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5th Annual Report
Volume 2

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CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

University of Minnesota

Georgia Institute of Technology

Milwaukee School of Engineering

North Carolina Agricultural & Technical State University

Purdue University

University of Illinois at Urbana-Champaign

Vanderbilt University

Dr. Kim Stelson, Director

Dr. Perry Li, Deputy Co-Director

Dr. Michael Goldfarb, Deputy Co-Director

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

RESEARCH PROJECTS

Thrust 1 - Efficiency

Project Name	PI / Department / Institution / Sponsor
1A.1 - Integrated Algorithms for Optimal Energy Use for Mobile Fluid Power Systems	Kim Stelson, Mech. Eng, University of Minnesota Andrew Alleyne, Mech. Eng, University of Illinois at Urbana-Champaign
1A.2 - Multi-Actuator Hydraulic Hybrid Machine Systems	Monika Ivantysynova, Ag. and Bio. Eng, Purdue University
1B.1 - Advanced Surface Design for a New Generation of Pumps and Motors	Monika Ivantysynova, Ag. and Bio. Eng., Purdue University
1B.2 - Surface effects on motor start-up friction	Ashlie Martini, Mech. Eng., Purdue University
1D - Nano-texturing for Fluid Power Lines and Pumps **(Pre-August 2010)**	Eric Loth, Aerospace Eng., University of Illinois at Urbana-Champaign
1D - Nano-texturing for Fluid Power Lines and Pumps	William King, Dept. of Mech. Sci. and Eng., University of Illinois Urbana-Champaign
1E.1 - Helical Ring On/Off Valve Based 4 Quadrant Virtually Variable Displacement Pump/motor	Thomas Chase, Mech. Eng., University of Minnesota Perry Li, Mech. Eng, University of Minnesota
1E.2 – High Speed On/Off Valves to Enable Efficient and Effective Fluid Power Systems	John Lumkes, Ag. and Bio. Eng., Purdue University Monika Ivantysynova, Ag. and Bio. Eng., Purdue University Perry Li, Mech. Eng, University of Minnesota
1E.3 – High Efficiency, High Bandwidth, Actively Controlled Variable Displacement Pump/Motor	John Lumkes, Ag. and Bio. Eng., Purdue University Monika Ivantysynova, Ag. and Bio. Eng., Purdue University
1E.4 – On/Off Valve Based Piston-by-Piston Control of Pumps and Motors Using Mechanical Methods	Perry Li, Mech. Eng, University of Minnesota Thomas Chase, Mech. Eng., University of Minnesota
1G.1 - Tribofilm Structure and Chemistry in Hydraulic Motors	Paul Michael, Fluid Power Institute, Milwaukee School of Engineering Thomas Wanke, Fluid Power Institute, Milwaukee School of Engineering
1G.2 - Nano-Additives to Improve Pumping Capacity	Eric Loth, Aerospace Eng., University of Illinois at Urbana-Champaign

Project Name	PI / Department / Institution / Sponsor
Acquiring Vehicle Drive Cycle with Fleet Data	Monika Ivantysynova, Sponsors: Confidential
Advanced Energy Saving Hydraulic System Architecture	Monika Ivantysynova, Sponsors: Confidential
Advances in External Gear Machines Modeling	Andrea Vacca, Sponsors: Casappa SpA
Design, Simulation and Control of Hydraulic System Topographies with Integrated Energy Recovery	John Lumkes, Sponsors: NFPA (National Fluid Power Association) Education and Technology Foundation
Development of Drive Train Control Concepts for Power Split Hybrid	Monika Ivantysynova, Sponsors: Confidential
Displacement controlled actuator for mobile application	Monika Ivantysynova, Sponsors: Confidential
Displacement Controlled Hex Productivity/Controllability Study	Monika Ivantysynova, Sponsors: Caterpillar
Hybrid power train for special truck applications	Monika Ivantysynova, Sponsors: Sponsors: Confidential
Mechanical Implementation of Waved Surface and Waved Piston Technologies	Monika Ivantysynova, Sponsor: Purdue Research Park Task funds
Modeling and Analysis of Swash Plate Type Axial Piston Pump Piston/Cylinder and Slipper/Swash Plate Interface.	Monika Ivantysynova, Sponsors: Confidential
Performance Prediction and System Control through Coupled Multi-domain Models - A Comparison Study	Monika Ivantysynova, Sponsors: Sponsors: Confidential
Prototype Design of a Hydraulic Hybrid Powertrain	Monika Ivantysynova, Sponsors: Sponsors: Confidential
SGER: Green Energy via Control-Based Design of Free-Piston Stirling Engines	Eric Barth, Sponsor: National Science Foundation

Thrust 2 – Compactness

Project Name	PI / Department / Institution / Sponsor
2A – Chemofluidic Hot Gas Vane Motor/Pump	Michael Goldfarb, Mech. Eng., Vanderbilt University
2B.1 – Free-Piston Engine Compressor	Eric Barth, Mech. Eng, Vanderbilt University
2B.2 – Miniature HCCI Free-Piston Engine Compressor	David Kittelson, Mech. Eng., University of Minnesota William Durfee, Mech. Eng., University of Minnesota

Project Name	**PI / Department / Institution / Sponsor**
2B.3 - Free Piston Engine Hydraulic Pump	Zongxuan Sun, Mech. Eng., University of Minnesota
2C.1 - Compact Energy Storage - Open Accumulator	Perry Li, Mech. Eng., University of Minnesota
2C.2 - Advanced Strain Energy Accumulator	Eric Barth, Mech. Eng, Vanderbilt University
2D - Multi-Functional Fluid-Power Components Using Engineered Structures and Materials	Doug Cook, Applied Technology Ctr., Milwaukee School of Engineering
2E - Model-Based Systems Engineering for Efficient Fluid Power	Chris Paredis, Mech. Eng, Georgia Institute of Technology
2F - MEMS Proportional Pneumatic Valve	Thomas Chase, Mech. Eng., University of Minnesota
2G - Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems	Robert Webster, Mech. Eng., Vanderbilt University Jun Ueda, Mech. Eng., Georgia Institute of Technology
Architecture Models for Fluid-Power Systems	Chris Paredis, Sponsors: John Deere, Inc.
Control Based Design of Free Piston Stirling Engines	Eric Barth, Sponsors: Vanderbilt University
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	Perry Li, Terrence Simon, J. Van de Ven, Eric Loth & S. Crane., Sponsors: National Science Foundation
Energy Storing Orthosis	William Durfee, University of Minnesota, Sponsors: National Institute of Health
Functionally Graded Metallic Lattice Components (FGMLC) for Advanced Propulsion Components	Vito Gervasi, Milwaukee School of Engineering, Sponsors: DARPA
Open Accumulator Compressed Air Storage Concept for Wind Power	Perry Li, Terrence Simon, University of Minnesota, Sponsors: University of Minnesota’s Institute on the Environment – Initiative for Renewable Energy and the Environment
Optimization Environment for the Architecting of Micro-grids in Ultra Low Energy Communities	Chris Paredis, Georgia Institute of Technology, Sponsors: United Technologies Research Center
Precision Pneumatic MRI Compatible Robotic Surgery	Eric Barth, Sponsors: The Martin Companies

Thrust 3 – Effectiveness

Project Name	**PI / Department / Institution / Sponsor**
3A.1 : Multimodal Human Machine Interfaces	Wayne Book, Mech. Eng., Georgia Institute of Technology Eui Park, Industrial and Systems Eng., North Carolina Agricultural and Technical State University Steven Jiang, Industrial and Systems Eng., North Carolina Agricultural and Technical State University

Project Name	PI / Department / Institution / Sponsor
3A.2 - Passive Pneumatic and Chemo-fluidic Actuators	Perry Li, Mech. Eng., University of Minnesota
3A.3 - Human Performance Modeling and User Centered Design	Steven Jiang, Industrial and Systems Eng., North Carolina Agricultural and Technical State University Zongliang Jiang, Industrial and Systems Eng., North Carolina Agricultural and Technical State University Eui Park, Industrial and Systems Eng., North Carolina Agricultural and Technical State University
3B.1 - Passive Noise Control in Fluid Power	Ken Cunefare, Mech. Eng, Georgia Institute of Technology
3C – Simulation of Cavitation and Noise in Fluid Power	Steven Frankel, Mech. Eng., Purdue University
3D.1 - Leakage Reduction in Fluid Power Systems	Richard Salant, Mech.Eng., Georgia Institute of Technology
3D.2 – New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems	Scott Bair, Mech. Eng., Georgia Institute of Technology
3D.3 – Improved Seal Design Based on Adaptive Materials	Barney Klamecki, Mech. Eng., University of Minnesota
3E – User Centered Human-Machine Interface for an Excavator	Silvanus Udoka, Industrial and Systems Eng., North Carolina Agricultural and Technical State University
A Characterization of the Pressure-Viscosity Response of Two Fomblin Oils	Scott Bair, Georgia Institute of Technology; Sponsors: Oak Ridge National Laboratory
Construction of a High-Pressure Viscometer	Scott Bair, Georgia Institute of Technology; Sponsors: The Timken Company
Construction of a High-Pressure Viscometer	Scott Bair, Georgia Institute of Technology; Sponsors: Laboratoire de Mécanique des Contacts et des Structures, INSA de Lyon
Development of an Experimental Pressurized Thin-Film Couette Viscometer and Consultation	Scott Bair, Georgia Institute of Technology; Sponsors: TOTAL Oil Company, Solaise
MRI-R2: Development of a Precise and High Speed Hydrostatic Dynamometer System for Research and Education in Automotive Propulsion Systems	Zongxuan Sun, David Kittelson, Kim Stelson, University of Minnesota, Sponsor: National Science Foundation
Shaft Pumping by Laser Structured Shafts with Rotary Lip Seals	Richard Salant, Georgia Institute of Technology, Sponsors: University of Stuttgart/ Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)

Test Beds

Project Name	PI / Department / Institution / Sponsor
Test Bed 1: Excavator	Monika Ivantysnova, Ag. and Bio. Eng., Purdue
Test Bed 3: Hydraulic Hybrid Passenger Vehicle	Kim Stelson, Mech. Eng., University of Minnesota Perry Li, Mech. Eng., University of Minnesota
Test Bed 4: Rescue Robot	Michael Goldfarb, Mech. Eng., Vanderbilt University Wayne Book, Mech. Eng., Georgia Institute of Technology
Test Bed 6: Orthosis	Elizabeth Hsaio-Wecksler, Mech. Science and Eng., University of Illinois at Urbana-Champaign Andrew Alleyne, Mech. Eng., University of Illinois at Urbana-Champaign William Durfee, Mech. Eng., University of Minnesota

EDUCATION AND OUTREACH PROJECTS

Project Name	Project Leaders / Institution
A.1 – Interactive Exhibits on Fluid Power	J. Newlin, Science Museum of Minnesota
A.3 – Fluid Power Video	Linda Western, University of Minnesota
B.1 – Research Experiences for Teachers (RET)	Will Durfee, University of Minnesota
B.2 – Project Lead The Way	Linda Western, University of Minnesota
B.3 - Hands-on Fluid Power Workshops • B.3a - Hands-on Pneumatics Workshop • B.3b - Portable Fluid Power Demonstrator and Curriculum • B.3c - Workshops	Will Durfee, University of Minnesota John Lumkes, Purdue University Will Durfee, University of Minnesota
B.4 - gidaa STEM Programs • B.4a - gidaa K-12 STEM Camp • B.4b - Shooting for the Starts Robotics Program	Alyssa Burger, University of Minnesota
C.1 – Research Experiences for Undergraduates (REU)	Will Durfee, University of Minnesota
C.2 – Fluid Power OpenCourseWare	Will Durfee, University of Minnesota
C.3 – Fluid Power Projects in Capstone Design Courses	Will Durfee, University of Minnesota
C.4 – Fluid Power Courses	All CCEFP Faculty
C.5 – giiwed'anang North Star Alliance	Alyssa Burger, University of Minnesota

Project Name	Project Leaders / Institution
D.1 – Fluid Power Scholars/Interns	Linda Western, University of Minnesota
D.2 - CCEFP Network • D.2a - Database • D.2b - Resume Bank • D.2c - Boarding Pass • D.2d - Alumni Society	Alyssa Burger, University of Minnesota
D.3 – Advanced Fluid Power Engineering Workshops	CCEFP Industrial Liaison Officer, University of Minnesota
D.5 – CCEFP Webcasts	Alyssa Burger, University of Minnesota
D.6 - Publications • D.6a Press Releases and Articles • D.6b Academic Journal Special Issues	Linda Western, University of Minnesota
E.1 - External Evaluation of Selected Education and Outreach Activities	Michael Michlin, Center for Applied Research and Educational Improvement (CAREI)

TECHNOLOGY TRANSFER

No projects to report at this time.

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

Research Team

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

1. Statement of Project Goals

The goal of this project is to identify means of regulating power generation and distribution in mobile fluid power systems that maximize the overall system efficiency and demonstrate them on center test beds. From our previous work in the study of energy management strategies (EMS) we have concluded that there is no single strategy which is optimal for all applications [2, 6, 8]. Therefore, we propose to develop a toolbox of EMS design methods and decision algorithms which will identify the best design method for a chosen application. These algorithms will select the optimal design from the EMS toolbox based on a number system attributes such as knowledge of duty cycle, ability to store energy, and problem constraints. In this way, we plan to improve the energy efficiency of mobile fluid power applications without any loss in their performance. The first center test bed that we are targeting is the passenger vehicle where our goal is to demonstrate a 100% improvement in fuel economy over non-hybrid vehicles.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

This project explores how to achieve optimal energy usage in the general class of fluid power systems by (a) understanding when to use available power sources (b) achieving smooth transitions between different modes of operation. Deterministic dynamic programming can be used to find the optimal behavior for an assumed drive cycle but cannot be used in real time. To design real time implementable energy management strategies that address both barriers, three methods are being studied: rule based, stochastic dynamic programming, and model predictive control. These methods have been identified as being most successful for hybrid electric vehicles [1, 4, 5, 7] and all three are being studied in the context of mobile fluid power systems because each method has unique advantages/disadvantages. This study will include HIL testing using an augmented earthmoving vehicle powertrain simulator (A-EVPS) that includes energy storage as well as the hydraulic hybrid passenger vehicle test bed. This will lead to the development of an EMS design toolbox which will be used in conjunction with decision algorithms to choose the design method best suited for a given application.

Figure 1: Augmented Earthmoving Vehicle Powertrain Simulator

To design the decision algorithms it will be necessary to identify the system attributes which correlate to EMS design strengths and weaknesses. Two potential attributes are constraints and knowledge of the duty cycle. By imposing constraints on the optimization problem, one is able to capture many real world considerations, such as limitations on the accumulator's state of charge, engine on/off cycling, and emissions. Introducing these considerations as constraints enables the EMS to intelligently utilize the DOF's within the powertrain to meet these as well as performance and efficiency demands. Similarly, knowledge of the duty cycle is a key attribute which differentiates the EMS design methods as well as mobile fluid power applications. Systems which follow a prescribed duty cycle, such as construction equipment, could be effectively controlled using a rule-based strategy in which some knowledge of the duty cycle is assumed when constructing the EMS. However, applications which do not follow prescribed duty cycles, such as passenger and rescue vehicles, would be best suited to stochastic dynamic programming and model predictive control where little assumption of the duty cycle is needed. All of this information will be incorporated into the decision algorithm.

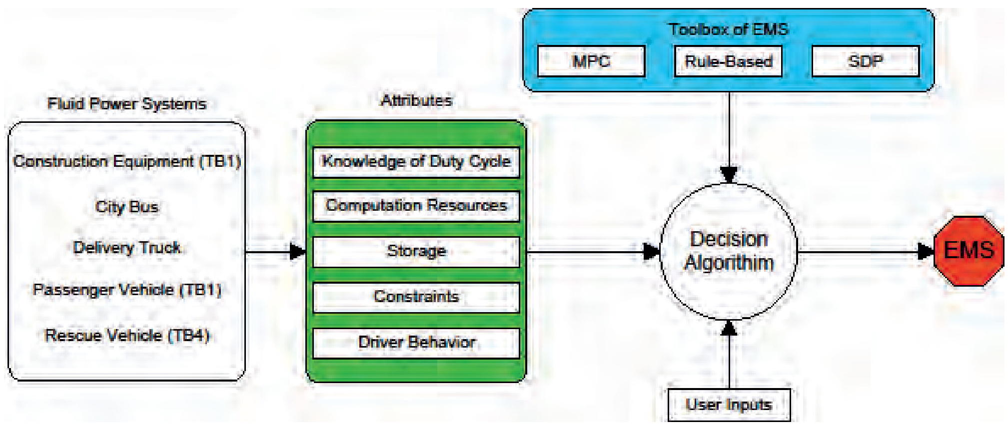

Figure 2: Decision algorithm

With the integration of multiple research efforts within the CCEFP, we are able to study optimization of the powertrain architecture, multiple EMS design methods, and conduct simultaneous hardware-in-the-loop studies (using TB3 and the A-EVPS), enabling us to take a much broader view of the energy management problem. Other work on hydraulic hybrid powertrains has focused on larger vehicles, using a parallel or series architecture, and optimized over a fixed drive cycle [3, 9]. Two of the major gaps that we plan to address are taking advantage of the hydromechanical powertrain architecture and developing an EMS toolbox that integrates the advantages of the rule-based, SDP, and MPC approaches. The hydromechanical configuration is more complex, but offers the potential to for greater efficiency and performance. Also, while other researchers have focused on establishing the merit of a single strategy we recognize that there is no single EMS design method which will give optimal performance for all applications. Rather, each design approach has its own unique advantages/disadvantages and a decision algorithm is needed to identify the optimal design approach.

B. Achievements

The focus of the past year has been to mature the rule-based, SDP, and MPC based EMS designs so that they are ready for hardware-in the-loop studies and to finish construction of the augmented earthmoving vehicle powertrain simulator. During this time, we have been working closely with TB3 to finalize how the EMS will integrate with the mid and low level control already in place within the test bed. We have begun to design a dynamic programming algorithm which uses this control structure. This supports the future integration of the rule-based, SDP, and MPC based solutions onto TB3. All three design methods will first be tested using the A-EVPS while TB3 is undergoing its redesign. Once the redesign is complete, each design method will be tested on TB3. By using the A-EVPS and TB3, we are able to begin hardware implementation sooner and will have a richer set of data to use when developing the decision algorithm.

Deterministic dynamic programming is an optimization technique that finds the globally optimal solution. This method uses Bellman's principle of optimality, starting at the end of the drive cycle and finding the optimal solution at each time step to determine the optimal solution for the entire cycle. While this guarantees the global optimal solution, it is not directly implementable in a physical system because it assumes the future is completely known. However, this gives an idea of the fuel economy a given architecture can obtain, and a suboptimal rule-based strategy can be extracted from the results.

This method was used to develop a control strategy for the redesigned TB3, which is shown in Figure 3. This is an input-coupled, power-split architecture that uses a planetary gear set to combine the mechanical power of the engine and the hydraulic power of the pump/motors. This architecture also has the ability to operate in 4 distinct modes: hydromechanical (HMT), parallel, pump/motor T only, and pump/motor S only. Hydromechanical mode operates just as shown with the engine either clutched or declutched, parallel mode locks pump/motor S with the engine clutched, pump/motor T only mode is the same as parallel with the engine declutched, and pump/motor S only mode operates with the engine declutched and pump/motor T locked. Dynamic programming was used with engine speed and operating mode as the control variables. The engine was modeled using fuel consumption data from the manufacturer of the diesel engine installed on the vehicle. For the hydraulic units, two cases were tried – ideal units with no losses and actual units based on manufacturer efficiency data at different operating points. The ideal units resulted in a fuel economy of 126 miles per gallon (mpg), while the actual units resulted in 86 mpg. However, these results are not feasible in a physical vehicle due to rapid engine on/off and mode switching. To account for this, a fuel consumption penalty was added to the objective function each time the engine turned on/off and operating mode changed. To give results that reduced switching, a penalty of 1 was used for engine switching and 0.1 for mode switching. This gave a fuel consumption of 106 mpg for the ideal case and 61 mpg using the actual units.

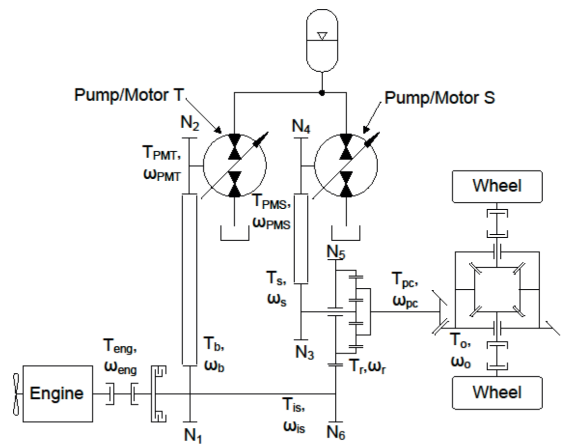

Figure 3: Schematic of redesigned TB3

The results using dynamic programming with the engine and mode switching penalties for the actual units is shown in Figure 4. As shown in the second plot, the entire volume of the accumulator is used. The third plot shows the engine turning on to charge the accumulator, and once fully charged the engine turns off with all power being delivered to the wheels solely by the hydraulics. The fourth plot shows the operating mode of the vehicle – mode 1 for HMT, mode 2 for parallel (if engine is clutched) or pump/motor T only (if engine is declutched), and mode 3 for pump/motor S only. HMT is used to charge the accumulator, pump/motor T only is used to power the vehicle during relatively constant speed, and pump/motor S only is used to

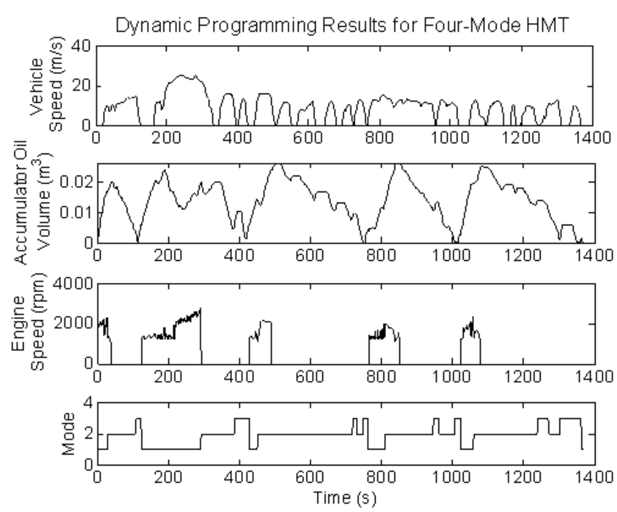

Figure 4: DP results for four-mode HMT

accelerate and decelerate the vehicle from a stop. This can be used as a starting point to develop a rule-based strategy for the test bed.

To ensure results from this project can be implemented on the test bed, close collaboration with the test bed team was used to ensure that component models and the control architecture are the same. The test bed team utilizes a three-tier control architecture – high-level control, mid-level control, and low-level control. The focus of this project is the high-level control, which takes vehicle velocity, acceleration, and driver command as inputs and outputs the optimal accumulator power to the mid-level controller. The mid-level controller determines the engine and hydraulic units operation, which is feed to the low-level controller to realize those actions on the physical vehicle. To be compatible with the test bed, some modifications needed to be made to incorporate accumulator power. The mid-level controller was obtained from the test bed team and implemented in the dynamic programming algorithm. The accumulator power to minimize system losses was then calculated at each time step. This has only been implemented for HMT mode, but will be expanded to the other modes for full operation.

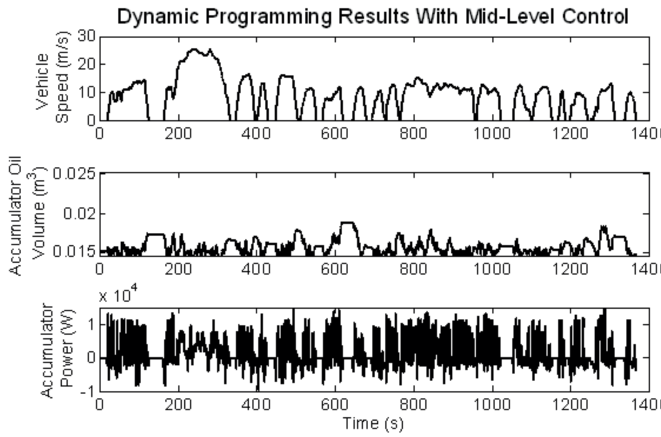

Figure 5: DP results with mid-level control

Stochastic dynamic programming (SDP) is an optimization algorithm that uses drive cycles probabilities rather than the drive cycle itself. The result is a causal, implementable control law without further analysis of the results. This method was used for a parallel hydraulic hybrid vehicle [6]. While it gave a solution that was implementable in simulation, further work is needed before hardware implementation due to frequent engine on/off switching.

In the next year, the dynamic programming results incorporating the mid-level controller will be finalized and used to find a solution that is feasible on the test bed. A rule-based strategy will be extracted from the results and will be implemented on the A-EVPS and the test bed to modify and verify the simulation. Stochastic dynamic programming will also be used to develop a control strategy for the A-EVPS and modified to take into account the mid-level controller on TB3.

During the past year, the fidelity of the Model predictive control based EMS has been significantly improved. MPC is a feedback controller which employs a discrete model of the system to express the system response over a finite horizon as a function of a sequence of inputs. In this way minimization of a chosen cost function reduces to selecting the appropriate sequence of inputs. The first element of the input sequence is applied to the system, and then the process is repeated at the next time step. Previously, the MPC based solution assumed that the pump/motor efficiencies were constant overall operating conditions and it was designed to track a desired wheel velocity. Now, the MPC based EMS

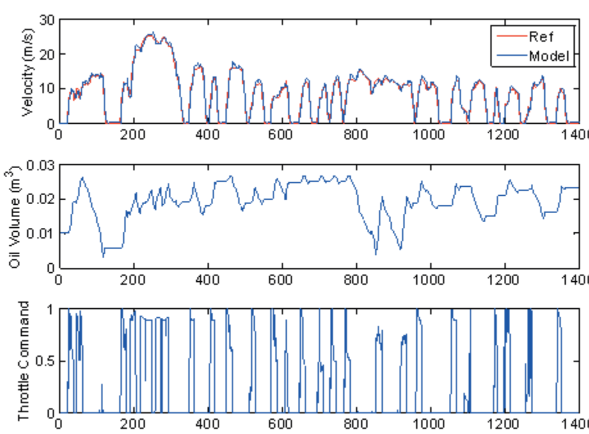

Figure 6: Simulation results for MPC based EMS

accounts for the variation in pump/motor efficiency by approximating the efficiency map as a pair of bilinear equations and then linearizing these bilinear relationships when performing the prediction. This enables the MPC to accurately predict pump/motor response within its prediction horizon. Furthermore, to facilitate future integration with TB3, the MPC was modified to track a desired wheel torque instead of a desired wheel velocity. This modification was made because there is a direct correlation between desired torque and the gas/brake pedal positions. With these improvements, the MPC is able to translate pedal position into the throttle, displacement, and applied brake force commands which will satisfy the operators demand while optimizing powertrain efficiency.

A simulation study was conducted using the improved MPC to study the relationship between accumulator size, dwell time, and fuel economy. The goal of the MPC was to track a desired wheel torque while optimizing the efficiency of the engine. A dwell time constraint on engine operation was imposed to prevent high frequency cycling of the engine on and off. Figure 6 shows the powertrain response for one case of the simulation study. From the results presented in Figure 7, one can see that as the accumulator size increases, the dwell time for optimum fuel economy increases. This is because for short dwell times the engine is cycled rapidly and therefore spends more time in inefficient regimes. For long dwell times, the accumulator can become fully charged before the dwell time is reached, forcing the engine to operate at a lower power output and therefore less efficiently. The results are part of a paper that has been submitted to the 2011 American Controls Conference.

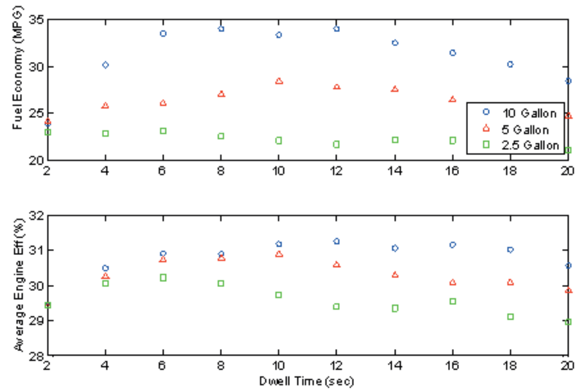

Figure 7: Performance comparison for different accumulator sizes and dwell times using MPC

The next step for the MPC based solution is to be studied in hardware-in-the-loop test using the recently completed augmented earthmoving vehicle powertrain simulator. This system originally consisted of an electric motor connected to a variable displacement pump which supplied power to three load cells via a valve manifold. Each load cell employs a proportional pressure relief valve which can be used to adjust the load. It has been used in the past to study optimal control of traditional electro-hydraulic powertrains. This system has since been augmented to include a 5 gallon accumulator for energy storage. Now, using this series architecture we are able to study a much richer class of energy management problems because we can decouple the engine operation from the load using the stored energy.

In the coming year, the focus of project 1A.1 will be to evaluate the effectiveness of the rule-based, SDP, and MPC based energy management strategies on real systems. We plan to complete initial HIL studies of both the SDP and MPC based solutions during the second quarter of 2011. These results will be used to revise the control strategies as needed and to identify the critical attributes to be used when defining our decision algorithm.

Expected Milestones and Deliverables

- Experimental study of rule-based and MPC based EMS using A-EVPS [3/2011]
- Experimental study of SDP based EMS using A-EVPS [6/2011]
- HIL study using redesigned TB3 [8/2011]
- EMS design toolbox [10/2011]
- Decision algorithm [12/2011]

C. Member company benefits

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

D. References

[1] Borhan, H.A., et al. Predictive energy management of a power-split hybrid electric vehicle. 2009. Piscataway, NJ, USA: IEEE.

[2] Deppen, T.O., A.G. Alleyne, K.A. Stelson, J.J. Meyer. Predictive Energy Management for Parallel Hydraulic Hybrid Passenger Vehicle. Proc. of the ASME Dynamic Systems and Control Conference. DSCC 2010.

[3] Filipi, Z., et al. Combined optimization of design and power management of the hydraulic propulsion system for the 6 x 6 medium truck. International Journal of Heavy Vehicle Systems, 2004, 11(3-4):372-402.

[4] Johannesson, L., et al. Assessing the potential of predictive control for hybrid vehicle powertrains using stochastic dynamic programming. 2007. IEEE Transactions on Intelligent Transportation Systems, 8(1): 71-83.

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[8] Stelson, K.A., et al. Optimization of a passenger hydraulic hybrid vehicle to improve fuel economy. in Proceedings of the 7th JFPS Symposium on Fluid Power. 2008.

[9] Wu, B., et al., Optimal power management for a hydraulic hybrid delivery truck. Vehicle System Dynamics, 2004. 42(1-2): p. 23-40.

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

Research Team

Project Leader:	Prof. Monika Ivantysynova, Purdue University, School of Mechanical Engineering, Dept. of Agricultural & Biological Engineering
Graduate Students:	Christopher Williamson, Josh Zimmerman, Rohit Hippalgaonkar, Jess Rose
Undergraduate Students:	Enrique Busquests
Industrial Partner(s):	Bobcat, Caterpillar, Parker Hannifin, Moog, Husco

1. Statement of Project Goals

The goal of the original project 1A2 was to develop system architectures and control methods for optimal power management in multi-actuator mobile hydraulic machines using displacement-controlled linear and rotary actuators. These concepts reduce overall machine fuel consumption through use of displacement-controlled actuators by avoiding throttling losses, allowing energy recovery and using control methods to achieve effective machine power management. The goal is to demonstrate that at least 40% reduction of energy consumption for typical working cycles of multi-actuator machines compared to the state of the art of machines is achievable.

The project 1A2 goals are to reduce energy consumption, reduce production costs, and simplify systems for displacement controlled mobile, multi-actuator machines. In the previous phase of project 1A2, energy efficiency was doubled by implementing displacement controlled actuator circuits. The renewal project will further reduce energy consumption by developing hydraulic hybrid circuits for energy storage and regeneration which will allow load leveling of the engine for more efficient operation. One goal is to further improve the fuel savings beyond the 40% already seen by the test bed to a total fuel savings of 50% from the standard Bobcat excavator system. Simultaneously, it is a target to reduce the rated engine power of the machine by 50% while maintaining the productivity of the original machine. The new system design will also allow cost savings by downsizing the combustion engine and hydraulic oil cooler. The hydraulic and electrical systems will be simplified by the development of methodologies for variable displacement “smart pumps” with optimized swash plate controls and integrated electronics. System design and simulation will be completed by Q2 2011 and testing on TB1 by Q2 2012.

2. Project Role in Support of Strategic Plan

The project primarily addresses the efficiency barrier by developing new system concepts and control strategies for multi-actuator mobile machines. The project also addresses the compactness barrier since displacement-controlled systems allow higher operating pressures and a reduction of interfaces and components. The project will result in an excavator hydraulic system with hydraulic energy storage and integrated electro-hydraulic control hardware. The project leverages past and current research in multi-actuator systems and on-road hybrid vehicles while confronting the barriers of efficient systems, control and energy management, and compact integrated systems. The emphasis on reducing the cost of both operation and production is significant since cost has previously been a limiting factor in market acceptance of displacement controlled hydraulic systems. Smart pump technology will facilitate advancements in hybrid on-road vehicles as well as displacement controlled linear actuators

3. Project Description

A. Description and explanation of research approach

Project 1A2 focuses on improving the overall efficiency of mobile hydraulic machines with multiple linear and rotary actuators. Advances in system efficiency are obtained through:

1. Displacement-controlled (DC) actuator systems that eliminate valve metering losses.
2. Real-time control of power generation and transmission in order to maximize operating efficiency of diesel engine and hydraulic pumps.
3. Energy recovery without additional storage devices by sharing power between actuators.
4. Optimizing swash plate regulation systems to create smart pumps for DC actuator technology.
5. Development of multi-actuator DC hydraulic systems with energy storage (DC hydraulic hybrid systems) to maximize energy recovery and reduce rated engine power requirements.
6. Real-time control of power generation and transmission of DC hydraulic hybrid systems in order to maximize operating efficiency of diesel engine and hydraulic pumps.

Actuators for hydraulic manipulators are traditionally powered by a single hydraulic pump and controlled by directional control valves arranged in series or parallel. Such configurations incur energy losses due to metering flow through the valves and do not allow energy to be recovered from aiding loads. Alternative system designs, such as displacement control, that reduce valve power losses and allow energy recovery promise significant fuel savings.

Another area for improvement is power management where the engine, pumps, and actuators are actively controlled to produce and distribute the required power while each component operates as close as possible to its highest efficiency. In the first phase of the project, power management of the displacement control system with no energy storage capabilities was studied. In the second phase of the project, hydraulic hybrid displacement control systems with energy storage capabilities will be analyzed.

Hybrid vehicles have been studied for many years in the transportation sector and more recently there has been a growing interest in the hybridization of off-highway vehicles such as construction, mining and agricultural machines due to both increasing fuel costs as well as more stringent emission regulations continuing to be placed on the industry. Much of the focus has been on electric hybrid systems where companies such as Case, Kobelco, and Komastsu have released or announced the release of hybrid construction equipment to the market. Little focus however seems to have been placed on purely hydraulic hybrid systems. The completion of the first phase of Project 1A2 and demonstrations on Test Bed 1 within the CCEFP have shown that displacement controlled actuation could prove to be an enabling technology for purely hydraulic hybrid systems because it provides for energy recovery and the ability to implement optimal power management strategies for minimizing fuel consumption.

In the future this project will focus on multi-actuator hydraulic hybrid machine systems to further reduce fuel consumption beyond that achieved in the first phase of Project 1A2. The research approach will encompass a range of topics each aimed at further optimizing displacement controlled actuation on multi-actuator hydraulic hybrid machines. These research topics can be grouped into two main categories: first, research pertaining to the design and simulation of displacement controlled actuation hydraulic hybrid systems and second, research aimed at optimal design of pump control systems to improve performance, compactness, and cost of displacement controlled actuators.

State of the art in multi-actuator off-highway machine power management

Significant research has been done on power management for vehicle drivetrains based on hydrostatic transmissions (HST) and power-split drives. Ossyra (2004) presented a control method for HSTs involving two real-time optimization loops: one feedback loop for the engine based on steady-state efficiency characteristics and the other for the HST based on detailed steady-state loss models of the hydraulic pump/motor units. However, there has been little work on engine power management for mobile hydraulic machinery in which the primary energy consumers are working functions rather than the propulsion drive. A Japanese industrial R&D group controlled pump flow rates and engine speed on an excavator to improve overall efficiency by about 10% (Kakuzen et al., 1988). An Asian research group showed 26% fuel savings using similar methods (Chun and Seo, 1993). A group in Canada constructed a displacement-controlled forestry machine, but did not report fuel measurements (Lawrence et al., 1995). Recently, Alleyne et al. have developed control methods for optimizing the powertrains of earthmoving vehicles with respect to energy consumption (Montgomery and Alleyne, 2006). No previous research exists on power management for excavators or similar machines using pump-controlled actuators.

One advantage of displacement control for power management is that each actuator is powered by an independently controllable pump. This arrangement offers more degrees of freedom than valve-controlled systems in which the actuators are arranged in parallel and powered by a single pump, thus allowing more opportunity for optimizing operation.

State of the art in multi-actuator off-highway hybrid vehicles

Research on hybrid highway vehicles has been ongoing for many years. The motivation for this is clear because the primary operating cost of a passenger vehicle is fuel. In off-highway machines, such as construction equipment, time is much more costly than fuel so system design has traditionally been focused on maximizing machine power and productivity and not on fuel consumption. Recent increases in fuel costs have given some motivation to look for more fuel efficient designs although the greatest push for fuel efficient hybrid systems has been increasing emission regulations placed on OEMs by governments (Kagoshima et al., 2007). In the United States a new set of federal emissions regulations referred to as the Tier emission standards was implemented in the 1990s. The Tier standards represent a scheduled reduction in emissions to be allowed in off-road diesel engines which are to be phased in over time. As each new phase rolls in manufacturers are being forced to find new innovative methods to reduce their machines emissions without reducing productivity. This and similar standards being issued by governments around the world are driving advancements in hybrid technology for off-road machines.

Current research trends in hybrid off-road machinery seem to be copying the electric hybrid approach taken by hybrid passenger vehicle manufacturers. Several systems have already been announced for sale on the market. Komatsu released the PC200-8 hybrid 22 ton crawler excavator for sale in 2008. The series hybrid systems consists of a generator driven by the diesel engine, an electric motor to drive the swing (rotation of the upper structure) and a capacitor bank to recover and deliver energy rapidly (Evans, 2009). Komatsu is claiming 25-30% fuel savings from the standard model although the machine cost has been reported to be from 25-50% more (Evans, 2009; Heavy Construction Equipment Going Hybrid, 2008; Komatsu Scores First with Hybrid Excavator, 2007; Yuko, 2008). Since Komatsu's release of their hybrid excavator several other companies including Case, Doosan, Hitachi, and Sumitomo have developed electric hybrid excavators of the same general design and size and either announced their release to the market or unveiled prototypes (Wilkins, 2009; Yuko, 2008).

All of the above mentioned hybrids have maintained their original hydraulic systems for controlling the boom, stick, and bucket functions which require linear actuation. Kobelco has introduced a more complex hybrid system (Kagoshima et al., 2007) which allows for energy recovery from the boom cylinder and reduced metering losses. This system is again a series hybrid where the engine drives a generator and there is an electric motor for the swing drive. However, in this system there are also three more electric motors for powering the pumps controlling the remaining actuator functions. Because the boom function has the most potential for recoverable energy it is actuated with electro-hydrostatic actuation. Besides excavators, Volvo announced the release of the market's first electric hybrid wheel loader which offers 10% fuel savings and higher performance than the traditional machine and Deutz and Atlas Weyhausen have teamed up to build a prototype electric hybrid wheel loader.

There seems to have been much less interest in industry in purely hydraulic hybrid systems using accumulators to recover and store energy. CAT developed such a system for a 50 ton excavator (Gaved, 2004) where energy was recovered from boom operations. They claimed an average fuel savings of 25-30% with the machine operating 5% faster than the standard system. While the savings were similar to that promised by newer electric hybrids it has received little attention.

B. Achievements

Achievements include productivity and fuel measurements of the completed displacement controlled hydraulic system on Test bed 1, development of optimal power management algorithms for multi-actuator displacement controlled hydraulic systems and implementation of them on Test bed 1, and a feasibility study for designing a hybrid DC hydraulic system for Test bed 1 with a reduced engine size. Methods and results for each of these topics are discussed briefly in the Test bed report. In addition to the achievements described below, a number of publications have resulted from the work on Project 1A2. These publications are listed in the references at the end of this document.

Machine Power Management

The proposed control system for a DC multi-actuator hydraulic system with machine power management is laid out in Figure 1. Operator joystick signals are interpreted as desired flow rates $\mathbf{Q}_d$ to the actuators. The operator also specifies a maximum engine speed $n_{e,max}$. The power management algorithm is a high-level system control layer that interprets the operator's inputs and determines the subsystem operating points that will best satisfy the desired motion. The power optimization routine calculates the combination of pump displacements $\boldsymbol{\beta}_d^{\dagger}$ and engine speed $n_{e,d}$ that will result in the lowest instantaneous rate of fuel consumption (note that the only the instantaneous rate is considered because the system does not have an energy storage device). The current actuator pressures $\boldsymbol{\Delta p}$ and other loads (such as a charge pump at pressure p_{cp}) are also considered. It should be noted that $\mathbf{Q}_d$, $\boldsymbol{\beta}_d^{\dagger}$ and $\mathbf{\Delta p}$ are $k\times1$ vectors, where k is the number of DC actuators. The power management also limits the engine torque in order to enforce the desired speed and prevent stalling. The $\boldsymbol{\beta}_d^{\dagger}$ vector is passed to the low-level hydraulic system control layer that regulates the pump displacements $\boldsymbol{\beta}$ and actuator positions $\mathbf{x}_{act}$.

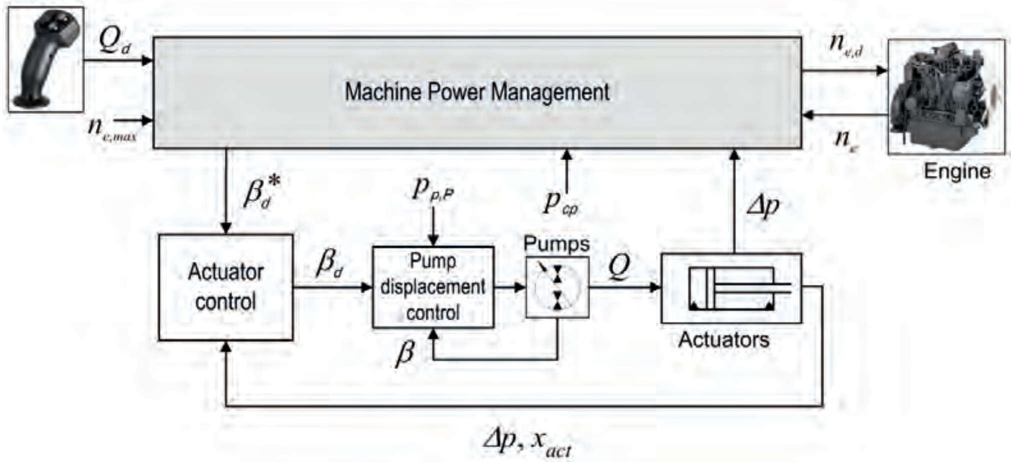

Figure 1: Block diagram of multi-actuator control system with power optimization

The total maximum pump torque is much higher than the maximum available engine torque. Hence, a speed control law is necessary to avoid stalling the engine. For optimal operation, it is also desirable to maintain the engine speed near the set point established by the optimization algorithm. Engine speed can be controlled with a simple proportional control law in which the commanded pump displacements $\boldsymbol{\beta}_d^{\dagger}$ (and hence the pump torques) are reduced according to the engine speed error .

To demonstrate the proposed power management method, Test bed 1 with DC actuators is simulated. The duty cycle consists of 2.7 minutes of digging in loose soil. Actuator loads and reference trajectories are based on measurements from the DC excavator test bed. Results from two simulations are presented: with a constant engine speed set point (no power management) and with power management. Figure 2 shows how the engine operating point changes during the simulation. The simulated power management reduces fuel consumption by 13.1%.

