on cells, bacteria, and DNA.

10. 2007 “Wild Music” (principle investigator)
A traveling exhibition on the biological origins of music and how we share music with other animals.

Synergistic Activities

Organizing and leading a long series of annual seminars on the relationship of the humanities to science held at meetings of the Association of Science-Technology Centers

Museum staff liaison with the Minnesota Astronomical Society

Presentations on science learning and exhibits at annual meetings of the Association of Science-Technology Centers

Collaborators & Other Affiliations

Collaborators within the last 48 months

William K Durfee, Professor and Director of Design Education, University of Minnesota Molly Kelton, doctoral student in mathematics education at San Diego State University Troy Livingston, VP for Innovation and Learning, Museum of Life + Science, Durham, NC Ricardo Nemirovsky, Professor of Mathematics Education, San Diego State University Alana Parkes, Exhibit Planner, Museum of Science, Boston, MA

Glenn M Schmieg, Professor of Physics (ret), University of Wisconsin, Milwaukee

Paul Tatter, former Executive Director, Explora, Albuquerque, NM Tracey Wright, Education Researcher, TERC, Cambridge, MA

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.

Closely Related Products

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.

Significant Products

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

<u>Professional Preparation</u>

M.I.T	Mechanical Engineering	BS 1963
M.I.T.	Mechanical Engineering	MS 1963
M.I.T.	Mechanical Engineering	ScD 1967

<u>Appointments</u>

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

<u>Closely Related Products</u>

1. Yang, B. and Salant, R. F., "Soft EHL Simulations of U-cup and Step Hydraulic Rod Seals," <u>Journal of Tribology</u>, Vol. 131, pp. 021501 -1 – 021501-7, 2009.

2. Salant, R. F., Yang, B. and Thatte, A., "Simulation of Hydraulic Seals," <u>Journal of Engineering Tribology</u>, Vol. 224, pp. 865-876, 2010.

3. Thatte, A. and Salant, R. F. "Visco-Elastohydrodynamic Model of a Hydraulic Rod Seal during Transient Operation," <u>Journal of Tribology</u>, Vol. 132, pp. 041501-1 – 041501-13, 2010.

4. Yang, B. and Salant, R. F., "EHL Simulation of O-ring and U-cup Hydraulic Seals," <u>Journal of Engineering Tribology</u>, Vol. 225, pp. 603-610, 2011.

5. Thatte, A. and Salant, R. F., "Effects of Multi-Scale Viscoelasticity of Polymers on High Pressure, High Frequency Sealing Dynamics," <u>Tribology International</u>, Vol. 52, pp. 75-86, 2012.

<u>Significant Products</u>

6. Salant, R. F., Maser, N. and Yang, B., "Numerical Model of a Reciprocating Hydraulic Rod Seal," <u>Journal of Tribology</u>, Vol. 129, pp. 91-97, 2007 and <u>STLE/ASME Tribology Conference</u>, San Antonio, pp. Trib-06-1052, 2006.

7. Yang, B. and Salant, R. F., "Numerical Model of a Reciprocating Rod Seal with a Secondary Lip," <u>Tribology Transactions</u>," Vol. 51, pp. 119-127, 2008 and <u>62nd Annual Meeting, STLE</u>, 2007.

8. Shen, D. and Salant, R. F., "A Transient Mixed Lubrication Model of a Rotary Lip Seal with a Rough Shaft," <u>Tribology Transactions</u>, vol. 49, pp. 621-634, 2006 and <u>61st Annual Meeting, STLE</u>, 2006.

9. Thatte, A. and Salant, R. F., "Transient EHL Analysis of an Elastomeric Hydraulic Seal," Tribology International, Vol. 42, pp. 1424-1432, 2009.

10. 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.

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 & Other Affiliations 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.

Kim A. Stelson
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

Dutta, R., F. Wang, B. F. Bohlmann and K. A. Stelson, “Analysis of Short-Term Energy Storage for Mid-Sized Hydrostatic Wind Turbine,” *Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control*, Vol. 136, No. 1, 2014.

Ramdan, M. I. and K. A. Stelson, “Optimized Single-Stage Power-Split Hydraulic Hybrid City Bus,” *ASME/BATH 2013 Symposium on Fluid Power and Motion Control (FPMC 2013),* 6-9 October 2013, Sarasota, FL.