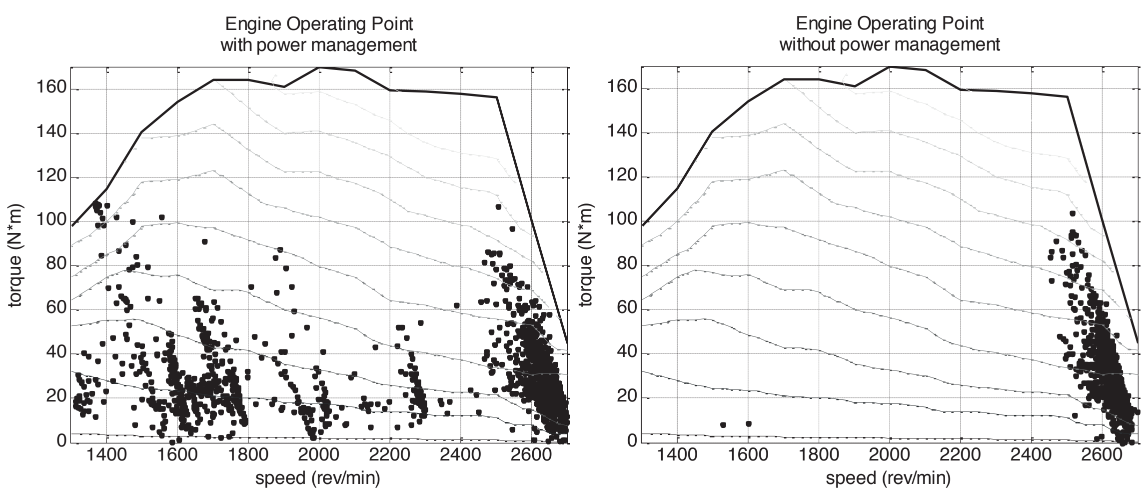

Figure 2: Simulated engine operating point with and without power optimization

This power management algorithm was implemented on Test bed 1 and fuel measurements were made for an artificial pipe laying cycle with and without the power management. Because pipe laying requires a lot of precision it involves slow actuator motions and has low power requirements. This gives a lot of freedom for power optimization and the measurements resulted in 50% fuel savings for the cycle.

DC Hydraulic Hybrid Feasibility Study
A simple way to add energy storage to a DC hydraulic system is to use a parallel hybrid system architecture. Such a system could be created for the test bed by simply adding an additional pump/motor in parallel with the 4 DC actuators currently installed. The simulation model previously created for the DC excavator test bed was modified to include the additional pump/motor (18 cc/rev) and accumulator (5 L). Measurements from the productivity study where an expert operator was performing a truck loading cycle as fast as possible were used to generate actuator trajectories and loads for the cycle. this cycle was selected because it is very aggressive representing the extremes of the power requirements for the DC actuators. As previously stated one of the project goals is to be able to reduce the required engine power of the machine by 50%. To check the feasibility of this goal the simulation was controlled to limit the engine power output to be 50% of the current test bed engine power where power requirements of the cycle above that level would be met by the hydraulic accumulator and the additional pump/motor.

Planned Achievements following the reporting period:
Project 1A2 is scheduled to conclude in June 2012. Tasks planned for the upcoming years include:

- Task 1: Design multi-actuator hydraulic hybrid circuit [3-6 months]
- Task 2: Develop simulation model of excavator dynamics, energy use and heat transfer [6 months]
        - Simulink models of 5-ton and 20-ton excavators including engine, hydraulic system, and machine structure [Dec 2010]
        - Thermal model of DC hydraulic system [June 2011]
- Task 3: Develop power management control law for multi-actuator hybrid system [3 months]
    - Deliverables:
        - Analytical control design and analysis [June 2011]
        - Control code incorporated in Simulink model for managing engine operating point and accumulator state of charge [June 2011]
- Task 4: Simulate system operation and estimate energy savings [6 months]
- Task 5: Analyze existing pump control systems [6 months]
    - Sub-task 1: Gather data for existing swash plate control mechanisms and control valves. Include high speed on/off valves, 4-way proportional valves, and possibly other control valve configurations.
    - Sub-task 2: Analyze control system design. Assess the influence of design parameters on outputs of interest, including dynamic response, energy use, packaging size, and cost.
- Task 6: Optimize pump control system design [6 months]
- Task 7: Select and integrate pump control electronics [6 months]
- Task 8: Fabrication and testing of prototype smart pump [6-9 months]
- Task 9: Implementation and testing of hydraulic hybrid excavator [6-9 months duration]

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. 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 project have shown that up to 40% fuel savings can be achieved which would clearly be a benefit to OEM companies within the center
- The improved efficiencies and potential for reduced engine power made possible by the technologies being developed in this project will help OEMs meet upcoming emission regulations under the TIER emissions standards
- The improved efficiencies offered by the technologies developed in this project will reduce the cooling requirements for mobile machines saving cost and space for machine production
- The work which will be done to optimize swash plate regulation systems for displacement controlled actuators will aid in reducing the cost of bringing the technology to production

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Project 1B.1: New material combinations and surface shapes for the main tribological systems of piston machines

Research Team

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Industrial Partner(s): Parker Hannifin, Sauer-Danfoss

1. Statement of Project Goals

The goal of this project is to discover the impact of material combinations and advanced surface shaping on the reduction of energy dissipation and the increase of load carrying ability of the lubricating gaps of axial piston machines. While studying the role of material properties in combination with gap micro geometry through a fully-coupled fluid-structure-thermal and multi-body dynamics simulation model for the piston cylinder interface a better understanding of the complex physical phenomena characterizing lubricating gaps performance will be generated and used to propose new design solutions. The research will also extend the new piston-cylinder model to the other two main interfaces of axial piston machines – the slipper/swash plate interface and the cylinder block valve plate interface. This will allow studying advanced material combinations and unique surface shapes for the main tribological systems of axial piston machines.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

Primary Problem and Challenge Statement

Swash plate type axial piston machines are widely used today in industry. The hydraulic systems in which these machines are placed require the units to operate under a wide range of operating conditions, necessitated by system performance requirements. Unfortunately, at the present time, there is only limited range of operating conditions where these machines are highly efficient. The sealing and bearing gaps separating the movable parts of the rotating group (piston, slipper, and cylinder block) form the most critical design element of piston machines. These gaps, as illustrated in Fig. 1, determine the achievable machine performance (speed, pressure, and maximum swash plate angle) and overall efficiency. The energy dissipated in these sealing and bearing gaps is very significant and in fact represents up to 90% of entire machine loss at low swash plate angle and up to 60% at maximum swash plate angles. The main problem is to gain an understanding of the physical effects taking place in the gaps and find ways to reduce the energy dissipated by introducing new design features. The development of physical models which can be used to predict the energy dissipated in the gaps is fundamental to propose better gap designs, including novel material combinations and shaped surfaces. These innovative designs will lead to better machine performance and increased efficiency especially at low swash plate angles.

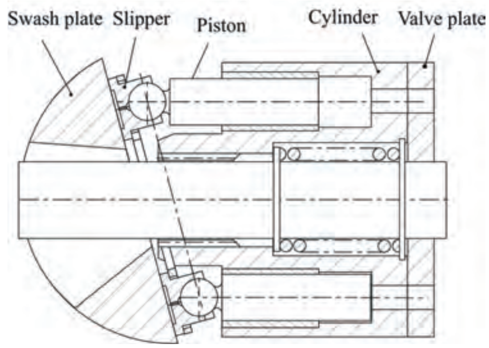

Figure 1: Lubricating gaps in an axial piston machine

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

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

Each of these aforementioned physical effects must be captured by the pump model, and moreover the interaction between effects must be captured as well. This creates a very complicated transient load fluid-structure-thermal solid body dynamics problem. As complicated as the problem may be, it is imperative to that the physical effects are captured to predict the effect new design modifications will have.

State of the Art

Due to very small gap heights the flow in lubricating gaps of piston machines can be assumed to be laminar. By assuming an incompressible Newtonian fluid, neglecting inertia forces and the change of pressure with the gap height as well as the derivative of fluid velocity in direction of gap length and breadth, and assuming an ideal roughness of surfaces, the Reynolds equation can be used for description of laminar flow in narrow gaps. Many computer programs and solution techniques for studying hydrostatic pumps lubricating gaps have been developed such as Dowd and Barwell (1974); Harris et al. (1993) and Tanaka et al. (1999). These works neglect the effects of significant physical phenomena influencing lubricating gap performance.

The program CASPAR, developed by Wieczorek and Ivantysynova (2002), is based on a non-isothermal gap flow model and considers the dynamic secondary motion of all moveable parts of a swash plate axial piston machine. This program, however, did not represent a fully coupled model considering simultaneously the impact of non negligible physical phenomena on the lubricating gap performance, i.e. surface elastic deformations and heat transfer. One of these phenomena is known as elastohydrodynamic lubrication and, in fact, the local surface elastic deformation of mechanical parts subjected to high operating pressures strongly influences the behavior and ultimately the efficiency of machines that are designed to operate with extremely low gap heights. Among all the various kinds of fluid machines, the field of hydraulic axial piston machines recently started to include EHD effects in different numerical models, introducing with a progressively higher level of detail the complex problem of fluid-structure interaction. Huang and Ivantysynova (2006) proposed models for the lubricating gaps of axial piston machines considering the EHD phenomenon. This work included the piston/cylinder interface and a special test rig was built, as presented by Ivantysynova et al. (2005), to measure the pressure and temperature fields in the tribological pair and validate the numerical results. However, none of these latter numerical studies proposed a complete integrated finite element model of the solid parts, communicating with a laminar gap flow model based on finite volumes. In fact, the use of external FEM software to predict the surface elastic deformation of the solid parts due to pressure loading introduced significant limitations to the flexibility and accuracy of the model. Furthermore, none of the studies included heat transfer phenomena trough the solid parts and their impact on the fluid boundary conditions.

B. Achievements

Research Approach and Previous Achievements

The old model of Huang and Ivantysynova (2006) has now been improved by the work of Pelosi and Ivantysynova (2008, 2009a) concerning the piston/cylinder interface. In particular, a complete new version of the model has been generated; improving numerical and computational algorithms, furthermore including the surface elastic deformation of the solid parts due to the pressure field is solved using an internal FEM solver directly coupled with the fluid domain. This has allowed for a more precise determination of the surface elastic deformation and solution of the EHD problem.

The heat transfer problem has been considered by Pelosi and Ivantysynova (2009b) in the solution of the piston/cylinder interface non-isothermal gap flow developing finite volumes models of the mechanical bodies, i.e. piston and bushing-cylinder assembly. The calculation of the heat generated in the gap and transferred to the solid parts allowed for the solution of the temperature distribution in the bodies and a more accurate estimate of the gap surface temperature to be used as a boundary for non-isothermal gap flow. The temperature distribution in the solid parts has been used to calculate the elastic deformation due to thermal loading. Thus, a fully-coupled fluid structure and thermal model for the piston/cylinder interface has been created, allowing for precise determination of fluid film thickness behavior.

Although progress had been made, there were limitations with the model. In particular, the Fluid-Structure-Interaction algorithm had problems achieving convergence. This is critical because without convergence, it is impossible for the simulation to progress. Also, the thermal model only accounted for a 'wedge' of the cylinder block and thus deformations were not as physically representative as possible.

Achievements during 2010

Piston Cylinder Thermal Model

Unlike the previous work which only accounted for a cylinder block wedge, for the first time a model was created that allows for simulation of the temperature and thermal deformation of the entire cylinder block in the piston interface. This removes the need for unnatural constraints that were present in the wedge model. Figure 2 is a plot of the temperature and thermal deformation of the entire cylinder block and piston and demonstrates a significant improvement in realism over the old wedge model.

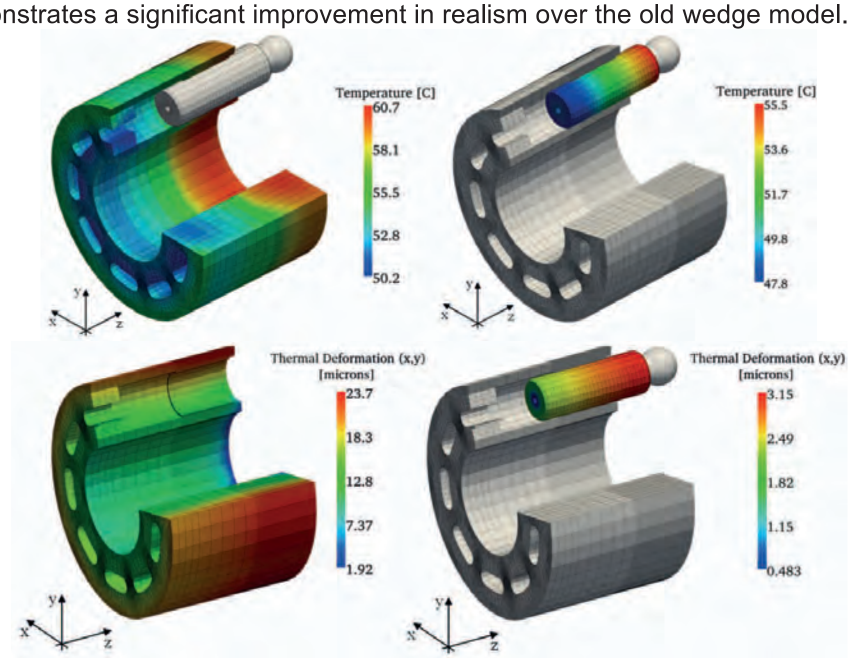

Figure 2: Temperature (top) and thermal deformation (bottom) of the pistion and the entire cylinder block

In order to reduce the complexity of the full block model, the unstructured cylinder block mesh has been simplified to a structured mesh where the secondary gradients on the numerical solution are neglected.

Since the temperature change in the fluid film is much faster than in the solid parts, the calculated energy dissipation is averaged over one revolution of the shaft and therefore the energy equation is considered as a quasi-steady-state problem for each time step. For each time step the fluxes of energy to the cylinder block and pistons from the lubricating interfaces are calculated based on the viscous energy dissipation in the fluid. In particular, the lubricating gap is split in half and one half of the energy dissipated is transferred to one surface and the other half to the other surface. At the end of one shaft revolution the total energy fluxes for each cell are averaged over the revolution time, to obtain heat flux information used as Neumann boundary condition for the piston and cylinder block sliding surfaces.

Calculation of the thermal deformation of the cylinder block in the Z direction is now possible because again, the entire block is modeled. However, the deformation countour is non-uniform and thus will have an impact on the fluid film hydrodynamic pressure buildup in the cylinder block / valve plate interface. Future work in the cylinder block / valve plate interface will take this physical effect into account.

Piston Cylinder Fluid Model

The piston cylinder fluid film model uses the Reynolds equation to model pressure buildup due to hydro-static/dynamic effects. The general energy equation is used to solve for the fluid temperature considering the heat generation due to viscous shearing of the fluid. Finally an empirical model is used to calculate fluid viscosity as a function of both temperature and pressure completing the non-isothermal fluid model. Although the governing physical equations have remained the same throughout this year's work, the numerical schemes used to solve the discretized equations have drastically changed.

The piston/cylinder lubricating interface pressure distribution is solved using a geometric multigrid algorithm. The geometrical simplicity of the interface and the use of a regular structured mesh allow the implementation of such a method. In particular, compared to the iterative SOR method used is prior models, a multigrid algorithm, employing grids of different mesh sizes, permits solving all wave-length components and provides rapid convergence rates. The multigrid strategy combines two complementary schemes. The high-frequency components of the error are reduced applying schemes like Jacobi or Gauss-Seidel and for this reason these methods are called smoothers. On the other hand, low-frequency error components are effectively reduced by a coarse-grid correction procedure. Because the action of a smoothing iteration leaves only smooth error components, it is possible to represent them as the solution of an appropriate coarser system. Once this coarser problem is solved, its solution is interpolated back to the fine grid to correct the fine grid approximation for its low-frequency errors.

Many different multigrid schemes have been developed, but the simplest is a two grid approach as shown in Fig. 3. The linear system representing the discretized Reynolds equation is relaxed on the fine mesh using a few sweeps of a GSSOR method. The residual of the relaxed solution is computed and an interpolation scheme is used to restrict this residual to the course mesh. The residual is used in the error calculation on the course mesh and this system is solved. The solution of the second system of equations is interpolated using a prolongation scheme back to the find grid and updates the initial solution. Finally a second pass of GSSOR on the find grid is used to smooth out any remaining high frequency error.

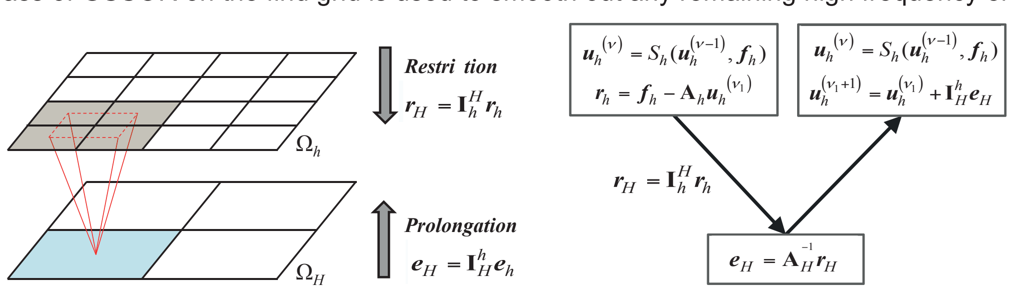

Figure 3: Two grid correction scheme represented geometrically (left) and algebraically (right)

The piston cylinder model actually has a number of more advanced multigrid schemes implemented, and are known as “V” and “W” cycles. Thus, for the first time in the piston/cylinder interface of axial piston machines, the Reynolds equation is solved using a geometric multigrid algorithm. This gives the model the ability to calculate a pressure field with a very low residual in a very short period of time.

Piston Cylinder Nonlinear Coupling Scheme

The complete solution scheme between the physical domains is illustrated in Figure 4. A shaft revolution is simulated, solving in time at discrete intervals, corresponding to a progressively increasing shaft rotation and different load condition. The core of the algorithm is represented by the Reynolds and energy equations. The inner loop determines the fluid pressure and temperature fields, solving iteratively the gap flow equations, updating the fluid properties and the surface elastic deformation due to the dynamic pressure field at each iteration step. The fluid dynamic pressure field and the solid boundaries surface elastic deformation are strongly related, making the numerical solution extremely delicate and stiff. The problem becomes a fluid-structure interaction analysis to be performed at each time step according to the changing oscillating load conditions. The pressure-deformation convergence is obtained using a smart under-relaxed iterative scheme, which adjusts the under-relaxation coefficients according to the residual behavior and convergence rate. Once a converged solution for the instantaneous fluid-structure interaction problem is reached, an outer loop based on a Newton iteration scheme, varies the piston shifting velocity to achieve a load balanced condition. The fluid pressure field must balance the external loads acting on the moving body. When a balanced condition is found, the proper squeeze motion is integrated to find the new position in the next simulation time step. This scheme repeats itself until the end of the revolution.

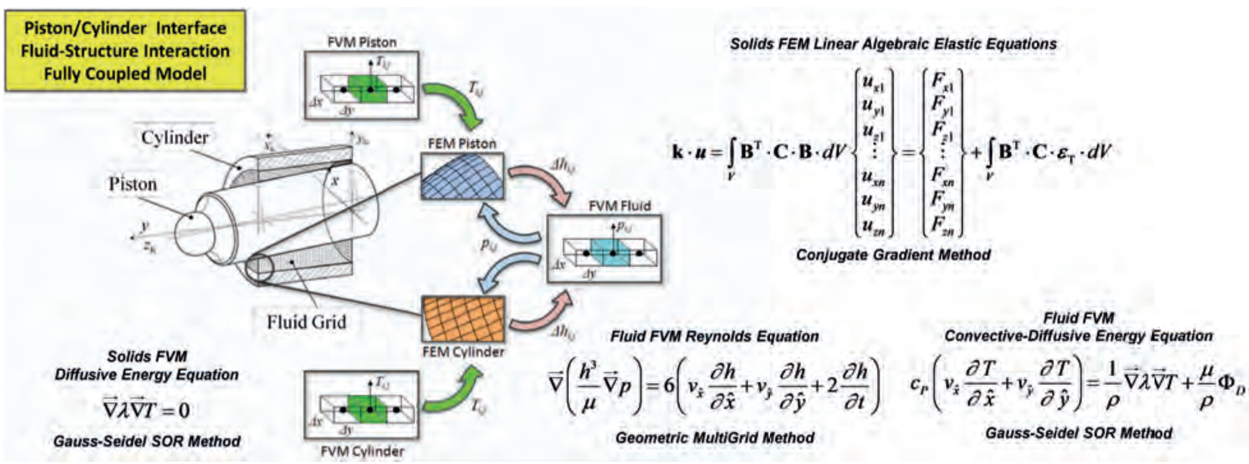

Figure 4: Piston/cylinder model overview

At each simulation step the thermal fluxes to the piston and cylinder are calculated. At the end of the revolution, the averaged heat fluxes are used to determine solid bodies temperature distribution. These temperatures are used in the following revolution as a more accurate boundary condition for non-isothermal gap flow calculations and to predict mechanical parts the thermal expansions. The most outer loop continues to iterate until stable temperature distributions in the solid parts are reached. This is truly a milestone as all of the physical effects and their interactions mentioned in the Challenge Statement for the piston cylinder interface are now fully captured.

Slipper Swashplate Model

The slipper model was also greatly improved during 2010. Many of the advancements made in the piston interface have been incorporated into the slipper model. However, it does not contain the thermal analysis of solid body temperature and deformation.

Future Work

There are three main areas of work in the piston interface:

- Validation of simulation results using special test rigs here at the Maha laboratory

- Simulation study on combining shaped pistons with standard and new materials
- Systematic study of each physical effect (pressure deformation, thermal deformation, solid body heating) and how they act in combination within the piston interface.

Additional work of investigating waved surfaces on both the valve plate and swash plate is planned.

C. Member company benefits

- Access to novel surface design methodologies improving lubricating gap performance and reducing energy dissipation
- Preferential patent licensing options

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

Research Team

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

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

One of the challenges for equipment designed to operate intermittently is static friction. Static friction, the resistance to the onset of motion, results in large inefficiencies at start-up and often requires engineers to oversize machine components for the sole purpose of overcoming start-up conditions. Unfortunately, static friction is a physical phenomenon that is not yet well understood, particularly when dealing with complex, lubricated interfaces. Consistent parameter definitions and reproducible experimental methods are necessary to understand static friction and its dependence on material properties and operating conditions. Characterization of static friction is a critical step towards enabling machine interfaces optimized for improved start-up efficiency.

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

The following is a summary of experimental methods reported in the literature. One of the first approaches was the inclined plane in which a flat test surface is placed on top of a tilting flat surface, and the tangent of the angle at which the top test surface starts sliding is identified as the static friction coefficient (1-5). In another early approach, a rotational device was used to measure both static friction and the deformation of test specimens under very light loads (~mN) (6). More recently, static friction has been measured using an instrument referred to as the centrifugal friction apparatus which measures the friction between a block and a rotating disk (7,8). Static friction between flat surfaces at higher loads has been studied using instrumentation with hydraulic cylinders introduced as a clamping mechanism (9,10). Lastly, static friction of point contacts under light loads (~mN) has been measured using modified pin-on-disk instruments (11-13). The applicability of previously reported experimental methods is limited by (i) restrictions on contact geometry, (ii) the range of accessible normal loads, and (iii) the ability to accurately determine the onset of motion. Perhaps the most significant limitation of nearly all previously reported methods for static friction measurement is their inability to accurately and consistently determine the onset of motion. Test standards to measure the coefficient of friction do not specify how this point should be identified (14). Therefore, most studies utilize visual inspection or other indirect methods to determine when displacement begins and therefore at what point the static friction coefficient should be calculated.

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

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

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

B. Achievements

<u>Progress To-Date</u>

During the first year of the project (2009) we developed a model for static friction in dry point contact. An outline of the key components of the model is shown in Figure 1. This model was validated by comparison to experimental data reported in the literature. Details are available in the previous year's annual report.

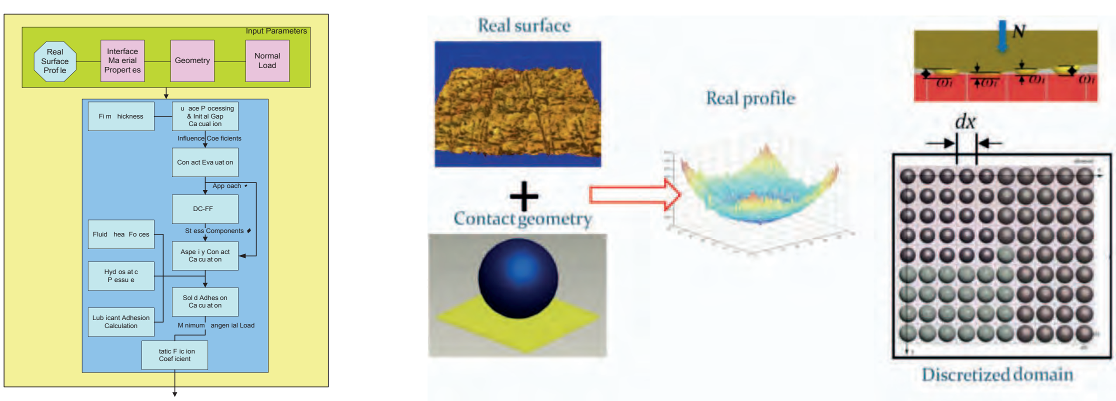
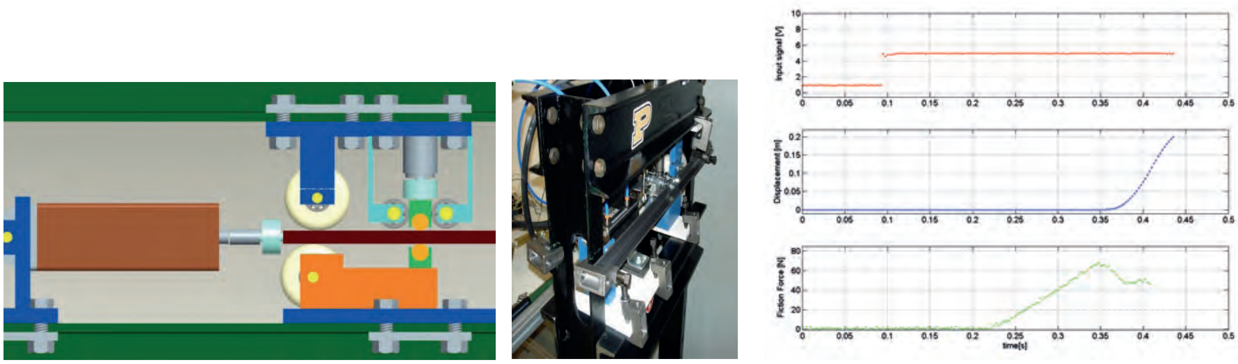


Figure 2: Flowchart and pictorial representation of the static friction model.

Last year (2010) we designed and built an experimental test rig for static friction measurement. The test rig was used to (i) validate the model for dry contact, (ii) study the effect of fluid material properties on static friction, and (iii) evaluate the performance of hydraulic oils formulated at MSOE. Details of the experimental rig (Figure 2a) and test conditions are available in (24) and (25). Most measurements were taken for contact between a cylindrical roller from a geroler motor and a flat test piece. The surfaces of the interface components were characterized prior to and after testing using a Phase Shift MicroXAM interferometric profilometer. Representative data from a single test at 150 N is shown in Figure 2b: the input signal sent to the electronic pressure regulator (top), the corresponding test plate displacement (center) and the friction force (bottom).



(a) (b)

Figure 2: (a) Schematic and photograph of the apparatus for measurement of the static friction coefficient, and (b) representative results (see text for details).

To summarize the experimental findings, we observed that for metallic line contact, (i) static friction decreases with load, (ii) static friction increases with viscosity at low load and decreases with higher viscosity at high load, and (iii) the kurtosis and skewness of the surface profiles after testing were greater for lubricated tests and more so with higher viscosity fluids. Taken together, these observations give some insight into the complex dependence of static friction on material properties and operating conditions. Illustrative results from these studies are shown in Figure 3.

It is commonly accepted that the static friction coefficient decreases with load and that this trend can be attributed to more plastically deformed asperities at higher load that can no longer resist shear. The connection between lubricant viscosity and static friction is less obvious. The difference between the observed viscosity effects at high and low loads suggests that there are two competing mechanisms: one dominant at low load and one dominant at high load. For the cases studied so far, the transition between the low and high load regimes appears to occur around 100 N. More generally, the normalized load at which the transition occurred is

$$W / R^2E^* = 1.12 \times 10^{-5}$$

where W is the normal load, R is the effective radius of the contacting components, and E^* is their effective modulus of elasticity.

The observed trends were explained by the following hypothesis that is currently under further investigation to evaluate its validity. In the low load regime, there can be expected to be highly pressurized fluid in the valleys of the surface roughness. The pressurized fluid supports the neighboring surface features thereby decreasing the number of asperities that plastically deform. Thus, at relatively low loads, increasing the viscosity will increase its ability to support the asperities that resist motion, which in turn results in an increase of static friction. However, at higher loads, another mechanism dominates. Specifically, higher loads will cause more asperities to plastically deform, regardless of lubricant viscosity. In this case, as the viscosity of the fluid increases, its ability to resist being squeezed out increases, the percent of solid-solid contact area decreases, and in turn the static friction decreases.

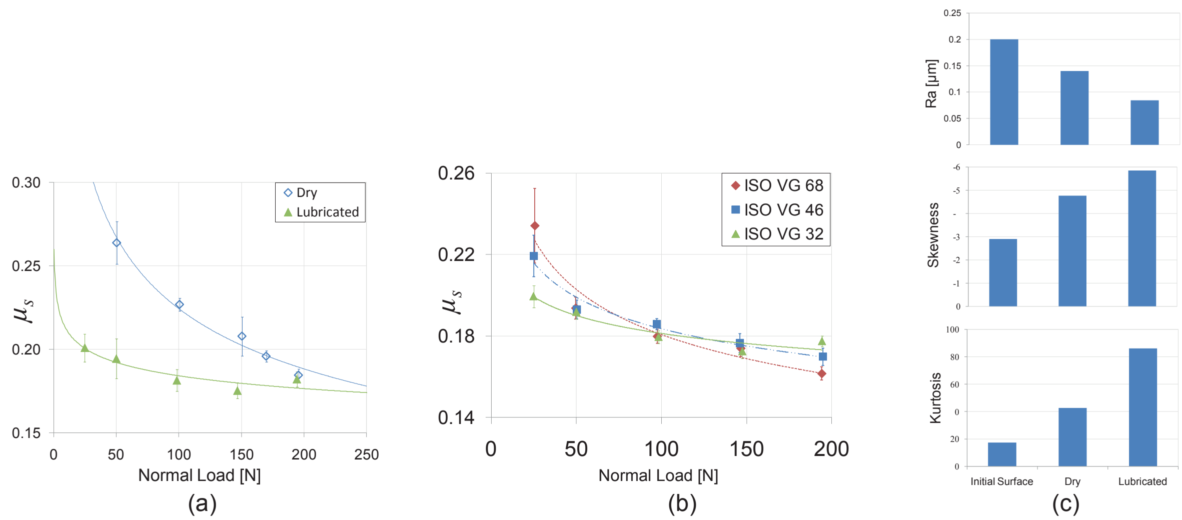


Figure 3: (a) Static friction coefficient for dry and lubricated and (b) with three different viscosity grade lubricants in line contact. (c) Statistical measures of surface roughness before testing and after dry and lubricated static friction tests. Parameters reported for the lubricated tests are averaged over the three fluids.

Working in collaboration with P. Michael at MSOE (Project 1G1) and S. Bair at Georgia Tech (Project 3D2) we evaluated the performance of hydraulic fluids in terms of their ability to reduce start-up friction. We studied five ISO VG 46 hydraulic fluids developed at MSOE and characterized at Georgia Tech that incorporated the same sulfur-phosphorus anti-wear chemistry but differed in base stock and additive composition (26). The results are shown in Figure 4. We are in the process of evaluating this data in conjunction with that measured at MSOE to develop correlations between fluid material properties and frictional performance.

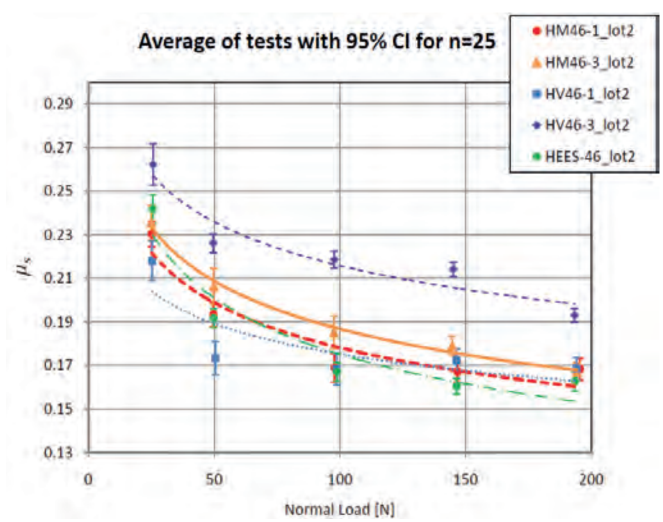


Figure 4: Static friction coefficient measured for hydraulic oils formulated at MSOE

Plans for Next Year

There are three primary objectives for the upcoming year:

- extend the test rig to perform measurements on flat-on-flat contacts,
- develop and validate the fluid module of numerical model, and,
- design, implement, and test textured surfaces for optimal start-up friction.

The tasks required to obtain these objectives are discussed in the following paragraphs.

Many hydraulic motors experience resistance to start-up caused by contact between two flat or conformal surfaces. For example, flat-on-flat contact will occur in the geroler/gerotor due to contact between the assembly and the side plate. The experimental studies we have performed to date have been for point (sphere-sphere or sphere-flat) and line contacts (cylinder-flat) only. An important next step for this research is extending the capabilities of test rig to enable flat contact. This will enable study of these contacts in general. In addition it will facilitate testing of different materials and surface features that are more easily applied (at least for preliminary testing) to flat surfaces. The component being developed to enable this is intentionally modular such that surfaces can be easily interchanged from test to test. A schematic of the new component is shown in Figure 5a.

Another critical next step for this project is to extend the modeling capabilities to include the effects of hydraulic oils. We have explored research done in this area before and found most modeling approaches to be empirical in nature. We intend to move beyond this approach and integrate fluid models that capture the material properties such as viscosity and density. The role of a lubricant is complex as it is dependent on the properties of the fluid and the solid as well as the applied load. The load dependence is of particular importance because increasing load can result in a transition from a regime where adhesion plays a significant role and the fluid increases the static friction to a regime where the lubricating properties of the fluid are dominant and the fluid acts to decrease static friction. Trends observed from the experiments will be used to both inform the modeling effort and as a means of direct validation.

Lastly, we have just begun a new collaboration with W. King at UIUC (Project 1D) who has expertise is in design and manufacturing of textured surfaces. We will use the model predictions to help guide the surface texture designs for optimal start-up friction and experimentally evaluate the performance of the resultant textured components. Results of preliminary studies of potentially advantageous surface textures identified using the model are shown in Figure 5b. To initiate this collaboration, Dr. King's graduate student visited Purdue in December 2010 to learn about the capabilities of the test rig and develop a plan for the first test surfaces. Initial testing is set to be performed on stainless steel with textures consisting of an array of squares ~100-200 microns side length, and from 5 to 20 microns deep, early in 2011.

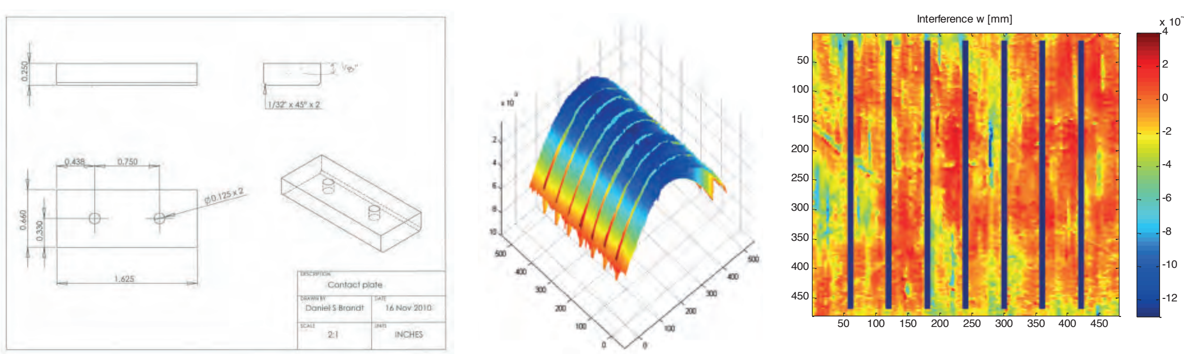


Figure 5: (a) Design of new component for the test rig to enable study of flat-on-flat contact with easily interchangeable surface features. (b) Example surface modification implemented in the static friction model and the approach distance of the two surfaces predicted by the model.

C. Member company benefits

Thus far, the fundamental research being performed in this project has not led to quantifiable benefit to CCEFP member companies. However, going forward, we anticipate that member companies will benefit from a variety of findings obtained through this project. From an applied perspective, member companies will receive detailed surface design criteria for optimization of start-up friction in hydraulic motors. On the fundamental level, member companies will have access to a new theoretical understanding of how surface characteristics affect start-up friction as well as a numerical modeling tool that implements this theory.

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1D: Nano-Texturing for Fluid Power Lines and Pumps (Pre – August 2010)

Research Team

Project Leader:	Prof. Eric Loth, Aerospace Engineering
Post Doc(s):	Dr. Ilker Bayer
Graduate Students:	Adam Steele, Ph.D.
Industrial Partner(s):	Caterpillar, John Deere, Eaton, Festo, Gates, Sauer Danfoss, Trelleborg, Haldex

Note that this is a companion report to Project 1D led by Prof. William King.

1. Statement of Project Goals

The objective of this pump research with nano-scale additives is to investigate whether small concentrations (ppm quantities that do not affect viscosity) of nano-structured solid lubricants and high strength particles with high aspect ratio (nano-scale diameters but micro-scale lengths) can reduce internal leakage in pumping systems

2. Project's Role in Support of the Strategic Plan

This project directly supports both the efficiency thrusts. It supports the strategic plan by increasing the fundamental understanding of nanotexture creation and properties in the context of oils, the critical fluid for hydraulic fluid power. Furthermore, the surface technologies can be used in the excavator and HHPV test beds to improve overall system performance.

3. Project Description

A. Description and explanation of research approach

A conformal coating process was investigated to transform surfaces with inherent micro-morphology into superhydrophobic surfaces with nano-scale to micro-scale hierarchical surface structure using wet chemical spray casting. Nanocomposite coatings composed of zinc oxide nanoparticles organosilane quaternary nitrogen compound are dispersed in solution for application. The coating is applied to a micro-patterned polydimethylsiloxane (PDMS) substrate with a regular array of cylindrical microposts as well as a surface with random microstructure for the purpose of demonstrating improved non-wettability and a stable superhydrophobic state for water droplets. Coating surface morphology is investigated with an environmental scanning electron microscope (ESEM) and surface wettability performance is characterized by static and dynamic contact angle measurements.

B. Achievements

Upon coating application by spray casting with an organic compound to a regular array of cylindrical micro-posts, superhydrophobic surfaces with nano-scale to micro-scale hierarchical topology were successfully created (Figure 1). This is the first methodology developed to accomplish this, to the authors knowledge. These surfaces yielded a significant improvement in contact angle, hysteresis, and sliding angle due to the assembly of hierarchical structuring (Figures 2 and 3). This method represents a relatively simple fabrication scheme, given a surface with pre-existing microstructure, for superhydrophobicity using a spray casting technique. It also may be quite economical as it does not require the use of expensive processing steps or particular substrate materials. In fact this concept was applied to a surface as simple as sand paper, and yielded large performance increases in non-wetting (Figure 4). Thus, it may be adaptable to larger surface area application in systems such as marine vehicles, stain resistant materials and clothing, and fluid power system components.

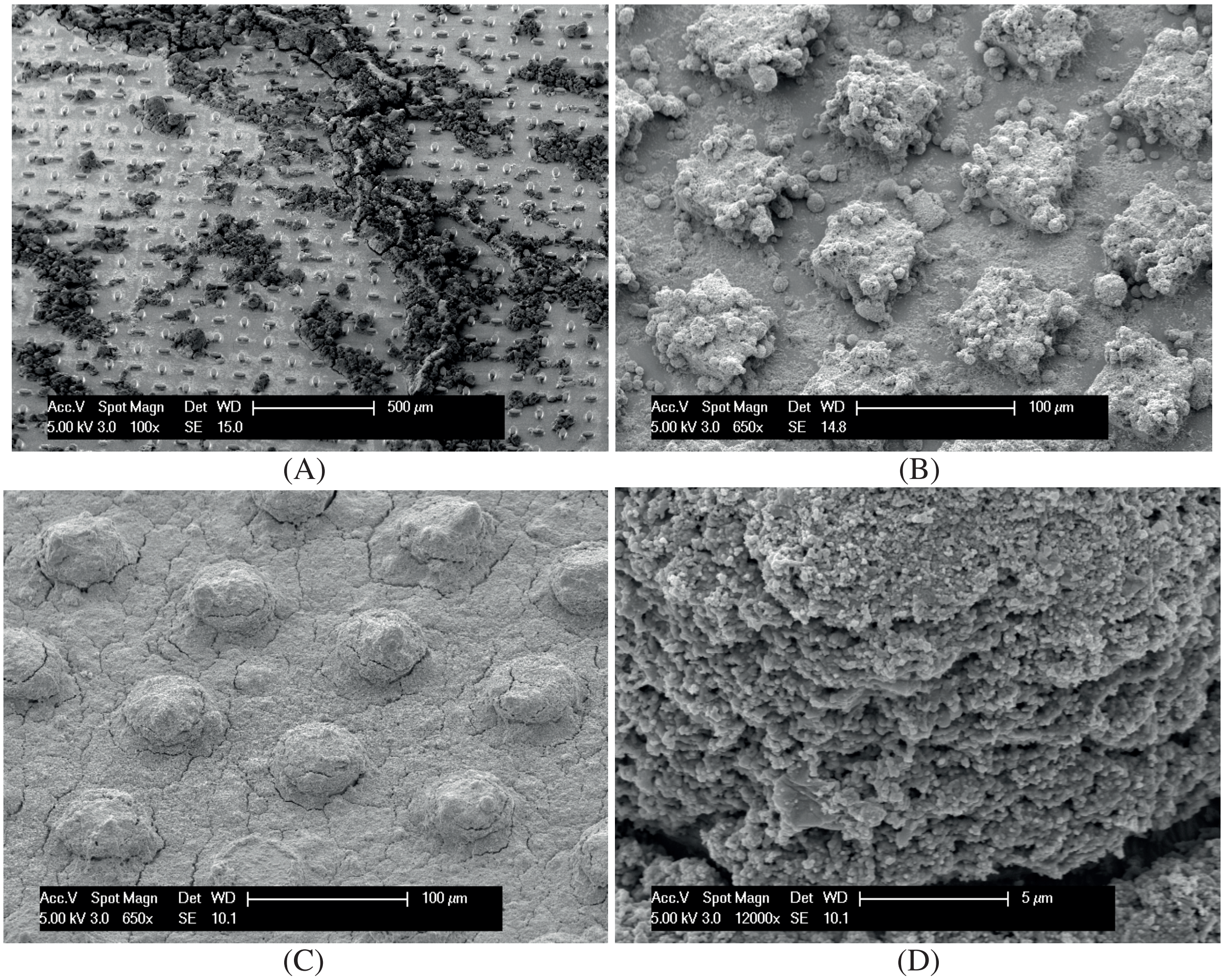


Figure 1. ESEM images of spray coatings of (A) water:PMC:NP; (B) ethyl acetate:PMC:NP; and (C) NC-MP50 nanocomposites; (D) close up of NC-MP50 micropost to reveal nano-texture.

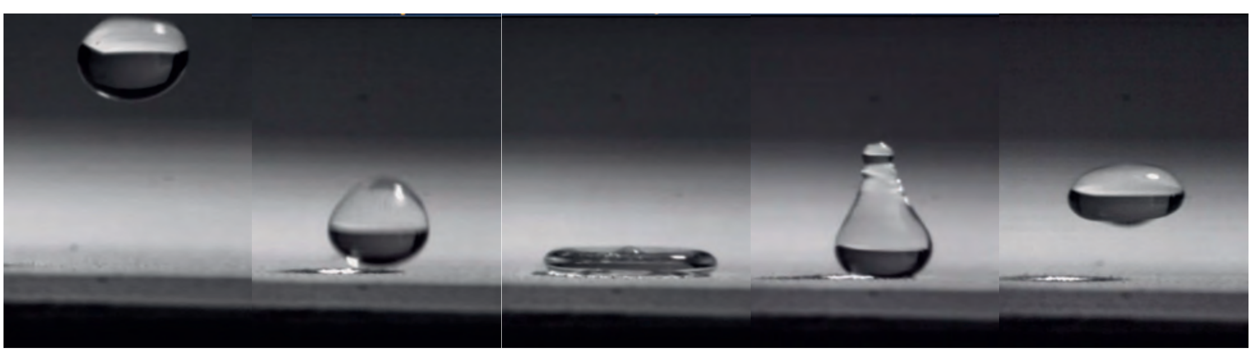


Figure 2. High speed camera frames of a 20 μL bouncing water droplet on the NC-MP10 superhydrophobic surface.

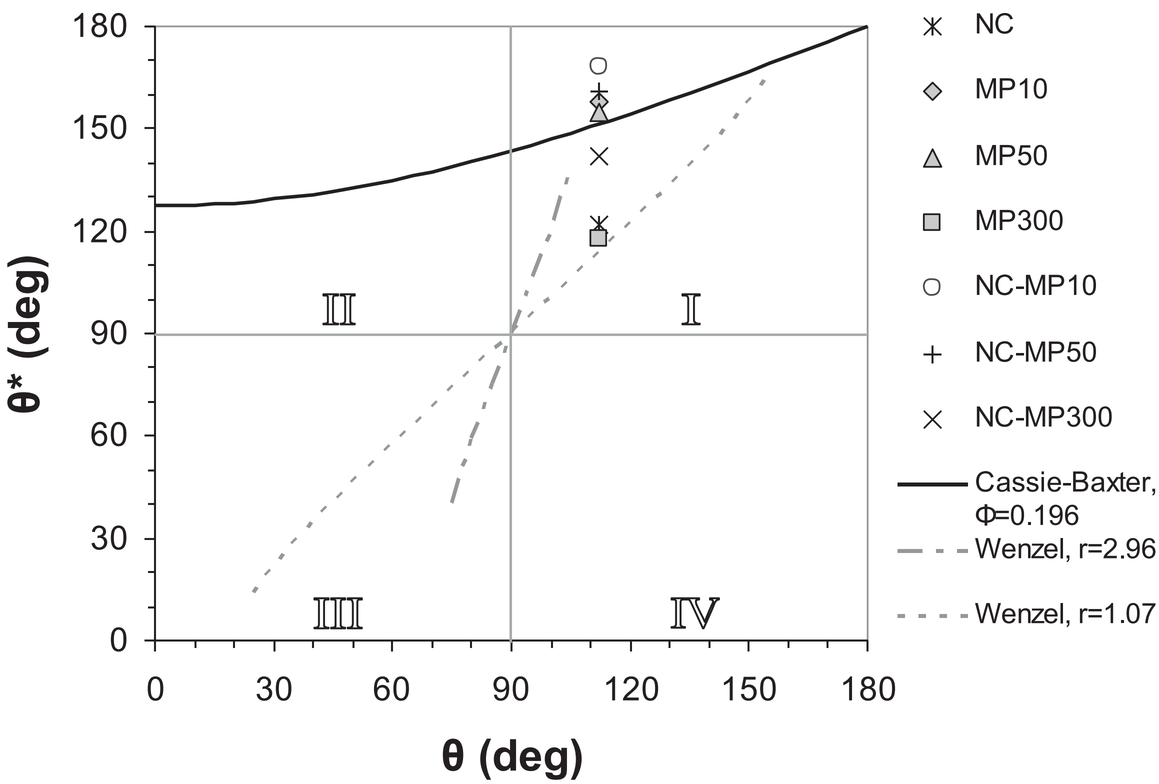
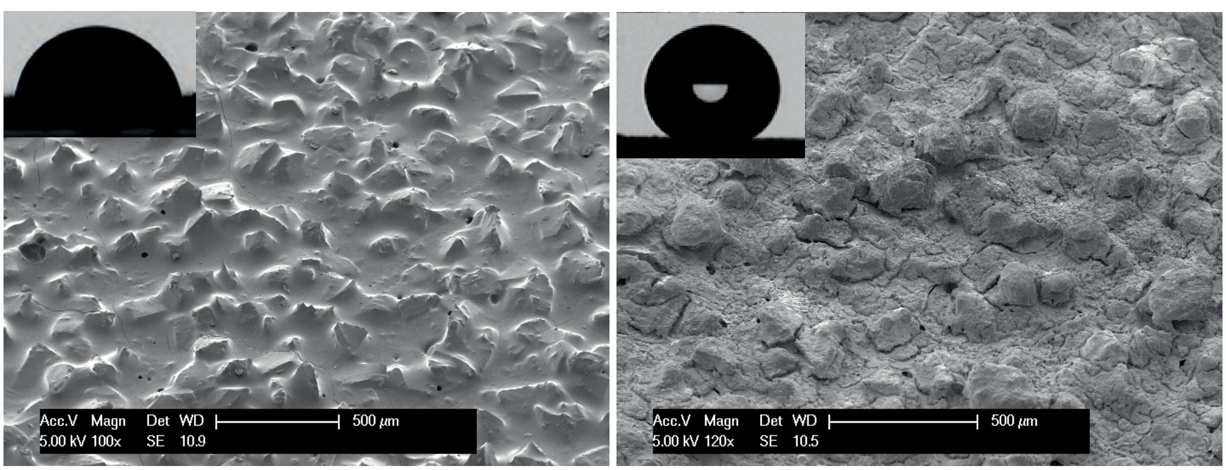


Figure 3. Apparent static contact angle as a function of equilibrium contact angle for 10 μL water droplets with an uncertainty of three degrees.



(A) (B)

Figure 4. ESEM images of (A) fine sandpaper and (B) NC spray coated fine sandpaper both with 10 μL droplet inset images.

In a second study, nano-structured polyurethane/organoclay composite films were fabricated by dispersing moisturecurable polyurethanes and fatty amine/amino-silane surface modified montmorillonite clay (organoclay) in cyclomethicone-in-water emulsions. Upon thermosetting, water repellent self-cleaning coatings were obtained with measured static water contact angles exceeding 155◦ and low contact angle hysteresis (<8◦). Electron microscopy images of the coating surfaces revealed formation of self-similar hierarchical micro- and nano-scale surface structures. The surface morphology and the coating adhesion strength to aluminum substrates were found to be sensitive to the relative amounts of dispersed polyurethane and organoclay in the emulsions. The degree of superhydrophobicity was analyzed using static water contact angles as well as contact angle hysteresis measurements (Figure 5). Combining this process with the ability of organoclay to assemble into hierarchical structures, superhydrophobic composite coatings can be developed (Figure 6).

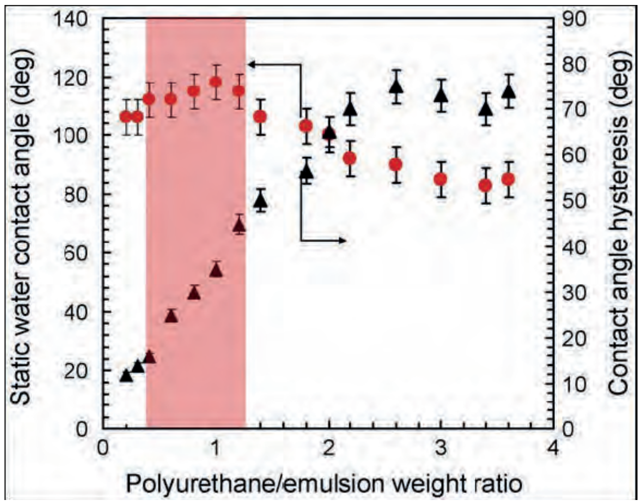


Figure 5. Surface wetting characteristics of polyurethane/cyclomethicone composite coatings measured in apparent static water contact angle and contact angle hysteresis as a function of polyurethane to emulsion weight ratio.

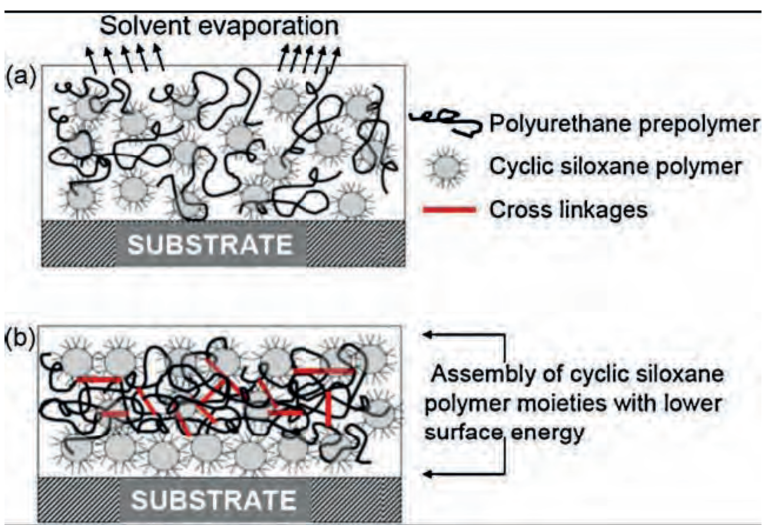


Figure 6. (a) Schematic representation of polyurethane dispersion within the cyclic siloxane (cyclomethicone) polymer network and subsequent solvent evaporation from the coatings.
(b) Schematic illustration of polyurethane crosslinking within the cyclomethicone polymer network forming a SIPN. As a result of polyurethane cross-linking and associated polymer chain mobility, cyclomethicone polymers can assemble along the coating–air and substrate–coating interfaces.

C. Member company benefits

This project has been advised by our industry through quarterly nano-champ meetings. This has led to technical interactions. For example, Gates Corporation provided nitrile samples (the material used for hydraulic hoses) to which we applied our nano-textured material. Gates then conducted heat-treatment tests on these surfaces consistent with temperatures used for annealing hydraulic hoses, after which we confirmed that the coatings maintained their hydrophobicity. We have also recently submitted a journal paper to Applied Physics Letters with Lance Miller of Gates. Finally, we have just received a high performance gear pump from Haldex with the goal of applying our low friction nanocomposite materials to internal surfaces. This collaboration will help insure that our approach is also applicable to industrial objectives.

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1D: Micro- and Nano-Texturing for Low-Friction Fluid Power Systems (From August 2010 on)

Research Team

Project Leader:	Prof. William King, Department of Mechanical Science and Engineering, University of Illinois Urbana-Champaign
Graduate Students:	Ashwin Ramesh
Undergraduate Students:	Joseph Liu
Industrial Partner(s):	Trelleborg, Eaton, Gates, Caterpillar, John Deere, Gates

Note that this is a companion report to Project 1D (Pre-August 2010) led by Prof. Eric Loth.

1. Statement of Project Goals

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

This is a new project, beginning August 2010. It follows from a similar project of different goals, which graduated in August 2010. The previous 1D project will submit a separate report for the work done before August 2010.

2. Project Role in Support of Strategic Plan

Friction between lubricated surfaces is one of the main energy losses in fluid power systems. Surfaces having reduced coefficient of friction will result in improved energy efficiency for today's fluid power systems.

3. Project Description

A. Description and explanation of research approach

Friction between lubricated sliding surfaces can be reduced when one or both surfaces have surface roughness or surface microstructures [1, 2]. The mechanism behind this friction reduction is based on the textures serving as lubricant reservoirs thereby ensuring constant supply of lubricant to the surfaces in relative motion. Micro-texturing also leads to the creation of lift and hence increased separation between the surfaces. For a fixed separation between two surfaces, micro-texturing of one or both of those surfaces can lead to reduced sliding friction.

Only a few published papers have investigated how microstructures affect sliding friction, either through small-scale laboratory tests [3-5] or numerical simulations [6-8]. These papers have shown the general feasibility of microstructures for friction reduction. However, there has been little research on how to design microstructures for a specific application. A gap remains in understanding how to choose the optimum parameters of the texture in order to obtain the best performance in terms of lift and friction. There exist some numerical models [9]; however, they concentrate on low Reynolds number flows ($Re < 1$) and use the Reynolds equation to solve the fluid flows [14]. Thus one of the gaps to address is the engineering design rules and to do so over a larger range of *Re*.

Very little research has been done on how to manufacture microstructures in real materials and on a scale relevant to the fluid power industry. Laser Surface Texturing (LST) has been proposed to make arrays of microscopic dimples directly into metal parts [10, 11]. The LST method is expensive, difficult to scale up and creation of dimples other than circular ones is difficult. Thus the second gap to address is the manufacture of microtextured surfaces in industrially-relevant materials, sizes, and shapes.

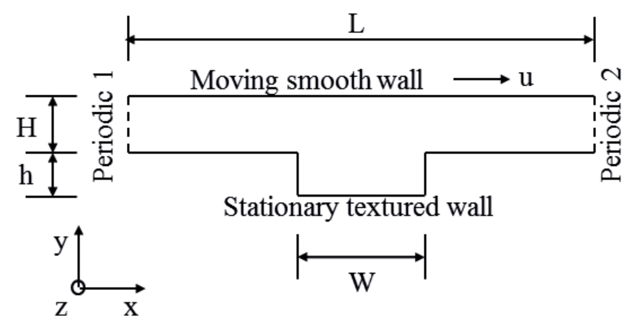
Within the scope of this 2-year project, we aim to develop design rules for friction-reducing microstructures as relevant for the fluid power industry, fabricate microstructured surfaces and characterize their coefficient of friction under lubricated sliding conditions, and extrapolate these results to fluid power applications.

B. Achievements:

The first stage of the project has focused on developing design rules for how various parameters of the microstructures affect the drag characteristics of surfaces in relative motion. A finite element model of the fluid flow behavior is used to predict drag force and lift as a function of microstructure size, shape, and periodicity.

Figure 1 shows the computational domain. The simulation cell consists of a single micro-texture having width *w*, depth *h*, and pitch *L*. The cell has periodic boundary conditions. The film thickness *H* is held constant in these simulations which is the case in many fluid power applications. The non-textured smooth wall moves with a constant velocity (*u*) while the textured wall is stationary. The model uses a 2-D CFD fluid flow solver to solve the Navier-Stokes equation. Typical values for gap spacing *H* are 5 - 20 μm, typical values for velocity are 1 – 12 m/s. The fluid is mineral oil with a constant viscosity of 1.5 Pa-s and constant density 800 kg/m^3. The Reynolds number *Re*, calculated based on the film thickness, is in the range 10^{-3} to 10^2. Hence, the use of Navier-Stokes solver is necessary, as the Reynolds equation is not suitable for this entire range [14].

Our goal is to understand how to select the various geometric parameters for given operating conditions. Although there are a few papers [12, 13] that use this approach to study the micro-texture fluid interactions, only a little work has been published on optimizing these parameters. Moreover, some of the texture geometries considered in these papers are not realizable in the real world. Our approach here is to characterize the features based on a set of non-dimensional numbers such as depth to film thickness ratio (*h*/*H*), aspect ratio (*h*/*W*), texture packing density (ρ=*W*/*L*) and other parameters such as pressure, velocity and viscosity.



Range:
H = 5 - 20 μm
h = 1 μm - 100 μm
W = 10 μm - 1 mm

Definitions:
h/H: Depth to film thickness ratio
h/W: Aspect ratio
ρ = W/L: Texture density

Figure 1: Schematic of the simulation cell for square groove geometry. Shown are the geometrical parameters like film thickness (*H*), depth (*h*), width (*W*) and pitch (*L*), boundary conditions for the model, and the range of values for these parameters and definitions used.

The friction force between the surfaces and the pressure acting on the top wall are calculated from the simulation. The friction force is calculated as the surface integral of shear stress at the top surface. The friction ratio is calculated by finding the ratio of friction force between a textured and smooth surface in relative motion to the friction force between two smooth sliding surfaces. Friction ratio less than 1 indicates a reduction in friction, which is an improvement compared to smooth surfaces. The hydrodynamic load is calculated by the surface integral of the pressure acting on the top wall. The force ratio is calculated as the ratio of the friction force to the hydrodynamic load. Low friction force ratio is desired, as this minimizes the friction force and maximizes the hydrodynamic load between the surfaces.

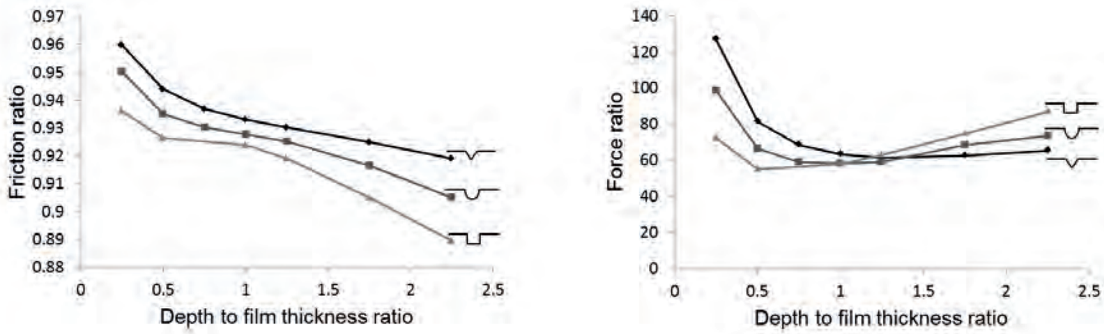


Figure 2: Effect of texture geometry on friction and force ratio for ρ=W/L=0.24, H = 10 μm, u = 12.1 m/s, Re = 6.5e-2. Left – friction ratio of textured to untextured surfaces. Right – ratio of friction force to load on top wall. The legends on the graphs indicate the different geometries considered. The width (W), depth (h) and pitch (L) are the same for the three geometries.

To start, we used the simulations to compare sliding friction for surfaces having three different geometries: circular, square or triangular grooves. The comparison was made for *h*=2.5–25 μm, *W*=40 μm, and *L*=168 μm. Velocity *u*=12.1m/s, which corresponds to *Re*=6.5e-2. Figure 2 shows how variation in texture depth affects the friction ratio and the force ratio. These plots are shown for the three different texture shapes. Friction ratio is smallest for the square groove. Reduced friction is desired for reducing losses in a fluid power system, and thus square grooves are preferred. In terms of the force ratio, the optimal film thickness ratio is near 0.5 for square grooves.

The next step was to determine the texture size that leads to smallest friction for various operating conditions. Figure 3 shows the friction ratio and force ratio as a function of microstructure depth. Deeper textures are preferred, since friction ratio can be decreased by increasing texture depth. For deeper textures, there is more fluid available between the surfaces, and the microstructures may serve as fluid reservoirs. Moreover, a minimum in the force ratio curve indicates minimum friction and maximum hydrodynamic load which is at film thickness ratio 0.5 – 1 for this range of Reynolds numbers and texture densities.

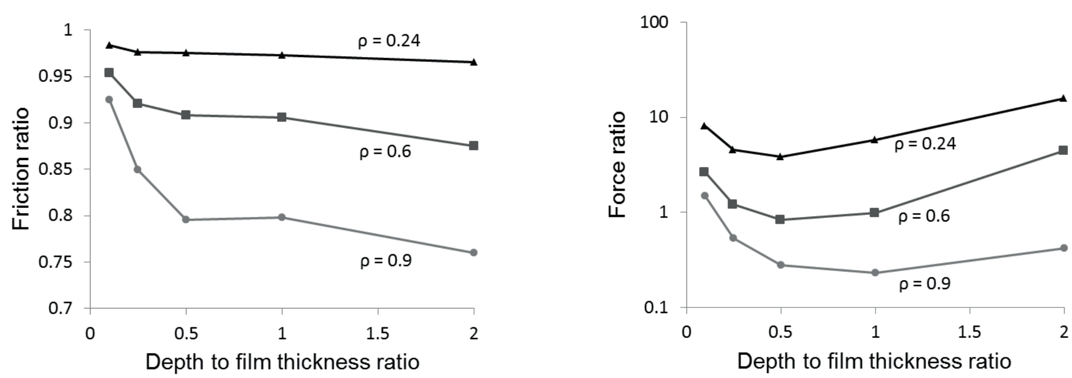


Figure 3: Effect of texture depth of square geometry as a function of texture density (ρ) for L = 168 μm, H = 10 μm, u = 12.1m/s, Re = 6.5e-2. Left –friction ratio of textured to untextured surface. Right – ratio of friction force to load on top wall. The graph shows the positive effect of texturing as the friction force is lower when textured as against untextured parallel sliders (friction ratio < 1)

Figure 4 shows the friction ratio and force ratio as a function of microstructure width *W*. Friction decreases with increase in width. However, there exists a certain critical width of the micro-textures beyond which there is an insignificant reduction in friction force. Although, more study is needed, for these conditions the optimal width was around 100 μm.

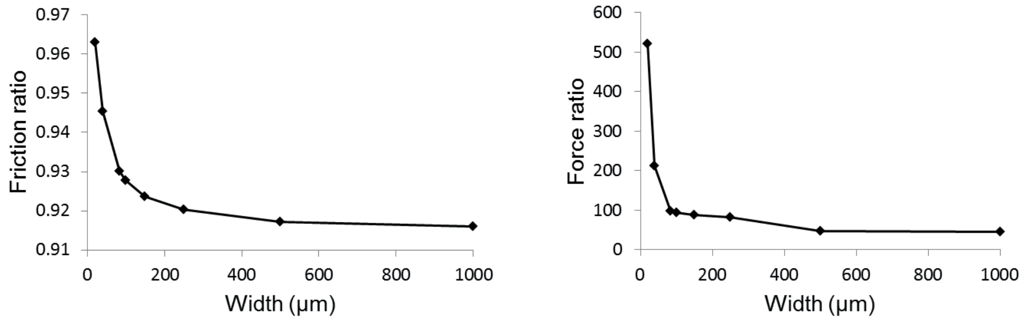


Figure 4: Effect of texture width (W) on friction and force ratio for ρ = 0.5, h = 10 μm, H = 10 μm, u = 12.1m/s, Re = 6.5e-2. Left –friction ratio of textured to untextured surface. Right – ratio of friction force to load on top wall. Beyond W=100 μm, the percentage change in friction and force ratio is insignificant.

Once the texture geometry parameters are obtained from the model, we propose to fabricate micro-structured samples initially on a small scale (later scaling up as appropriate) and test the sliding friction characteristics of these surfaces. We also propose to fabricate these patterns on non-flat surfaces using techniques developed by Prof. King's research group [15-17]. Figure 5 shows some samples of cast aluminum that have been patterned using investment casting. This allows us to fabricate micro-textures on large surfaces and also on curved surfaces with radius of curvature as low as 0.3 mm. Moreover, this technique can be extended to various other metals like stainless steel.

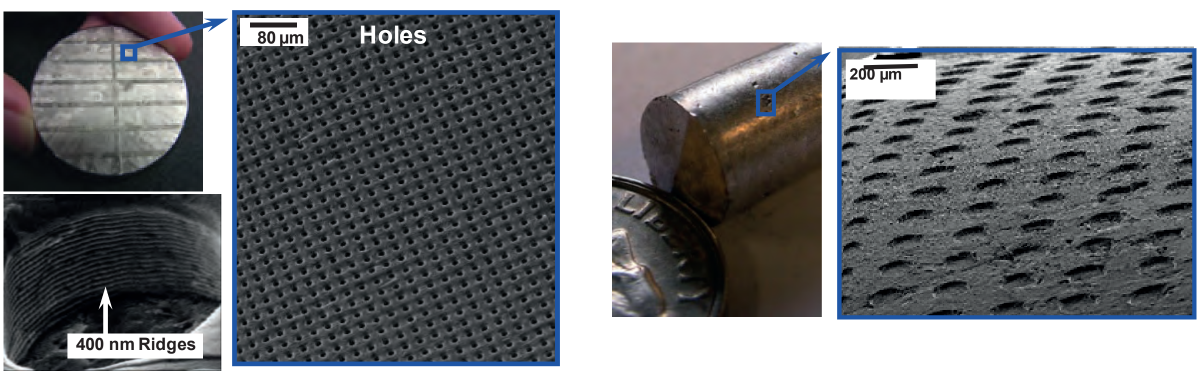


Figure 5: Metal surfaces fabricated with surface micro-textures. Left - 4" diameter metal disk with surface micro-textures. The fabrication process allows replication of sub-micron textures. Right – a metal roller having surface micro-textures [15].

The fabrication process begins with micro-texturing single crystal silicon and the patterns are then transferred to flexible rubber. The rubber is bent into an appropriate 3-D shape and then used for ceramic investment casting. The metal is then vacuum cast into the ceramic at high temperatures.

C. Member company benefits

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

In 2008, Professor King started a company, Hoowaki LLC, based on the technology shown in Figure 5. 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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1E.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor

Research Team
Project Leader: Prof. Perry Y. Li, University of Minnesota, Mechanical Engineering
Other Faculty: Prof. Thomas R. Chase, University of Minnesota, Mechanical Engineering
Graduate Students: Haink Tu, Rachel Wang, and Mike Rannow
Industrial Partner(s): Eaton, Parker Hannifin, Sauer-Danfoss, and others

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

This project addresses the efficient component/operation barrier by enabling throttle-less control approaches that replace the use of inefficient throttling valves. It also addresses the compactness barrier by enabling variable displacement functionality using compact, inexpensive fixed displacement components. 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.

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. One such VVDPM implementation based on a 4-way tandem on/off valve is shown in Fig. 1.

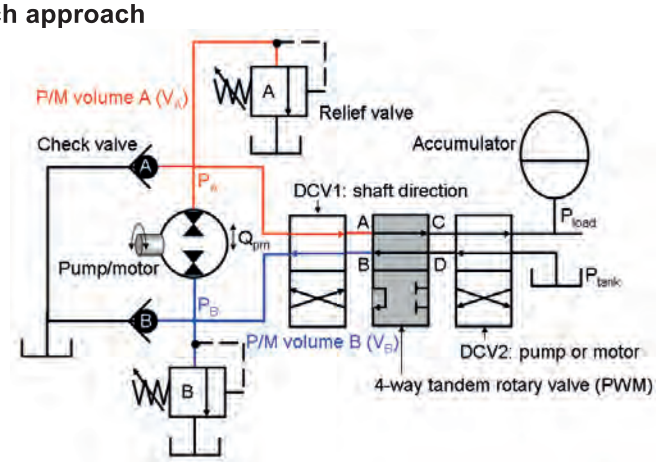

Figure 1: Hydraulic schematic of a VVDPM using a 4-way tandem rotary on/off valve

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. Our approach is to develop novel rotary PWM on/off valves that use continuous rotary motion to generate on/off switching. These rotary valves do not need to start and stop; therefore, the only power required is that to overcome friction, which is 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 Fig. 2.

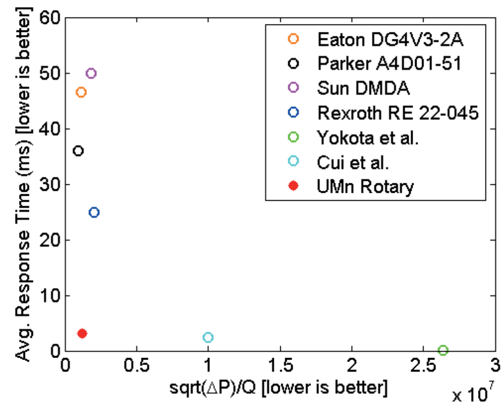

Figure 2: Effective flow area and response times of existing on/off valves

B. Achievements

Progress in the past year has been primarily focused on the development of two rotary valve prototypes that will be integrated into VVDPMs for demonstration on Test Bed 3, the hydraulic hybrid passenger vehicle. The first prototype is based on the spool valve architecture that has been under development since the inception of the CCEFP. This architecture has evolved from a 3-way self-spinning design for the control of fixed displacement pumps to a 4-way tandem design for the control of pump/motors. The second prototype is based on a novel ring valve that has just recently been proposed with the goals of improving valve efficiency in VVDPMs during high pressure, high PWM frequency operation.

Over the past year, significant effort has been made to improve the efficiency of the 4-way tandem spool valve prototype when used as the wheel speeder pump/motor in the input coupled HMT architecture used in Test Bed 3. This has culminated in a re-design of the valve for external actuation. Optimization results indicate that relying on self-spinning to rotate the spool when using the VVDPM in Test Bed 3 over the EPA Urban Dynamometer Driving Schedule (UDDS) results in a large penalty on efficiency. The self-spinning PWM frequency is proportional to the flow rate squared [4]. Therefore, the valve must be sized to maintain a minimum valve PWM frequency during portions of the drive cycle where the flow rate through the valve is low. However, a majority of the drive cycle requires a higher flow rate, so excessive throttling losses are incurred across the valve. Self-spinning also drives the spool diameter to its lower bound in order to reduce viscous friction and the corresponding torque requirements for self-spinning. As a result, additional throttling occurs due to the reduced internal axial passage diameter that ports flow from the inlet section of the valve to the outlet sections. The overall efficiency benefit of rotating the valve using an external actuator over the UDDS is shown in Fig. 3.

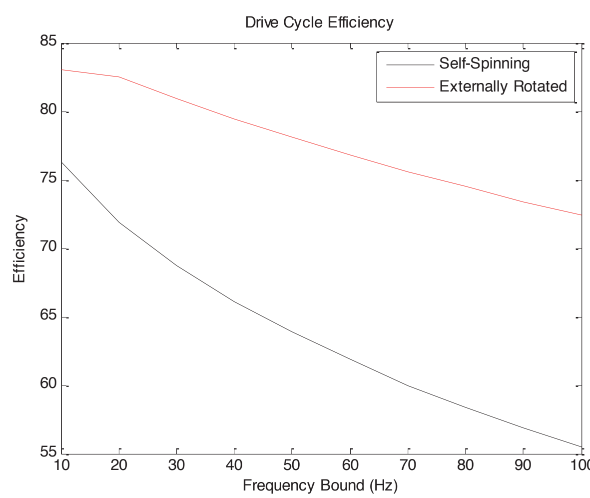

Figure 3: Efficiency comparison between self-spinning and externally actuated rotary valve

An additional benefit of external actuation is that the fluid flow through the rotary valve is no longer constrained to be uni-directional. This feature allows for the elimination of DCV1 in Fig. 1, which was previously required to rectify the flow direction for self-spinning. The absence of DCV1 eliminates the throttling losses associated with the additional component. In addition, the internal compressible volume of the rotary valve is reduced.

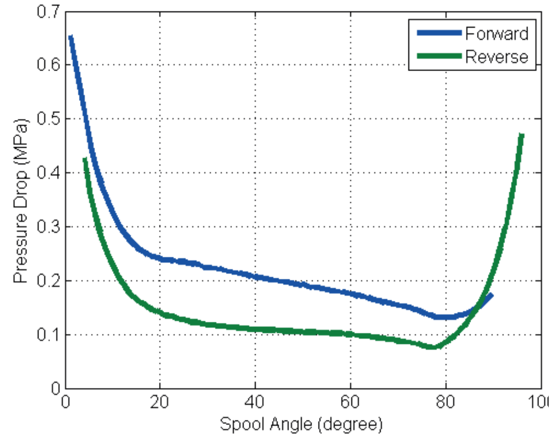

Figure 4: Pressure drop across 4-way valve spool with respect to angle and flow direction

In order to ensure that no penalties in efficiency are incurred by allowing bi-directional flow through the valve, the CFD analysis of the 4-way spool valve was augmented to study the effects of reverse flow. In particular, the pressure drop characteristic of the spool with respect to flow direction was explored to determine whether or not the existing self-spinning spool geometry would be suitable when exposed to reverse flow. Figure 4 presents CFD results showing the pressure drop across the spool with respect to angular position for a moving mesh transient simulation with the valve rotating at 20Hz. The results show that flow direction has a minimal effect on the pressure drop across the spool. Therefore, DCV1 can be eliminated and bi-directional flow allowed with little impact on efficiency. In addition, the solid model of the self-spinning valve can be scaled to accommodate the new parameters of the externally driven design without the need to re-design the underlying base geometry.

A two degree-of-freedom rotating and translating driving mechanism was synthesized and designed in order to realize external actuation on the prototype valve. The proposed driving mechanism utilizes a decoupled sealing approach to isolate the rotational and translational sealing functions, thereby allowing full sealing using standard o-rings. A schematic of the final mechanism design is illustrated in Fig. 5.

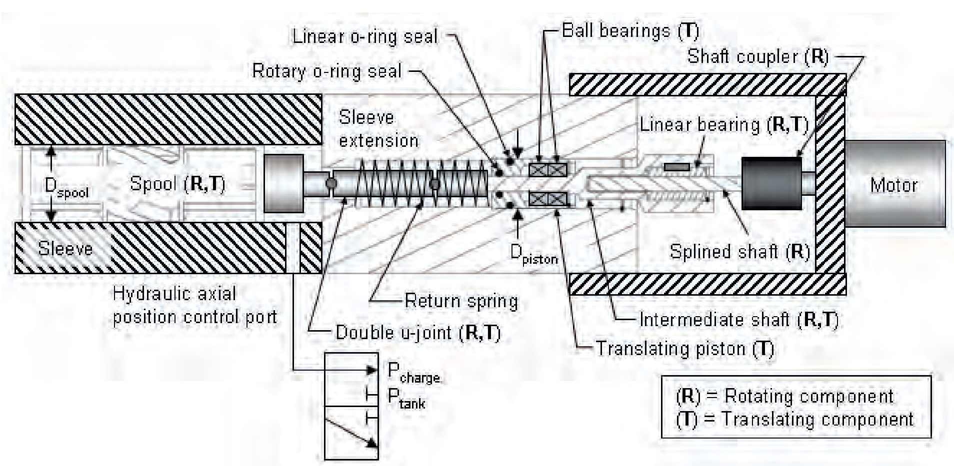

Figure 5: Schematic of 2 DOF external rotary valve driving mechanism

The mechanism consists of an intermediate shaft that rotates relative to a translating piston. Since the piston only translates, a standard reciprocating o-ring seal can be used to seal it. The purpose of the piston is to support the shaft as it rotates while simultaneously allowing the piston/shaft assembly to translate. Because the shaft only rotates relative to the piston, a standard o-ring seal on the inner diameter of the piston can be used to seal the rotary motion. A double u-joint, which accommodates angular and parallel misalignment, is used to connect the intermediate shaft to the valve spool. Torque is transmitted from an electric motor to the intermediate shaft via a splined linear bearing that allows relative linear motion between the intermediate shaft and the electric motor. The axial position of the valve spool is actuated hydraulically based upon the area difference between the spool and translating piston.

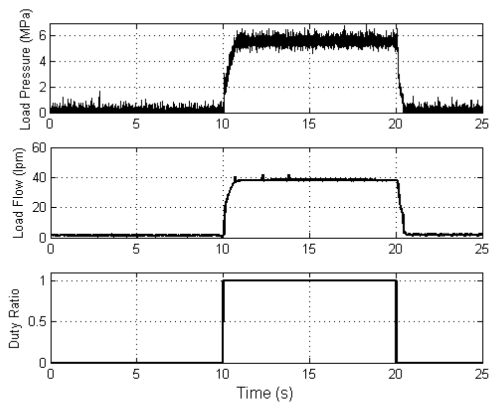

Figure 6: Load pressure (top) and load flow rate (middle) corresponding to the commanded step change in duty ratio (bottom)

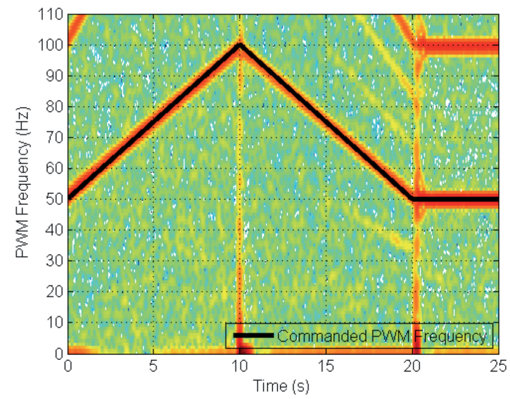

Figure 7: Short Time Fourier Transform of inlet pressure overlaid with commanded PWM frequency

Figures 6 and 7 present open-loop experimental test results of the drive mechanism using the previously developed 3-way rotary valve test stand. A step command to the axial position control valve was issued between 10 and 20 seconds, corresponding to a change in valve duty ratio from 0 to 1 (refer to bottom plot of Fig. 6). This resulted in a full stroke change in VVDPM displacement. The top and middle of Fig. 6 show the corresponding step changes in output load pressure and flow rate, both of which exhibit a rise time of approximately 600ms. The response of the VVDP is dominated by the dynamics of the accumulator on the load line. Faster response can be achieved, although at the expense of increased output pressure ripple, by either decreasing the accumulator volume or pre-charge [1].

Figure 7 shows the frequency content of the inlet pressure, which is pulsed at the PWM frequency, when a ramp command in PWM frequency is issued concurrently with the step change in spool duty ratio. A Short Time Fourier Transform (STFT) of the inlet pressure reveals that the frequency content of the signal is consistent with the commanded PWM frequency. This indicates that the PWM frequency can be controlled independently of duty ratio, which enables control options such as selectively increasing the valve's angular velocity during transitions or increasing PWM frequency around 50% duty ratio, where ripple magnitude is highest.

A back-stepping non-linear control algorithm based on the pressure dynamics of the axial actuation chamber has been derived and simulated to control the valve's axial position. The controller is currently being implemented on the test stand. In parallel to the axial position controller, a non-linear control strategy for implementing direct displacement control on a single hydraulic actuator using the VVDP is also being investigated. The controller is being developed to perform actuator trajectory tracking while maintaining a low system operating

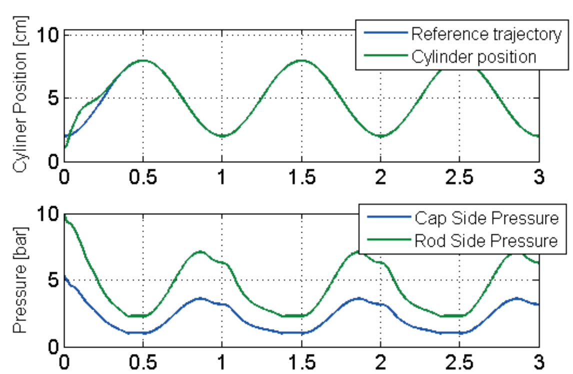

Figure 8: VVDP direct displacement control simulation results

pressure. A rigorous stability analysis of the actuator in all modes of operation has been conducted. The controller guarantees that the pressures in the two actuator chambers will neither cavitate nor go unbounded. Figure 8 presents preliminary simulation results of the direct displacement controller. The results show good tracking performance for a sinusoidal cylinder position trajectory. In addition, low system pressure is maintained while avoiding chamber cavitation.

	Spool	Ring
N	3	6
ID	-	40mm
OD	12.7mm	53mm
Length	93mm	34.6mm
V_{comp}	14.3cc	2.1cc
$\pi_{friction}$	3.4W	79.3W
$\pi_{leakage}$	64.5W	87.4W
$\pi_{compressibility}$	286W	40.4W
π_{total}	354W	207W

Table 1: Comparison of geometry and losses between self-spinning spool valve and preliminary ring valve

In conjunction with the ongoing research on the 4-way spool valve, the analysis and design of the next generation ring valve has begun. To date, the underlying structure and geometry of the ring valve has been proposed and a patent disclosure is in the process of being filed. Methods to pressure balance the ring as well as reduce friction have also been proposed. Leakage, compressibility losses, and friction have been characterized analytically by extending the analysis from the spool valve. Transition throttling losses, as well as techniques to reduce these losses in the ring valve, are in the process of being investigated. In order to assess the viability of the new valve, a preliminary comparison has been made to the 4-way self-spinning spool valve. Only losses that are independent of flow rate, such as friction, leakage, and compressibility, are considered since the geometry of the spool valve has been optimized over the UDDS with time varying flow rate while the preliminary sizing of the ring valve was done using a fixed flow rate.

Table 1 compares the geometric parameters of the spool valve with an example ring valve sized for 15lpm, which is roughly the mean flow rate over the UDDS. Flow independent losses are compared assuming an operating pressure of 21MPa, the target vehicle accumulator pressure, and a PWM frequency of 100Hz. Compressibility losses are estimated assuming .2J/cc per switch based on compression from atmosphere to 21MPa using the Yu bulk modulus model [5] with 10% air entrainment. Table 1 shows that compressibility losses are greatly reduced in the ring valve compared to the spool valve, although at the expense of friction. Leakage is similar between the two designs. Overall, the results show that for application conditions similar to those encountered in Test Bed 3, the ring valve exhibits approximately 42% lower loss than the spool valve. In particular, the ring valve is amenable to high pressure operation due to its substantial decrease in compressible volume, V_{comp}. While throttling losses, one of the dominant losses in VVDPMs, was not considered in this comparison, it is expected that throttling losses will be lower in the ring valve due to the larger achievable flow area and a simpler flow path.

Expected Milestones and Deliverables

The re-designed prototype 4-way tandem externally driven spool valve is targeted for fabrication by the end of February 2011 with bench testing complete by the end of June 2011. Implementation of the VVDPM onto Test Bed 3 will begin towards the end of summer 2011. Concurrently, the analysis of the ring valve is targeted for completion by the end of winter 2011 with optimization, computational fluid dynamic analysis, and mechanical design complete by the end of summer 2011. Prototypes should be available for testing by the end of 2011 or early 2012.

C. Member company benefits

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

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

Research Team

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Undergraduate Student:	Wayne Jeffers
Industrial Partners:	Parker Hannifin, Eaton, Husco, Moog

1. Statement of Project Goals

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

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

The valves considered in this project are axisymmetric positive contact sealing. In most conventional systems, as working pressure is increased, efficiency tends to decrease due to increased leakage and compressibility losses. It becomes increasingly difficult to seal using sliding surfaces (i.e. spool overlap and kidney/valve plates) and positive contact sealing surfaces are preferred at higher pressures to minimize leakage losses. One example high pressure application, pumps, usually rely on check valves in place of kidney valve plates and in doing so become fixed displacement unidirectional machines. High pressure, high speed on/off valves can enable a high pressure pump/motor to become variable displacement and bidirectional if the actively controlled valves replace the check valves such as in project 1E.3. This has benefits in the compactness thrust and urban vehicle test bed since high pressure and high efficiency hydrostatic transmissions become possible. Although positive contact seat type valves are preferred for minimizing leakage and tolerance requirements, the geometry of the seat leads to potentially large flow forces that make them difficult to actuate directly using electromagnetics, which saturate at a much lower equivalent pressure. New and innovate valves designs are needed that minimize the effects of the flow forces while retaining (or improving) the dynamic capabilities of switching type valves. Some work is addressing this issue through pressure balancing ports within the moving poppet (Lauttamas, et al. 2006).

There are four basic areas where fundamental science is being applied in this project. Past research has shown that numerical calculations do not accurately predict the magnitude and effects of steady state and dynamic flow forces (Johnston, et al., 1991). Because of this, CFD analysis is used to allow a more accurate description of these forces (Vaughan, et al., 1992) and the results will be used to construct a reduced order analytical model accurate enough for and capable of being embedded into a systems level model. Electromagnetic transients, as seen in high frequency eddy currents, affects the transient force of the actuator (Brauer and Mayergoyz, 2004; Piron, et al., 1998). Effects of eddy currents can be reduced with novel driving methods (peak & hold shaping, momentary reversed currents, and minimization of magnetic diffusion time constants). Area three includes the mechanical dynamics, impact forces, and contact sealing models. The combination of high pressures coupled with high switching speeds has the potential to negatively affect the reliability and lifespan of high speed valves. Finally, the behavior of the fluid is also important at the higher pressures and high switching speeds. This aspect of the project will be supported by other work within the center and is necessary to complete the system model of switching valves.

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

B. Achievements

The modeling toolbox and fundamental understanding of high speed valves developed in previous years have now been leveraged to support the rapid development of a prototype digital pump/motor for project 1E.3. Using the tools from this project and responding to the valve requirements determined by colleagues on project 1E.3 (Merrill and Lumkes, 2010); two new valve configurations (1.5 and 2.0) have been designed, modeled, and simulated.

"1.5 Stage" (Figure 1): A moving mass is first accelerated by an electromagnet and then impacts the poppet and rapidly opens the valve. Simulation predicts that because of the energy stored in the moving mass, faster valve transition times are possible (Wilfong et al., 2010). The valve is returned to the closed position by springs. Since most problems with flow forces on seat type valves occur at very small valve openings, this valve design minimizes these effects by causing a rapid transition through this operating regime. Due to concerns with reliability (impact style) and difficulties optimizing the design over a wide range of operating conditions, the decision was made to prioritize the fabrication and testing of the 2.0 design.

"2.0 Stage" (Figure 2): This configuration is a bi-directional check valve where a pilot stage is used to select which pressure ports open or close the primary poppet valve. This configuration is designed to support project 1E.3 where it has several unique advantages:

1) it can auto switch to act as a check-ball pump without any electrical input required
2) it has defined fail-safe operating modes in the event of sensor or controller failures
3) the flow forces across the seat type valve are the same as the actuation forces, thus as the flow forces increase at higher flows, so does the pressure differential to actuated the primary poppet
4) the pilot stage "selector" valve allows the main poppet to be switched mid-stroke and regardless of whether the unit is acting as a pump or motor, thus enable full four-quadrant capability, important for the hydraulic hybrid vehicle and excavator test best projects. Since the pilot stage only selects the pressure ports a smaller electromagnet can be used requiring less electrical input energy. A provisional patent has been filed.