Whitten, M. and K. A. Stelson, “Determining Water Content at Saturation for Three Common Wind Turbine Gearbox Oils: Mobilgear SHC XMP 320, AMSOIL EP Gear Lube ISO-320 and Castrol Optigear A320,” *ASME/BATH 2013 Symposium on Fluid Power and Motion Control (FPMC 2013),* 6-9 October 2013, Sarasota, FL.

Wang, F. and K. A. Stelson, “Model Predictive Control for Power Optimization in a Hydrostatic Wind Turbine,” *The 13th Scandinavian International Conference on Fluid Power, SICFP2013,* 3-5 June 2013, Linköping, Sweden, pp. 155-160.

Deppen, T. O., A. G. Alleyne, J. J. Meyer and K. A. Stelson, “An Energy Management Strategy for Hydraulic Hybrid Vehicles,” *Proceedings of the 2012 American Control Conference,* June 27-29, 2012, Montréal, Canada.

Deppen, T. O., A. G. Alleyne, J. J. Meyer and K. A. Stelson, “Optimal Energy Use in a Light Weight Hydraulic Hybrid Passenger Vehicle,” *Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control*, Vol. 134, no. 4, July 2012.

Wang, F. and K. A. Stelson, “Minimizing the Power Dissipation in the Piston-Cylinder Gap Using a Barrel-Shaped Piston,” *Bath/ASME Symposium on Fluid Power & Motion Control (FPMC 2012),* 12-14 September 2012, Bath, UK, pp. 123-133.

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.

Wang, Y., Z. Sun and K. A. Stelson. "Modeling, Nonlinear Tracking Control and Experimental Investigation of a Transient Hydrostatic Dynamometer," *Proceedings of the 2010 American Control Conference,* 30 June – 2 July 2010, Baltimore, MD.

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.

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).

Zongxuan Sun
Department of Mechanical Engineering
University of Minnesota, Twin Cities Campus

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

1/2014 – present	Co-Deputy Director, NSF Engineering Center for Compact and Efficient Fluid Power
8/2012 - present	Associate Professor, Department of Mechanical Engineering, University of Minnesota
8/2007 - 8/2012	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

Products

1. Li, K., Sadighi, A. and Sun, Z., "Active Motion Control of a Hydraulic Free Piston Engine", IEEE/ASME Transactions on Mechatronics, 2013, DOI: 10.1109/TMECH.2013.2276102.
2. Li, K., Sadighi, A. and Sun, Z., "Motion Control of a Hydraulic Free-Piston Engine", Proceedings of the American Control Conference, Montreal, Canada, pp.2878-2883, June 2012.
3. 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.
4. 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.
5. 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.
6. 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.
7. Zhang Z. and Sun, Z., "A Novel Internal Model-Based Tracking Control for a Class of Linear Time-Varying Systems", ASME Transactions on Journal of Dynamic Systems, Measurement and Control, Vol. 132, 011004, January, 2010.
8. 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.
9. 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.
10. Kuo, T., Sun, Z., Kang, J., Eng, J., Chang, C., Brown, B., Najt P. and Chang, M., "Method for Transition Between Control Auto-Ignition and Spark Ignition Mode in Direct Fuel Injection Engines", US patent 7,370,616, 2008.

Synergistic Activities

- Organizer and panelist, Panel discussion "Engine and Combustion Modeling for Model-Based Control," The 2013 SAE World Congress, Detroit, MI.
- Guest editor, "Active Automotive Safety Systems", IEEE Control System Magazine, 2010.
- Session co-organizer, "HCCI Control", The 2010 SAE World Congress.
- Session co-organizer, "Engine Control", The 2009 SAE Powertrain and Fluid Systems Conference.
- Mentor, for minority summer students, GM Research and Development Center, 2002, 2003.