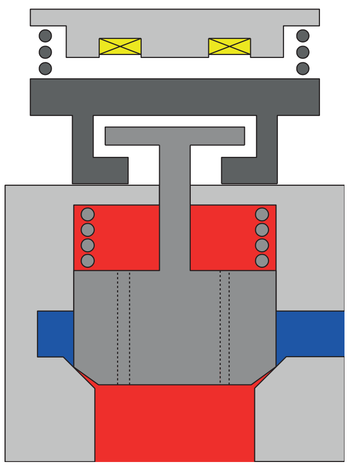

Figure 1: "1.5 Stage" Valve

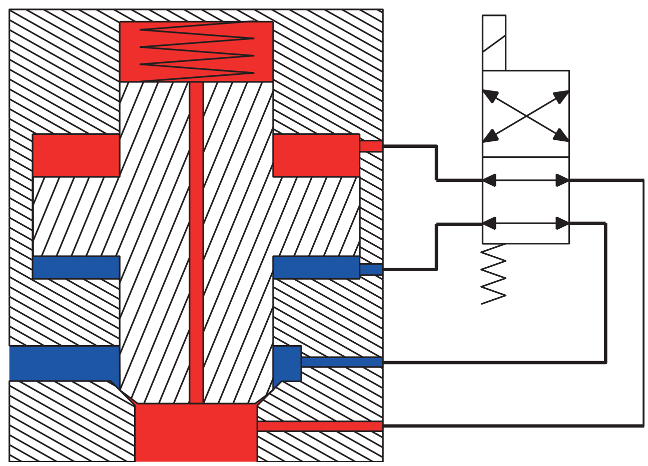

Figure 2: "2.0 Stage" Valve

During this review period significant progress has been made on the 2.0 stage. The main stage of the 2.0 valve was modeled and design parameters were optimized to decrease pressure loss, back flow, and transition times. From this work two prototype main stage valves were made using a local machine shop (Figure 3 & 4).

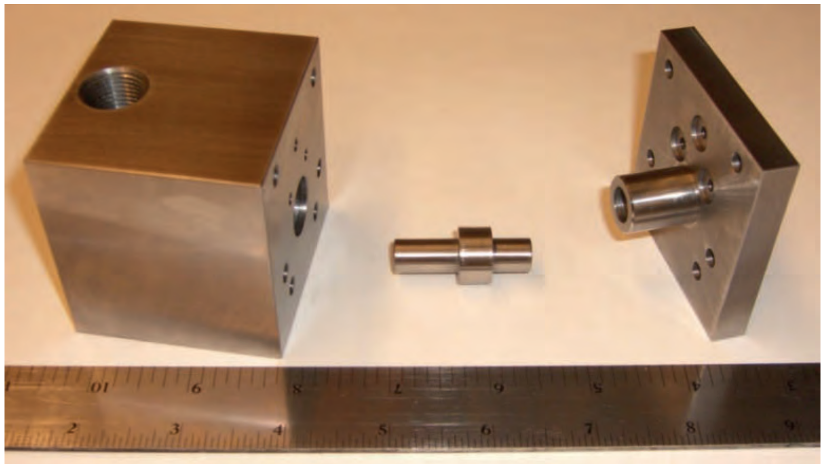

Figure 3: 2.0 valve main stage prototype assembly

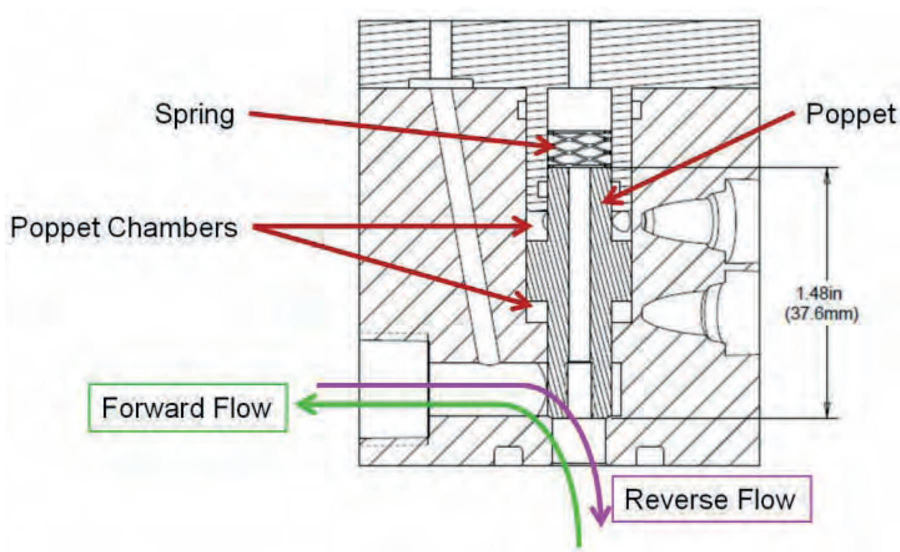

Figure 4: 2.0 valve main stage prototype section view

Experimental testing and validation are underway for the 2.0 valve main stage. Steady state testing for the valve has been completed. Both forward and reverse flow scenarios were tested while the valve was operating at full flow capabilities (maximum flow area through valve was used). The results from this steady state testing can be seen in Figure 5. When using these valves on the digital pump/motor of project 1E.3, a maximum Δp will be 6.5 bar. Dynamic testing has also been completed. As seen in Figure 6, the valve operates at full flow and is then quickly shut. There is a lag between the blue command line and then red experimental line because of the dynamics of the first stage valve used.

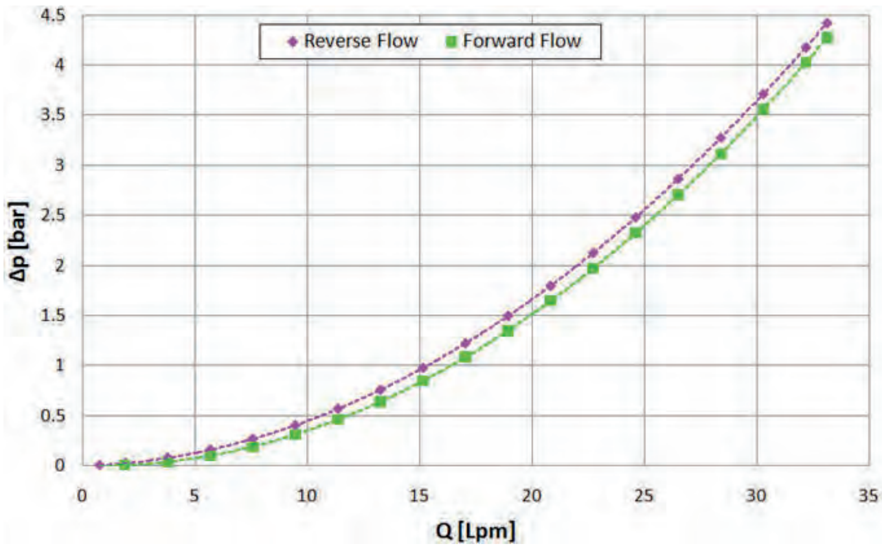

Figure 5: 2.0 valve main stage steady state testing

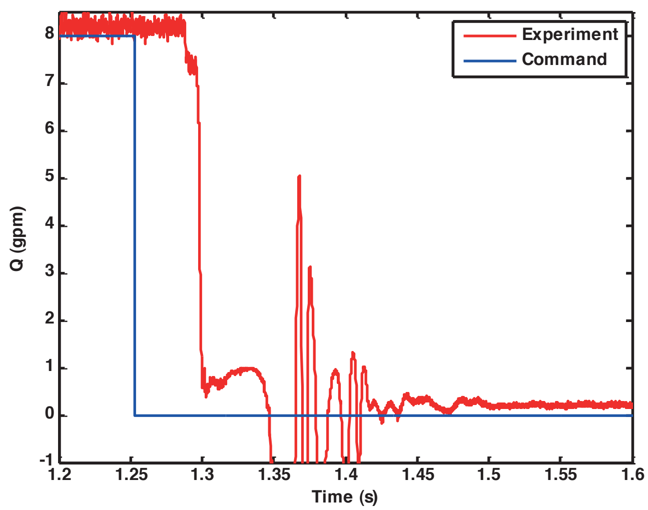

Figure 6: 2.0 valve main stage dynamic testing

Future plans for this project include further testing and development of the 2.0 valve first stage and continued implementation of the valves into project 1E.3 and test beds 1 and 3. The bidirectional check valve (2.0) has been installed on a single piston digital pump/motor test stand and experimental characterization will continue.

The design and simulation tools from earlier project efforts will also be applied to designing an innovative integrated first stage selection valve that can be tested in project 1E.3. This improved valve package can then be leveraged into a prototype pump motor (project 1E.3) as well as test beds 1 and 3.

C. Member company benefits

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

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

Research Team

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Other Faculty:	Prof. Monika Ivantysynova, Mechanical Engineering, Purdue University
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Graduate Students:	Michael Holland, Kyle Merrill
Undergraduate Student:	Ashley Johnson
Industrial Partners:	Eaton, Parker-Hannifin, Poclain, Sauer-Danfoss

1. Statement of Project Goals

The goal of the project is to develop a hydraulic pump/motor that incorporates actively controlled high speed on/off valves connected to each cylinder to replace the valve plate. The coupled dynamic model of the hydraulic pump/motor developed during this project is crucial to facilitate the development of the pump/motor. Unit displacement is electronically controlled by on/off valve timing, not by a swash plate or other typical means. Pump/motors of this design can have increased efficiency due to reduction of friction, leakage, and compressibility losses as well as increased displacement control bandwidth (Artemis, 1990; Caterpillar, 1999; Jokela et al., 1995; Merrill, et al., 2010; Nieling et al., 2005; Reichert and Murrenhoff). Supporting tasks include using the model to characterize and predict pump/motor efficiency, define the dynamic response and flow requirements of on/off valves required to provide significant improvements in efficiency and dynamic response over traditional pump/motors, simulate different operating strategies and characterize the effects on pump/motor efficiency (valve timing effects, partial fill methods, etc.), and to experimentally validate the model, design, and operating strategies. For experimental validation a prototype pump/motor will be built and tested.

2. Project Role in Support of Strategic Plan

The project will overcome a major system efficiency limitation in the fluid power industry by providing high bandwidth and efficient four quadrant pump/motor. This will be accomplished by providing an accurate simulation model to predict the effects of using actively controlled on/off valves to replace the valve plate timing in hydraulic pump/motors, and leveraging results from projects 1E.1 and 1E.2 on high speed valve designs. The variable displacement pump/motor will maintain high operating efficiencies at lower displacements, be capable of four quadrant operation, and exhibit high operating bandwidths. Improving pump/motor efficiency, particularly at lower displacements and throughout four quadrant operation will strengthen existing markets and enable new markets by improving efficiency and effectiveness. A project outcome is the construction and testing of a prototype to validate the concepts developed in years one and two of the project. The project directly supports Goals 1 and 2 on the Strategic Action Maps (Improve efficiency of existing FP applications, develop 4 quadrant pump/motor and fluid powered hybrid passenger car, and increase efficiency of FP pumps and motors).

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

3. Project Description

A. Description and explanation of research approach

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

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

The innovation for this project involves applying fundamental science and latest design and simulation tools to provide insight on the interacting dynamics and accompanying tradeoffs associated with independently and actively controlling the port timing for each piston in hydraulic axial or radial piston pump/motors. The project is developing fundamental insight into the design tradeoffs for actively controlled pump/motors and will provide these tools to industry. Actively controlled pump/motors as focused on in this project are more likely to be successful than past attempts because of several reasons 1) electronic and sensing capabilities have progressed significantly in the past decade, 2) new fundamental knowledge has been gained in the area of pump/motor design [Ivantysynova, 2004; Manring, 2001] and can be used in this project, 3) computational power and simulation tools are allowing for coupled multi-domain system models to be optimized, 4) the high cost of energy is making component efficiency an important consideration in operating costs, 5) previous and ongoing research on high speed on/off valves is providing the enabling technology, and 6) the CCEFP provides a unique critical mass of researchers, industry, and resources to successfully overcome the barriers.

The fundamental research barriers occur at the intersections of different physical domains represented during the short (< 1ms) transitions between high and low pressures, and the valves opening and closing. As the references make clear, the concept of actively and independently controlling the valve plate areas through the use of high speed valves is not new (Artemis, 1990; Jokela et al., 1995). What will allow the barriers to be overcome through this project is the ability to accurately model the interactions between the different physical domains and design the components to act as an optimized system capable of meeting the metrics of the project. In addition, the advanced electronics required to implement such a system have only recently become available at the processing speed, reliability, and cost levels needed. Even if the simulation and experimental results demonstrate improved performance, many practical challenges still remain. Reliability and redundancy of key components (valves and sensors) are critical when considering possible failure modes, electronics and sensors must be robust and embedded on the pump/motor to be competitive with existing units, new packaging options should be considered since the pump/motor valves are now independently controlled and not geometrically constrained, and new system level operating strategies could be possible with “smart pumps” containing embedded microprocessors and the ability to adapt to different load requirements.

B. Achievements

Project 1E.3 made important progress in several key areas. There has been continuing and valuable collaboration with project 1B on understanding the internal losses within the pump. The pump/motor valve loss and piston leakage effects on efficiency have been simulated utilizing the Matlab/Simscape modeling tool (Merrill, et al. 2010), there has been experimental testing of pump chamber voiding (Holland, et al., 2010), and there has been leveraging of results from Project 1E.2 (high speed on/off valves) and working with 1E.2 to design optimized valves specifically focused on meeting the valve performance requirements for this project (Wilfong and Lumkes, 2010). Unique valves designs have been developed in 1E.2 (provisional patent filed on one of the valves) that are now being evaluated using the pump/motor system simulation and experimental test stand developed in this project.

The Matlab/Simscape 7 piston pump/motor model has been updated to include simulation of the motoring modes. Figure 1 shows the motoring efficiency of three different operating methods to achieve partial motoring displacement. With pumping all three methods showed better efficiency than the state-of-the-art pump/motor units. However, because of how a piston operates while motoring, the partial flow-diverting method shows reduced efficiency compared with flow limiting.

The experimental testing has also progressed and the valve prototype resulting from collaboration with project 1E.3 has been installed in the single piston pump/motor test stand and data is being collected. With the single-piston pump/motor test stand configured as shown in Figure 2, the test stand was able to operate in both flow-limited and flow-diverting pumping modes with the 1E.2 valve at 500rpm. Plots demonstrating the unit operating at 100% displacement (operating as a check ball pump), ~50% displacement, and 0% displacement (idle) are shown below in figures 3-6 for flow limiting and flow diverting operating modes. Flow out of the displacement chamber is positive. The operating conditions for these figures are: Speed, 500 rpm; Inlet pressure, ~14bar; Outlet pressure, ~42bar; and Stroke, 22mm.

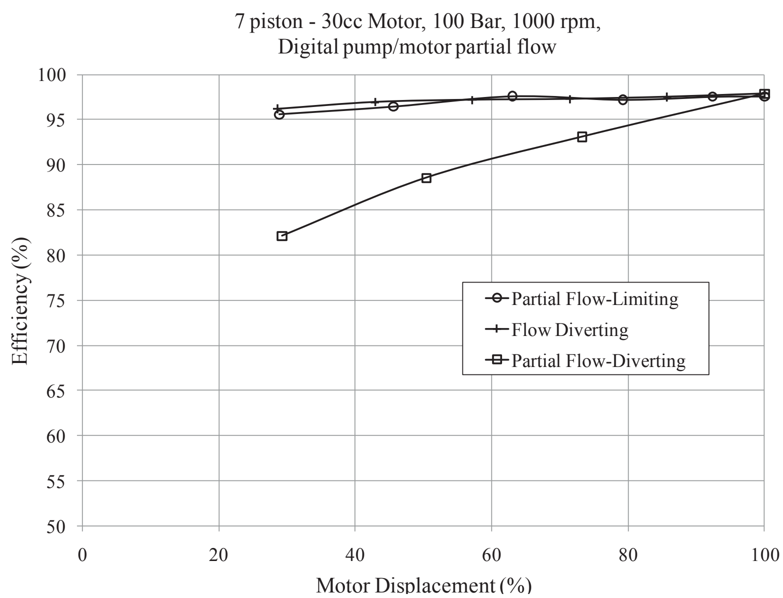

Figure 1: Pump valve loss and piston leakage, motoring efficiency

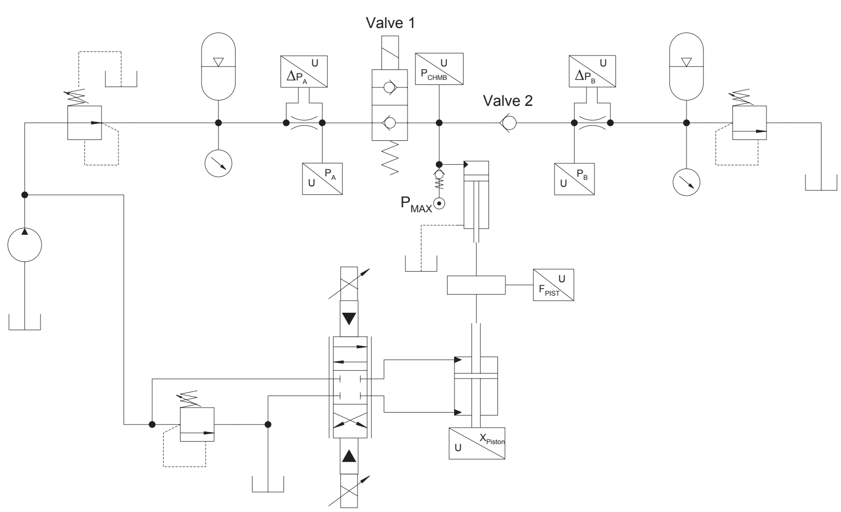

Figure 2: Single Piston Pump/Motor Test Stand Configuration

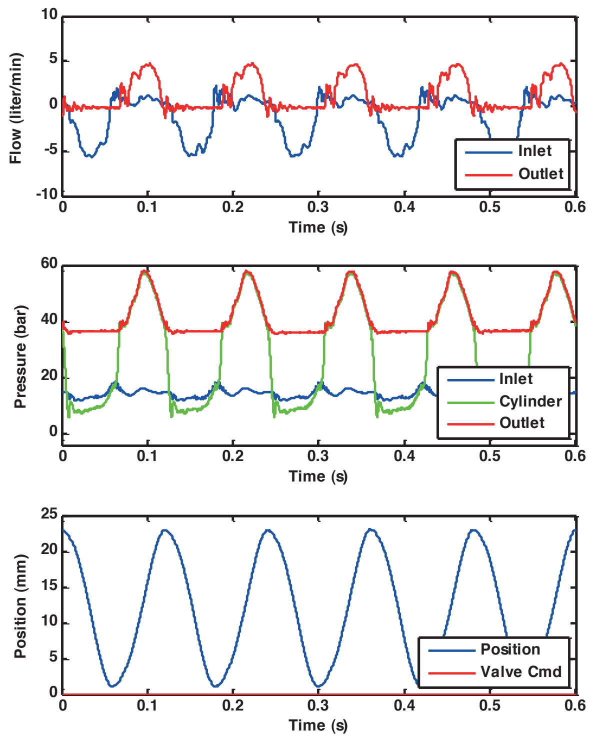

Figure 3: 100% displacement

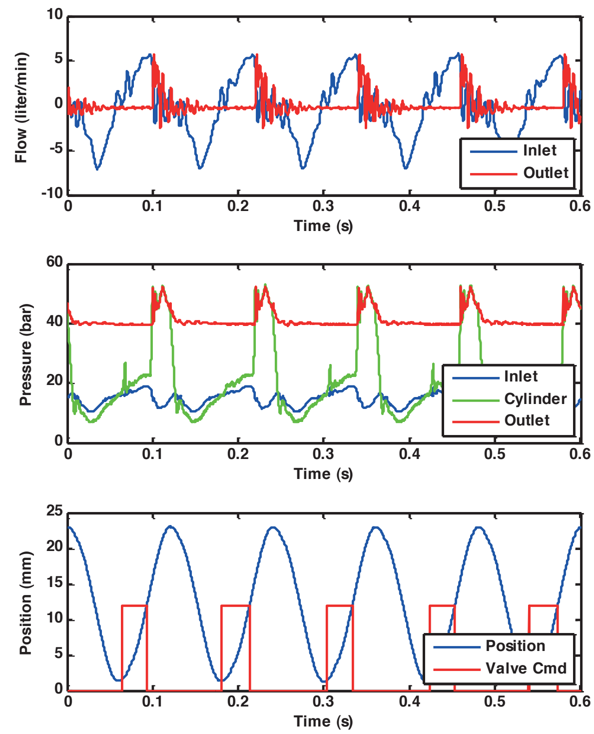

Figure 4: Flow-diverting, ~50% displacement

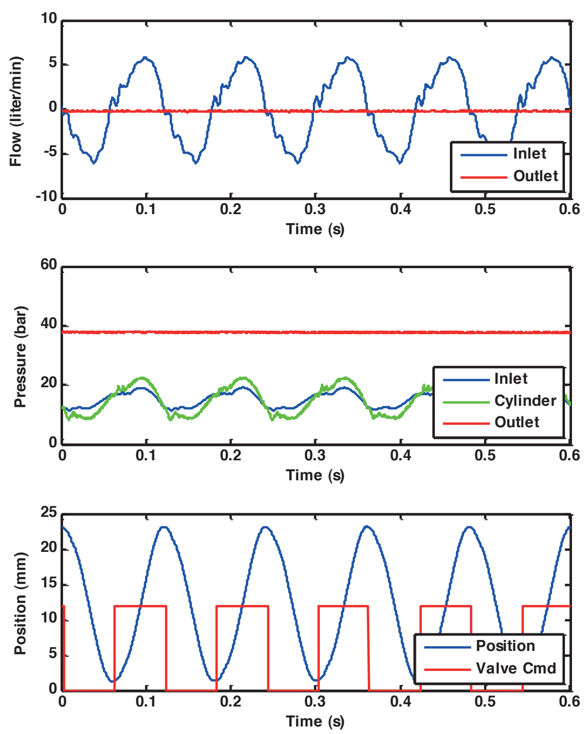

Figure 5: Flow-diverting, 0% displacement (idled)

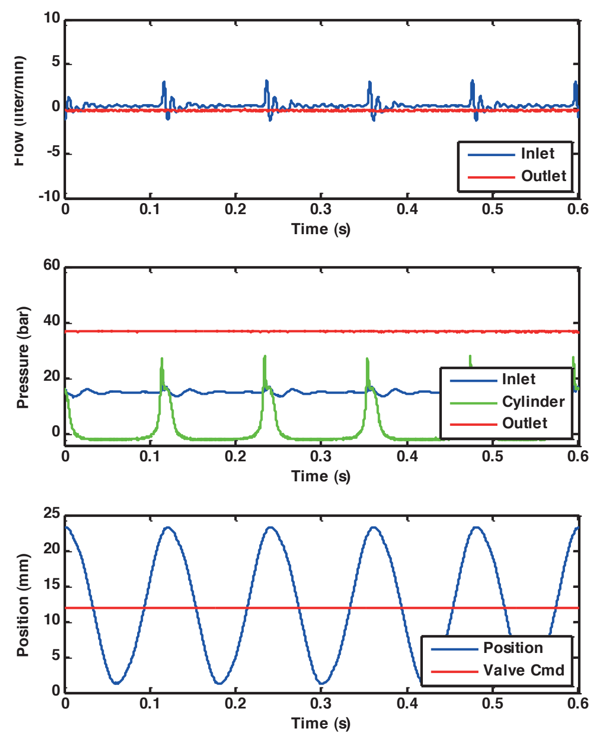

Figure 6: Flow-limited, ~0% displacement (idled)

The future work for Project 1E.3 includes further simulation and optimization for multi-chamber pump/motors and expanded experimental validation in the laboratory. With a 7 piston pump/motor model completed and initial single piston pump/motor experimental testing completed, the focus will be on utilizing the model for control strategies studies and optimization, and an expanded focus on validating these experimentally, along with the effect of operating strategies on efficiency and noise. Also, the one piston test rig will help in developing the proper valve timing for the different methods of achieving partial displacements.

Finally, a multi-piston digital pump/motor will be designed, built and tested during the next project year. The results from the current single piston pump/motor test stand will be used during the design of the multi-piston pump/motor. Once a multi-piston pump/motor has been built, implementation on test bed 1 (Excavator) and/or test bed 3 (Hydraulic Hybrid Vehicle) will commence. This will showcase the system efficiency improvements that a high efficient, high bandwidth pump/motor component would contribute.

C. Member company benefits

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

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

Research Team

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Industrial Partner: Sauer-Danfoss

1. Statement of Project Goals

The goal of this project, which was initiated in summer 2010, 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 initial phase consists of synthesizing a check ball pump which achieves piston-by-piston displacement control using a single rotary valve for all pistons, rather than two solenoid valves for each piston. The variable check valve pump will be based on a fixed displacement design supplied by an industrial partner. The second phase of the project will be to extend the concept to create a digital displacement pump/motor.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

Typical hydraulic variable displacement pumps and motors cannot be operated efficiently across the full displacement range, especially when the displacement is small. This dramatic loss of efficiency is a significant barrier to the creation of efficient hydraulic systems. This barrier is particularly evident in the case of hydraulic hybrid passenger vehicles [Test bed 3].

This project focuses on piston type pumps. In axial piston pumps, a significant amount of energy is lost through the three lubricating gaps: at the port plate, around the piston, and at the slipper/swash interface, as shown in Figure 1 [1]. Bent axis designs eliminate the slipper/swash gap, but they still lose energy through the port plate and around the piston. The losses do not decrease as the displacement decreases, which degrades the efficiency at low displacements. In addition, changing the displacement typically requires the displacement control actuator to work against the system working pressure, which demands high power to achieve reasonable control bandwidth. Displacement variation methods tend to be large, complex, and expensive.

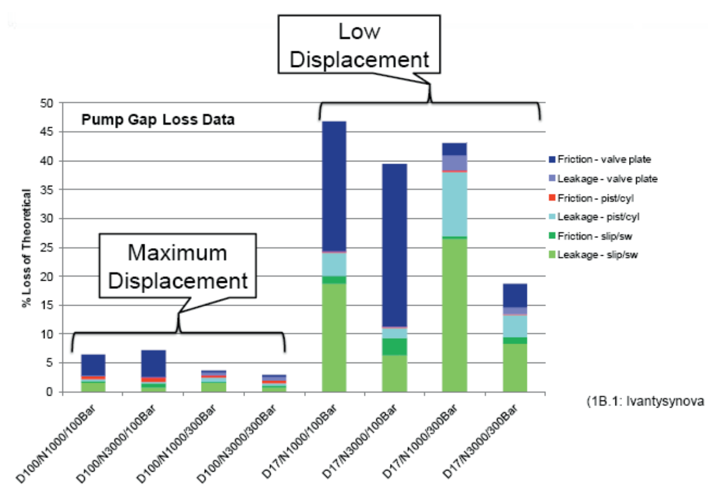

Figure 1: Losses in the lubricating gaps of an axial piston pump (from [1]).

Many different methods have been proposed to improve the efficiency of piston type pumps and motors. The state-of-the-art ones include “check valve” pumps and “digital displacement” pump/motors.

Check valve pumps are a variant of axial piston pumps. They drastically reduce operational losses by eliminating the port plate and a leakage path at the slipper/swash plate interface. These pumps are typically fixed displacement.

Variable displacement check valve pumps do exist (see [3]). These pumps vary the displacement by disabling each piston for a part of the pumping stroke, causing the piston losses to remain constant with displacement. The mechanism for varying the pump displacement in [3] requires a significant amount of force and does not appear to be designed for online adjustment. The check valve concept cannot be extended to motors.

Digital displacement pumps displace each piston through its full stroke over every cycle but apply high pressure to the piston over only a portion of its cycle. Digital displacement pumps vary the displacement through the use of active latching check valves driven by electromagnetic actuators [4]. By deactivating entire pistons, the leakage losses associated with the inactive pistons are completely eliminated. Thus, a portion of the loss will scale down with the displacement. If a slipper/swash plate is used, its leakage will scale down with displacement, as will the friction at the slipper/swash plate interface. Since check valves are also used in this design, the losses associated with a valve plate are eliminated. They are particularly effective at raising the efficiency at low displacements.

While digital displacement pumps have high efficiency, they do exhibit a number of restrictions. The use of latching check valves requires that flow only pass through the pump/motor in one direction. Thus it cannot be a 4-quadrant device without the use of an additional valve. Second, the active check valve approach prohibits self-starting of the unit in motor mode, since the check valve cannot open against high pressure. This creates the need for yet another valve. In addition to the required external valves, each piston requires two actively controlled valves, leading to larger size, higher cost, and more complex control circuitry. Solenoid valves are typically used. Operating solenoid valves repeatability is challenging due to the variation on valve delay and the nonlinear effects associated with electro-magnetic operation. An additional feature of piston-by-piston control is the creation of a larger flow ripple resulting from the deactivated pistons.

The CCEFP has a project devoted to addressing some of the short comings of the digital displacement design in Project 1E.3. The focus of that project is to replace the active check valves with active two or three-way valves to avoid the problems with flow direction and motor self-starting. In addition, this approach provides the flexibility to use either piston-by-piston or partial-stroke variation.

While the approach of 1E.3 is attractive for some applications, it has restrictions for others. The design of the active valves must be done to ensure fast transition time, large flow area, and low actuation power. Without some form of energy recapture, these 3 goals cannot be improved simultaneously. As the speed increases, the power required to accelerate the valve spool increases at a cubic rate. Increasing the flow area also tends to increase the transition time. In addition, the timing of the valves must be repeatable for efficient control of the pump/motor. The use of 2 high-speed active valves (or 1 closed-center 3-way valve) and the associated circuitry per piston may significantly increase the cost, size and reliability of the pump/motor.

This project investigates an alternative for achieving piston-by-piston control using a single valve having a unique two degree of freedom rotary design. The approach developed in this project is to combine the efficient check valve pump concept with a two degree-of-freedom rotary valve to achieve efficient pump/motor control. The active valves are eliminated in the proposed design. The valving is instead realized mechanically by applying an on/off rotary valve concept. This concept was initially developed in CCEFP project 1E.1 (see [5], [6]), where a high-speed rotary on/off valve was created for pulse width modulation of hydraulic flows. The valve is not used for pulse width modulation in this application. Rather, the valve is used to encode the high-speed on/off action into the rotary motion, while the timing of the on/off switch is adjusted by changing the axial position of the valve. Through this separation, the repeated, high speed switching is accomplished through continuous rotary motion without any acceleration or deceleration. The lower bandwidth timing control is achieved using linear motion.

Adapting the rotary valve concept into this project will allow piston-by-piston control to be achieved with less space, cost, and complexity than that required by available designs. In addition, the rotary actuation for the on/off valve can be provided by the pump/motor itself, ensuring precise timing of the on/off valve with respect to the pump/motor rotation. In this way, the piston type pump/motor can potentially be efficient, compact, and cost effective.

The variable displacement check valve pump concept is similar to that used in Reference [4], but our design utilizes piston-by-piston variation rather than partial-stroke variation. Each piston can be fully activated (connected to load through a check valve), disabled (connected to tank), or partially activated (fast switching between open and close of the port connected to tank). If every piston is operated in either fully activated or fully disabled mode, the variation of the displacement will be discrete. A continuous displacement variation is achieved by partially activating only one of the available pistons.

This project begins by constructing a model to predict system efficiency and dynamic response. The focus of the research will be on the development of the valving strategies to facilitate piston-by-piston control of pumps and motors. An experimental prototype of a variable check-ball pump will be constructed and demonstrated in the first phase. The design will be extended into a variable displacement pump motor in the second phrase.

B. Achievements

The initial phase of this project is aimed at demonstrating the feasibility of using piston-by-piston displacement variation for improving pump/motor efficiency. The approach in progress is to model individual sources of energy loss and how they scale with the displacement. The goal is to show that the mechanism of disabling pistons has an advantage over the current approach of varying the stroke length. The losses that are under investigation for the piston by piston approach are: compressibility loss, transition loss in the disabling valve, piston friction, piston leakage, viscous pipe loss, and valve actuation power and leakage. Some of these losses will be unique to the piston by piston approach, such as the transition loss, some viscous pipe loss, and the valve actuation and leakage. The intent is to show that a system can be designed in which these losses are less than the losses contributed by the valve plate and slipper/swash plate interface.

An example of the loss determination is shown in Figure 2, which shows the slipper bearing friction for a variety of piston dead volumes. The excess dead volume contributes additional force to the swash plate on the intake stroke as the high pressure fluid decompresses. This is caused by the “ideal” timing produced by the check valves (as opposed to a valve plate). The additional friction contribution is minimal compared to the benefit of eliminating the compressibility loss from the system (pump case only).

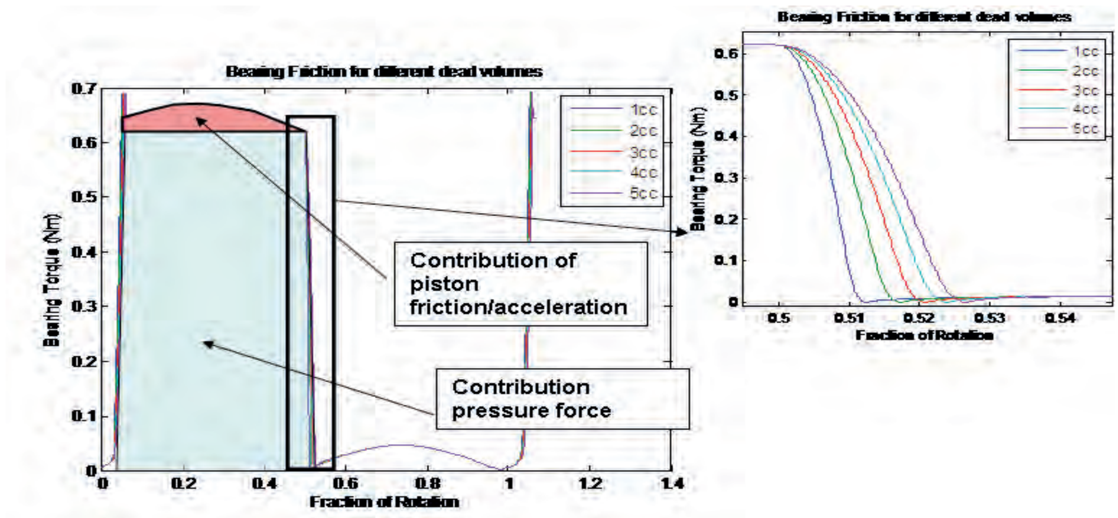

Figure 2: Slipper bearing friction showing the contribution of compressed energy stored in the piston dead volume

An example of a piston by piston only loss is shown in Figure 2, which shows the loss associated with throttling through the transitioning discharge valve for different transition times and fraction of the stroke disabled. For a fast transitioning valve, this loss may be insignificant, but that must be contrasted with the power required to achieve the fast transition. Another question raised by the transition loss is whether it will be experienced by all pistons, or only one piston per rotation. This depends on the disabling strategy employed.

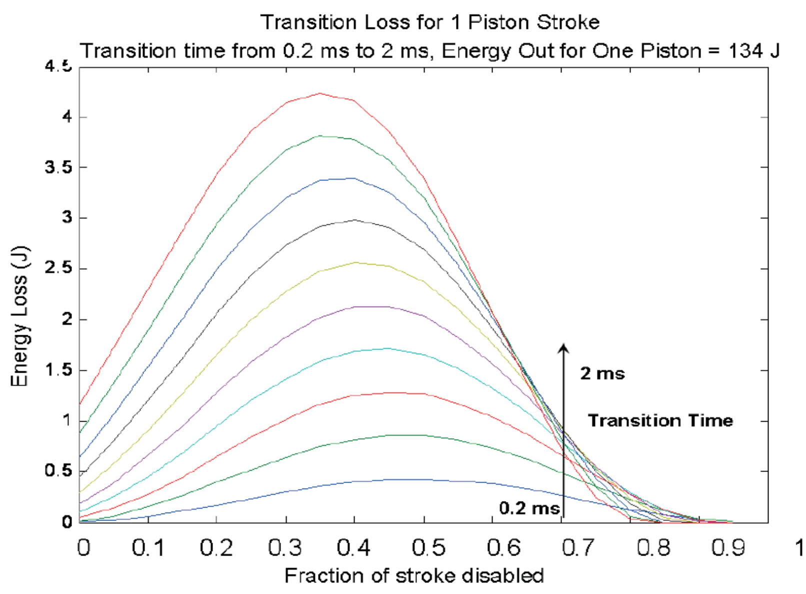

Figure 3: Transition loss through the disabling valve for transition times varying from 0.2 ms to 2 ms

Individual pistons can be disabled in two different ways: different numbers of whole pistons can be disabled for a full rotation, or all of the pistons can be disabled for a variable fraction of the rotation. While the first approach will reduce some losses, such as the transition loss and valve actuation power (since there are fewer valve switches), the second approach will provide a smoother output flow. In addition to modeling the losses, this project is also looking at comparing the flow ripple for different disabling strategies. Figure 3 shows the magnitude of the kinematic flow ripple for different approaches. In this figure, the flow ripple from an ideal variable displacement pump (VDP) is compared to a piston by piston pump with whole pistons disabled in sequential order (Whole Sequential), all pistons disabled for part of the stroke (Partial), whole pistons disabled in a cross-pump pattern (Whole Non-seq.), and an ideal on/off valve applied to the full pump output. It can be seen that, while the partial stroke disabling does produce a smaller flow ripple than the whole piston approach, the difference is not too great when a non-sequential pattern is used.

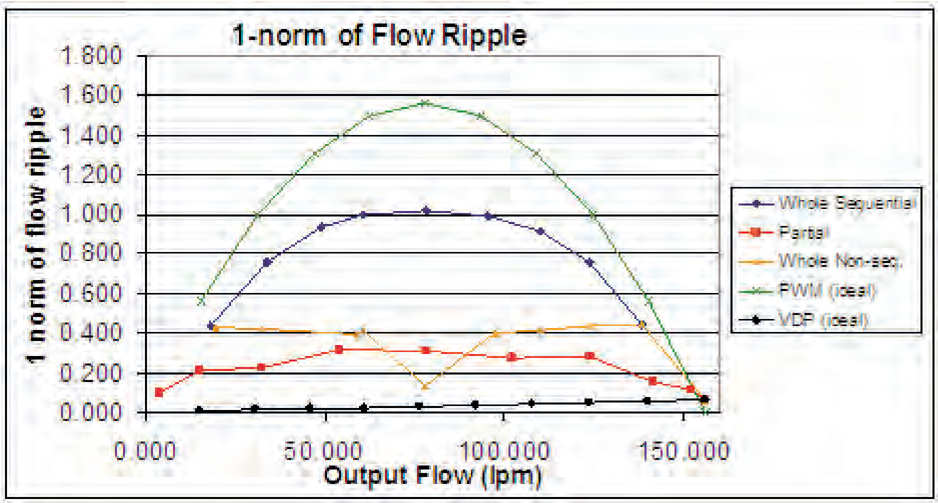

Figure 4: Magnitude of the flow ripple for different piston disabling strategies

These are a few examples of the initial modeling work that is still in progress. Concurrently, the team is working on designs for the valving strategy that will be used to accomplish piston by piston control. The valve structure will be based around the rotary on/off valve that has been under development in Project 1E.1, which provides fast switching that is timed with the valve rotation. By coupling this to the pump shaft, repeatable timing can be achieved. The current design work revolved around the transfer of the on/off signal from the rotary valve to the pump pistons. The approaches being considered are: direct on/off, pilot valves, 3-dimensional cams. The direct on/off approach will use the rotary valve to directly enable/disable the pistons this has the advantage of simplicity and low actuation power, but it will likely lead to significant leakage through the valve. To avoid leakage, pilot driven poppet valves can be used which increase the complexity and require a pilot pressure source, but allow for the use of poppet valves to eliminate high pressure leakage. A third approach is to us a rotary driven cam to disable individual pistons, but this will require a 3D cam, which often presents wear problems resulting from point contacts.

Expected Milestones and Deliverables

The loss analysis and the feasibility evaluation of the proposed piston-by-piston variable displacement pump/motor will be finished by the end of February 2011. A piston disabling strategy will be accomplished by the end of March 2011. A complete design of the variable displacement pump will be delivered by the end of April 2011. A pump prototype will be available for testing in May 2011. The mechanism of varying the displacement of a pump/motor will be finalized by the end of year 2011, with a complete design of the pump/motor prototype. The prototype will be available for testing by the end of March 2012, and the testing will be finished by the end of May 2012. The pump/motor will be integrated with Test bed 3, and be demonstrated on the HHPV by the end of August 2012.

C. Member company benefits

Development of new digital displacement control strategies, creation of new high efficiency pump/motor architecture, expansion of modeling methods to digital hydraulics.

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

Research Team

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Industrial Partner(s):	Afton Chemical, Eaton, ExxonMobil, Parker Hannifin, Poclain Hydraulics, RohMax USA, Sauer-Danfoss, Shell Oil

1. Statement of Project Goals

The research objective of this project is to improve hydraulic fluid power efficiency by systematically investigating tribofilm structure and chemistry in hydraulic motors.

2. Project Role in Support of Strategic Plan

This project will increase the efficiency and energy density of hydraulic fluid power systems by identifying how tribofilm structure and chemistry affect starting torque and low-speed friction in hydraulic motors. Understanding this relationship will make possible the formulation of hydraulic fluids that improve motor efficiency. This has strategic importance within the CCEFP because low-speed motor efficiency often determines the minimum displacement (size) and operating pressure of mobile hydraulic equipment. The findings will be combined with the piezoviscosity research of Bair and static friction research of Martini to improve efficiency in both the hydraulic hybrid passenger vehicle and excavator test beds.

3. Project Description

A. Description and explanation of research approach

This project targets hydraulic motor efficiency by investigating the fluid properties that influence friction and tribofilm formation. In previous research we determined that boundary friction, thin-film traction, pressure-viscosity and thermochemical fluid properties influence hydraulic motor efficiency under low-speed, high-torque (LSHT) conditions.(1) Boundary friction coefficient, as measured in a High Frequency Reciprocating Rig (HFRR), was found to correlate with motor efficiency through a broad range of motors and temperature conditions.(2,3) In this next phase of research, we will compare the tribochemical films formed in a reciprocating tribometer to those formed in hydraulic motors. It is hypothesized that similarities in tribofilm structure and chemistry account for the apparent correlation between motor efficiency and HFRR boundary friction measurements.

Translating HFRR boundary friction measurements to full scale equipment is a challenge. Boundary friction is affected by many factors including load, entrainment velocity, surface topography, metallurgy, and lubricant chemistry. Even with these parameters defined, it is difficult to replicate real tribological contacts in a benchtop tribometer due to local contact geometries, temperatures and time dependencies.(4) Characterizing tribofilm structure and chemistry presents its own set of challenges. Table 1shows that boundary lubrication film thickness varies from tens to hundreds of nanometers. These features are not only smaller than normal design tolerances; they push the detection limit of procedures such as Energy Dispersive Spectroscopy and Fourier Transfer Infrared Spectroscopy.

Feature size	Type of interface	Reference
2 nm (20 Å)	Langmuir-Blodgett monolayer films produced by vapor deposition	(5)
5 to 10 nm	Analysis depth of XPS at a 0.05 to 1 atomic % detection limit	(6)
15 nm	Sulfur-phosphorus antiwear films formed by ashless lubricants	(7)
100 to 300 nm	Zinc dialkyldithiophosphate films formed by engine oils	(7)
100 to 300 nm	Thickness of wear particles produced in Geroler	(8)
500 nm	Interaction volume in EDS under low-voltage conditions	(9)
20 μm	Cylinder bore wear in radial piston motor after 1100 hr. test	(10)

Table 1: Dimensions of tribological features

Parker Hannifin, Poclain Hydraulics and Sauer-Danfoss supplied orbital (geroler), cam-lobe, and bent axis motors for our research project. Two motors of each type were provided, along with extra rotor sets, vanes, and pistons. The efficiency of each motor will be determined in MSOE's hydraulic motor dynamometer. After efficiency testing, one of the motors of each type will be disassembled. The surface topography and tribofilm chemistry of rotors, vanes and pistons from the motors will be evaluated via mechanical profilometry, Scanning Electron Microscopy and Energy-Dispersive Spectroscopy (SEM/EDS). Initially two simple zinc-containing hydraulic fluids will be evaluated. These fluids were selected because zinc dialkyldithiophosphate (ZDDP) produces a relatively thick tribochemical film. (7) It is hoped that a thicker film will facilitate our efforts to locate the areas where tribochemistry is occurring. Film structure and composition will be compared to those produced by ZDDP in the High Frequency Reciprocating Rig. If we are able to locate ZDDP tribofilms in the motors, we will repeat this testing with a friction modified ZDDP formulation. The conventional wisdom is that friction modifiers reduce friction by forming Langmuir-Blodgett monolayer films. Recent investigations indicate that friction modifiers work synergistically with ZDDP to produce low-friction tribofilms that are thinner than those produced by pure ZDDP, but not monolayers. Understanding the nature of the tribofilm in motors is key to reducing friction.