Collaborators & Other Affiliations

Collaborators and Co-Editors: Shih-Ken Chen, Burak Gecim, Kumar Hebbale, Chi-Kuan Kao, Hsu-Chiang Miao (GM), T.-C. Tsao (UCLA), G. Zhu (MSU), David Kittelson, Kim Stelson, Will Northrop, Michael Manser, Juergen Konczak, Henry Liu, David Du (UMN), Sonja Glavaski, Qinghui Yuan, Ben Morris (Eaton), John Brevick (Ford)

Graduate Advisors and Postgraduate Sponsors: T.-C. Tsao (UCLA)

Thesis Advisor or Postgraduate-Scholar Sponsor: Dr. X. Song (GM), Dr. Z. Zhang (Tsinghua University, China), Dr. A. Sadighi (US Hybrid), Dr. P. Gillella (Parker), Dr. Y. Wang (Seagate), V. Gupta (Cummins), A. Heinzen (GM), M. McCuen (Chrysler), V. Mallela (Schlumberger), C. Wu, A. Zulkefli, K. Li, Y. Yoon, C. Zhang, Y. Wang, M. Yang (UMN)

Jun Ueda
School of Mechanical Engineering
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

Closely Related Products

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.

Significant Products

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

Andrea Vacca
Assistant Professor
Maha Fluid Power Research Center
School of Mechanical Engineering/Dept. of Agricultural and Biological Engineering
Purdue University

Professional Preparation

Univ. of Parma, Italy	Mechanical Engineering	Master Degree (with honors)	1999
Univ. of Florence, Italy	Energetics (Energy Systems)	Ph.D.	2005

Appointments

3/2010 – Present	Assistant Professor, ABE and ME, Purdue University
9/2005 – 3/2010	Assistant Professor (with Tenure), Industrial Engineering Dept., University of Parma, Italy
9/2002 – 9/2005	Assistant Professor, Industrial Engineering Dept., University of Parma, Italy

Closely Related Products

1. Ritelli G.F., Vacca A., 2013, *Energetic and Dynamic Impact of Counterbalance Valves in Fluid Power Machines*, Energy Conversion and Management (Elsevier), 76 (2013) pp. 701-711
2. Zhou J., Vacca A., Manhartsgruber B., 2013, *A Novel Approach for the Prediction of Dynamic Features of Air Release and Adsorption in Hydraulic Oils*, ASME Journal of Fluid Engineering, Vol. 135(9), Sept 2013.
3. Opperwall T., Vacca A., 2013, *A combined FEM/BEM model and experimental investigation into the effects of fluid-borne noise sources on the air-borne noise generated by hydraulic pumps and motors*, IMechE Proceedings of the Institution of Mechanical Engineers, Part C, Journal of Mechanical Engineering Science, April 22, 2013
4. Dhar S., Vacca A., 2013, *A Fluid Structure Interaction-EHD Model of the Lubricating Gaps in External Gear Machines: Formulation and Validation*, Tribology International (Elsevier) 62 (2013), pp. 78–90
5. Vacca A., Guidetti M., 2011, *Modelling and Experimental Validation of External Spur Gear Machines for Fluid Power Applications,* Simulation Modelling Practice and Theory (Elsevier)*,* 19 (2011), pp. 2007–2031

Significant Products

6. Dhar S., Vacca A., 2012, *A Novel CFD- Axial Motion Coupled Model for the Axial Balance of Lateral Bushings in External Gear Machines*, Simulation Modelling Practice and Theory, 26 (2012) 60–76.
7. Cristofori D., Vacca A., Ariyur K., 2012, *A Novel Pressure-Feedback Based Adaptive Control Method to Damp Instabilities in Hydraulic Machines,* SAE Int. Journal of Commercial Vehicles, vol. 5(2):2012.
8. Vacca A., Cristofori D., 2011, *The Modeling of Electro-Hydraulic Proportional Valves*, ASME Journal of Dynamic Measurement, System and Controls, Vol.134, Issue 2, 021008.
9. Casoli P., Vacca A., Berta G.L., 2010, *A Numerical Procedure for Predicting the Performance of High Pressure Homogenizing Valves*, Simulation Modelling Practice and Theory vol. 18 (2010)
10. Casoli P., Vacca A., Franzoni G., Berta G.L., 2006, *Modelling of fluid properties in hydraulic positive displacement machines*, Simulation Modelling Practice and Theory vol. 14 (2006).