B. Achievements

Summary: The boundary friction, mixed-film lubrication, thermophysical, and pressure-viscosity properties of prototype fluids were characterized. These hydraulic fluids were evaluated in geroler, axial piston, and radial piston motors under low-speed and starting conditions in accordance with the ISO 4329-1 and ISO 4392-2 standard test methods. Correlations between motor efficiency and fluid boundary friction, traction, thermophysical and pressure-viscosity coefficients were identified. The relative impact of these fluid properties was found to vary with motor design. The results indicate that fluid boundary friction, pressure-viscosity, and thermal conductivity properties have a profound effect upon hydraulic motor efficiency.

Test Fluids: Five ISO VG 46 hydraulic fluids have been evaluated. These fluids incorporated the same sulfur-phosphorus antiwear chemistry but differ in base stock and additive composition as shown in **Table 2**. The HM46 straight-grade hydraulic fluid was formulated with solvent-refined (Group I) mineral oil base stocks. The HV46 multigrade hydraulic fluids were formulated with catalytically-refined (Group III) base stocks and a polymethacrylate (PMA) Viscosity Index (VI) improver. HV46-2 differed from HV46-1 in that it one fifth of the VI improver had been replaced by functionalized block-polymer PMA chemistry. The HV46-3 formulation was similar to HV46-1 but contained the friction modifier glycerol monooleate (GMO). Trimethylol propane (TMP) trioleate base stock was used in the HEES46 formulation. All blends, with the exception of the HM46, were formulated to a nominal 200 VI.

ID	Base oil	Description	VI	HFRR Friction Coef. 50C	P-V Coef. α * GPa^{-1} 50C	Thermal Cond. mW/cm/K
HM 46	Group I MO	Typical straight-grade hydraulic oil	104	0.115	18.1	1.340
HV46-1	Group III MO	High VI oil w/ PMA viscosity modifier	191	0.108	15.9	1.440
HV46-2	Group III MO	High VI oil w/ novel polymer chemistry	188	0.106	16.2	1.440
HV46-3	Group III MO	High VI oil w/ GMO Friction modifier	190	0.100	16.0	1.445
HEES46	Biodegradable synthetic ester	TMP Trioleate	239	0.085	12.2	1.640

Table 2: Test fluid descriptions and fluid coefficients measured at 50C

Working in collaboration with A. Martini of Purdue (Project 1B2), S. Bair of Georgia Tech (Project 3D2), and M. Devlin of Afton Chemical (industrial collaborator), the static friction, pressure-viscosity, boundary friction, thin-film traction and thermochemical properties of hydraulic fluids were characterized. Static friction coefficients were determined at Purdue using the experimental test rig developed by Martini and Garcia. Low-shear viscosities (μ) were measured using a high-pressure falling body viscometer designed by Bair of Georgia Tech. Pressure-viscosity coefficients (α), were determined from measurements at pressure, p, of 0.1, 25, 50 100 150 250 and 350 MPa. Boundary lubrication regime friction coefficients were measured using a PCS Instruments High Frequency Reciprocating Rig (HFRR), mixed-lubrication regime traction coefficients were measured using a PCS Instruments Mini-Traction Machine (MTM) and thermal conductivity tests were performed using the heated probe method per ASTM D-5334. (Some of these results are included in Table 1.)

Geroler, axial, and radial piston motors were used in the efficiency studies. Specifications for the motors are provided in **Table 3**. Motors were subjected to manufacturer specified break-in conditions prior to testing. Startability and LSHTtests were performed in a hydraulic dynamometer per ISO 4392-1 and ISO 4392-2 methods. The hydraulic circuit schematic is shown in Figure 1.

Motor	**Size (cc)**	**Speed Rating (rpm)**	**Pressure Rating (psi)**
Axial Piston	100	3300	6000
Geroler	325	440	4500
Radial Piston	190	410	6525

Table 3: Description of Test Motors

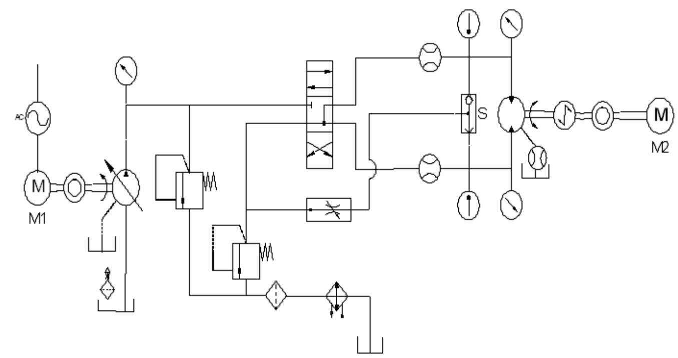

Figure 1: Circuit Diagram for Motor Tests

The minimum starting efficiency for each fluid-motor combination is shown in Figures 2 and 3. The starting efficiency of the Geroler and Axial Piston motors benefited from an increase in VI. All of the high VI (HV) fluids were more efficient than the 100 VI (HM) fluid. The biodegradable synthetic ester (HEES) was more efficient than the mineral oils. In the radial piston motor, HEES46 alone improved starting efficiency over baseline.

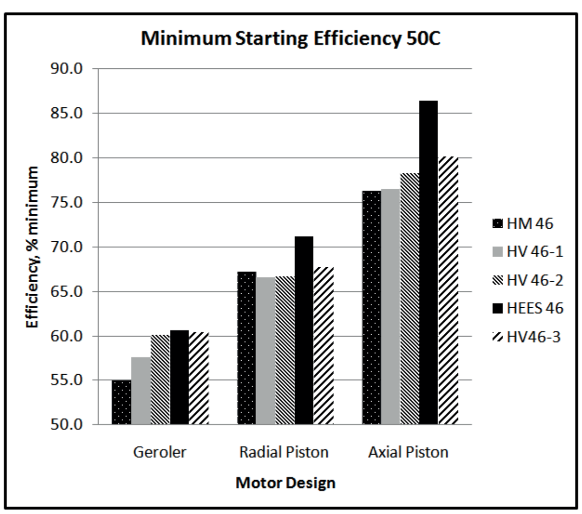

Figure 2: Minimum starting efficiency, 50°C

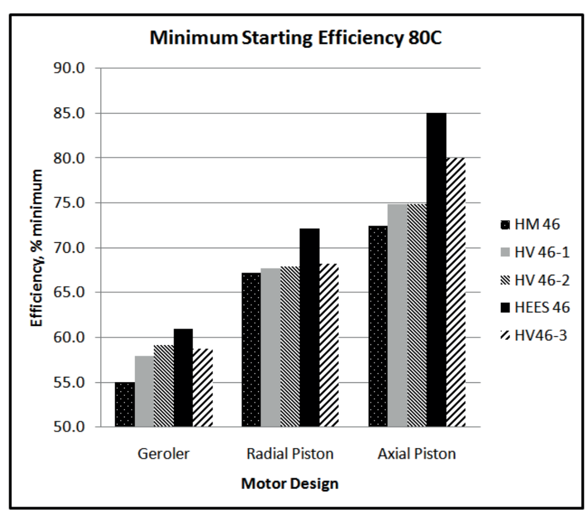

Figure 3: Minimum starting efficiency, 80°C

- *Geroler, Improvement over baseline – 11%*

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

Correlations:
Linear correlation coefficients (r) for startability and fluid properties were determined.(3) These correlation coefficients are shown in Table 4. The fluid properties that show a high degree of correlation with motor efficiency are emphasized in bold type. The r values for boundary friction and pressure-viscosity are negative, since a reduction in friction and pressure-viscosity coefficients results in improved efficiency.

	Boundary Friction, HFRR	Pressure Viscosity, α*	Kinematic Viscosity	Specific Heat	Thermal Conductivity
Geroler 50C	-0.78	-0.80	0.76	0.13	0.70
Geroler 80C	-0.60	-0.90	0.77	0.04	0.90
Radial 50C	-0.89	-0.86	-0.13	0.61	0.86
Radial 80C	-0.91	-0.96	0.26	-0.49	0.96
Axial 50C	-0.98	-0.94	0.14	-0.46	0.93
Axial 80C	-0.92	-0.98	0.42	-0.24	0.90

Table 4: Correlation coefficient (r) for startability and selected fluid properties

These results reveal that starting efficiency in the above hydraulic motors is related to the boundary friction coefficient (a function of both fluid and surfaces) and certain fluid material properties. Specifically, startability improves with decreasing boundary friction coefficient, decreasing pressure-viscosity coefficient, and increasing thermal conductivity. The effects are more significant at higher temperatures. This is understandable from a mechanical standpoint; higher temperatures reduce fluid film thickness. In terms of surface chemistry, higher temperatures also increase the energy of molecular collisions, thus accelerating tribochemical reactions.

Although we have just begun to probe the mechanisms underlying these relationships, we anticipate that they will be complex given the variety of contacts in hydraulic motors. During start-up, motors are likely to contain contacts experiencing all regimes of lubrication, from hydrostatic to boundary. It is hypothesized that improved boundary film formation in several key tribological contacts can increase motor efficiency. It is in the areas listed in **Table 5**, that the Tribofilm Structure and Chemistry will be investigated.

Geroler	Radial Piston	Axial Piston
Stator – Vane	Cam – Roller	Piston Shoe – Swash Plate
Vane – Geroler Star	Piston – Cylinder Bore	Piston – Cylinder Bore
Geroler Star – Valve Plate	Cylinder Block – Valve Plate	Cylinder Block – Valve Plate

Table 5: Tribological pairs in hydraulic motors

Plans for Next Year
Task 1: Characterization of pistons and vanes from hydraulic motors
- Piston and vane dimensions, weight, surface profile
- Initial SEM/EDX analysis of pistons and vanes

Task 2: Characterization of prototype hydraulic fluids
- SEM/EDX analysis of tribofilms from HFRR
- High pressure rheology – Scott Bair, Georgia Tech
- Static friction coefficients – Martini, Purdue

Task 3: Dynamometer testing of fluids
- Testing of prototype fluid efficiency in LSHT and startability tests
- SEM/EDX analysis of surface composition

Task 4: Evaluation static friction model

- Installation of modified pistons and vanes in motors
- Evaluation of motor starting and LSHT efficiency
- Validation of static friction model

B. Member company benefits

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

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1G.2: Nano-Additives to Improve Pumping Capacity

Research Team

Project Leader:	Prof. Eric Loth, Aerospace Engineering, University of Illinois
Post Doc:	Dr. Ilker Bayer
Graduate Students:	Adam Steele, Ph.D. and Phil Martorana, M.S.
Industrial Partners:	Caterpillar, John Deere, DeGussa, Eaton, Sauer Danfoss, Shell

1. Statement of Project Goals

The objective of the pump research with nanotexturing is to improve lubrication inside fluid power machinery using nano-textured coatings. This is motivated by the growing field of lubrication with nano-structured solid films. If this is successful, both fluid line and pump efficiency may be enhanced. An important and growing field of lubrication lies in the use of nano-structured solid films instead of oils or greases due to the films' superior mechanical properties and environmental benefits.

2. Project's Role in Support of the Strategic Plan

This project directly supports the efficiency thrust. It supports the strategic plan by increasing the fundamental understanding of nano-additives in the context of oils, the critical fluid for hydraulic fluid power. Furthermore, the additives are planned to be used in the excavator and HHPV test beds to improve overall system performance.

3. Project Description

A. Description and explanation of research approach

Improving the efficiency of liquid pumps is an area of continually increasing importance in the fluid power industry. The overall efficiency of a pump is a combination of two components: the volumetric efficiency and the torque (or mechanical) efficiency (Figure1). Mechanical efficiency is a measure of the power lost due to fluid shear and internal friction, while the volumetric efficiency is a measure of the power lost due to fluid compressibility and internal leakage. These definitions show that the physicochemical state of the fluid running through a pump is just as important to the efficiency as the physical design of the pump.

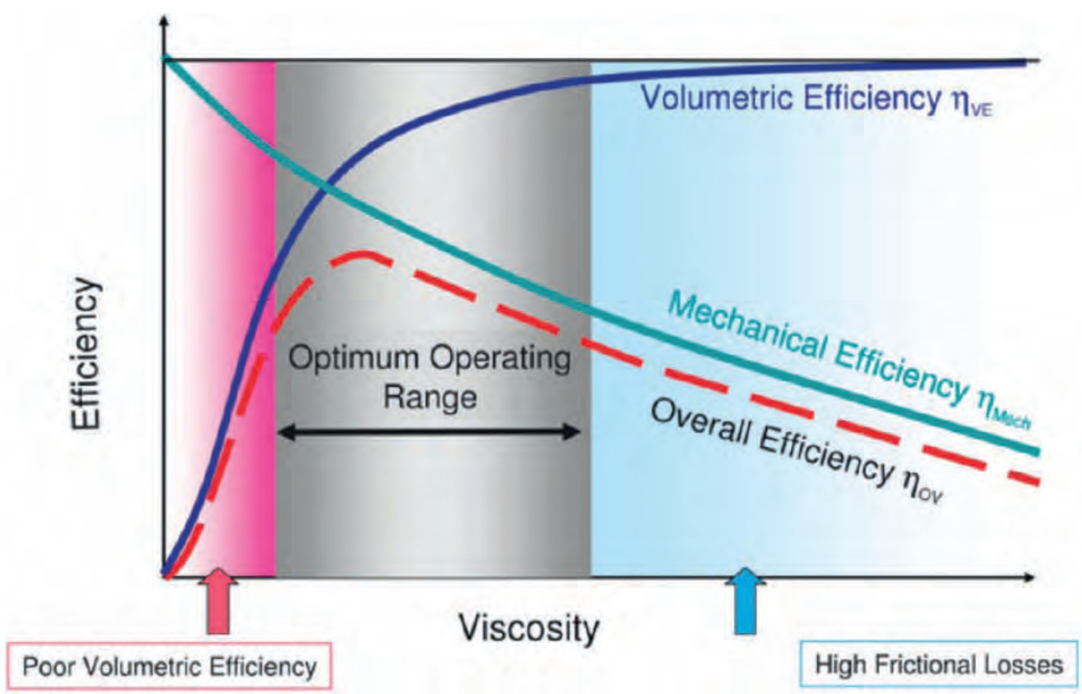

Figure 1: Typical efficiency regimes of a hydraulic pump

The objective of the study is to investigate the effects of micro-/nanoscale carbon-based additives in a closed hydraulic loop. In particular, the effects of different additive concentrations on external gear pump performance are examined. The additives were used as colloidal suspensions in ethanol with the help of dispersants. Comparisons are presented on the basis of the measured power consumption, measured volumetric flow rates, and calculated overall efficiencies at different concentrations of solid additives (including a baseline case with no additives in the closed hydraulic loop). Possible postrun structural changes in the additives were qualitatively analyzed using pre- and postrun ESEM images of the additives isolated from the colloidal suspensions. Pump inlet and discharge pressures, volumetric flow rate, and power consumption data were recorded as different concentrations of the colloidal suspensions were run through the system. As a baseline without additives, ethanol (dynamic viscosity of 0.9 cP) and mineral oil (dynamic viscosity of 4.5 cP) were chosen as the test fluids, and the results were compared to those of Bielmeier et al.

B. Achievements

We show that fine graphite flake and carbon nanofiber dispersed ethanol solutions can potentially replace conventional hydraulic fluids in gear pump-driven hydraulic circuits operating below 1 MPa gauge pressure. Low-viscosity hydraulic fluids are generally detrimental to pump life. However, both graphite and carbon nanofiber dispersions in ethanol within a concentration range of 195-1500 ppm can sustain hydraulic circuits with increases in pump efficiency and without modifying the viscosity of ethanol. Pump inlet pressure, volumetric flow rate, and electric power consumption data were recorded over a range of pump discharge pressures. Pump power consumption at a given differential pump pressure was found to remain approximately constant for all suspensions. However, increases in both volumetric flow rate and overall pump efficiency were observed when pure ethanol was replaced by the nanostructured carbon/ethanol solutions. To the authors' knowledge, this is the first study to show that nanostructured carbon additives can increase volumetric efficiency without significantly increasing the viscosity of the working fluid, ethanol. Higher concentrations (>400 ppm) of the additives produced more profound positive effects than the lower concentrations (Figure 2). Additionally, we observed that the additives deposited permanently on gear and enclosure surfaces creating low shear strength films which can help reduce friction. Qualitative examination of environmental scanning electron microscope images of colloidal graphite and carbon nanofiber additive morphology before and after extended run periods indicated that graphite retained significant resilience, whereas carbon nanofibers appear to have undergone some scission.

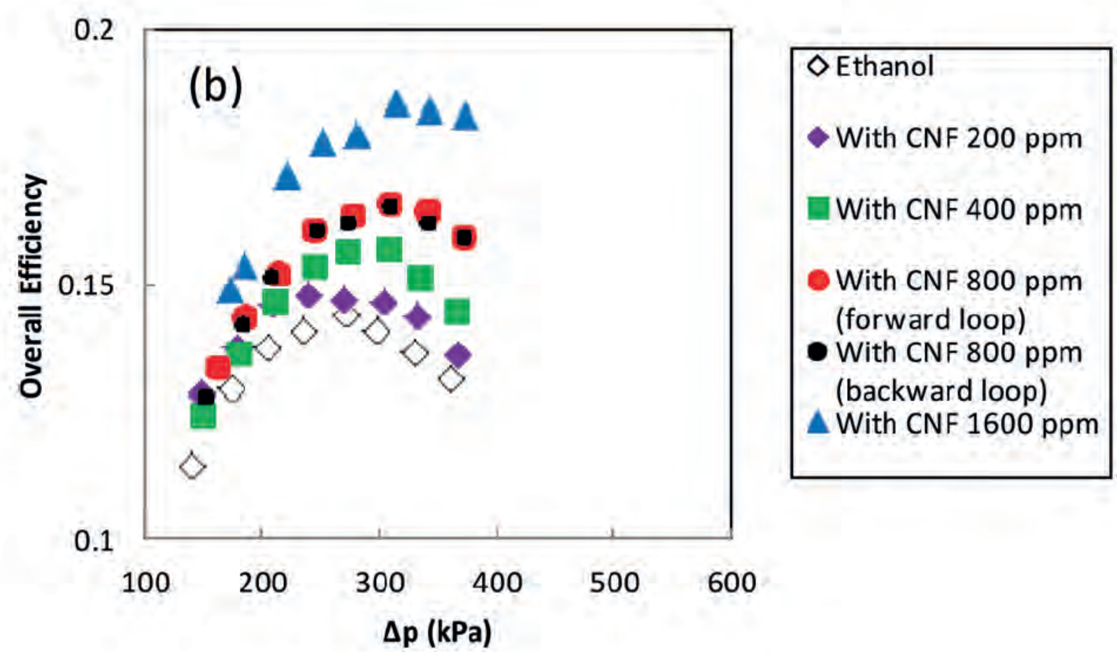

Figure 2: Effect of nanostructured carbon additive concentration on overall efficiency

C. Member company benefits

This project was advised by our industry partners through quarterly "nano-champs" meetings. This has led to several technical interactions. For example, Shell provided our group with hydraulic fluids with various carbon nano-tube dispersions.

D. References

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Project 2A: Chemofluidic Hot Gas Vane Motor

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

1. Statement of Project Goals

The goal of this project is to develop, demonstrate, and characterize the performance of a monopropellant-powered vane motor for use in high bandwidth actuation of a hydraulic pump. The first five years will primarily involve development of the motor, which is expected to deliver a continuous power in excess of 1000 W/kg (approximately a factor of five better than rare-Earth magnet brushless electric motors). The second five years will integrate the motor into a closed-loop-controlled throttle-less hydraulic actuator to provide compact hydraulic power for small-scale fluid-powered systems, such as compact robots.

2. Project Role in Support of Strategic Plan

One of the stated objectives of the Center is to develop compact (i.e., human-scale) fluid powered systems. Project 2A provides a means of efficiently powering and controlling human-scale fluid-powered systems. The chemofluidic hot gas vane motor is not subject to the quenching or scavenging problems found in a small-scale IC engine. In addition, unlike an IC engine, it can provide bidirectional, high-bandwidth motion and high torque at zero speed (rpm). As such, the motor can be used for throttle-less actuation, therefore bypassing the fluid heating and inefficiency problems that plague the systems mentioned above. Further, the liquid propellant that powers the proposed approach is not flammable, the motor can be easily started and stopped, has zero fuel consumption on idle, does not require air (i.e., can be used underwater or in space), and has completely safe reaction products (i.e., can be used indoors). The objective of project 2A is to develop, demonstrate, and energetically characterize a complete, closed-loop controlled, throttle-less actuation system in a human-scale robot (specifically in the compact rescue crawler test bed). If successful, project 2A will enable the use of high power density fluid-power actuators in human-scale robots, and thus will contribute directly to the fulfillment of the Center's vision.

3. Project Description

A. Description and explanation of research approach

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

B. Achievements

Several prototypes have been designed, fabricated, and tested since the start of the project. The most recent motor prototype was experimentally shown to provide a power density of approximately 800 W/kg. This compares favorably to a good, brushless electric motor which has a power density of approximately 160 W/kg. We have also recently begun characterizing the motor efficiency experimentally.

This project has been funded since June 2006. During this time, the investigators have developed multiple iterations of the vane motor. Three of the experimentally characterized prototypes are shown in Figures 1-3, and the performance data corresponding to these prototypes is given in Table 1. The project objectives for the motor power density and continuous torque were 1000 W/kg and 0.5 Nm, respectively, which were originally chosen to be five times better than state-of-the-art rare-earth magnet brushless DC motors. As indicated in Table 1, the vane motor prototype V2.6 (and V2.7) achieved of power density of over 800 W/kg and a maximum continuous torque output of 0.7 Nm (see Figure 4). The prototype achieved over 80%

of the power density target and the torque target was exceeded. As a result, the focus of the current investigation has moved from power density and torque to motor efficiency.

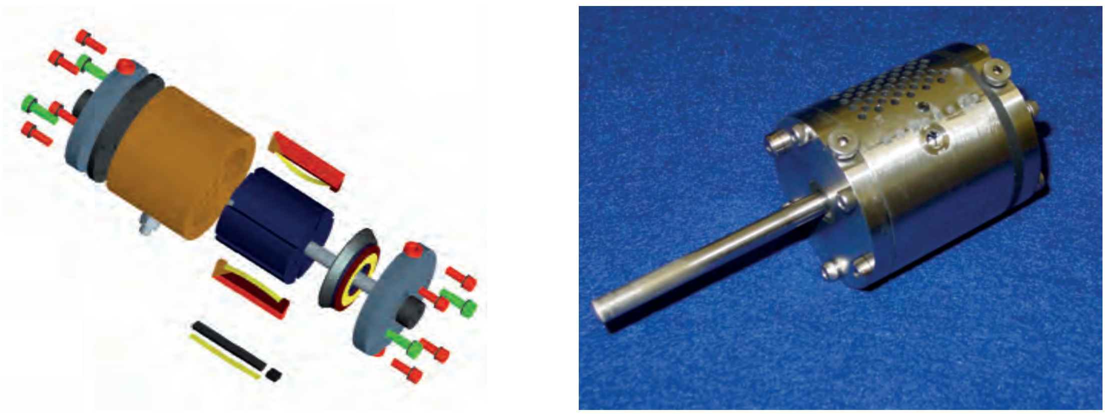

Figure 1: Version V1 vane motor prototype.

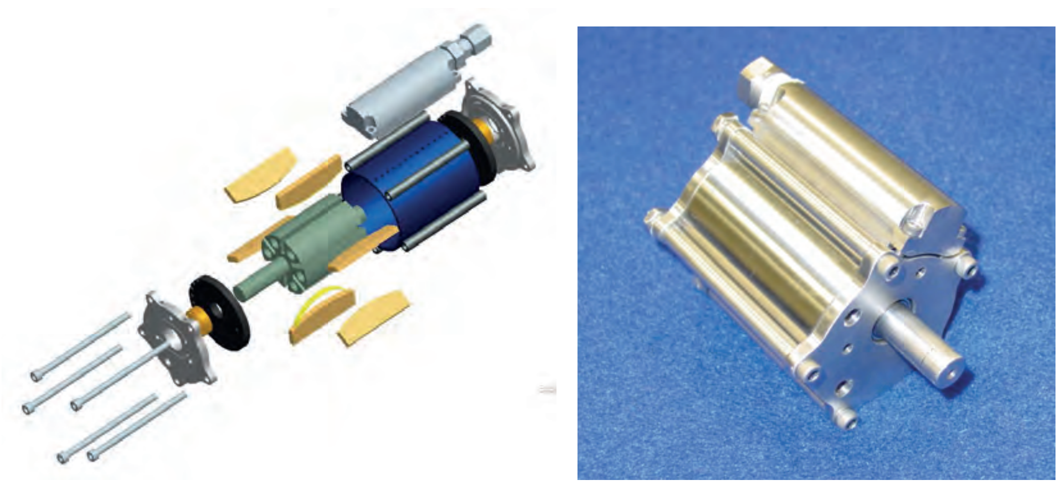

Figure 2: Version V2.1 vane motor prototype.

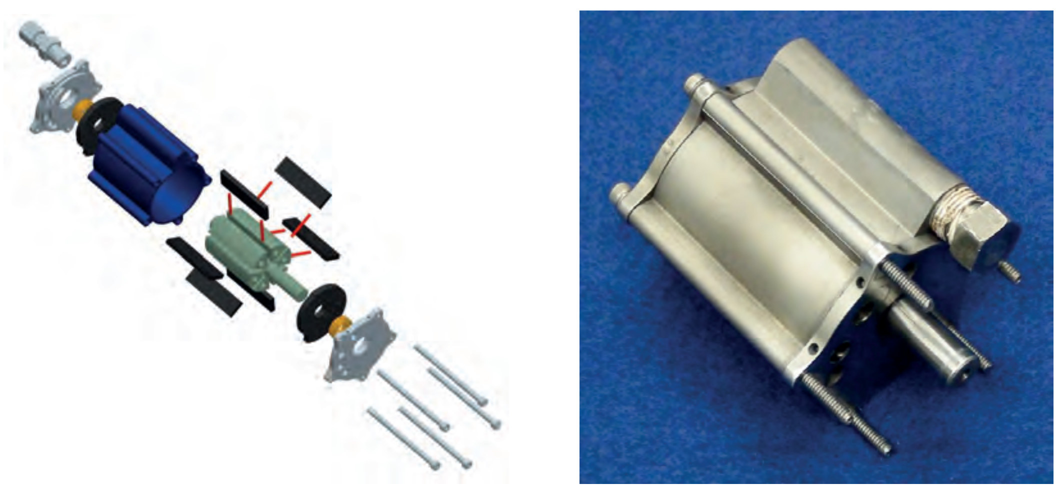

Figure 3: Version V2.7 vane motor prototype.

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

Table 1: Performance characteristics of vane motor prototypes.

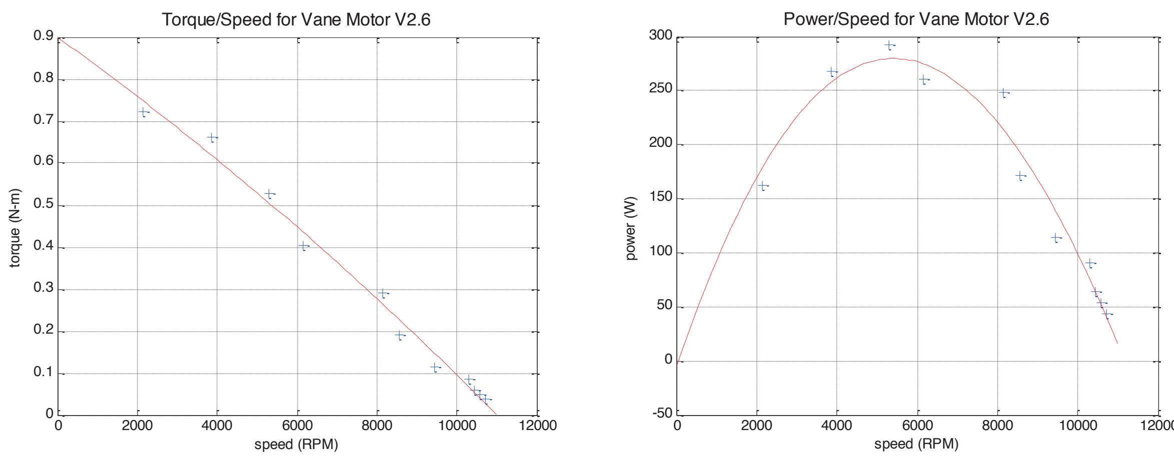

Figure 4: Torque and power curves for vane motor prototype V2.6.

Figure 5 shows the version V2.7 motor prototype on an efficiency test stand. For these experiments, thermocouples were placed on the catalyst pack, the motor body, and in the exhaust flow; the flow rate of the propellant was measured; the brake was controlled to maintain a constant speed; and the brake torque and shaft speed were recorded. Based on these measurements, the motor running with a 70% solution of hydrogen peroxide was shown to have an efficiency of 2.4% at steady-state operation, which is 32% of Carnot efficiency for the 70% peroxide solution. In order to achieve higher efficiency, the motor must be run with a higher percentage peroxide solution. An 80% concentration enables a significant gas expansion ratio prior to vapor condensation. The adiabatic decomposition temperature of 80% peroxide, however, is 920°F, compared with 450°F for 70% peroxide. Although efficiency measurements were attempted with 80% peroxide solution with the V2.7 motor prototype, the motor seized after approximately 30 seconds, due to thermal expansion of the rotor. A new version of the motor designed to operate with an 80% peroxide solution was designed and built and is shown in Figure 6.

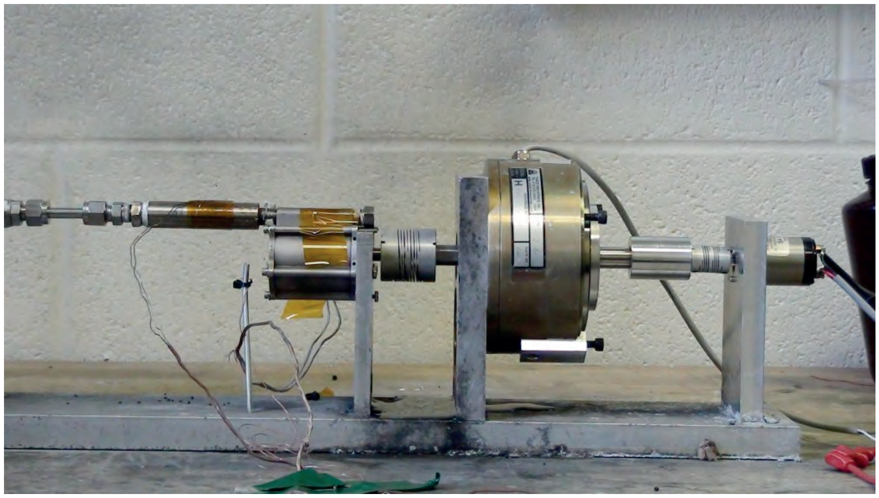

Figure 5: Version V2.7 vane motor on dynamometer test stand and instrumented for motor efficiency measurement.

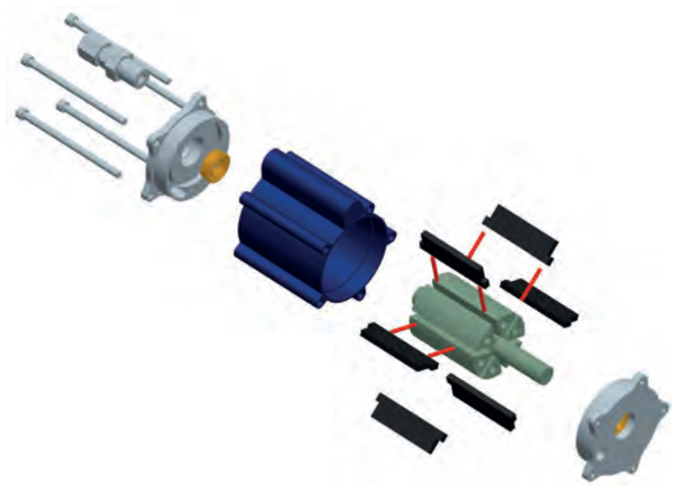

Figure 6. Version 2.8 of the vane motor (not yet fabricated), which was designed to accommodate 80% peroxide.

The objective of year 5 research has been to perform design revisions to the vane motor that enable continuous operation of the motor with 80% peroxide (i.e., adiabatic decomposition temperature of ~900°F), and to approach the 16% efficiency indicated by year 4 experiments with 70% peroxide. Thus far in year five we have developed three new versions of the motor relative to the fabricated version shown in last year's report (currently on V2.10, relative to V2.7 shown in the report). We have achieved run times of several minutes with the new versions, but we have not yet achieved continuous operation with 80% peroxide and this remains the objective of our current work. At the time of this writing, there are four more months remaining in year 5, during which we hope to achieve the state milestones of continuous operation with 80% peroxide with a measured efficiency of 16%.

Summary of research plans for the next two years

The research in years 5 and 6 consists of implementing a redesign of the motor prototype to accommodate 80% peroxide and testing the efficiency of energy conversion with the goal of achieving approximately 30% of Carnot efficiency, which is approximately 16% overall efficiency for an 80% peroxide solution. The motor design proposed for 80% peroxide is shown in Figure 6. All low-temperature materials have been eliminated from the motor, as are the face seals (which are present in the V2.7 motor shown in Figure 3), which were the source of seizing in the V2.7 trials with 80% peroxide.

Once this efficiency is achieved, the next focus of the work is to integrate the vane motor with a fixed displacement piston pump to produce hydraulic power. The integrated vane motor and piston pump design is shown in Figures 7-9. The investigators will characterize the hydraulic power characteristics, with the objective of achieving 100 W/kg hydraulic power density and 1000 psi pressure capability.

Finally, the investigators will initiate the integration of the vane motor hydraulic power supply with Test Bed 4 (the compact rescue crawler).

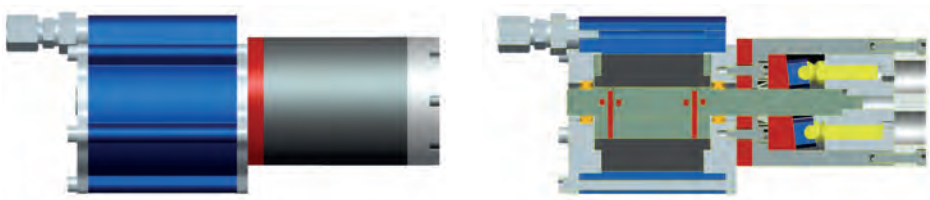

Figure 7: Integration of vane motor with fixed-displacement piston pump.

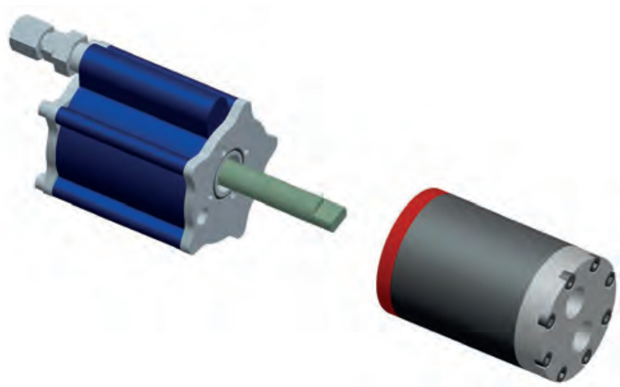

Figure 8: Integrated vane motor and piston pump.

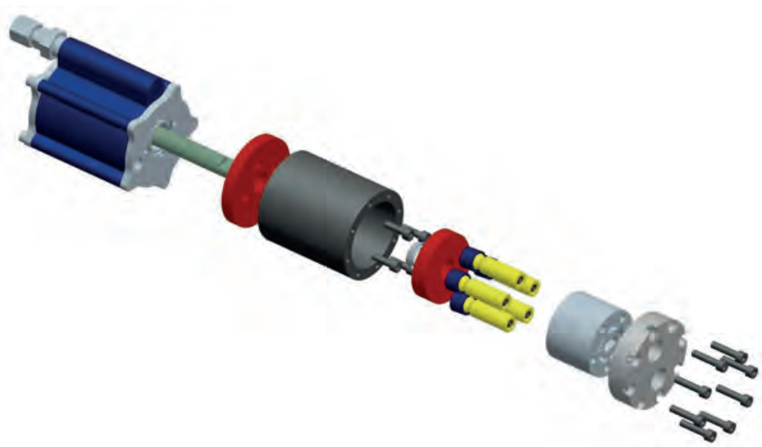

Figure 9: Exploded view of integrated vane motor and piston pump.

Project 2B.1 is also being developed as a power source for human scale actuated systems. To our knowledge, no similar approaches are being developed outside the Center. A company named Oxford Catalysts has developed a monopropellant fuel, which appears more energetic and arguably safer than the peroxide we are currently using. We are exploring it as a potential replacement fuel.

C. Member Company Benefits

If successful, this project will provide a compact power source for hydraulic machines. As such, if successful, this work will provide whole new potential markets for the member companies.

2B.1: Free-Piston Engine Compressor

Research Team

Project Leader:	Prof. Eric Barth, Vanderbilt University, Mechanical Engineering
Graduate Students:	Joel Andrew Willhite, Chao Yong, Vanderbilt University, Mechanical Engineering
Undergraduate Students:	Stephanie Carusillo (REU), University of Florida

1. Statement of Project Goals

The goal is to develop a compact high energy density pneumatic power supply applicable to untethered fluid-power applications. This will be achieved by modeling, designing, building and testing a free-piston engine utilizing spark-ignited fuel that is specifically load matched to the task of compressing air. Target metrics for the device include 100W average continuous output power of 80 to 100 psig compressed air, 1.5 kg dry weight, greater than 1500 kJ/kg energy density, and a footprint 3 inches in diameter and 20 inches in length. This device will be integrated into the Compact Rescue Crawler Test bed by 2012. Fundamental research will result in a generalized design method for the exploitation of free-piston engine dynamics for optimizing the efficiency and power density of the energetic conversion and transduction processes between chemical stored energy, kinetic energy of the free-piston, compression and pumping work, and stored pneumatic potential energy. This model-based design methodology takes a combined system dynamic / thermodynamic perspective that uniquely addresses the role of dynamic elements and effects seen to have a larger role in free-piston engines than more standard kinematic engines. Correspondingly, a generalized control methodology for free-piston engines will be formulated and applied.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

The need for an effective portable power supply for human-scale robots has increasingly become a matter of interest in robotics research. Current prototypes of humanoid robots, such as the Honda P3, Honda ASIMO and the Sony QRIO, show significant limitations in the capacity of their power sources in between charges (the operation time of the humanoid-size Honda P3, for instance, is only 20 to 25 minutes). Given the low energy density of state-of-the-art rechargeable batteries, operational times of these systems in the 100W range are restrictive (Dunn-Rankin, et al, 2005). This limitation becomes a strong motivation for the development and implementation of a more adequate source of power. Moreover, the power density of the actuators coupled to the power source needs to be maximized such that, on a systems level evaluation, the combined power supply and actuation system is both energy and power dense. Put simply, state-of-the-art batteries are too heavy for the amount of energy they store, and electric motors are too heavy for the mechanical power they can deliver, in order to present a viable combined power supply and actuation system that is capable of delivering human-scale mechanical work in a human-scale self contained robot package, for a useful duration of time (Goldfarb, et al, 2003).

The total energetic merit of an untethered power supply and actuation system is a combined measure of 1) the source energy density of the energetic substance being carried, 2) the efficiency of conversion to controlled mechanical work, 3) the energy converter mass, and 4) the power density of the actuators. With regard to a battery powered electric motor actuated system, the efficiency of conversion from stored electrochemical energy to shaft work after a gear head can be high (~50%) with very little converter mass (e.g. PWM amplifiers); however, the energy density of batteries is relatively low (about 350 kJ/kg specific work for Li-ion batteries after the gearhead), and the power density of electrical motors is not very high (on the order of 50 W/kg), rendering the overall system heavy in relation to the mechanical work that it can output. With regard to the hydrocarbon-pneumatic power supply and actuation approach presented here relative to the battery/motor system, the converter mass is high and the total conversion efficiency is shown to be low. However, the energy density of hydrocarbon fuels, where the oxidizer is obtained from the environment and is therefore free of its associated mass penalty, is in the neighborhood of 45 MJ/kg, which is about 2 orders of magnitude greater than the energy density of state of the art electrical batteries. This implies that even with poor conversion efficiency (one order of magnitude less than battery/motor systems), the available energy to the actuator per unit mass of the energy source is still at least one order of magnitude greater than the battery/motor system. Additionally, linear pneumatic actuators have approximately an order of magnitude better volumetric power density and a five times better mass specific power density (Kuribayashi, 1993) than state of the art electrical motors. Therefore, the combined factors of a high energy-density fuel, the efficiency of the device, the compactness and low weight of the device, and the use of the device to drive lightweight linear pneumatic actuators (lightweight as compared with power comparable electric motors) is projected to provide at least an order of magnitude greater total system energy density (power supply and actuation) than state of the art power supply (batteries) and actuators (electric motors) appropriate for human-scale power output.

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

The use of free piston engines for compressors is not a new idea. In fact, the first free piston machine designed by Pescara in 1928 was used as an air compressor (Pescara, 1928). Free piston engine compressors were used through the mid-twentieth century, such as the Junkers-designed compressor used in German submarines (Nakahara, 2001). Other applications for the technology were investigated, such as gas generators for use in automobiles (Klotsch, 1959; Underwood, 1957) and small power plants. However, the lack of adequate sensing and control technology led to the free piston engine being largely abandoned after 1960 (Johansen, et al, 2002). Modern electronic controls available today have led to a second generation of free piston engine research. Most of this research, however, uses free piston engine technology for hydraulic pumps (Beachley and Fronczak, 1992; Achten, et al, 2000)) and small-scale electrical power generators (Aichlmayr et al, 2002a, 2002b, 2003), not as air compressors. An extensive review of early free-piston engine compressor and gas generator applications as well as the recent resurgence in research in free piston hydraulic pumps and linear alternators has been conducted by Mikalsen and Roskilly (2007).

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

B. Achievements

Funded by the CCEFP, Riofrio, et al (2007a) designed a free piston engine compressor specifically for a lightweight untethered air supply for actuation of traditional pneumatic cylinders and valves, using hydrocarbon fuels as an energy source. The piston, acting as an inertial load, converts the thermal energy on the combustion side of the engine into kinetic energy, which in turn compresses air into a reservoir to be used for a pneumatic actuation system. This early work verified some of the notions of the idea irrespective of device design.

A second device by Riofrio et al (2007b), a free liquid-piston compressor (FLPC), was designed using a liquid trapped between elastomeric diaphragms as a piston. The liquid piston eliminated the blow-by and friction losses of standard piston configurations (2007b). This device incorporated a combustion chamber that was separated from an expansion chamber. Once the high pressure combustion gasses were vented into the expansion chamber, PV work was converted to inertial kinetic energy of the piston. The separated combustion chamber kept air/fuel injection pressure high prior to ignition for efficient combustion, and allowed for air/fuel injection that was decoupled from power and return strokes of the engine cycle. The separated combustion chamber and the high pressure injection of both air and fuel allowed for an engine devoid of intake and compression strokes. Achievements included:1) Experimentally validated dynamic model of the pressure dynamics due to combustion, combustion valve inertial dynamics, expansion chamber pressure dynamics, compressor chamber pressure dynamics, reservoir pressure dynamics, 2) Experimental characterization of prototype I efficiency (2.03% overall efficiency from chemical potential to stored pneumatic potential energy in the reservoir – the target metric is 3.25%) and power (52 watts – the target metric is 100 watts), 3) A design-based diagnosis of prototype I led to a number of quantified design tradeoffs and conclusions for subsequent designs, 4) Prototype II (FLPC) was designed, has a much smaller footprint than prototype I, and incorporates design changes to overcome the inadequacies of prototype I, 5) A full dynamic simulation of prototype II was used in its design to size and scale with respect to design tradeoffs between desirable effects and losses, 6) The formulation of a "virtual dynamic cam" framework was initiated as a generalized method for the control of free-piston and dynamically dominant engines without a kinematic index (crankshaft).

The work then shifted toward exploiting the geometry of the liquid piston to create a high inertance, which advantageously slows the dynamics of the system without the penalty of adding more mass. This design change was pursued to address the inefficiencies due largely to the separated combustion chamber configuration, which was revealed by the dynamic modeling. A schematic of this new design is shown in Figure 1. A patent on this device was filled this year. (Barth and Willhite, 2010).

In Willhite and Barth, 2009, a dynamic model of a free liquid piston that exploits piston geometry to produce a high inertance was developed for use in a free piston engine compressor. It was shown that for the size scale targeted, advantageous piston dynamics can be achieved with a reduced piston mass compared to a rigid piston design. Previous work revealed certain complications associated with the fast dynamics of the piston motion. Following from this motivation, the concept of inertance was exploited to slow the dynamics of the piston motion while concomitantly reducing the mass of the piston. It was shown that a high inertance liquid piston with a mass of 0.414 kg has the equivalent dynamic response of a 12.5 kg liquid piston of uniform cross sectional area. It was also shown that the required "inertance tube" section of the high inertance liquid piston exhibits insignificant viscous losses for the geometries considered. Finally, the dynamic response of the high inertance liquid piston resolved significant issues when incorporated into a free-piston engine compressor device. These issues are: 1) valve sizing, 2) complications associated with a separated combustion chamber, and 3) a balanced engine. It was also shown that the viscous losses associated with the liquid piston are negligible for the application discussed.