Synergistic Activities

- co-author of the book: Berta, G.L., Vacca, A., 2004, Sperimentazione sui Motori a Combustione Interna (in italian), Monte Università Parma Editore – Collana Saperi.
- developed a Fluid Power Lab at the University of Parma, Italy (2005 - 2009)
- Conference Organization activities: Editorial co-Chair for 2013 ASME/Bath Fluid Power and Motion Control Conference; Session organizer for SAE COMVEC 2010,2011,2012,2013 and 2014, Scientific board member and Session organizer for FPNI (Fluid Power Net International) – PhD Symposium 2010 and 2012; Session organizer for 8th Int Fluid Power Conference, 2012.
- SAE – Fluid Power & Hydraulic division chair, 2011-present.
- Associate Editor for International Journal of Fluid Power, 2011-present.
- ASME – Fluid Power System Division– Executive Committee member, 2012-present.

Collaborators & Other Affiliations
Graduate Advisors: Prof. B. Facchini, Prof. F. Martelli, University of Florence, Italy
Prof. P. Berta, University of Parma, Italy
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 Barth, University of Illinois, Monika Ivantysynova and John Lumkes, Purdue University).
Former colleagues at University of Parma, Italy: G.L. Berta, P. Casoli, A. Gambarotta.
Other academic collaborators: Ariyur K. (Purdue), Manhartsgruber B. (University of Linz, Austria), Massimo Milani (University of Modena) Roberto Paoluzzi (IMAMOTER - C.N.R)
Collaborators from industry: M. Guidetti and R. Casappa (Casappa), G. Franzoni, Quast D., Leise P., Collett R. (Parker Hannifin), Pizzo B. (Concentric), Fornaciari A. (Walvoil), Coutandind D. (AvioGroup), Nagel N.J. (Triumph Aerospace), Kassen G., Gulati N. (CNH), Weber S. (Sun Hydraulics), Lamirand Y. (MGI Coutier), Ramhfeld R. (Sauer Danfoss)

Total number of graduate students supervised: 29 Undergraduate Research Students: 25

Pietro Valdastri
Department of Mechanical Engineering
Vanderbilt University

Professional Preparation

University of Pisa	Laurea in Electrical Eng	2002
Scuola Superiore Sant'Anna	Ph.D. in Biomedical Eng	2006

Appointments

Vanderbilt University	Assistant Professor in Gastroenterology	2012 – Present
Vanderbilt University	Assistant Professor in Mechanical Eng	2011 – Present
Scuola Superiore Sant'Anna	Assistant Professor in Biomedical Eng	2008 – 2011

Closely Related Products

[1] M. Simi, R. Pickens, A. Menciassi, S. D. Herrell, and P. Valdastri. Fine tilt tuning of a laparoscopic camera by local magnetic actuation: Two-port nephrectomy experience on human cadavers. *Surgical Innovation*, 2012. In press, available on-line.

[2] C. Di Natali and P. Valdastri. Remote active magnetic actuation for a single-access surgical robotic manipulator. *International Journal of Computer Assisted Radiology and Surgery*, 7:S169–S171, 2012. Recipient of the OLYMPUS ISCAS Best Paper Award 2012.

[3] C. Di Natali, T. Ranzani, M. Simi, A. Menciassi, and P. Valdastri. Trans-abdominal active magnetic linkage for robotic surgery: Concept definition and model assessment. In *Robotics and Automation (ICRA), IEEE International Conference on*, pages 695–700, 2012.

[4] M. Simi, N. Tolou, P. Valdastri, J.L. Herder, A. Menciassi, and P. Dario. Modeling of a compliant joint in a magnetic levitation system for an endoscopic camera. *Mechanical Sciences*, 3:5–14, 2012.

[5] T. Ranzani, C. Di Natali, M. Simi, A. Menciassi, P. Dario, and P. Valdastri. A novel surgical robotic platform minimizing access trauma. In *Proc. of 4th Hamlyn Symposium on Medical Robotics*, pages 15–16, London, UK, 2011. Recipient of the Best Oral Presentation Award 2011.

Significant Products

[6] M. Simi, M. Silvestri, C. Cavallotti, M. Vatteroni, P. Valdastri, A. Menciassi, and P. Dario. Magnetically activated stereoscopic vision system for laparoendoscopic sin- gle site surgery. *IEEE/ASME Transactions on Mechatronics*, 2012. In press, available on-line.

[7] P. Valdastri, M. Simi, and R. J. Webster III. Advanced technologies for gastrointestinal endoscopy. *Annual Review of Biomedical Engineering*, 14:397–429, 2012.

[8] P. Valdastri, E. Sinibaldi, S. Caccavaro, G. Tortora, A. Menciassi, and P. Dario. A novel magnetic actuation system for miniature swimming robots. *IEEE Transactions on Robotics*, 27(4):769–779, 2011.

[9] M. Piccigallo, U. Scarfogliero, C. Quaglia, G. Petroni, P. Valdastri, A. Menciassi, and P. Dario. Design of a novel bimanual robotic system for single-port laparoscopy. *IEEE/ASME Transactions on Mechatronics*, 15(6):871–878, 2010.

[10] P. Valdastri, C. Quaglia, E. Buselli, A. Arezzo, N. Di Lorenzo, M. Morino, A. Menciassi, and P. Dario. A magnetic internal mechanism for precise orientation of the camera in wireless endoluminal applications. *Endoscopy*, 42(6):481, 2010.

Synergistic Activities

Olympus ISCAS Best Paper Award, 16*th* Annual Conference of the International Soci- ety for Computer Aided Surgery (ISCAS) 2012; Best Oral Presentation Award, ASME Design of Medical Devices Conference 2012; Best Oral Presentation, Hamlyn Sym- posium on Medical Robotics 2011; Best Technology Presentation, 19*th* International Congress of the European Association of Endoscopic Surgery 2011; Best Paper Award, Eurosensors 2008. IEEE RAS, IEEE EMBS, EAES, ASEE member.

Contributing Associate Editors-in-Chief of World Journal of Gastroenterology, Baishi- deng Publishing Group Co., Limited. Associate Editor for IEEE ICRA 2013. Reviewer for IEEE Transactions on Robotics, IEEE/ASME Transactions on Mechatronics, IEEE Transactions on Biomedical Engineering, IEEE Transactions on Magnetics. Developed a new course *Miniaturized Wireless Mechatronic Systems* at Vanderbilt University. The class is a combination of lectures, literature readings, hands-on lab programming of wireless microcontrollers, modeling interactions between the mecha- tronic system and the surrounding environment, and a significant research project. Recent seminars given at: University of Illinois-UC, Tennessee State University, Univer- sity of Colorado - Boulder, Imperial College of London, EPFL, and Tianjin University.

Collaborators & Other Affiliations

Recent Collaborators. Akos Ledeczi (Vanderbilt University), Mark Rentschler (Uni- versity of Colorado - Boulder), Peter Volgyesi (Vanderbilt University).
Graduate Advisor. Paolo Dario (Scuola Superiore Sant'Anna).
Advisees – Ph.D. Primary Adviser (4): Trevor L. Bruns and Charreau S. Bell (Vanderbilt University, expected 2016), Christian Di Natali and Marco Beccani (Van- derbilt University, expected 2015).
Advisees – Ph.D. Co-Adviser (1): Massimiliano Simi (Scuola Superiore Sant'Anna, expected 2013).

James D. Van de Ven
Mechanical Engineering Department
University of Minnesota

Professional Preparation

South Dakota School of Mines and Technology	Mech. Engr.	B.S. 2001
University of Minnesota-Twin Cities	Mech. Engr.	Ph.D. 2006
ERC for Compact and Efficient Fluid Power, Univ. of MN	Mech. Engr.	Postdoctoral 2006-2007

Appointments

Assistant Professor, August 2011 – present, Mechanical Engineering Department, University of Minnesota-Twin Cities, Minneapolis, MN

Assistant Professor, August 2007 – present, Mechanical Engineering Department, Worcester Polytechnic Institute, Worcester, MA.

Postdoctoral Research Associate, July 2006 – July 2007, ERC for Compact and Efficient Fluid Power, University of Minnesota, Minneapolis, MN.