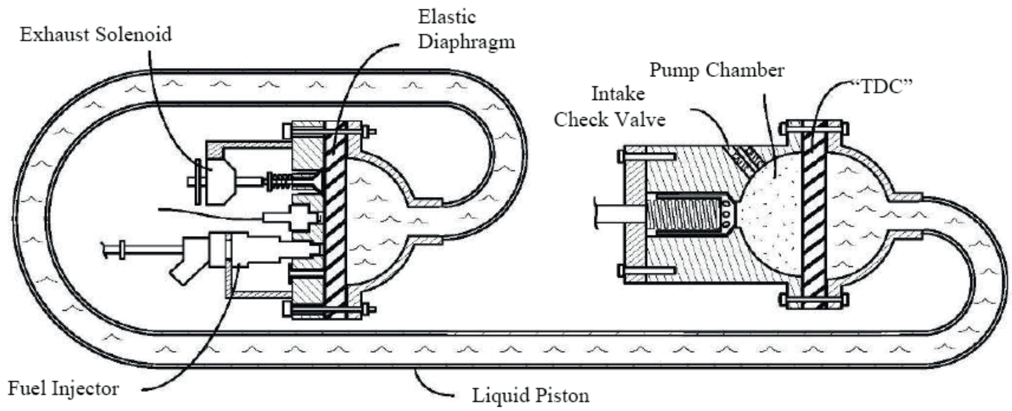

Figure 1. Schematic of HIFLPC at effective TDC.

Willhite and Barth 2010a focused on accurately modeling the liquid piston diaphragm stiffness, injection valve capacity and dynamic response, and pump check valve dynamics. A discussion of the implications of these parameters on the overall FLPC design and performance was also presented. The aim of this modeling was to enable an optimization of overall system performance.

An optimization of piston dynamics to achieve performance goals of the High Inertance Free Liquid Piston engine Compressor (HI-FLPC) was presented in Willhite and Barth 2010b. Simulation studies were conducted to optimize liquid piston dynamic characteristics for overall system performance, and the results were discussed.

Willhite et al 2011a, the first part of a two-part journal paper submission, presented detailed component and system modeling. An inertance-based dynamic model for the liquid piston was developed, validated, and incorporated into a system model of the device. Critical model parameters for components and subsystems of the model were experimentally characterized independently for use in the system model. Simulations were performed that support the effectiveness of the liquid piston dynamics on overall performance of the HIFLPC. Specifically, the piston provides a desirable load against combustion, and its kinetic energy is well-matched to drive the compressor load. Willhite et al 2011b, the companion paper, presented the design and experimental evaluation of a full prototype of the High Inertance Free Piston Engine Compressor. A model-based design for a high inertance liquid free piston engine compressor was developed. An experimental prototype of the device was fabricated and experimentally evaluated. Consistent operation of the device was achieved, and efficiency and power output of the device as tested were assessed. Test data was used to validate the dynamic model developed for the device. Model-based studies investigated the effect of varying liquid piston dynamics on overall system performance. The transduction efficiency from chemical to pneumatic potential in the reservoir was measured to be in the range of 3.45-6.63%. These significant results suggests that pneumatic systems using the HIFLPC as a power source would exhibit system energy densities comparable to, if not better than, the best electromechanical systems. Combined with the inherent advantages of pneumatic actuators over DC servomotors, devices like the HIFLPC position pneumatically actuated systems as an attractive option for human-scale, untethered robotic systems.

Future work for the HIFLPC will include the development of a closed-loop controller capable of achieving consistent and efficient operation of the device over a full range of reservoir loads. Work has begun along these lines as described in Yong and Barth (2009).

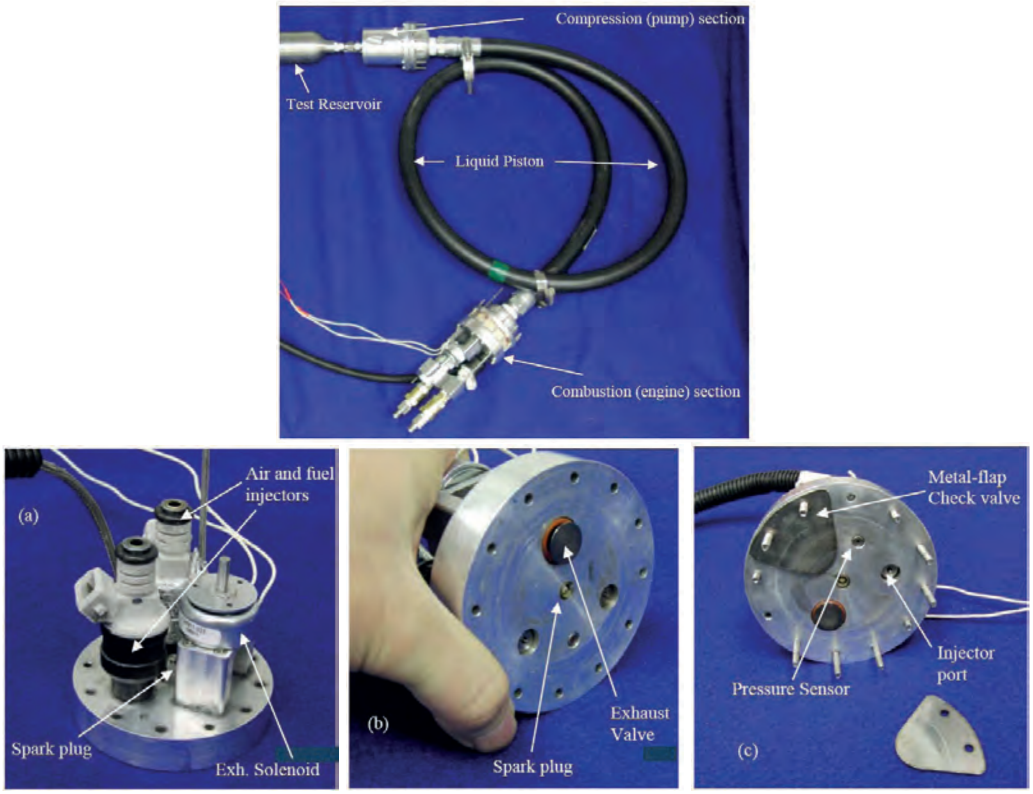

Figure 2. Experimental prototype of HIFLPC. Shows entire device at top, (a) combustion head top, (b) combustion head interior, (c) combustion head with injection check valve

Expected Milestones and Deliverables

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

Milestone 1: High Inertance Prototype Completed [7/31/10] *DONE*
- Task: Unloaded tuning *DONE*
- Task: Constant load energetic characterization *DONE*

Milestone 2: Prototype Energetically Characterized at Ideal Conditions [10/31/10] *DONE*
- Task: Full model experimental validation *DONE*
- Task: Injection controller for varying loads (reservoir pressures)
- Task: Energetic Characterization over operating envelope

Milestone 3: Controlled Prototype Energetically Characterized [5/31/11]
- Task: System test powering a single-degree-of-freedom pneumatic actuator performing arbitrary tasks – varying duty cycle, varying average power outputs, varying engine orientations and motions. Assessment: 1) engine performance, efficiency, 2) total system efficiency including actuation (suggest energetically savvy actuation control strategies for use on TB4)

Milestone 4: Hardware Simulated CRC-like Operating Conditions [10/31/11]

Milestone 5: Stand-alone Power Supply System Completed [3/31/12]
- Task: Ship to Georgia Tech, work with Georgia Tech to resolve any issues

Milestone 6: Power Supply Fully Characterized on Test bed [5/31/12]

C. Member company benefits

A compact, high energy density fluid power supply is a key enabler to new, untethered human scale applications. CCEFP member companies will be able to use this technology to expand their product offerings and increase the size of the fluid power market.

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

Research Team

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

1. Statement of Project Goals

The objective of this project is to continue development a compact high efficiency air compressor providing 10 W of pneumatic power that can be used for the Test Bed 6 ankle foot orthosis (AFO) and for other applications needing a tiny fluid power supply. The power source is a free piston engine operating in a homogeneous charge compression ignition (HCCI) two-stroke cycle, integrated with a free-piston air compressor. This engine compressor package, coupled with a fuel tank, will provide much higher power density and energy density than a battery – motor package, thus enabling a more compact design and longer run time of tiny fluid power systems.

2. Project Role in Support of Strategic Plan

This project is necessary to achieve Goal 3 of the CCEFP: portable, un-tethered, human-scale application. The targeted transformational barrier for accomplishing this goal is the lack of compact fluid power systems. The project is specifically directed towards Test Bed 6 with its stringent requirements for wearable components. The power requirements for the active AFO drive the engine design for this project. Our initial target is a fluid power output at the lower end of the orthosis range, 10 W but the concept will also work for delivering higher power.

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. With the experimental results, appropriate models with fitted parameters can be chosen to better simulate the engine, which in turn will guide the design and optimization of further generations of prototypes. These optimizations will include improvements in compactness and efficiency as well as reductions in emissions, noise, and heat rejection.

B. Achievements

Brief Overview of Previous Achievements

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

The general design concept for the free piston engine compressor is shown in Figure 1. It utilizes a two-stroke free piston engine as the power source. On the engine side, the fuel air mixture induction is done by piston upward motion drawing the mixture from the carburetor into the crankcase through an intake reed valve. Then the piston downward motion compresses the mixture inside the crankcase and supplies it to the cylinder using Schnuerle type scavenging to fill the cylinder with fresh charge in preparation for combustion. On the compressor side, the compressor piston's reciprocating motion supplies compressed air to the output. While the downward motion of the pistons is driven by the expansion of products of combustion in the engine cylinder, the upward return motion is driven mainly by the metal rebound spring.

With the design concept specified, modeling of various components was carried out, including mixture induction, valve dynamics, scavenging and blow-by leakage. These models aimed to determine the unique characteristics of miniature size engines. CFD simulation was also conducted to determine the flow coefficients in valves and describe mixture induction. However, with no experimental data, those models were not verified and used various unknown coefficients.

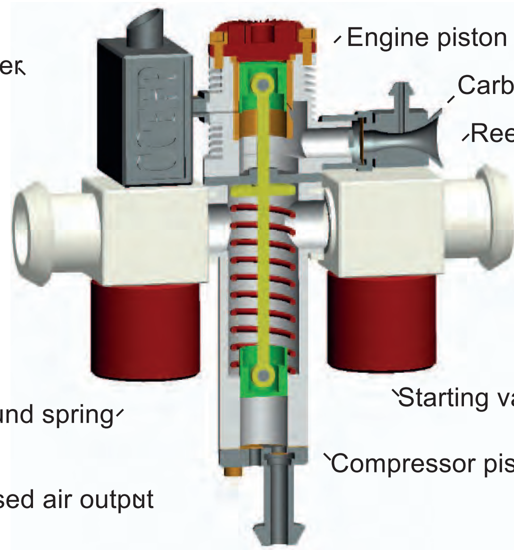

Figure 1 Miniature HCCI Free-Piston Engine design concept

An overall engine compressor model was built in MATLAB SIMULINK application, based on the sub-models constructed. The overall model was capable of simulating the starting and steady-state operation of the engine compressor. The overall efficiency of the engine compressor, which is the energy of the delivered cooled compressed air divided by the fuel energy, was simulated to be 5.9%. A generation 1 prototype engine was built, based on the parameters given by the overall engine compressor model. This work is described in a paper was published on Small Engine Technology Conference, Penang, Malaysia, 2009 [1].

Achievements in the past year (Feb. 2010 – Dec. 2010)

As stated above, in the Feb. 2009 – Jan. 2010 period, mathematical models were constructed to simulate various components of the engine. However, the models were not verified, and used various unknown coefficients. To address this problem, experimental tests were conducted on existing components, to determine coefficients and verify sub-models.

<u>Experimental tests of model engines</u>

Currently available miniature size IC engines are those used in model aircraft, cars, etc. The model engines that are similar to the size of the authors' design, about 1 cm^3 displacement, have these features: air-cooled, two-stroke, crankcase compression, loop scavenging, carburetor fuel-induction, piston without piston rings, glow or HCCI ignition and hemispheric combustion chamber. These features result in compactness, high power density, simple components, reliability, ease of starting, easy maintenance, and low cost; all of which are desired by hobbyists. The work of Ogawa, et al., [2], Raine, et al., [3] and Ma, et al., [4] revealed that model engines have much more severe cycle variation than full-scale engines.

For the work described here, components of a 1.47 cm^3 AP .09 two-stroke model airplane engine were used to develop engine sub-models. An experimental apparatus was built to measure the performance of the engine. The engine intake air flow, fuel consumption, in-cylinder pressure, crankshaft position and brake output were measured. The data were collected by a National Instrument data acquisition system. Engine friction was also measured. Friction in a miniature engine has different characteristics from a full scale engine due to a much larger surface to volume ratio. Furthermore, the fuel for miniature two-stroke model engines contains up to 20% lubricating oil to help lubricating and cooling the engine. Thus, friction related to the thick layer of lubrication oil introduces different behavior from that in full scale engines.

Friction modeling
Friction was determined by taking the difference between the power delivered to the piston by gas pressure and output shaft power. The mechanical efficiency was around 70% at low speed, and dropped rapidly at speeds higher than 10,000 cycles per minute (cpm). To model the friction, the friction force was fitted to a quadratic function of speed. Figure 2 shows a comparison between experimental measurements and fitted results.

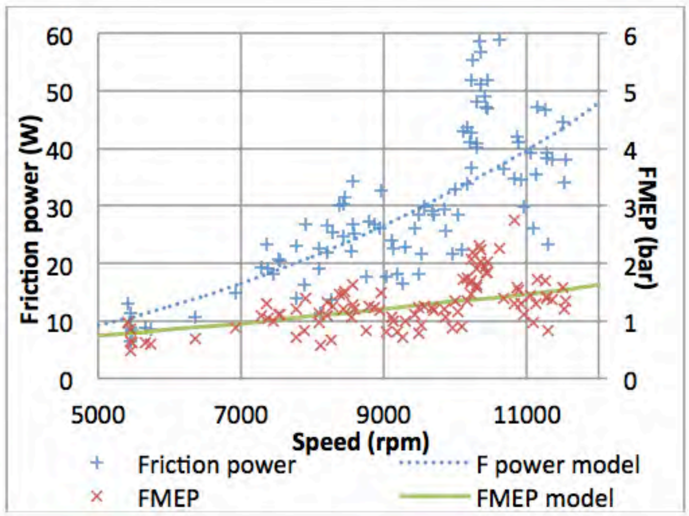

Figure 2 Friction model and experimental data

Scavenging modeling
In a two-stroke engine, exhausting combustion products and inducting fresh fuel-air mixture takes place at the same time during the scavenging process. The fresh mixture 'pushes' the exhaust out of the cylinder. This process involves inevitable loss of fresh mixture directly out of the exhaust port, i.e., fuel air mixture short circuiting. Also, there is more residual exhaust remaining inside the cylinder after the gas exchange process compared to a four-stroke engine.

The two-stroke engine scavenging process is described by two parameters, the delivery ratio, which indicates how much mixture is delivered to the cylinder during scavenging, and the charging efficiency which indicates how much fresh mixture is eventually retained inside the cylinder. A scavenging model, should established the relationship between delivery ratio and charging efficiency. The scavenging model used here assumes perfect mixing and direct short circuiting. The perfect mixing portion of the fresh charge enters the cylinder and mixes with the gases inside the cylinder instantly to form a homogeneous mixture, while the remaining charge goes out of the cylinder directly. This model yields

$$\eta_C = 1 - e^{-(1-s)\lambda}$$

where η_C, λ and s are charging efficiency, delivery ratio and short circuiting fraction, respectively. This model fits the experimental data very well for a variety of different operating conditions.

Cycle variation modeling
Cyclic variation is the phenomenon that at a same engine setting, engine cycles vary in terms of the combustion strength, ignition timing, combustion duration, etc.. In a free-piston engine design, the cyclic variation can be very harmful, since the piston movement is determined by the combustion process instead of a crankshaft. Thus, a cycle with weak combustion can result in insufficient travel of the piston and ineffective scavenging for the next cycle, stalling the engine.

Two-stroke engines have much more severe cyclic variation problems than four-stroke engines due to the nature of the scavenging process [5]. To determine the strength of the cyclic variation, experimental data from the model engine were analyzed. 181 cycles at the same engine speed, load and carburetor setting were analyzed, and the distribution of the charging efficiency was found to fit well to a normal distribution whose probability function $f(s)$ can be described by

$$f(s) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(s-\bar{s})^2}{2\sigma^2}}$$

With average short circuiting ratio $\bar{s}$ determined by the scavenging model, and parameter σ determined by the fitting with the experimental data. The experimental data fits with a normal distribution with

$$\sigma/s = 6\%$$

The experimental data were also used to verify and fit the sub-models of several other components, including combustion timing, heat release rates and leakage. Further details of these analyses are given in the project's paper presented at the Small Engine Technology Conference 2010 [6].

Engine compressor overall model

An overall model for the engine compressor was constructed based on the experimentally fitted and verified sub-models using the MATLAB SIMULINK tool. SIMULINK is a very effective graphical interface for designing, simulating and testing dynamic systems. With the SIMULINK model, the starting and operation can be simulated, with all sub-models in place. The overall model was used to examine factors the influence engine compressor performance.

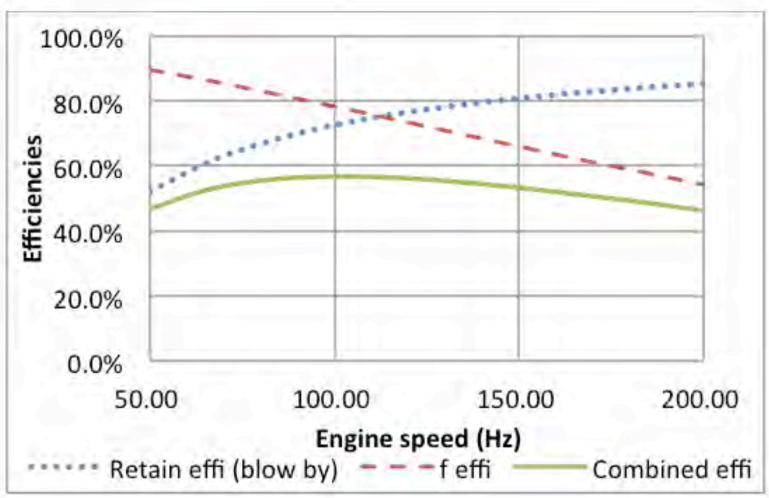

Figure 3 Trade off of several efficiencies with engine speed

Trade offs between leakage and heat transfer, and friction determine the optimum operating speed of the engine. The overall engine compressor model can be used to determine optimum speed. High engine speed reduces leakage and heat transfer losses but increases friction losses. This trade-off can be simulated and the results are shown in Figure 3. The retention efficiency indicates how much mixture is retained inside the cylinder without leaking through the cylinder-piston gap. It is quite low at low speed, i.e. at 50 Hz operation about half of the cylinder charge is lost due to leakage. On the other hand, the mechanical efficiency drops with increasing speed. From the overall efficiency curve, the engine's optimum operating range is between 100 and 150 Hz.

With the engine operating speed specified, the engine size could be determined because the target power output was known. This target could be met using standard components. Thus, the engine compressor was designed to utilize an AP .09 model engine cylinder liner component, which has a bore of 12.5 mm and stroke of 12 mm. The free piston engine can be considered a resonant spring-mass system consisting of the rebound spring and the piston assembly. The combustion inside the engine cylinder accelerates the mass spring system and converts expansion work to kinetic energy and potential energy in spring and air compression while friction and discharge of compressed air dissipates energy. Spring stiffness and piston assembly mass are the main parameters to determine the engine operating speed. A preloaded spring with a spring constant, k=1500 N/m, and a preload of 10 N was used. The piston assembly mass was determined to be 40 grams. This led to a natural frequency near 100 Hz.

The engine compressor was modeled with the cycle variation built into the overall model. A trace of piston position in several consecutive cycles is shown in Figure 4. From the simulations, the engine piston shows variation in the bottom dead center (BDC) position, due to different combustion strengths in those cycles. However, for the simulated level of cyclic variation, the piston always passes past the nominal BDC position, enabling adequate scavenging for the next cycle.

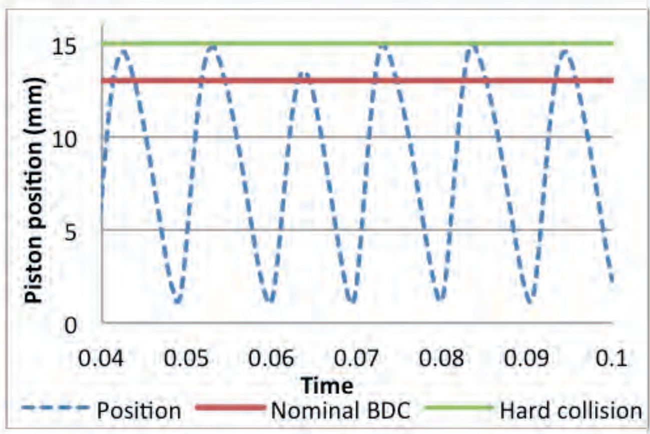

Figure 4 Simulation of engine compressor piston position trace in consecutive cycles

With all the inefficiencies modeled, the engine compressor outputs 17.6 W of cooled compressed air, while an overall efficiency of 4.6% was achieved.

Expected Milestones and Deliverables

Task 1: Second generation prototype

Based on the improved and optimized model of the engine compressor, a new prototype will be designed and built, taking into account of friction, cycle variation, blow-by leakage and other factors.

Timeline: 5 months (Jan. 2011 – May 2011)

Deliverable: Optimized operating engine.

Task 2: Prototype compressor development and system integration

A compact, fast response compressor valve system will be designed and tested. Then the compressor will be integrated with the engine and the system optimized and tested. Again simulation tools will be used to assist design optimization. Once optimized, the system will be tested with a prototype AFO.

Timeline: 3 months (June 2011 – Aug. 2011)

Deliverable: Operating prototype free piston air compressor

Task 3: Computational Fluid Dynamics (CFD) simulations

CFD simulation will be incorporated to simulate the scavenging process of the two-stroke engine. This is especially important in a free-piston engine where piston motion is not defined as in a

crankshaft engine. The effect of operation speed, piston stroke length and size scale will be investigated.
Timeline: 4 months (May 2011 – Aug. 2011)
Deliverable: CFD model for miniature size two-stroke engines

C. Member Company Benefits
CCEFP member companies will be able to use this technology to expand their product offerings and increase the size of the fluid power market.

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Project 2B.3: Free Piston Engine Hydraulic Pump

Research Team

Project Leader: Prof. Zongxuan Sun, Mechanical Engineering, University of Minnesota
Graduate Students: Ke Li, Wilson Santiago
Undergraduate Student: Jesse Behnke
Industrial Partners: Ford Motor Company

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

It will address two transformational barriers as outlined in the ERC strategic plan: compact power supply and compact energy storage. It will directly support the test bed: hydraulic hybrid passenger vehicle and it is also applicable to the excavator test bed.

3. Project Description

A. Description and explanation of research approach

For mobile applications including both highway vehicles and mobile heavy equipment, fluid power is currently generated onboard using a crankshaft based internal combustion engine (either gasoline or diesel) with a rotational hydraulic pump (see Figure 1). The main drawbacks of this configuration are the relatively low efficiency and complex design of both the ICE and the hydraulic pumping system due to the dynamic operating requirements. An alternative approach is to supply fluid power using a free piston engine with a linear hydraulic pump. As shown in Figure 2, combustion in the right cylinder will push the inner piston to the left and outer piston to the right, which will compress the gas in the left cylinder and generate high pressure fluid in the hydraulic chamber. Similarly combustion in left cylinder will return the inner piston to the right and outer piston to the left. This configuration has the potential to significantly increase the ICE and pump efficiency while increasing system modularity. Specifically, the ICE efficiency can be improved with the variable compression ratio, advanced combustion such as homogeneous charge compression ignition (HCCI) and less fiction due to the elimination of the crankshaft. The pump efficiency can be improved with reduced fiction and leakage due to a simpler design. The dynamic and modular nature of the free piston engine driven hydraulic pump makes it very attractive for mobile applications by converting liquid fuel to fluid power on demand without a large energy storage device.

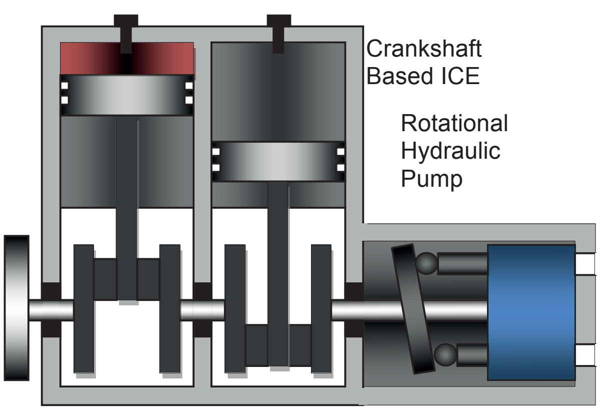

Figure 1. Crankshaft Based ICE with Rotational Hydraulic Pump

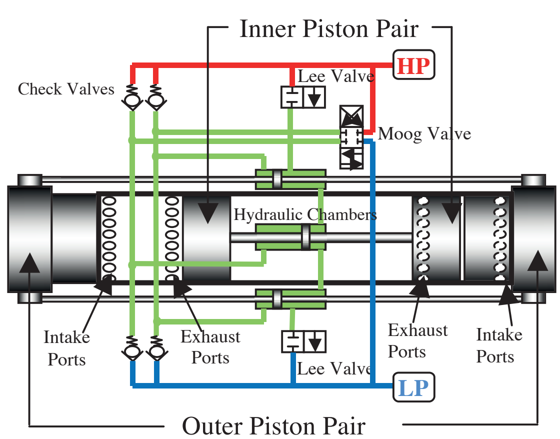

Figure 2. Free Piston Engine with Linear Hydraulic Pump

Previous work [1-5] on free piston engine has shown limited success mainly due to the complex dynamic interactions between the combustion and the fluid power in real-time. As shown in Figure 2, since the combustion process in one cylinder affects the compression in the other, it is very challenging to control the piston/pump motion, specifically the stroke length and compression ratio under this arrangement. Also to control the pump displacement or flow rate, varying the operating frequency of the free piston engine pump in real-time is required. This further complicates the piston/pump motion control problem [6-8]. Significant efficiency gain compared to the conventional system (crankshaft based ICE driven rotational pump) has been reported by several researchers [1-5]. However, there are still fundamental issues remaining with the existing systems. One area is the intake and exhaust processes of the free piston engine pump, where scavenging [5-9] is commonly used. The scavenging design, although relatively simple, attributes to low efficiency and increased emissions. The other area is the combustion phasing control that has a direct impact on fuel efficiency, especially for the HCCI combustion [10-13] that depends on auto-ignition. The combustion phasing is a function of the piston motion, compression ratio, as well as the fresh charge and residual mixture. In summary, precise piston/pump motion control and the ability to regulate the charge mixture are required to further improve the efficiency and performance of the free piston engine driven hydraulic pump.

Research Approaches

To address the above challenges, we propose to investigate the two fundamental technical barriers of the free piston engine driven hydraulic pump. One is the seamless coordination of the combustion and the fluid power. The other is the design optimization of the system. To support the proposed research, our industrial partner Ford Motor Company has donated a free piston engine driven hydraulic pump to the University of Minnesota. Figure 3 shows the picture of the system.

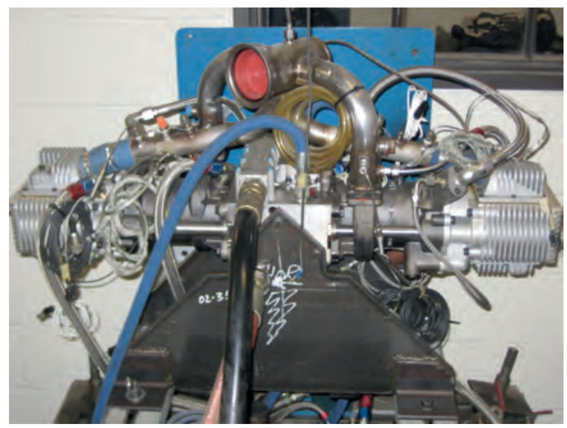

Figure 3. Picture of the Free Piston Engine Driven Hydraulic Pump

<u>Real-time Control of the Combustion and Fluid Power</u>

Due to its unique configuration, the combustion and the fluid power are coupled dynamically. The fast and complex dynamics of those events make the coordination very challenging, which however is required to ensure a stable operation. For a hydraulic free piston engine with 100mm stroke and 5mm clearance at the top dead center, a 1% variation of the piston motion (1mm) will results in a 20% variation in the compression ratio, which will further affect the combustion performance. As shown in Figure 4, the piston/pump motion is periodic with respect to the position of its stroke. If the operating frequency is fixed, the piston motion is also periodic in time [1]. Repetitive control [14-15] can then be applied to achieve precise positioning. However, the operating frequency needs to be changed in real-time to vary the displacement of the hydraulic pump, which in turn makes the piston motion cyclic but aperiodic with respect to time. This phenomenon poses a fundamental challenge to the trajectory tracking problem. We propose to build a dynamic model for the free piston engine pump and apply our recently developed time-varying internal model based control [16-17] to achieve precise piston motion.

<u>Design Optimization of the Free Piston Engine Driven Hydraulic Pump</u>

To increase system controllability as well as efficiency, we will investigate alternative designs for the free piston engine driven hydraulic pump. Specifically, we propose to replace the hydraulic system shown in Figure 2 with digital hydraulics and replace the scavenging process with an electro-hydraulic camless valve actuation system. First, as shown in Figure 5, the check valves and the Moog valve have been replaced with digital valves. The pump flow can be routed to either the low pressure tank or the high pressure supply in real-time. It can also be used as a control means for piston/pump motion by controlling the hydraulic chamber pressure using the digital valves. It is also possible to combine the four digital valves into two to reduce cost. We will investigate the optimization of the free piston engine pump displacement control for a series hydraulic hybrid vehicle. System simulation to evaluate the fuel economy, emissions and performance of the vehicle will be conducted. Second, we propose to control the intake and exhaust process with an electro-hydraulic camless valve actuation system [18-21] enabled by the on board high pressure fluid. This technology is capable to regulate the mixture of the fresh charge and the residual gas on a cycle to cycle basis and is critical to realize optimal combustion phasing control.

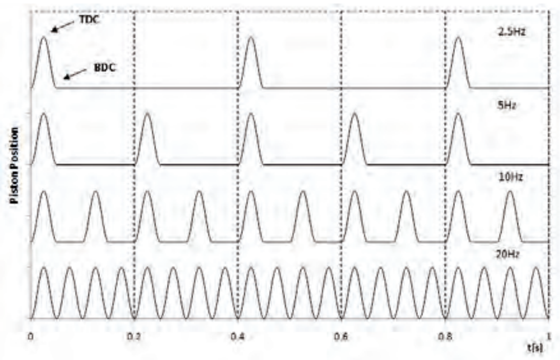

Figure 4. Piston/pump motion

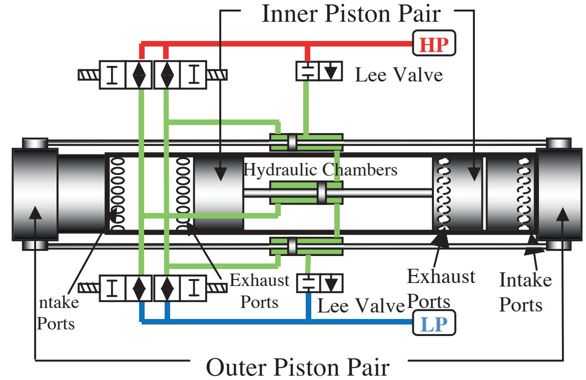

Figure 5. Free Piston Engine with Digital Hydraulic Pump

B. Achievements

A control-oriented dynamic model of the free piston engine driven hydraulic pump has been built to simulate the dynamic interactions among combustion, scavenging, piston dynamics and hydraulic dynamics. The combustion process of the gas mixture is modeled as HCCI. The combustion is seen to be heavily influenced by the gas exchange process since the mass flows during intake and exhaust port opening/closing determine the air to fuel ratio and the amount of trapped residual gas that would be carried to the next cycle. Thus, a two zone gas exchange model was built to capture the mass flows between the ambient and the engine. The output from combustion, gas exchange, and hydraulic system are passed to the piston dynamics to calculate the piston acceleration, velocity and displacement, which would then be fedback to the sub-systems. Figure 6 shows the interconnection between the sub-models, which demonstrate the intrinsic feedback nature of the system. The model allows both steady state outputs and transient response. And it has been tested under various hydraulic loading conditions. Figure 7 shows the comparison of the piston motion of the FPE with a conventional ICE.

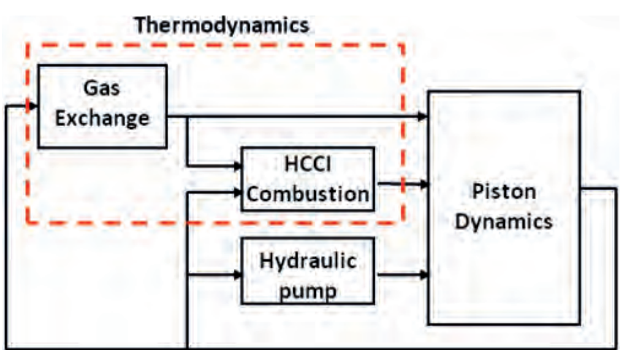

Figure 6. Block Diagram Showing the Interconnection between the Engine Sub-models.

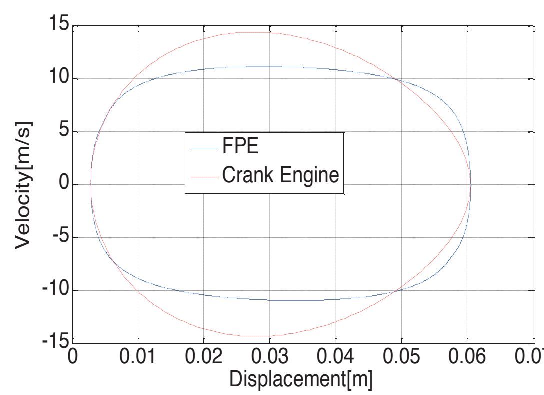

Figure 7. Piston Position and Velocity Profile from the Dynamic Model

As an initial step, a PID controller has been implemented in the simulation program to control the compression ratio to avoid excessive in-cylinder pressure. Compression ratio was found to be greatly influenced by the fuel injected each cycle. Thus, fuel mass was used as the control input. The program records the compression ratio from last cycle, compares it with the reference compression ratio and calculates the amount of fuel that should be injected to the chamber for the current cycle. Steady state and transient hydraulic chamber pressure are shown in Figure 8. The PID controller would add or reduce the amount of fuel according to the load change to maintain the desired compression ratio, and it can help bring the engine to the reference compression ratio with small steady state error in a relatively short period.

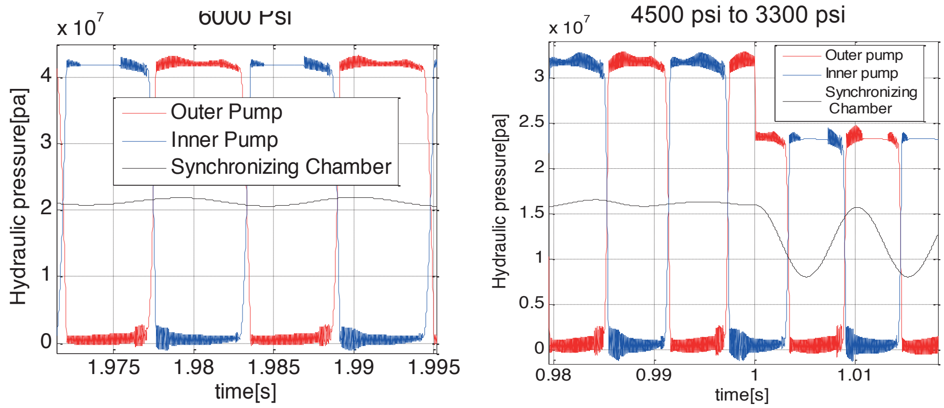

Figure 8. Steady and Transient Hydraulic Chamber Pressure

Pressure traces of the combustion chamber are shown in Figure 9 at light load. Combustion in the light load case occurs too late which would result in a poor combustion efficiency. It is due to the fact that the combustion duration of the lean fuel and air mixture under light load is longer compared to the rich mixture. In order to maximize the efficiency, we need to control the combustion phasing so that the combustion occurs right after the piston has reached the top dead center (TDC). This can be done by various means. For example, adjusting the exhaust pressure to alter the residual gas fraction, and pre-heating the intake charge to advance the start of combustion. With our model, we investigate the possibility of varying the combustion phasing through hydraulic intervention. At the end of the compression, the main hydraulic control valve (Moog valve) is activated to reverse the hydraulic force direction, thus the piston velocity is decreased and the piston will need more time to return. By adjusting the duration and size of the valve opening, we are able to make the combustion occur right after the piston TDC. Figure 9 also shows the pressure trace after the hydraulic control was implemented, the efficiency were calculated to be 5% higher than the case without the hydraulic control.

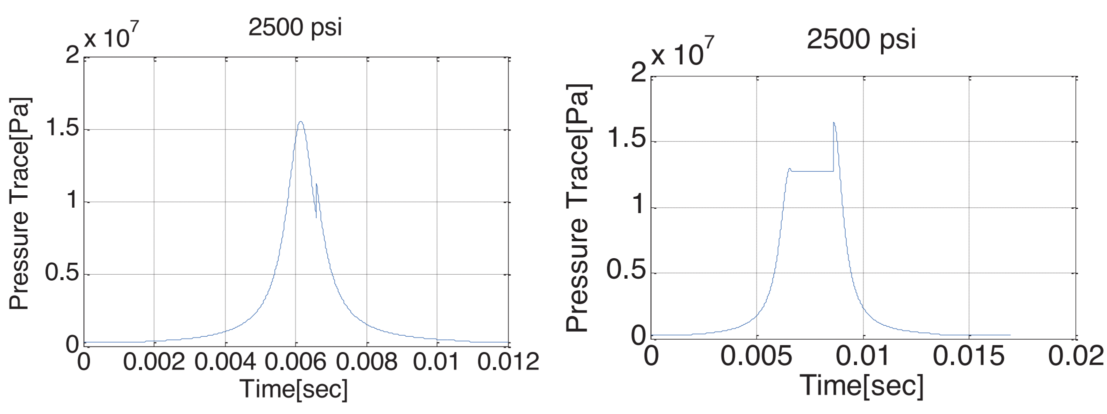

Figure 9. Combustion Chamber Pressure at Low Load without and with Hydraulic Intervention

In summary, we have built a dynamic model for the system that includes HCCI combustion, two zone scavenging, the hydraulic dynamics and the piston dynamics. We have also investigated control strategy for regulating load control, compression ratio control and combustion phasing control. The model has been tested extensively for different operating conditions. Observations from the dynamic model will help develop advanced controls next year.

Plan for Next Year

- *Finish system installation in the lab*

  To conduct engine experiments and collect data, several engine sub-systems need to be installed. The driver for Moog and Lee valves were identified and will be purchased. The inner piston lubrication system was found to be independent from the outer piston lubrication system, and the pump motor for the inner piston lubrication needs to be sized before purchase while the outer piston lubrication can be ordered as a package from Woerner Inc.. Sensors need to be monitored in real time include: displacement transducer, pressure transducer and thermocouples connected to the combustion chamber and hydraulic chamber. The fuel mass and signal to the hydraulic control valves are the control inputs. Real time control and data acquisition will be realized by the dSpace system.
- *Validate the dynamic model*

  The engine will be first tested with the “motoring” mode during which the piston pairs are actuated by high pressure fluid from the accumulator, and the hydraulic model can be validated through the test. The engine “pump” mode, during which the combustion energy from the fuel is converted to fluid power, will be tested, and the combustion and gas exchange model can be validated through the test.
- *Design the control system based on the developed model*

  Once the dynamic model is validated, control system will be developed, and the model would serve as a powerful tool for the development. The PID control will be developed first and then the time-varying internal model based control will be designed. Computer simulation will be conducted first to evaluate the performance of the control system.
- *Implementation of the control system in the lab*

  The control system will be tested in the lab after we confirm that the system has desired performance through the computer simulation.

Milestone and Deliverables

- Task 1: Modeling of the free piston engine driven hydraulic pump [6 months]
  - Deliverables:
    - Combustion model [9/30/2010]
    - Mechanical and fluid system model [9/30/2010]
    - Integrated system model [12/31/2010]
- Task 2: Control of the free piston engine driven hydraulic pump [12 months]
  - Deliverables:
    - System setup and model validation [6/30/2011]
    - Control design and simulation of the closed loop system [8/31/2011]
    - Bench test of the closed loop system [12/31/2011]
- Task 3: Design of new free piston engine driven hydraulic pump [6 months]
  - Deliverables:
    - New design concept [3/31/2012]
    - Simulation of the new design concept [5/31/2012]

C. Member company benefits

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

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2C.1: Compact Energy Storage - Open Accumulator Approach

Research Team

Project Leader: Prof. Perry Y Li, Mechanical Engineering, UMN
Other faculty Prof. Terry Simon, Mechanical Eng., UMN
Graduate Students: Andrew Rice, UMN

1. Statement of Project Goals

The goal of this project is to increase the fluid power energy storage density by an order of magnitude. The potential and feasibility of a novel "open accumulator" approach, as well as solutions to its technical barriers are investigated. At 35MPa, the open accumulator is potentially an order of magnitude more energy dense than existing closed accumulators. The approach will be considered successful if a system with continuous and transient power and energy requirements suitable for a small passenger vehicle (760kJ storage, 20kW continuous power, 100kW transient power) is 5 times more compact than using existing approach.

2. Project Role in Support of Strategic Plan

Lack of compact energy storage is preventing regeneration and hydraulic hybrid technology from being deployed in compact applications, such as hydraulic hybrid passenger vehicles, where energy densities of existing hydraulic accumulators are 100 times lower than those of electric batteries. An order of magnitude improvement in energy density (i.e., energy storage per unit volume) is required to capture braking energy from higher speeds and gravitational potential energy when going downhill. It has also been identified recently such an increase in energy density would make fluid power competitive as a storage device for wind power. Fluid power energy storage has traditionally been based on compressed gas. Various approaches to improving energy density exist, including (1) increasing working pressure, (2) reducing total volume, and (3) chemical reaction based concepts. All these approaches (e.g. high pressure, hiding accumulators in structural elements, combination with phase-change/chemical reaction based storage as long as compressed gas is an intermediate medium in the energy conversion) are worth exploring and can be combined with the present approach.

3. Project Description

A. Description and explanation of research approach

In current practice, an accumulator is used to store hydraulic energy. Typically, it consists of a chamber containing a fixed mass of inert gas whose pressure increases and whose volume decreases as hydraulic fluid is pumped into the accumulator. Energy is stored by pumping pressurized hydraulic oil into the accumulator and is regenerated as the compressed gas pushes the stored oil back into the hydraulic circuit. Since the gas is always contained within the accumulator, we refer to it as a *closed accumulator*. The energy density of a closed accumulator is optimized when an expansion ratio of approximately 2-3 is employed. Since the closed accumulator must accommodate the expanded gas volume, an expansion ratio beyond the optimal leads to an increase in volume and an overall decrease in energy density.

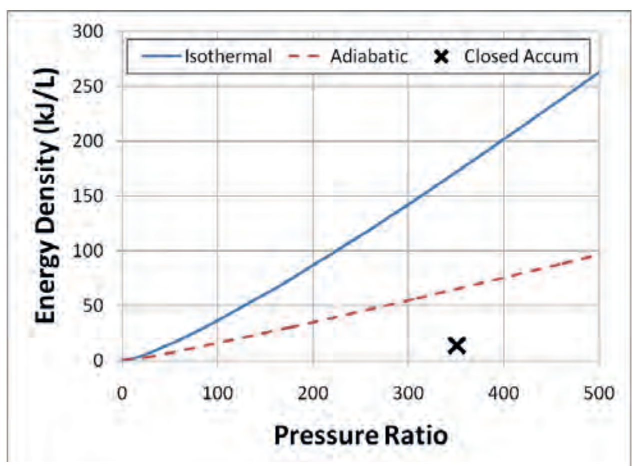

Figure 1: Theoretical energy densities of proposed open accumulator and conventional closed accumulator.