Closely Related Products

1. Van de Ven, J., 2012, “Fluidic Variable Inertia Flywheel and Flywheel Accumulator System,” U.S. Patent Application, Pub. No.: US2012/0011960 A1.
2. Van de Ven, J., 2009, “Increasing Hydraulic Energy Storage Capacity: Flywheel-Accumulator,” International Journal of Fluid Power, v. 10, n. 3, p. 41-50.
3. Van de Ven, J., and McInnis, J., 2011, “Design and Experimental Results of a Bench Top Flywheel-Accumulator for Compact Energy Storage,” National Conference on Fluid Power, International Fluid Power Exposition, Las Vegas, NV, March 23-25, 2011.
4. Strohmaier, K., Cronk, P., Knutson, A., and Van de Ven, J., 2014, “Experimental Studies of Viscous Loss in a Hydraulic Flywheel Accumulator,” National Conference on Fluid Power, International Fluid Power Exposition, Las Vegas, NV, March 4-8, 2014, 0369-000017.
5. Strohmaier, K., and Van de Ven, J., 2013, “Constrained Multi-Objective Optimization of a Hydraulic Flywheel Accumulator,” ASME/BATH 2013 Symposium on Fluid Power & Motion Control, Sarasota, FL, Oct. 6-9, 2013, FPMC2013-4425.

Other Significant Products

1. Wilhelm, S., and Van de Ven, J., 2013, “Design and Testing of an Adjustable Linkage for a Variable Displacement Pump,” Journal of Mechanisms and Robotics, v. 5, n. 4, 041008.
2. Van de Ven, J., 2013, “On Bulk Modulus in Switch-Mode Hydraulic Circuits - Part I: Modeling and Analysis,” Journal of Dynamic Systems, Measurement, and Control, v. 135, n. 2, 021012.
3. Van de Ven, J., 2013, “On Bulk Modulus in Switch-Mode Hydraulic Circuits - Part II: Experimental Results,” Journal of Dynamic Systems, Measurement, and Control, v. 135, n. 2, 021014.
4. Van de Ven, J., and Katz, A., 2011, “Phase-Shift High-Speed Valve for Switch-Mode Control,” Journal of Dynamic Systems, Measurement, and Control, v. 133, n. 1.
5. Van de Ven, J., and Erdman, A., 2007, "Laser Transmission Welding of Thermoplastics: Part I: Temperature and Pressure Modeling," Journal of Manufacturing Science and Engineering, v. 129, n. 5, p. 849-858.

Synergistic Activities

Developments in Research

During the past six years, Dr. Van de Ven has been involved of eight projects resulting in provisional patents in the field of energy conversion and storage including a flywheel-accumulator, a high energy density open accumulator, a hydro-mechanical hybrid drive train with independent wheel torque control, two unique high-speed on-off hydraulic valves, constant pressure accumulator, locking soft switch, and an adjustable linkage pump. Through these and other projects, the PI mentored over 30 graduate and undergraduate research assistants. In the past seven years, Dr. Van de Ven has published over 40 journal and conference papers and given over 35 technical presentations.

Innovations in Teaching

The PI's innovations in teaching are in three main areas: 1) The use of active learning in the engineering classroom as a way to engage students and promote student centered learning. 2) Integrating graduate and undergraduate students in a research community through regular laboratory research meetings designed to provide students presentation practice in a safe environment, creating personal accountability for their work in front of their peer group, promoting documentation and organization of research material on a regular basis, and seeing how each individual work fits into a larger picture. 3) Promoting and developing collegiate level fluid power content as the Leader of the collegiate level Education and Outreach of the Center for Compact and Efficient Fluid Power. In this role Van de Ven is generating content for the Fluid Power OpenCourseWare site, including video capturing lectures on fluid power for a MOOC currently under development. Dr. Van de Ven was selected as Mechanical Engineering Teacher of the Year in 2011 and Advisor of the Year in 2010 at WPI.

Professional Service

Dr. Van de Ven has served the professional community in numerous ways including: Leader of the collegiate level Education and Outreach of the Center for Compact and Efficient Fluid Power, Technical Committee member for 2011 International Fluid Power Exposition, Educational Program co-chair for 2014 International Fluid Power Exposition, session chair at numerous conferences, reviewer for numerous journals and conferences, and organizer of the 2009 New England Manipulation Symposium.

Collaborators and Other Affiliations

Collaborators and Co-Editors

Allard, Adam (US Hydraulics)
Chase, Thomas (University of Minnesota)
Crane, Stephen (LightSail Energy)
Demetriou, Michael (WPI)
Erdman, Arthur (University of Minnesota)
Fischer, Gregory (Worcester Polytechnic Institute)
Gennert, Michael (Worcester Polytechnic Institute)
Hynes, Tod (XL Hybrids)
Lados, Dianna (Worcester Polytechnic Institute)
Li, Perry (University of Minnesota)
Loth, Eric (University of Virginia)
Michalson, William (WPI)
Olinger, David (Worcester Polytechnic Institute)
Padir, Taskin (Worcester Polytechnic Institute)
Rufo, Mike (Boston Engineering)
Simon, Terrence (University of Minnesota)
Smith, Brian (KaZaK Composites)
Stelson, Kim (University of Minnesota)
Tary, Imre (KaZaK Composites)
Tryggvason, Gretar (University of Notre Dame)
Weagle, David (dw-link Incorporated)

Graduate Advisors and Postdoctoral Sponsors

Erdman, Arthur – Professor – University of Minnesota – Ph.D. Advisor
Li, Perry – Associate Professor – University of Minnesota – Postdoctoral Sponsor
Stelson, Kim – Professor – University of Minnesota – Postdoctoral Sponsor

Graduate Students Advisees: Total Graduated: 11

Bacon, Brandon (WPI)
Banwat, Prasanna (WPI)
Beckstrand, Brandon (WPI)
Corby, Sebastian (UMN)
Cusack, Jessy (WPI)
Forbes, Tyler (WPI)
Gaffuri, Paul (WPI)
Jorgenson, Richard (WPI/UMN)
Judge, Andrew (WPI)
Katz, Allan A. (WPI)
McInnis, Jennifer (WPI)
Mies, Ben J. (WPI)
Samant, Rohan (WPI)
Savage, Cleveland (UMN)
Strohmaier, Kyle (UMN)
Sullivan, Thomas (UMN)
Tian, Hao (UMN)
Triana, Dominic (UMN)
Wang, Lak Kin (WPI)
Wu, Jeslin (WPI)
Wilhelm, Shawn (WPI/UMN)
Wong, Lak Kin (WPI)

Feng Wang
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

Zhejiang University	Mechanical Engineering	PhD.	2009
Zhejiang University	Mechanical Engineering	B.S.M.E.	2003

Appointments

2010 – present	Postdoctoral associate in Dept. of Mechanical Engineering, University of Minnesota
2003 – 2009	Research associate in Dept. of Mechanical Engineering, Zhejiang University

Closely Related Products

1. R. Dutta, F. Wang, B. Bohlmann, K. Stelson, 'Analysis of Short-term Energy Storage for Mid-size Hydrostatic Wind Turbine', accepted, under revision, submitted to ASME Journal of Dynamic Systems, Measurement, and Control, 2012.
2. F. Wang, B. Trietch and K. A. Stelson, 'Mid-sized wind turbine with hydro-mechanical transmission demonstrates improved energy production', to be appear in Proc. 8th International Conference on Fluid Power Transmission and Control (ICFP 2013), Hangzhou, China, 2013.
3. R. Dutta, F. Wang, B. Bohlmann and K. A. Stelson, "Analysis of short-term energy storage for mid-size hydrostatic wind turbine," in Proc. ASME Dynamic Systems and Control Conference, Fort Lauderdale, FL, USA, 2012, selected as top 20 outstanding finalist papers.

Significant Products

4. K. A. Stelson and F. Wang, "Minimizing the power dissipation in the piston-cylinder gap using a barrel-shaped piston," in Proc. Bath/ASME Symp. Fluid Power Motion Control, Bath, U.K, 2012.
5. F. Wang, M. Ramdan, and K. A. Stelson, "Comparison between hydraulic hybrid and electric hybrid in passenger vehicles using ADVISOR 2004," in Proc. 52nd National Conf. Fluid Power, Las Vegas, USA, 2011, NCFP I11-2.2.
6. K. A. Stelson and F. Wang, "A simplified model to optimize positive-displacement hydraulic pump and motor efficiency," in Proc. Bath/ASME Symp. Fluid Power Motion Control, Bath, UK, 2010, pp417-429.

Synergistic Activities

Technical advisory work to the REU (Research Experience for Undergraduate) student, 2012;
Technical advisory work to the senior design of the REU student, 2012-2013;

Collaborators & Other Affiliations

Collaborators within the last 48 months (other than students listed):

Kim Stelson, Brad Bohlmann, Mike Gust, Zongxuan Sun, all from University of Minnesota;

Ph.D. Students Supervised:

None

Ph.D. and M.S. Advisors:
None

Research Visitors:
None

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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 Institute 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

Closely Related Products

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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