In the proposed open accumulator approach [1], the compressed gas is exhausted to the atmosphere during expansion, and intake is also taken from the atmosphere during compression. This results in a much higher expansion ratio (350 at 35 MPa), and the available energy from the compressed gas with the same volume is increased by 6.5 times. Furthermore, since the expanded air is exhausted to the atmosphere, the system needs not account for the volume of the low-pressure air, nor the volume of the displaced hydraulic oil. This decreases the total volume by 3.3 times. A potential 20 fold increase in volumetric energy storage density for the same compressed gas pressure can be achieved at conventional hydraulic pressure (35MPa) (Fig. 1). The main challenges in realizing the open accumulator concepts are (1) maintaining safety in compressing and expanding atmospheric air; (2) maintaining power density; (3) providing efficient input and extraction of energy; and (4) controlling heat transfer and temperature variation associated with the large compression and expansion ratios. These challenges are being addressed by utilizing a safe choice of materials, proposing a system architecture that maintains constant pressure, offering a specialized compressor/motor design, and optimizing heat transfer and using thermal storage materials.

B. Achievements

External fundings

Continuation CCEFP funding past June 2010 for project 2C.1 has been declined. So, one priority in the past year was to secure external funding to continue research. To this end, we shifted our application emphasis from the energy storage for vehicles to utility scale energy storage, specifically for off-shore wind power. These larger scale applications (in the order of MW power and MWhr energy capacity) are better match for the open accumulator concept than the vehicle application. For the vehicle application, the volume requirement to achieve efficient isothermal compressor/expander becomes much more significant than the volume needed for energy storage. The much larger energy storage needs and the large size of the wind turbine installation makes the compressor/expander size relatively unimportant and therefore more acceptable. How the open accumulator concept is adapted for off-shore wind energy storage and advantages of the approach will be presented in [2]. With this shift in focus, we have been successful in securing two grants:

- A one year, $68,000 seed grant from the University of Minnesota, Institute on the Environment, Initiative for Renewable Energy and the Environment (IREE).
- A four year, $2,000,000 grant from the National Science Foundation, Emerging Frontier for Research and Innovation (EFRI)

The latter is one of 4 awards in the renewable energy storage topic and is in collaboration with U of Virginia (E. Loth), Worcester Polytechnic Institute (J. Van de Ven), and industry partner Lightsail Energy Inc. Both Profs. Loth and Van de Ven were involved with the CCEFP (as PI and Post-doc).

Optimal compression/expansion profiles

In addition to orienting our research for the wind energy storage, we have in the past year also extended our results on optimal compression/expansion profiles. Our past result have determined compression and expansion trajectories such that for a given efficiency, the time of compression/expansion is minimized (equivalently power is maximized) or vice versa, given that a constant heat transfer capability, as summarized by the heat transfer coefficient (h) and heat transfer surface area (A) product. It was shown that compared with other ad-hoc linear and sinusoidal trajectories, the optimal trajectories provide 3 to 5 fold increase in power density at the desired 90% efficiency [3]. Each optimal trajectory consists of an adiabatic process, followed by an isothermal process, and a final adiabatic process.

The constant “hA” assumption, however, is not valid for our liquid piston compression/expansion concept [4], where the heat transfer area changes with the state of compression/expansion as the heat transfer surface area is progressively submerged or exposed in the compression and expansion respectively. In the past year, the constant “hA” assumption is therefore relaxed by a more general assumption that “(hA)” is a function of the air volume in the compression/expansion chamber. For this scenario, the optimal compression/expansion trajectories also consist of adiabatic segments at the beginning and the end of the process, but the isothermal process that exists in the constant “hA” case is now replaced by a temperature difference profile is inversely proportional to the ‘$\sqrt{hA(V)}$:

$$hA(V)(T(V) - T_0)^2 = \lambda T_0 \tag{1}$$

where V signifies volume dependence of hA and of the temperature T, and λ is a constant that determines the efficiency/power density tradeoff. Notice that Equation (1) reduces to an isothermal condition when “hA” is a constant.

Figure 2 shows the efficiency versus power trade-off for a 6.34cm diameter, 31.7cm long cylinder using the optimal, linear and sinusoidal profiles. Notice that at 90% efficiency, the power obtained using the optimal profile is 5 and 10 folds that of the linear and sinusoidal profiles.

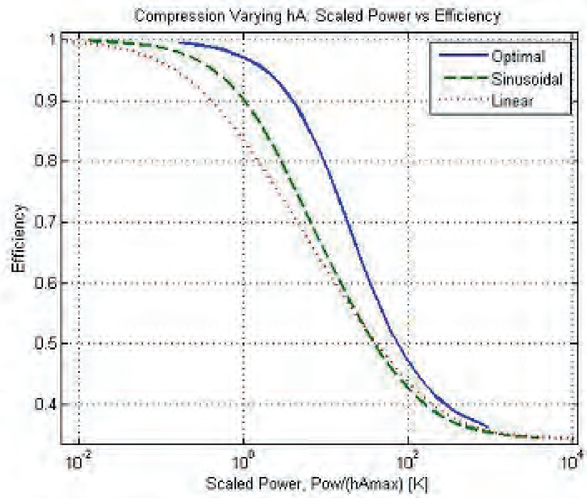

Figure 2: Efficiency/power trade-off for optimal and ad-hoc trajectories for a cylinder compression/expansion chamber.

Heat transfer augmentation experiments

We have modified the liquid piston compressor/expander of the 3rd experimental prototype system to study methods for improving heat transfer. The flexi-glass compression/expansion chamber has been reinforced by steel shield (with windows) for extra safety (Figure 3). It is capable of studying effect of surface area augmentation (via insertion of porous materials) on heat transfer and will be soon be capable of studying effect of injection of water sprays. Preliminary experiments have been conducted on the set-up with and without additional of steel gauze mesh. We are currently validating the instrumentation in order to draw conclusions from the results. We are also increasing the capability of the driving device to achieve faster and more controllable compression/expansion profiles.

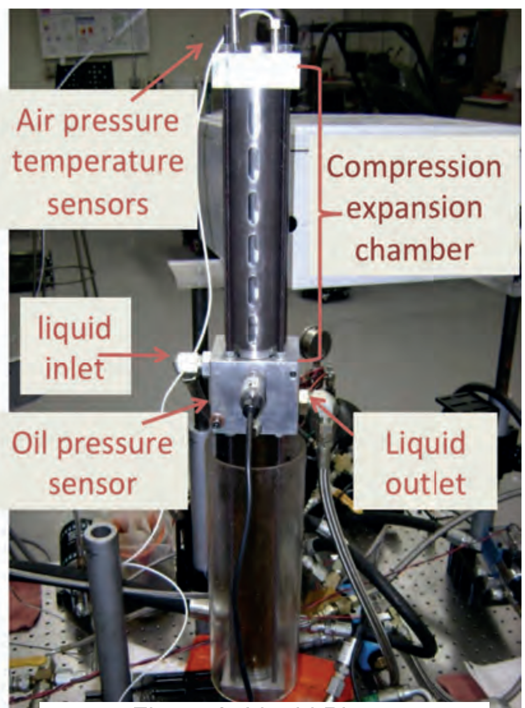

Figure 3: Liquid Piston Compression/Expansion Experiment

Expected Milestones and Deliverables

This project is currently being continued with non-CCEFP funding focusing on large scale wind energy storage.

C. Member company benefits

If successful, significant increase in fluid power energy storage will enable new applications. Our work on improving compressor/expander efficiency-power density will impact those industries as well.

D. References

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2C.2: Advanced Strain Energy Accumulator

Research Team

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Industrial Partners:	Bosch-Rexroth and Gates Rubber

1. Statement of Project Goals

The research objective of this work is to extend the current state of knowledge in the use of strain energy storing materials for the engineering design of compact energy storage devices. Specifically, this project seeks a low cost, low/no maintenance, high energy density accumulator primarily targeted toward a fluid powered automotive regenerative braking system (hydraulic hybrid). As opposed to the open accumulator concept (project 2C.1) requiring a compressor and a compressible fluid power subsystem, the strain energy accumulator will act as a traditional hydraulic accumulator linked only to a hydraulic drive system. This project will focus on extending the energy storing capabilities of accumulators for the specific purpose not of flow smoothing, but of storing large amounts of hydraulic energy with an energy density appropriate for applications such as regenerative braking in passenger vehicles. The envisioned high energy density accumulator will be appropriate for either series or parallel hydraulic hybrid vehicles. The metric for success of the project will be an experimental prototype capable of storing up to 200 kJ of energy (3500 lbs at 35 mph) at a peak power of 90 kW (35 mph to zero in 4.5 second) in a package of acceptable weight and volume for a compact to midsized passenger vehicle (accumulator system energy density >10 kJ/liter). This metric will enable implementation in a passenger vehicle for city driving. Additional significant benefits of this research potentially include solutions to more traditional accumulator problems including cost, pre-charge issues, and fluid contamination from gas diffusion through the bladder.

2. Project Role in Support of Strategic Plan

This project will contribute to the Center's goal of breaking the barrier of a lack of compact energy storage. The task of designing new compact energy storage devices is central to the Center's vision of "significantly reducing energy consumption" by "enabling the migration of fluid power to passenger cars". As identified in a recent NSF site visit, compact energy-dense storage solutions are critical to the success of this migration. This project addresses the knowledge level of this goal (explore new energy density concepts) by seeking a design to provide the enabler (improve energy density of storage mechanisms) and ultimately the needed system capability (reduce size and weight of FP systems to work in passenger vehicles) for this important goal [4]. This project will be demonstrated on Test bed 3.

3. Project Description

A. Description and explanation of research approach

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

Hydraulic accumulators are energy storage devices commonly used to provide supplementary fluid power and absorb shock. One particularly interesting recent application of these devices is regenerative braking. Although a theoretically appealing concept, hydraulic regenerative braking is difficult to implement due to some major inherent weaknesses of conventional accumulators. The primary weakness of spring piston accumulators that prohibits them from being used in hydraulic regenerative braking is their low gravimetric energy density. Using linear analysis, spring steels and titanium alloys have a gravimetric energy density of around 1-1.5 kJ/kg [1]. Consequently, in order to store enough energy to bring a mid-sized 4-door sedan (mass=3500 lb (1590 kg)) to rest from 35 mph (15.65 m/s), the accumulator spring would have to weigh somewhere from 130 kg to 195 kg. In automotive manufacturing, where minimizing vehicle weight is vital, including such a heavy component would be largely impractical.

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

With regard to inefficiency, if the energy stored in the compressed gas of such an accumulator is not retrieved soon, the heat flow from the gas to its immediate surrounding results in much less energy being retrieved. Pourmovahed et al. showed that with as little as 50 seconds passing between gas compression and expansion, a piston-type gas accumulator's efficiency can fall to about 60% [1]. Since a vehicle remains immobile at a stop light for such a length of time or longer, this makes gas bladder and piston accumulators with a gas pre-charge less than ideal for hydraulic regenerative braking applications. Several methods to mitigate these heat losses have been proposed. For PAGP, one promising method involves placing an elastomeric foam into the gas enclosure. This foam serves the purpose of absorbing the generated heat during gas compression that would otherwise be transferred to the walls of the gas enclosure, and ultimately lost. The foam is capable of collecting a large amount of this generated heat and returning it to the gas when the latter expands. According to Pourmovahed, "the insertion of an appropriate amount of elastomeric foam into the gas enclosure…[can] virtually eliminate thermal loss" [2]. Incorporation of elastomeric foam has shown how accumulator efficiency can be vastly improved through slight modification. However, this modification still does not solve the maintenance issues associated with gas diffusion.

The purpose of this research is to investigate a new method of energy storage in a hydraulic accumulator suited for use in hydraulic regenerative braking. Unlike the use of foam, however, our approach departs from existing methods as opposed to modifying conventional technology. The advocated technique involves using strain as the mechanism for energy storage, as in the case of spring piston actuators. The difference from spring piston accumulators comes from the fact that an elastomer is chosen as the working material as opposed to a metal. An elastomeric bag or bladder will be designed and tested for its capacity to store and return energy by stretching in response to a hydraulic fluid being pumped in and out of it. This approach presents a new and unconventional method which aims to simultaneously avoid the susceptibility to heat losses and gas diffusion inherent to gas pre-charged accumulators, while attaining a higher gravimetric energy density than that of metallic spring piston accumulators. This design fundamentally avoids the gas diffusion problem given that the pressure gradient between gas and hydraulic fluid is opposite of that of a gas charged accumulator. Additionally, the design pursed will be advantageous due to low cost, relative simplicity and good manufacturability.

Material Selection

The selection of an appropriate energy storing material for the design of the high energy-density accumulator requires: 1) a high volumetric energy density, 2) a high gravimetric (or mass specific) energy density, 3) the ability to absorb and release the targeted power efficiently, 4) the ability to store the targeted energy efficiently for a duration on the order of minutes. A promising candidate energy storing class of materials includes elastomers such as polyurethane, nitrile rubbers, polyisoprenes, and natural rubber. Figure 1 below shows polyurethane as possessing an order a magnitude better volumetric energy density than steels (springs) and two orders of magnitude better gravimetric energy density than steels. The high elongation percentage of polyurethane' (500% to 700%) allows for a straightforward accumulator design that directly stretches the energy storing material without utilizing a transformer to scale pressure and displacement. Polyurethane also exhibits a fatigue strength of 5000 psi at 10,000,000 cycles.

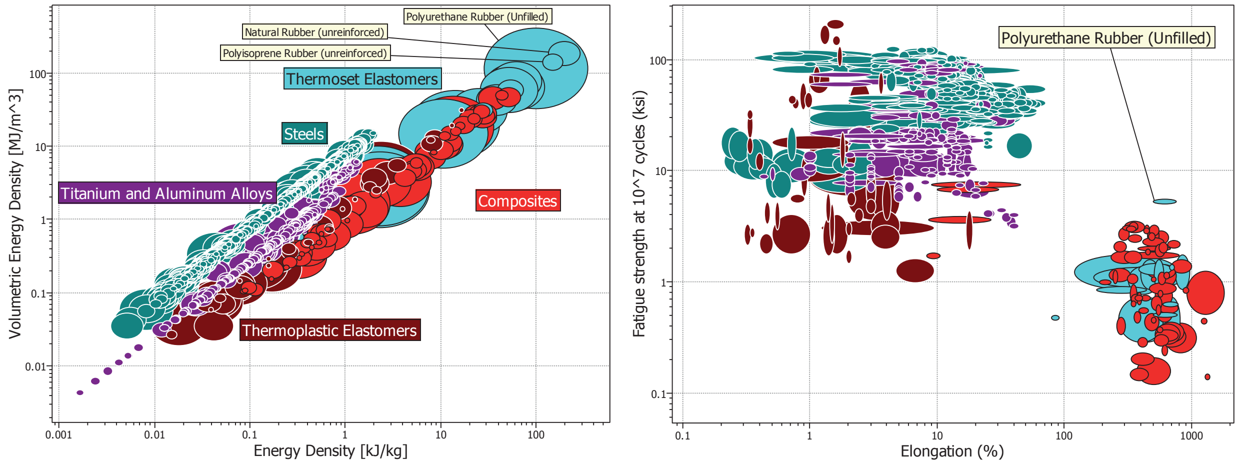

Figure 1: Material property charts (Cambridge Engineering Selector, 2008) showing volumetric energy density, gravimetric energy density, fatigue strength at 10,000,000 cycles, and elongation.

Scientific and Engineering Research Goals

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

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

B. Achievements

Previous to this reporting year, the following was achieved.

A volumetric **system** energy density upper bound was placed on a hydraulic accumulator system. This was done by assuming 1) that power is only transmitted hydraulically (note that this assumption is not the case for the open accumulator), 2) the maximum area under the PV curve occurs at constant pressure (this is not the case for a gas charged accumulator), and that an idea energy storage device occupies no more volume than the hydraulic fluid it stores. The resulting maximum volumetric energy density therefore equal to the working pressure. For a 5000 psi system, this is 34.5 kJ/liter.

A low pressure prototype demonstrated the following. Nearly constant pressure behavior was measured upon charging and discharging the bladder. A pre-strained region of the bladder near the fill port induced a “rolling” behavior along the inside of the shroud. The shroud extended the fatigue life by 4.5 times by limiting the radial expansion to well below the yield point of the material. An 85% round trip efficiency was measured for the latex bladder used.

A hyperelastic finite element model revealed the need to distribute material loading to optimize strain energy storage in the material.

During the reporting period for this year, the following was achieved.

The maximum theoretical thermal losses possible in a gas charged accumulator were compared with measured efficiencies from the literature. Under the assumption that in a gas charged accumulator for applications like regenerative braking in a hydraulic hybrid, the charging and discharging phases occur on time scales at least an order of magnitude faster than the holding times. In such instances, which easily arise when stopping at traffic lights, the heat transfer during the charging/discharging phases is also at least an order of magnitude lower than the heat transfer which occurs during the holding phases. In the extreme this can be captured by modeling the charging and discharging phases as adiabatic. The corresponding holding phase is then treated as occurring over a sufficiently long enough time for thermal equilibrium to be established between the accumulator and its environment. An energetic analysis of this worst case scenario reveals that conventional gas charged accumulators operated in the regime and time scales intended for our target application demonstrate a measured efficiency close to that described by the worst-case scenario. The empirical data point was obtained from charging a 500 psig nitrogen gas pre-charged piston accumulator (piston instead of a bladder separates the working fluid from the gas) to ≈ 3165 psig, and holding it in the charged state for 100 seconds [2]. Its roundtrip efficiency (neglecting frictional loss and only taking thermal loss into account) was calculated to be 60.1 %, as shown with an "x" on Figure 4. For the same pre-charge and charging pressures, the theoretical efficiency is 59.4 %.

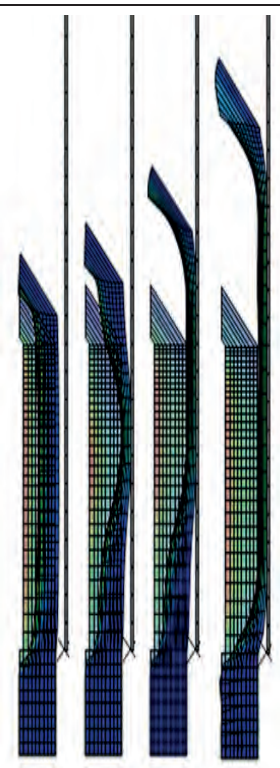

Figure 2: FEA modeling with contact

To justify the bladder configuration over some other configuration utilizing elastomeric strain energy storage, an experimental setup employing a conventional hydraulic piston was used to stretch polyurethane bands. The pressure and flow rate for charging and discharging the actuator were measured, and the device had a measured efficiency of ≈ 63 %. Additional test runs yielded similarly low efficiency values. Energy loss apart from the losses in the material may be attributed to hydraulic actuator piston friction, and friction between the PU cord and the steel plates it was woven through. In comparison, the efficiency of the α-prototype (reported on in last year's report) is about 20 % higher, as it was measured during fatigue testing. These practical tests helped justify the bladder approach as a more direct and efficient route toward storing and retrieving energy over other more complicated configurations.

Further work was performed on FEA modeling of the enshrouded bladder strain energy accumulator concept. Material data was added to the model and the model was enhanced to include dynamic effects and frictional characteristics associated with contact with the shroud. Four simulation frames showing the bladder's reaction to the flow of fluid into its cavity during the charging process are shown in Figure 2. The contours provide a qualitative check against the type of behavior observed during experimentation previously reported on. The second frame from the left shows bubble formation and the frames to the right of it show progressive bubble propagation along the shroud. Figure 2 increases model fidelity since it shows the model to have the same bladder behavior as was physically observed. Specifically, the modeled PV curve showed good agreement with the shape measured in previous tests of the low pressure prototype.

Using material data obtained from CCEFP member company Gates Rubber (NBR 6212), the stress-strain curve of the material showed a theoretical material energy density of 33 kJ/l provided that all of the material was uniformly utilized for energy storage up to the strain utilized from the stress-strain data (which at 450% elongation was well below yielding). Accounting for the hydraulic fluid, this would result in a system energy density of 17 kJ/l. The FEA modeling revealed a material energy density of only 4 kJ/l and a resulting system energy density of 3.6 kJ/l. Further investigation into the model revealed an effective transmission ratio between wall thickness of the bladder and the held hydraulic pressure of the fluid inside the inflated bladder. The thinner the wall, the better the strain was distributed in the material, but the lower the hydraulic pressure in the bladder. This fact necessitated a change in the bladder geometry from the original shape in order to utilize the full material energy density while keeping the hydraulic pressure high. A geometry was needed that could maximally and uniformly strain the material (as seen in the thin wall limit) to maximize material energy density, while concomitantly keeping a high hydraulic pressure. In fact, a geometry needed to be found that could achieve arbitrarily higher hydraulic pressures than maximum material stresses.

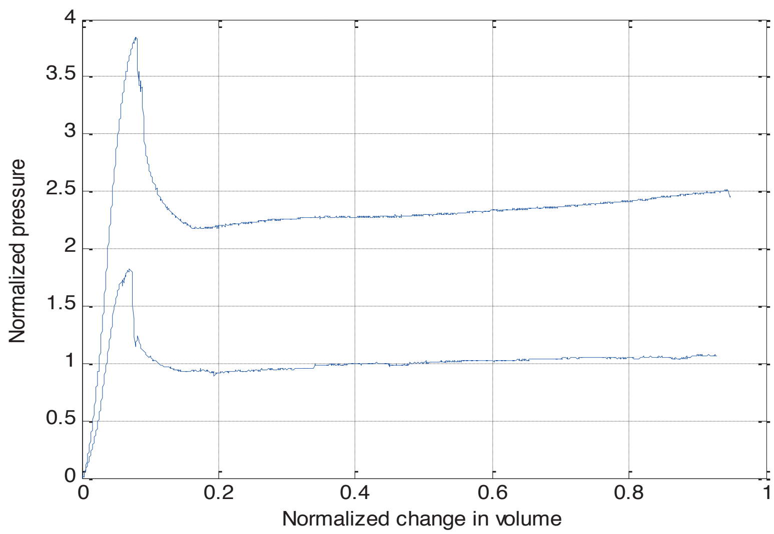

Figure 3: Experimentally measured pressure-volume traces of a concept to amplify hydraulic pressure while uniformly distributing strain in the bladder. The upper trace utilizes twice as bladder material as the lower trace.

Although it is disappointing that it cannot be fully revealed here due to patent and intellectual property issues, such a geometry was found. This is currently being submitted as a patent application and includes collaboration with Wayne Book at Georgia Tech. Figure 3 shows two normalized pressure-volume traces of an experimental setup. The lower trace employs a thin walled bladder that reasonably achieves maximally designed and uniform strain in the material. The second trace shows the new geometry using twice as much material as the first. The volume and pressure scales are the same for the two traces. As is evidenced by the volume under the PV curve, the second configuration also shows maximal and uniform strain in the material (actually with a slightly better distribution than the first) as indicated by the energy storage being doubled for double the material. This geometry is in fact able to achieve any arbitrarily high hydraulic pressure as scaled linearly by the amount of material used. This pressure amplification is limited only by the material properties of the shroud (not an elastomer). Future work will focus on this new geometry.

Expected Milestones and Deliverables

Milestone: FEA modeling completed [5/31/2011]

Milestone: Final prototype 1.x completed [7/31/2011]

- Task: Develop and implement control strategy for smooth controlled power transfer.

Milestone: HIL simulator of braking & accelerating a vehicle [10/31/2011]

- Task: Develop driving scenarios based on EPA driving schedules simulated via test rig. Characterize efficiency for different energy storage levels, power transfer rates, energy retention times (different driving styles/conditions)

Milestone: Metrics measured for prototype 1.x on HIL simulator [1/31/2012]

- Task: Based on the final v1.x prototype's ability to meet the target metrics, either select a new material or begin design for integration into TB3
- Task: Fabricate full-scale prototype for TB3 including all adapters and mounts.

Milestone: Prototype 2.0 completed and ready for TB3 installation [3/31/2012]

Milestone: Metrics measured on TB3 [5/15/2012]

Milestone: Final Evaluation [5/31/2012]

C. Member company benefits

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

D. References

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

Research Team

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Industrial Partner(s):	Orbitec (associated project), Parker Hannifin

1. Statement of Project Goals

The goal of Project 2D is to characterize the structural-thermal-acoustic coupling of three of the five unit-lattice structure types identified earlier to allow for the design of passive, noise-reducing, heat-dissipating fluid-power components. Structural-acoustic and thermal-structural couplings will be defined through virtual testing; and, physical, non-destructive testing for validation of the couplings will be conducted in Year 6. In collaboration with Test Bed 6 and Projects 2B.2 & 3B.1, heat-dissipating/-shielding and quiet PAAFO components will be designed and fabricated in Year 6. Based on research, the target level of noise attenuation by the structure is 9dB, at the "stop band;" however, Project 3B.1's work will complement this for greater total noise suppression. Passive, multi-functional structures will also be applied to components of the Parker PV046 axial-piston pump to integrate the desired noise reduction. Fluid-borne-noise attenuation afforded by the new components will be measured through Project 1G.1. Radiated noise will later be measured by Parker in their anechoic/fully-reverberant chamber, likely in Year 7, followed by potential implementation in both TB1 and TB3.

2. Project Role in Support of Strategic Plan

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

In collaboration with Test Bed 6, Project 2D will work to define a minimal-mass, heat-dissipating and/or noise-reducing structure, to achieve the goals set. While the Rev. 2 PAAFO is near the one kilogram target, the maximum output torque is much lower than desired. Increasing torque output will require a combination of higher pressure, improved efficiency and a larger actuator; therefore, thermal management and structural optimization are critical, regardless of the final choice for portable power generation. Additionally, this active orthosis must be safe and quiet to garner acceptance from the end-user. Component integration, heat dissipation and noise reduction through multi-functional component design will address this as well. Likewise, mass reduction and thermal management afforded by custom, multi-functional components will benefit Test Bed 4.

Hydraulic pumps and motors have been demonstrated to carry significant amounts of "dead weight. With additional considerations for multi-functional components, i.e. heat dissipating and noise reducing, efficiencies would be improved; and, noise would be reduced. Cooler operating temperatures of these devices also result in longer life for their components, and even the hydraulic fluid. Efficient pumps and motors, if light and quiet, are certainly beneficial to the goals of Testbeds 1 & 3, as well.

3. Project Description

A. Description and explanation of research approach

Fluid-power technology's competitiveness/market penetration, despite high theoretical volumetric and gravimetric energy/power densities, is significantly hindered by; the lack of efficient commercial components and the levels of noise generated.

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

Commercial heat sinks are limited by conventional fabrication limitations; and, primarily, do not bear significant structural loads, resulting in dead weight. Seepersad, et al. applied topology optimization to profiles of extruded geometries to determine the optimal load-bearing and heat-dissipating structure, under active cooling, for gas turbine engines [1]. This optimization was simplified by axial symmetry and minimal degrees of freedom. Research has also been conducted for "open-cell," load-bearing lattices as heat sinks, for both forced convection [2] and conductance [3]. The research proposed here will complement this prior work through multi-directional, geometry-dependent characterization of the selected unit-lattice structures for the definition of a load-bearing heat sink of minimal required mass.

In addition to thermal management, cellular materials are also used for noise suppression. Polymeric foam is a ubiquitous example; however, this material, primarily, absorbs the energy through cyclical mechanical loading of the polymer. The low stiffness and conductivity also significantly limit their application for load bearing and heat dissipation. Carbon and metal foams are much stiffer and more thermally conductive than their polymer counterparts [4]; but, tailoring of their properties to meet a specific application is exceptionally difficult. An engineered lattice can be optimized to meet the structural, thermal and noise-suppression requirements, and fabricated via additive manufacturing methods. This also allows for the integration of other component geometries into the lattice structure, such as the outer case of a pump, motor, actuator, valve, etc.

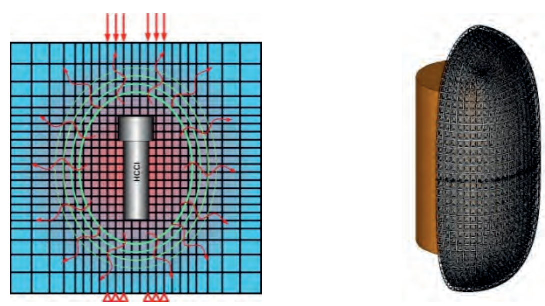

Figure 1: (Left) Sketch of the HCCI engine with an integrated noise-filtering and heat-dissipating structure to improve acceptance and safety when in proximity to people. (Right) Automated population of a "conformal" structure using the Ultracube and Cube in two successive layers.

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

B. Achievements

Structural optimizations:

Mass minimization was demonstrated for a commercial axial-piston-pump housing through structural optimization. Weight reductions of >20% and >40% were achieved using the properties of cast iron and titanium, respectively. Structural optimization was also applied to the geometry of the custom

PAAFO actuator to demonstrate the potential for additional weight reduction (Figure 2). Two papers have been written based on this custom, integrated actuator design [5, 6].

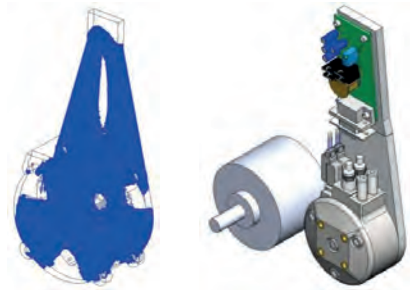

Figure 2: Topological optimization of an early revision of the custom actuator design (Left). As shown, additional mass reductions were possible (void areas). The bolt placement in the final design (Rev. 2, Right) resulted from this analysis.

Unit lattice characterizations:
The nine (9) geometry-dependent constitutive relations were completed for each of the five unit-lattice structures previously identified (Figure 3). Through future efforts these relations will be defined such that after an optimization routine, the constitutive relation matrices can be used to size the struts of the individual lattice unit cells, and the resulting masses of each will allow for selection. Two papers have been written based on the results of this work [7,8] and several presentations given.

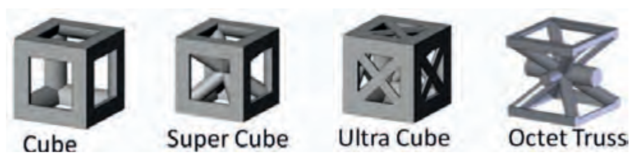

Figure 3: 4 of the 5 lattice unit cells in the automated structure-generation algorithm. Each hexahedral unit cell is comprised of eight mutually-orthogonal unit lattices. The “Hypercube” is not shown here.

Automated, stress-field-directed, minimal-mass, structure generation:
Project 2D worked to develop algorithms that would allow for the automated generation of a minimal-mass structure from the output of a finite-element analysis. At the end of Year 4 of the CCEFP, one database-driven approach allowed for the discretization of the stress field into iso-surfaces, and subsequent discretization of those surfaces into regions. Corresponding regions from one iso-surface to the next were then to be connected; however, additional routines are necessary to ensure alignment of these connections to the primary load path (Figure 4). The proposal to continue these efforts in Years 5&6 of the CCEFP as Project 2D.X was not accepted; but, other funding sources are being pursued. Two papers have been written based on the results of these efforts [7, 9].

Figure 4: Preliminary automated generation of 3-D multi-functional structure. (Left) Concept model, fabricated on MSOE-RPC’s SLS. (Right) Preliminary database-driven algorithm output.

Automated conformal structure generation:
In the near term, off-the-shelf software will be used for automated, conformal structure generation through scripting. Figure 5 shows an example of a conformal Cube-lattice structure generated in this manner from an arbitrary surface. This surface will be replaced by the combined geometries of the leg, the heat source(s), in the regions required for heat dissipation and noise suppression, and

Project 3B.1's exhaust routing. Combining this with structural optimization for regions of purely structural performance, a multi-functional, integrative orthosis structure will be generated.

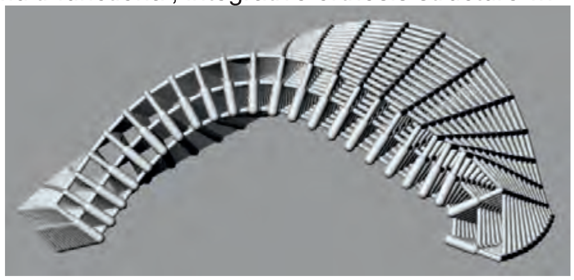

Figure 5: Automated conformal structure generation using the Cube lattice unit cell. As shown, the struts are sized independently in each of the orthogonal directions, at each layer.

Heat-transfer characterization:

To achieve multi-functional designs for complex geometry, without large cluster-computing requirements, Project 2D is currently working to define "bulk" thermal-conductivity characterizations for the Cube, Super Cube & Ultra Cube lattice unit cells, in six directions. An entire hexahedral element can be represented by the structural and conductivity constitutive matrices, then, rather than necessitating the further discretization of the structure and fluid within.

These characterizations are determined for simple conductivity and internal natural convection (Figure 6) as a base-line approximation of the performance of the final structure. Certainly, cross-flow between unit cells, entrained flow or even forced convection will improve heat transfer. Radiant heat transfer is neglected at this time.

Applying a thermal gradient, dT, across a unit cell, dx, and measuring the resultant heat flux, Q', through the cross section, A, one can determine the effective thermal conductivity, k, of the unit cells, including the combined conductivity of the solid and fluid (Schneider; Yu). This has been determined through virtual analyses for three of our structures: the Cube, Supercube, and Ultracube (Figure 3).

$$k\left[W/_{m\cdot K}\right] = \frac{Q' dx}{A\,dT}$$

Noise-suppression characterization:

The 2010 Summer REU research investigated the relative performance of metal foam to lattice structures as suppressors of noise. It was found that metal foam can achieve greater attenuation, through a depth of several centimeters, than a "sonic crystal" [10-19]. Viscous losses in the fluid absorbed the most acoustic energy within the foam's cellular structure, rather than destructive interference from reflection or local resonance. It was then concluded that the lattice structures could be scaled to the same average cell size to achieve noise suppression, while retaining the flexibility of customization for multi-functional operation.

Plans for next year:

- A presentation will be made at the 2011 International Fluid Power Expo (IFPE) to inform the general fluid-power community of the potential benefits of high-performance, multi-functional design of components. It is expected that this will foster support of the CCEFP, and generate opportunities for associated projects.
- The impact of internal natural convection within the unit on the thermal performance of the structure will be investigated in greater depth. Preliminary analyses suggest that the resultant convection currents absorb some of the heat, serving as a means of cooling for the heat source, without forced convection.

  This operation does not scale linearly; so, analyses must be conducted at multiple thermal gradients and length scales. Through the 2010 Summer REU work done in association with Project 2D, it was determined that a unit cell of approximately $(2.54\text{mm})^3$, would be good for noise damping.

Additionally, this operation must be investigated at varying orientations of the unit cell with respect to the principal direction of the thermal gradient. When designing components for heat dissipation, the local thermal gradient will be factored into the selection and scaling of the unit cells, based on effective thermal conductivity and potential for energy absorption through the generation of internal convection currents.

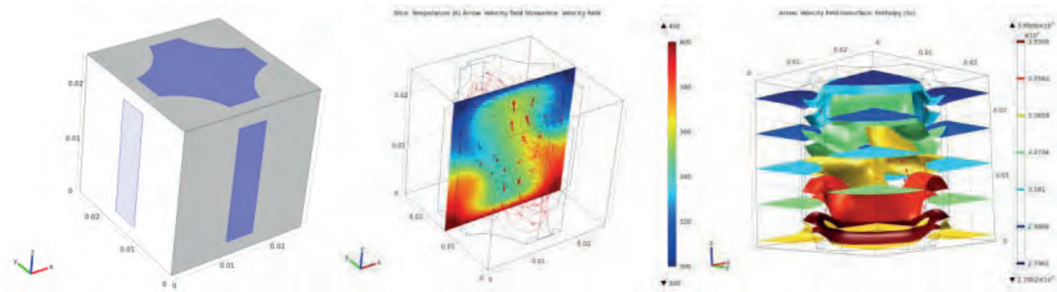

Figure 6: The 400K-to-300K thermal gradient across the 2.54cm unit cell of aluminum (gray) and air (blue) (Left) generates a fluid flow, driven by the buoyancy changes of the fluid as it is cyclically heated and cooled (Middle). This is evident in a plot of the enthalpy within the system (Right). The fluid circulation is lost work (unless it can somehow be harvested), and is a means of "absorbing" heat from sources, up to the order of 0.2W for a $(2.54cm)^3$ cubic volume ($12mW/cm^3$).

- Sample structures will be fabricated and tested for validation of the thermal-characterizations. This is one potential project for the 2011 Summer REU participant.
- Numerical and CFD analyses will be conducted to characterize the performance of the unit cells as noise suppressors at the 2.54mm length scale for 300Hz and 13 KHz, the operating frequencies of typical hydraulic pumps and the HCCI engine, respectively.
- A simple demonstrator for the application of lattice structures as noise-suppressors will be developed to validate the characterizations. This is another potential 2011 REU project.
- Collaborative efforts with TB6 will consider revisions of the custom actuator for improved efficiency, including energy recovery & harvesting. There is potential for the implementation of a "Walking Engine" thermodynamic cycle for the orthosis, proposed by Mr. Cook in 2009. This cycle will be disclosed by the end of Year 5 to allow for implementation on the test bed. The efficiency improvements afforded by this cycle are currently being investigated at UIUC. Thermoelectric energy harvesting will also be investigated as a means of improving overall efficiency.
- With the HCCI engine scheduled for completion in August 2011, a noise-reducing structure will be generated, in collaboration with Project 3B.1, for the integration of the engine into the orthosis, or as a separate wearable unit.
- Noise-reducing hydraulic pistons will be investigated, including collaboration with TB1 on additional improvements for these, and other pump/motor components. Piston fabrication and testing will occur in Quarter 3-4 of Year 6.

C. Member company benefits

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

High-performance and/or multi-functional component design concepts will be shared with the Center as well, generally as I.P. The interested member companies can tailor the designs for their specific needs, either on their own, or through associated projects. Members having their own concepts may also work with Project 2D to develop them, through associated projects.

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

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1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

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

Past Work. The need for a systems engineering framework for fluid-power systems has been recognized before with initial work by Krus et al. [1, 17-19] at Linköping University, Tilley et al. [3-4, 7, 9, 26-27, 34] at the University of Bath, and da Silva et al. [5-6] at the Federal University of Santa Catarina (Brazil), with more recent work by Pedersen [25] at Aalborg University and Schlemmer et al. [30-31] at the Technical University of Aachen. In this related work, the focus has been on traditional optimization approaches with a model of the objective at a single level of abstraction, sampled by the optimizer as a black box model, implemented in an imperative (rather than declarative) programming language. In addition, the work has focused almost exclusively on the modeling of the fluid power aspects of the system with only a few efforts allowing for seamless integration with other disciplines (e.g., structural mechanical, thermal, electrical, controls). Finally, the past work either focused on optimization of the sizing parameters of a specific architecture, or used expert systems to guide the selection of a feasible architecture. The efficient exploration and optimization of system architectures has not been addressed.

A new approach. In this project, the approach for realizing a systems engineering framework for fluid-power systems is based on the formal, declarative representation of knowledge. By capturing the knowledge formally, it can be more easily reused, allowing the cost of capturing and modeling the knowledge to be amortized over many re-uses. In addition, by representing the models in a declarative form (i.e., an implementation-independent formalization of the mathematical relationships), the models can be transformed, combined, and symbolically manipulated to create and solve system-level models that are larger and more comprehensive than could be practically achieved otherwise. Advanced solvers, such as Mixed-Integer Non-Linear Programming (MINLP) solvers or Equation-based Object-Oriented solvers for Differential Algebraic Equations can then symbolically manipulate the declarative equations to solve large system-level models much more efficiently than can be achieved with the current state of the art, i.e., imperative Matlab models with iterative optimizers. The combination of well-structured and formal modeling languages with model repositories and advanced solvers enables the design of fluid-power systems with a level of thoroughness and efficiency that was previously unachievable in both broadness of exploration and depth of analysis.

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

B. Achievements

In the past year, we have made significant progress towards the development and implementation of the different components of the framework in Figure 1. We have implemented this overarching framework in a fashion that can be easily applied by others within the CCEFP and that can be transferred to industry. The different layers of the framework have been integrated into a state-of-the-art commercial tool called ModelCenter by Phoenix Integration [20]. The model transformations for updating the optimization

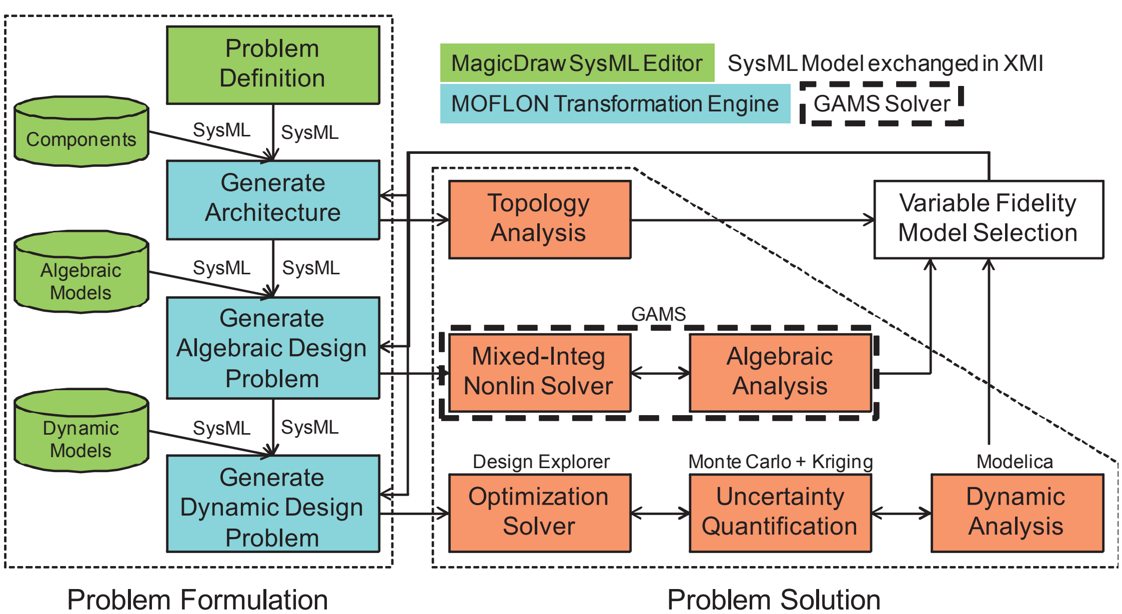

Figure 1: An overview of the proposed three-layer systems engineering framework.

problem have been integrated within ModelCenter so that updated optimization problems can be generated dynamically, within ModelCenter during the execution of the architecture exploration process. The metamodels, model libraries and corresponding model transformations have been described in [14], which was selected as the best paper of the 4th International Multi-Paradigm Modeling Workshop. An extended version of the paper has been submitted for inclusion in a volume of the Lecture Notes in Computer Science series [15].

Synthesis of System Architectures: From the components available in the model repository, one can configure different circuit topologies. We are investigating three different approaches for synthesizing architectures: design grammars [13], Markov Logic Networks (MLN) [28], and Mathematical Programming [35]. The goal is to determine which of these three approaches best unites optimization efficiency with the ease of expressing the domain knowledge. In our past work, we have used a generative design grammar to encode synthesis knowledge for the fluid-power domain [13]. However, it has become clear that the domain knowledge (i.e., What are promising fluid-power circuits for a given problem?) is not conveniently expressed in grammatical rules. It is specifically challenging to qualify carefully in which context a particular rule is applicable. As an alternative, we have explored an approach for synthesizing architectures based on Markov Logic Networks (MLN) [28]. In MLN, the domain knowledge is expressed not in grammatical rules, but as logical constraints that need to be satisfied for meaningful fluid-power circuits. The need for careful qualification of the applicability of these design constraints is relaxed by associating a probability with each constraint. An expert can qualify the constraint by indicating (with a weight) how likely it is that the constraint needs to be satisfied in the final circuit topology (e.g., a weight of 10 in the constraint 3 below). The fluid power domain has been modeled as consisting of components of different types, with ports that can be connected to each other, and with pressure and flow states that specify logically how fluid can flow through the components. The constraints representing this knowledge include logical assertions expressing the basic knowledge of the domain (e.g., constraints 1 and 2), assertions characterizing the inventory of components within the domain (e.g., constraint 5), and assertions defining what makes a plausible circuit (e.g., constraints 3 and 4).

```
1. componentHasType(component, compType!)
2. isConnected(x,y) <=> isConnected(y,x).
3. 10 providesFlow(x,s) => !receivesFlow(x,s)
4. isConnected(x,y)^receivesFlow(x,s)^!providesFlow(y,s)=>circuitHasType(k,Inval)
5. compType = {Load, Cylinder, Valve, Pump, Tank}
```

In an initial tests, a handcrafted MLN consisting of about 200 assertions successfully generated plausible circuits consisting of up to 8 components. The solution time ranged from a few seconds to 5 minutes. As compared to grammar-based approaches, MLNs have the advantages that efficient algorithms have been developed for learning also. Rather than explicitly defining the constraints and corresponding probabilities, the constraints could thus potentially be learned from a sample of existing circuit topologies. The learning ability will be explored further in future work.

A second new approach for capturing synthesis knowledge is based on Mathematical Programming [35]. The development of this approach occurred in two stages. First, we developed a method for sizing the components in a given (fixed) system architecture. Using formal model-transformations, the given system architecture is combined with algebraic models retrieved from a model library to automatically generate a model of the system requirements as a Mixed Integer Non-Linear Programming (MINLP) problem [10, 16]. Although such a MINLP model represents only a rough approximation of all the design objectives and requirements, it is still valuable because it can be solved very efficiently. By expressing the system behavior in declarative equations (rather than in a Matlab implementation), a solver such as BARON [29] in GAMS [2] can symbolically manipulate these equations and efficiently solve for component sizes that meet all objectives and requirements [32-33]. In a second stage, we are investigating the use of Mathematical programming not only for component sizing but for architecture synthesis also. Logical constraints (similar to the ones used in the MLN approach) can also be expressed in terms of algebraic equations. For instance, $A \rightarrow B$ (A implies B) can be represented equivalently in normal form as $\neg A \vee B$ (not A or B). This can be further transformed into $(1-A)+B \geq 1$, a linear inequality constraint in which A and B are integer variables that can be either 0 or 1 representing false or true. Through this transformation of logical constraints into algebraic constraints, the space of possible system architectures can be defined and searched using Mathematical Programming tools. We have implemented the same problem as for the MLN approach described above and found that the BARON solver in GAMS requires less than 1 minute to find a feasible solution, which is similar to the time required for solving the problem using the MLN solver.

When comparing the three approaches, the Mathematical Programming approach is the most promising based on the initial results. As compared to the two other approaches (design grammars and MLN), the Mathematical Programming approach has the benefit that it can combine the component-sizing problem with the architecture-exploration problem, solving the first two layers in the framework in Figure 1 simultaneously. While MLN and design grammars can generate plausible architectures quickly, they do not take into account all specific requirements expressed for a particular problem (e.g., required forces or velocities of individual functions). As a result, they require a nested sizing optimization to determine the component sizes and corresponding performance metrics. This can be computationally expensive. Note, also, that the mathematically optimal architecture and component sizes obtained by any of the three approaches are only good guesses for the particular problem due to the approximations made in the mathematical models. These guesses serve well as starting points for further analysis with more detailed models.

Detailed sizing optimization under uncertainty: The result of solving layers 1 and 2 in Figure 1 is a promising architecture with reasonable component sizes. To refine the solution further, a more detailed (and hence more costly) analysis is required. Similar to the model transformation approach used to generate algebraic models, a model transformation approach is used to generate system level dynamic models. This is possible thanks to the port-based, object-oriented nature of the Modelica language [8]. We have developed a Modelica library for fluid-power systems [24] and a mapping from SysML to Modelica to enable the automated generation of system-level models [10-11]. The computational cost of such dynamic simulations can be significant, especially when combined with uncertainty quantification. We have therefore developed an algorithm that uses a value of information metric to decide which analyses to perform at each step in the optimization/design process. We call this variable-fidelity optimization.

The approach is based on approximating Gaussian process (kriging) models combined with incremental search-space sampling based on a value of information metric. To incorporate models at multiple levels of fidelity, and hence improve the speed/cost of optimization [21-22], we have extended the kriging modeling approach [23]. Traditional kriging models are interpolation methods. To support multi-fidelity modeling, the kriging method has been adapted to allow for fitting (rather than interpolating) an approximate model based on samples with only limited accuracy and for which the accuracy may vary from one sample site to the next. In our algorithm, the surrogate model for the objective function has the following structure: $y = F^T\beta + \varepsilon + \varepsilon_m$, where $F^T\beta$ is a regression model, ε is the difference between the true objective and the regression model, and ε_m is the error between the true objective and a prediction from one of the (multiple accuracy) simulation models. As compared to traditional kriging modeling, it is the addition of the ε_m term that allows for multi-fidelity fitting. Both ε and ε_m are represented by Gaussian processes. They are assumed to have a static correlation structure that reflects that the errors, ε_m, if originating from different simulation models, are uncorrelated with each other and are also uncorrelated with the regression error, ε. Our approach is different from the seminal work by Kennedy and O'Hagan [12] in that this correlation structure simplifies the maximum least-squares estimation and does not impose the constraint that high-fidelity models can only be sampled at points where low-fidelity models have already been sampled. We have developed an implementation of this algorithm in Matlab and the initial results are very promising (see Figure 2).

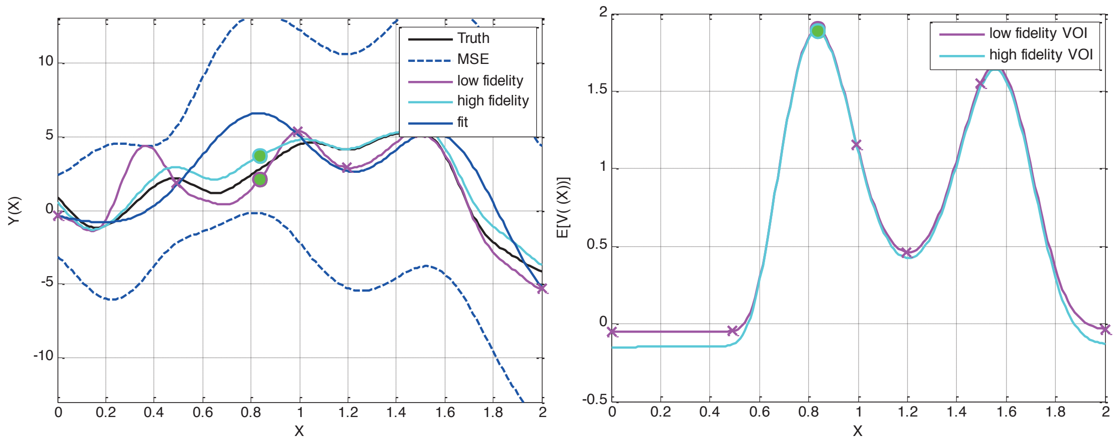

Figure 2: A step in the multi-fidelity optimization algorithm. The green circle indicates which point will be sampled next. As more samples are gathered, the fit (blue in left graph) approximates the truth (black) more closely. The algorithm terminates when the value of information (right graph) is negative everywhere.

Next Steps. In the coming year, we will build on our recent advances in the following directions:

- More detailed comparison of the three synthesis approaches: Through the use of larger-scope test problems, we will compare the performance of the three approaches according to both scalability and expressivity. Scalability will be characterized by measuring the CPU time required for solving test problems of increasing size, and by assessing the corresponding solution quality. It is expected that there will be a tradeoff between run-time and solution quality. The expressivity will be measured by the ratio between the number of intended system architectures and number of system architectures allowed by the representation approach.
- Extension of the algebraic formulations for the design of fluid power systems: Since many of the requirements of behavior in fluid power systems involve systems dynamics, we will investigate to what extent such dynamics can be accommodated in an algebraic modeling framework. Formulating the dynamics in terms of time-discretized algebraic equations is important because it allows the dynamic equations to be solved as boundary value problems, so that one can solve for component sizes efficiently.
- Extending the variable fidelity optimization algorithm: In the coming year, we will extend our implementation of the optimization algorithm to multiple dimensions. This will likely pose challenges in terms of the robustness and efficiency of the algorithm for fitting kriging models. However, given the computational cost of determining the objective function under uncertainty, the expense of the optimization algorithm is likely to be justifiable.
- Case studies: For testing and validation of the proposed framework, we will apply it to the hybrid vehicle test bed (TB-3). It is clear from the current work on the vehicle that the performance predictions depend strongly on a combination of drivetrain architecture, component sizing, and control strategy. In the current approach, each of these aspects has been considered individually, but because of the complexity of the problem, multiple aspects have not been considered in an integrated fashion. TB-3 will serve as an ideal test bed for this project: it will serve as a validation platform for the systems engineering methods and tools, while at the same time, it will benefit itself from the improved quality and reduced risk resulting from a broader and more detailed exploration of the design space.

C. Member company benefits

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

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2F: MEMS Proportional Pneumatic Valve

Research Team

Project Leader: Prof. Thomas Chase, Mechanical Engineering
Graduate Student: Nebiyu Fikru
Industrial Partners: Bimba Manufacturing and Enfield Technologies

1. Statement of Project Goals

The goal of this project is to create an efficient miniature proportional valve for controlling air flow in pneumatic systems based on Micro-Electrical Mechanical Systems (MEMS) technology. The valve is intended to operate at pressures up to 7 bar (700 kPa / 100 psi) with a pressure drop of no more than 1 bar (100 kPA / 14.5 psi) when operated at a flow rate of 40 slpm in the fully open state. Actuation efficiency is equally important to fluidic efficiency: the goal is to be able to hold a normally closed valve in the fully open state with an actuation power of 1 watt or less. The target envelope of the valve is 1 cm^3.

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

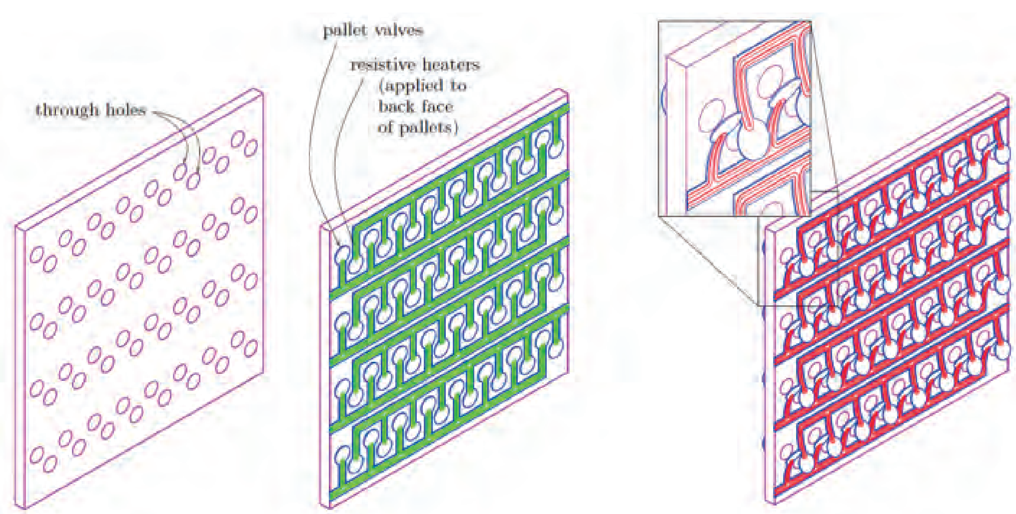
2. Project Role in Support of Strategic Plan

The contribution of this project is primarily in the area of compact integrated systems. However, the project also has potential to contribute to the center's goals of efficient components. Few pneumatic valves are available in the size range which is applicable to miniature fluid power systems, such as Test Bed 6. The proposed project is focused on developing a valve which improves on the compactness of the existing valves while also decreasing the power required to actuate it. Furthermore, the project will push the boundaries of reducing leakage through MEMS-type valves. Surmounting these barriers is helpful to advancing the feasibility of the Ankle-Foot Orthosis in Test Bed 6.

3. Project Description

A. Description and explanation of research approach

The concept of the MEMS proportional valve is introduced by reference to a visualization of the potential valve architecture, as shown in Figure **1:** Visualization of a MEMS proportional pneumatic valve.Figure 1. However, please note that the final valve architecture may differ substantially from the initial concept shown here.



(a) Port plate (b) Fully closed state (c) Fully open state

Figure 1: Visualization of a MEMS proportional pneumatic valve.

The valve is a two way normally closed proportional valve. The foundation of the valve is a port plate (Figure 1(a)). The port plate includes a matrix of through holes. The plate is placed in line with a pneumatic tube or channel. The air or other pneumatic working fluid flows freely through all holes in the fully open state. The fully open pressure drop is approximately equal to the resistance through all the holes in parallel.

Each through hole is equipped with a pallet valve (Figure 1(b)). The example embodiment shows each valve cantilevered off of a simple straight arm, but other valve support designs are possible. In the fully closed state, all through holes are completely closed by the pallets.

Commercial valves are characterized by their valve capacity (C_{valve}), a measure of the maximum flow rate of the valve for a given pressure drop. Flow rate depends on valve orifice size. Therefore, a MEMS based valve with macro flow capacity must have an effective orifice size which is equivalent to the non-MEMS based valves. For example, Enfield's LS-V05s, currently used in TB6, has a maximum aperture area of 5 mm^2. Unfortunately, microactuators cannot overcome the force imposed by pneumatic fluid passing through an orifice of this size.

This design is unique in obtaining macro-scale gas flow rates by ganging hundreds or thousands of micro-scaled actuators and orifices in parallel within a single flow stream. The effective orifice size is a composite of the individual orifices. The actuators and orifices can then be fabricated using MEMS type batch fabrication techniques. The primary benefit of this approach is that the resulting valve package is extremely compact and lightweight. Exploiting MEMS fabrication methods also enables the valve to be fabricated at low cost.

Proportional control of the flow can be obtained in either of two forms using the architecture suggested in Figure 1. First, all pallets can be partially opened by the same amount simultaneously. Second, a variable fraction of the valves can be fully opened. The second option requires wiring each actuator independently.

The state-of-the-art in miniature pneumatic valves is summarized in Tables 1 and 2. Table 1 reviews non-MEMS-based miniature valves. Table 2 reviews MEMS based valves. The tables illustrate that the flow rate capacities of the MEMS based valves proposed to date are two orders of magnitude smaller than the conventional valves. The maximum operating pressure is also typically much lower for the MEMS based valves.

To date, no MEMS based valve is available to replace traditional general purpose valves. Almost all MEMS based valves have been designed for some specific micro-scale application such as lab-on-a-chip systems [1-3], drug delivery [4], refrigeration [5], fuell cell [6,7] or micropropulsion [8,9].

Manufacturer	Model	Maximum Inlet Pressure (bar)	Flow Rate (slpm) for 6 bar venting to 5 bar
Enfield Technologies	LS-V05s	10	125
Clippard	EVP Series (0.04" dia)	3.5	14.3
Parker-Hannifin	HF Pro	3.5	31
IQ Valves	Standard PFCV (0.147)	9.3	114.2

Table 1: Flow rate capacities of non-MEMS based valves

Reference	Maximum Inlet Pressure (bar)	Flow Rate (slpm)
Kohl et al. [10]	2.5	0.36
Rich and Wise [11]	2	0.4
Yang et al. [12]	2.07	1.3
Fu et al. [13]	2	1.9

Table 2: Flow rate capacities of MEMS based valves

B. Achievements

This is a new project which began in June 2010. Accomplishments to date include: completing a literature review, re-scoping the project from the original proposal, developing a meso-scale concept demonstration prototype, benchmarking competitive valves, developing a design specification, designing a test stand, and developing modeling methods. These accomplishments are described in order below.

The project was begun by performing an extensive literature review to evaluate the state-of-the-art in MEMS pneumatic valves. This review was used to generate a paper with over 90 references which is to be presented at the 2011 National Conference on Fluid Power [14].

Re-scoping was implemented because of the arisal of an unforeseen opportunity for efficiently developing the proposed valve. In particular, we have modified the project plan to include the design and testing of a “meso-scale” valve which is sized between the macro- and micro-scales. The drivers for this change are described in the next paragraph. Furthermore, this addition warrants the development of a test stand for usage early in the project, where we had originally proposed its construction near the end of the project.

Piezo-electric materials provide a leading candidate for implementing the valve actuators due to their energy efficiency and fast response time. However, fabricating piezo-electric materials on the MEMS scale is challenging. Nevertheless, we discovered that 127 μm thick sheets of PZT, a piezo-electric material with a high ratio of deflection to applied voltage, can be purchased. While this stock material is too thick for utilization in a MEMS based valve directly, it is small enough to build a meso-scale valve having many of the characteristics of a MEMS valve.

Constructing the meso-scale valve enables us to develop a concept demonstration prototype early in the project. Its features are large enough to fabricate using conventional machining processes but small enough to be useful toward validating design models being developed for the final valve. We are in the process of finalizing the meso-scale piezoelectric valve at the time of this writing. A CAD model of the actuator, port plate and test stand housing is shown in Figure: 2.

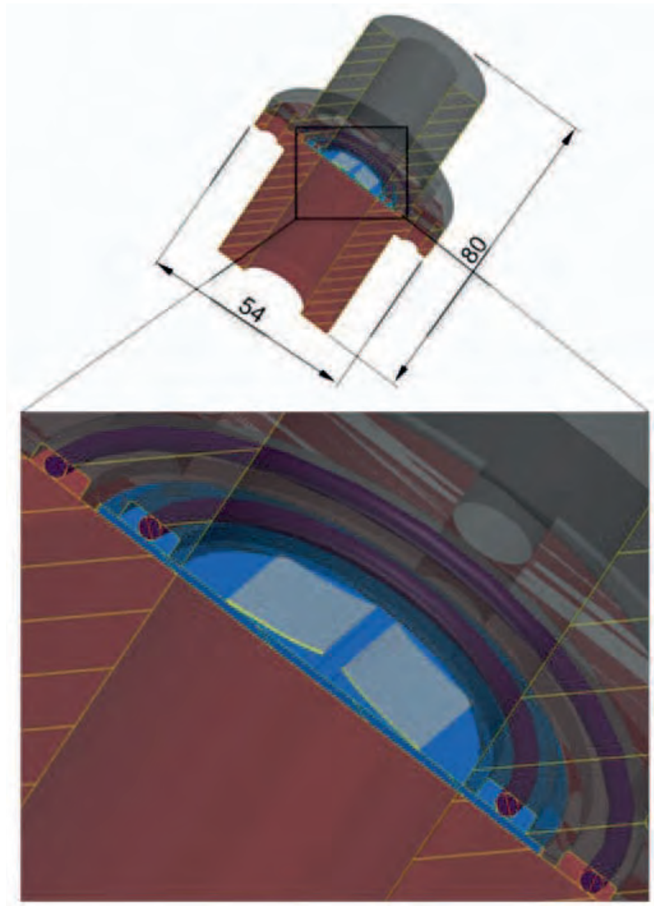


Figure: 2: Meso-scale concept demonstration prototype

We have completed a benchmarking chart of miniature pneumatic valves as part of determining the specifications for our valve. The benchmark specifications were derived from the vendor literature rather than actual testing. The flow rate values are estimated for an operating pressure of 6 bar venting to 5 bar. This baseline was chosen to compare all valves on an equal basis. However, some of the valves are not designed to withstand 6 bar. Therefore, flow rate values of these valves have been extrapolated from the manufacturer's data.

Target specifications for the final MEMS valve were developed by simultaneously considering the results of the literature review, the benchmarking chart and the target application of project TB6, the ankle-foot orthosis.

A test stand has been designed which is capable of testing both the meso-scale concept demonstration prototype and MEMS scale valves. A schematic of the stand is provided in Figure 3: Test stand architecture. The stand has been designed to conform to a relevant international standard, ISO 6358 [15]. The test stand utilizes stock components, except for the valve housing. The housing has been fabricated. We expect to have an operational stand by the end of the reporting period.

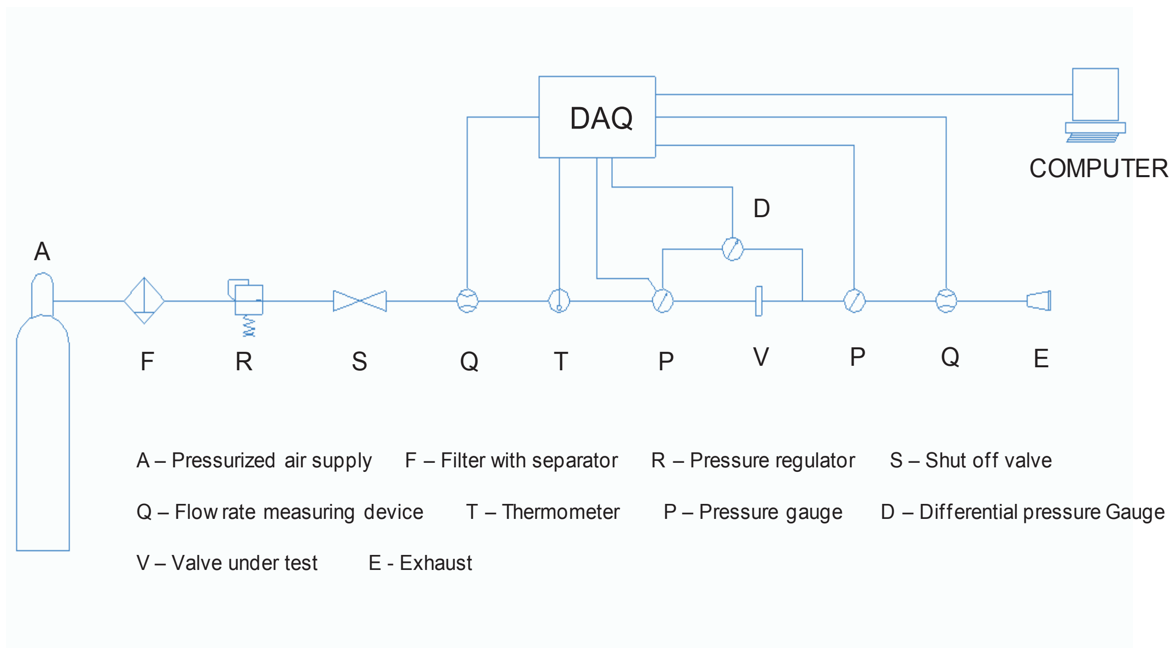


Figure 3: Test stand architecture.

The final accomplishment is the initialization of models used to support the design. We have developed basic models for the leading actuation strategies: piezo-electric, thermomechanical and electrostatic. The piezo-electric model is being used to size the orifice plate and actuators for the meso-scale concept demonstration prototype.

Plans for the next year include: fabricating and testing the meso-scale prototype, selecting an actuation strategy for the MEMS-based valve, and fabricating an alpha prototype of the MEMS scale valve.

Revised Major Milestones:

- Bench test setup completed – January 2011
- Concept demonstration prototype fabricated – April 2011
- Concept demonstration prototype tested – July 2011
- Actuation strategy selected – September 2011
- Alpha prototype constructed – December 2011
- Proportional controller demonstrated - March 2012
- Integration of MEMS valve into TB6 – July 2012

C. Member company benefits

CCEFP member companies can 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-level flow devices.

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

Research Team

Project Leader:	Prof. Robert J. Webster III, Mechanical Engineering, Vanderbilt Prof. Jun Ueda, Mechanical Engineering, Georgia Tech
Other Faculty:	Prof. Vito Gervasi, Rapid Prototyping Center, MSOE Prof. Eric J. Barth, Mechanical Engineering, Vanderbilt Prof. Yuichi Kurita, NAIST, Japan, Visiting Scholar, Georgia Tech
Graduate Students:	Diana Cardona, Melih Turkseven
Undergraduate Students:	Mohammad Rahman, Timothy McPherson, Sana Ali
High School Teachers (RETs):	Gabe Sterling, Sean Donnelly
Industrial Partners:	Martin Companies, Charlie Martin, CEO

1. Statement of Project Goals

The objective of the research 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 excellent 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 can be an essential enabler in both contexts, because traditional electromagnetic actuators fail (or cause artifacts in) intense magnetic fields. This research could open an entirely new industry to fluid power: Medicine (~1/6 of the Gross Domestic Product of the USA).

2. Project Role in Support of Strategic Plan

Fluidic energy transmission holds the promise of being an effective method of transmitting energy during imaging in an MRI where no other method exists today. The major technical barriers that are being targeted relate 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 in a medical application (new force sensors will ensure human safety when interacting with machines in an MRI). A successful demonstration of the technology will help to break a transformational barrier by applying fluid power in medicine. This aligns with the CCEFP vision "of transforming and fully exploiting fluid power into a compact, efficient and effective source of energy transmission."

3. Project Description

A. Description and explanation of research approach

MRI-compatible Actuators and Surgical Robots (Vanderbilt)

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

fMRI-compatible Sensors and Haptic Device (Georgia Tech)
Magnetic resonance imaging is one of the most useful methods available to study neuroscience, evaluate rehabilitation therapies, and perform image-guided interventions and surgeries. Functional MRI (fMRI) is a new technique that can observe the brain structure activities by measuring blood flow in a certain area such as motor cortex. Actuation and sensing technologies usable 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. A nonmagnetic fluid-powered haptic device that interfaces with a patient during an fMRI procedure is considered suitable.

Approach: This project will explore fundamental pneumatic control problems posed by the MRI environment. This is a different scale, which has different constraints than many existing fluid power systems today. The project will explore closed vs. open loop control of various MRI compatible systems and line dynamics will be interesting topics to study from a theoretical perspective. This project will study the interaction of design and control working to answer the open research questions: Is it possible to design your way out of a control problem using a pneumatic stepper motor for example? Are there particular designs that are more challenging to control, but offer performance benefits if such control is done well? Similarly, the medical environment itself poses interesting problems, as fluid power systems must be designed to be efficient, small, clean, and able to be sterilized, which are unique requirements. Furthermore, we intend to develop an analytical model that efficiently simulates complex dynamics of the integrated system for optimization. The project will develop a design methodology that resolves problems associated with the use in MRI/fMRI, in particular, limitation of space, non-magnetic requirement, and limitation in control/sensing.

B. Achievements

B.1: New design of MRI compatible actuators and systems

The basic concept of MRI compatible fluid powered surgical system is illustrated on Figure 1-1.

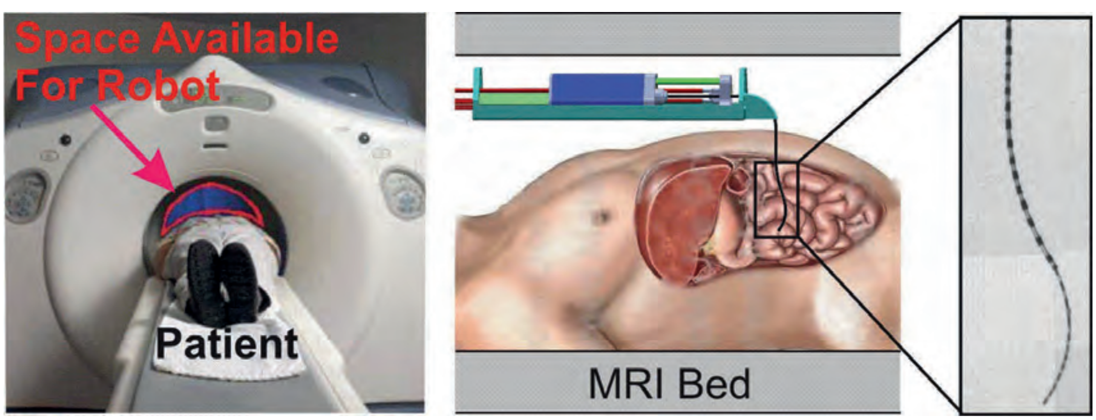


Figure 1-1: (Left) Photo of a patient in an MRI machine from the front shows the limited space available for a robot. (Center) A schematic of the MRI bore seen from the side illustrates how the robot and patient will fit within the machine. (Right) The robot deploys a steerable needle called an ‘active cannula’ made from multiple precurved superelastic concentric tubes.

The first step in creating such a system is the development of MRI compatible linear and rotary actuators, and developing control systems capable of accurately operating them. Toward this end, we have identified and obtained an MRI compatible pneumatic cylinder (Figure 1-2 – right). We have also set up a testbed for line dynamics research (Figure 1-2 – left).

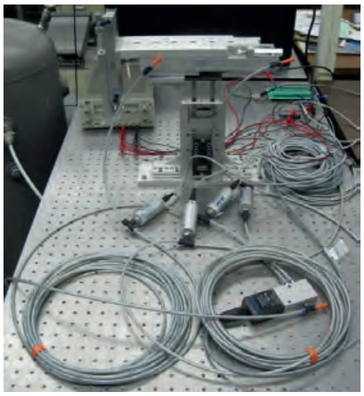


Figure 1-2: Line dynamics control testbed. This experimental setup consists of a pneumatic cylinder connected to a computer-controlled valve via long transmission lines. The figure on the right shows the MRI compatible pneumatic cylinders currently under investigation.

Fabrication of prototypes using these components is an important part of the research. The first prototype (Figure 1-3 – Left) is a non-MRI compatible active cannula actuation unit, which will enable us to perform active cannula experiments, while fully MRI compatible prototypes are under development. A second nearly-MRI compatible prototype is under construction (see Figure 1-3 – Right). This prototype will be made MRI compatible in the near future by replacing the metallic linear slides with plastic alternatives and the plan is to use it in initial in-scanner experiments.

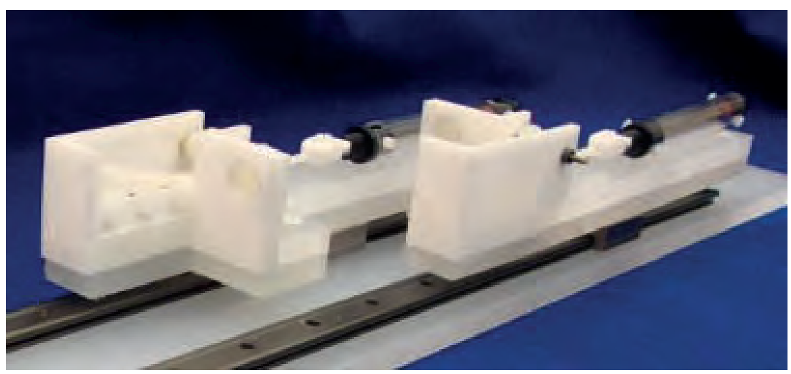


Figure 1-3: (Left) A first prototype active cannula actuation unit. (Right) A nearly-MRI compatible prototype robot with two linear actuators.

Future Work:
The immediate future goals are to create rotary pneumatic actuators and integrate them with the prototype shown in Figure 1-3 – right above. Meanwhile, we will pursue closed-loop control research on the active cannula using the non-MRI compatible robot design shown in Figure 1-3 – Left, and pursue line dynamics control research using the setup shown in Figure 1-2 – Left. The next major step will be to insert the prototype robot into the MRI scanner and perform targeting experiments based on image feedback.

B.2: New design of high-accuracy 6-axis force sensor (Georgia Tech)
The goal is to build a fully MRI-compatible sensor that is compact and highly accurate for a fluid-powered haptic interface. Fiber optic extrinsic sensor technologies are considered to be suitable for this project. Among different fiber optic sensing methods, reflective sensing by light intensity measurement is implemented. Although that type of sensing involves sub-millimeter assembly procedures, it is highly sensitive.

Force Sensor for Fluid-powered Haptic Interface
The sensing principle is widely used in the market and easy to setup. To use the same fiber as the source and the receiver, and to eliminate the instability in the light source a 2x2 coupler is used in the circuitry: A numerical approach for fiber to mirror light transmittance is initiated. The fiber optic cable in that work is assumed to be step index and mirror is assumed to be perfectly reflective. The modeling of light transmittance needs to be analyzed more deliberately and should be confirmed by experiments.

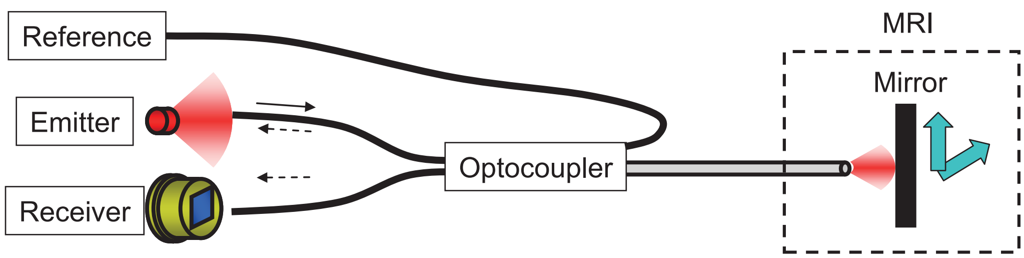
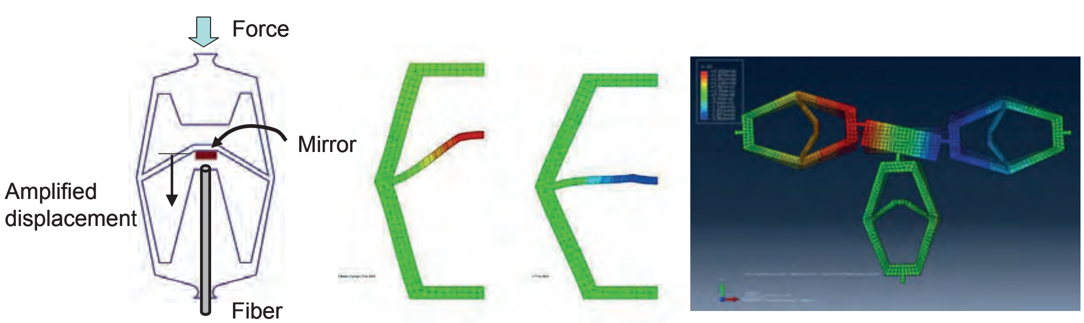


Figure 2-1: Sensing Principle in MRI: Light, transmitted by a fiber, passes through a fiber-mirror interface. The returning light is measured by a photodiode.

A displacement amplification mechanism (DACM) which is compact and convenient for sensing tasks in a limited volume has been designed. The goal is to suppress the hysteresis problem with these DACM units and further improve the resolution of the reflective sensing technique. The displacement of the top portion is amplified by the mini-link in the middle where the mirror is attached facing to the fiber. The amplification ratio is raised, its ability of decoupling is enhanced and it is made easier to assemble to fiber optic cable. Figure 2-2 shows a primitive model of the compliant structure. The design of the unit has been improved by a series of finite element simulations by using Abacus. The range of measurable force was adjusted to meet the maximum force created by a pneumatic actuator that we are planning to use.



(a) (b) (c)

Figure 2-2: (a) Structure of a prototype sensor; (b) Finite element model analysis; (c) Combination of multiple sensor unit.

Material Survey
The materials appropriate for MRI related works have been investigated in the literature. There are great constraints on the material selection for MRI compatible robotic devices; conventional

devices cannot function in such applications. Unfortunately, there is no universally applied standard for classifying materials for their compatibilities. There are various views and various standards for the definition of the compatibility criteria and for rating materials according to their compatibility levels. In MR chamber, 3 types of electromagnetic fields exist:

- Strong static magnetic field
- Rapidly changing magnetic gradient
- Pulsed RF fields

Rapidly changing magnetic field induces current on conductive materials, so conductivity becomes another parameter for the compatibility to MRI environment.

Ferromagnetic materials are completely inappropriate whereas many non-ferromagnetic metals are utilized with certain compromises. Plastics are known to be MRI friendly materials but they also bring some compromises due to their viscoelastic material properties. In many MRI compatible sensor applications the idea is to deform a non-metallic -mostly plastic- structure elastically and sense the displacement such deformations introduce. Aluminum, brass and copper are mentioned to be suitable for robotic applications among metals. Also PEEK, which is a thermoplastic, is shown to be more compatible than aluminum in terms of imaging quality. In this project, the body of the sensor is chosen to be plastic and certain design considerations are done accordingly. For actuation, fluid-power actuators, such as McKibben-type pneumatic muscles are suitable as they do not require ferromagnetic materials in principle.

Future work
The development of a linear encoder to measure the displacement of the device is in progress. To have multiple degrees of freedom sensor using these units, these units will be assembled to a haptic interface in different orientations. Phantom test will be conducted to check the MRI compatibility. Then the sensors will be integrated with actuators developed at Vanderbilt by the end of the first year. GT side will then investigate the dynamics of long pneumatic lines for stable control of a haptic interface in MRI by using modified passivity criterion for stable bilateral tele-operation.

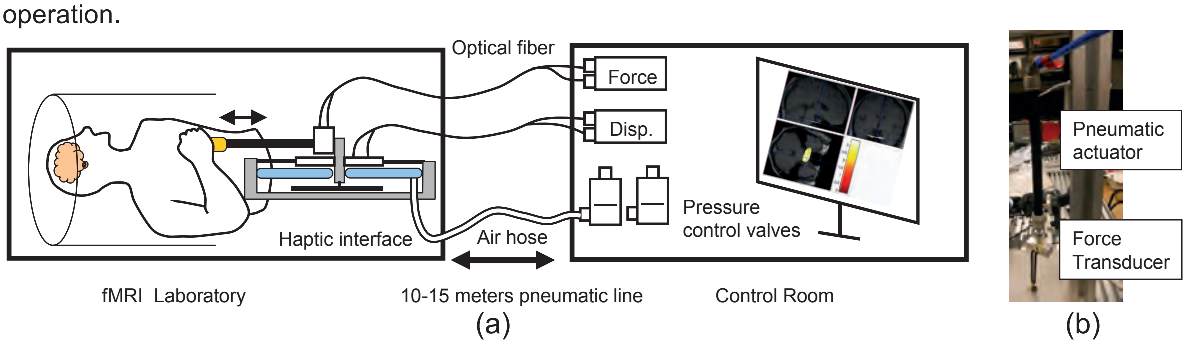


Figure 2-3: (a) Overview of a 1-DOF haptic interface that will be developed and tested at GA Tech: Two actuators in an antagonistic arrangement will produce bidirectional movement of an end-effector that interfaces with a subject in MRI. Each of the pneumatic actuators is remotely controlled by pressure valves located in a control room. Optical force and displacement sensors will be integrated for closed-loop control. (b) Force feedback control of a pneumatic actuator.

C. Member company benefits

Among the current member companies, some of the valve and actuator companies, such as Bosch Rexroth and Festo, may have an interest in this project. Martin Companies is interested in MRI compatible fluid-powered robotics. They have also expressed interest in joining the center as an industry affiliate. Panasonic (ActiveLink, Panasonic's in-house venture company) is showing their interested in developing assistive robots that evaluate stroke rehabilitation in fMRI.

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

Research Team

Project Leader:	Prof. Wayne Book, Mechanical Engineering, Georgia Tech
Other Faculty:	Prof. Steven Jiang, North Carolina A&T
	Prof. Zongliang Jiang, North Carolina A&T
	Prof. Eui Park, North Carolina A&T
	Prof. Perry Li, University of Minnesota
Graduate Students:	Mark Elton, Aaron Enes, Longke Wang
	(Heather Humphreys on an associated project is cooperating.)
Industrial Partner(s):	Caterpillar, John Deere, HUSCO International, Bobcat

1. Statement of Project Goals

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

2. **Project Role in Support of Strategic Plan**

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

3. Project Description

A. Description and explanation of research approach

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

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

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

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

B. Achievements

Work prior to 2010

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

Simulation based studies of interfaces. The true test of a novel human-machine interface (HMI) would be mounting the new HMI in the cab of the machine to be controlled and measuring changes in fuel economy relative to the standard HMI. Changing the controls of a machine is time consuming and can be expensive. In order to be able to quickly interchange and test new HMIs or iterations thereof, an excavator simulator has been constructed that simulates the mechanical and hydraulic dynamics of test bed 1 in its current pump-controlled state with the environment. The Bobcat Company donated an excavator for the operators to sit in while controlling the simulation.

The simulator is composed of three modules – the HMI interface, the dynamics simulator, and the graphics simulator. Each of these modules was specifically written in blocks so that they could be easily modified for future use (i.e. the control block can be easily modified or switched for a new one, or the pump simulator can be changed for a valve simulator to compare the dynamics of pumps versus valves). The simulator and modified versions thereof have been used at Georgia Tech and North Carolina A&T and have proved their robustness.

To complete the excavator simulator, a more extensive excavator-soil model was developed. Previous models found in the literature only examine trajectories where the bucket is coming towards the operator. No model for a bucket being pushed any other direction than teeth-first though the soil. The model developed here covers all of these possible scenarios. Also all previous soil simulations have only examined trajectories and soils where the soil can only exert a force on the bucket less than the force exerted on the soil by the bucket (i.e. loose sand). The new model developed allows the force applied by the soil to exceed the applied bucket force, and also includes wrist-soil interaction forces, an interaction not previously included in any model in the literature.

Blended Shared Control Previous work in Project 3A.1 resulted in a framework for a type of control we termed Blended Shared Control (SC). Blended SC allows the operator to cede authority to the machine to modify (either directly or indirectly) the original velocity commands such that the resulting motion results in a lower-cost task completion. This requires a three-part structure. First, the operator's intended task (e.g. slew left 60 degrees and raise boom 1 m) is inferred based on present and prior inputs. Second, the optimal control input for this task is computed subject to the constraints of the machine dynamics and the inferred task specifications. This ensures that the Blended SC algorithm does not alter the operator's intended task but rather enables the same task to be completed with lower cost. Third, the original operator input is combined with the optimal command in a manner which attempts to guarantee that the resulting command results in a lower-cost task execution.

Initial experiments on a single-DOF system showed Blended SC reduced task completion time when compared to manual control[2] and the Blended SC was transparent to the operators (i.e. there were no reports of "loss of control" when the subjects unknowingly interacted with the semi-autonomous agent).

Most recently the concept of Blended SC has been extended to multi-DOF hydraulic actuators, such as the industry-standard excavator (TB1). We introduced a model that expresses cyclical excavation tasks as a sequence of piece-wise monotonic motion primitives. Thus, we have the capability to predict an operator's intended task (essentially, the relative displacement of each of the actuators) from the parameters of the motion primitives, which are learned online using an approach based off of recursive least squares[3]. Further, for each motion primitive, there exists a closed-form optimal solution based on a refined kinematic excavator model that includes the single- and multi-functional flow constraints that dominate an excavator's steady state response. Depending on the functions being actuated, this optimal solution may lie on a one- to four-dimensional manifold in the excavator's input space[4]. The Blended SC algorithm is responsible for steering (either through direct modification or indirect cues such as haptic or auditory feedback) the operator's original input command towards the optimal input; this particular problem is an active research area.

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

(1) Singular perturbation theory was introduced to hydraulic control to simplify control design and make the results better fit for practical applications[5]. A full state controller is plausible but not advisable in the practice since the integrated system requires not only the control efforts but also controller itself have higher bandwidth. It turns out that an adequate controller design can neglect the highest system natural frequency while maintaining system stability and performance using singular perturbation methods.

(2) There are always some uncertainties in the hydraulic machines, e.g. varying loads of excavators; the classical adaptive control approach cannot converge to such varying parameters unless there is no measurement noise. However, measurement noise is inevitable in the practice. We are using recursive least squares method to keep system parameters errors to the minimum thus ensure system stability[6]. Furthermore, a simplified algorithm was applied to decrease controllers' calculation periods that make the algorithm is more fit for real time control.

(3) A new hydraulic test stand has been build up to verify the proposed algorithms. The hydraulic circuit is different from Purdue's pump control test bed and thus we can compare different pump driving circuit. We are verifying whether the trajectory tracking performance has been improved and the pressure oscillations (a common problem in the direct pump control) have been lessened.

Biodynamic Feedthrough and Its Alleviation This research investigates and seeks to mitigate the undesirable effects of biodynamic feedthrough in backhoe operation. Biodynamic feedthrough occurs when motion of the controlled machine excites motion of the human operator, which is fed back into the control input device. This unwanted input can cause significant performance degradation, which can include limit cycles or even instability. Backhoe user interface designers indicate that this is a problem in many conventional machines, and it has also proved to significantly degrade performance in the test bed used for this research.

This research utilizes a tractor-mounted backhoe that was previously developed at Georgia Tech. Dynamic models of this particular backhoe control system, including the biodynamic feedthrough, have been developed. Cab vibration control was selected as a means to mitigate the biodynamic feedthrough effect. Several variations of controllers were developed and tested in simulations, including both active and passive vibration compensation. Both use the working implement itself to reduce the cab motion, rather than adding additional hardware. In this case, the backhoe arm has dual functionality, to perform excavation operations and to cancel cab vibration. Both input shaping and active damping approaches proved to significantly reduce cab vibration both in simulation and in hardware, with minimal cylinder tracking performance degradation and without additional actuators.

Work in 2010

During the current reporting period a number of academic and related research milestones were reached. Aaron Enes completed his Ph.D. research and studies on shared control. Longke Wang completed all but the final writing of his Ph.D. dissertation on control of pump displacement for motion control. Heather Humphreys completed her M.S. degree on biodynamic feedthrough, its effect on backhoe performance and control techniques that help to alleviate it. This is an associated center project that is supported by donations from John Deere and the fellowships held by Ms Humphreys. Both Heather and Mark Elton (MS 2009) are continuing for their Ph.D. degrees.

Shared Control The initial research of Blended SC culminated in Summer 2010 with an experimental study. Over thirty operators (including experts and novices) completed a number of "excavation-like" tasks using the virtual excavator test bed developed by Mark Elton. The effects on task completion time of Blended SC and conventional manual control were studied. The results showed that excavation productivity is up to 15 percent greater using Blended SC compared to manual control with no electronic assistance. A brief overview of the experimental results will be presented at a major industry conference in Spring 2011[7], and further research write-ups are now being prepared.

Pump displacement control Research on pump displacement control culminated in December 2010. The research consists of four main results: (1) Applied singular perturbation theory to fluid power system. (2) A novel hydraulic circuit for single rod cylinders, (3) a stable adaptive robust control of variable displacement pump, (4) developed a hybrid algorithm to achieved desired trajectory tracking.

Result (1) can be used to release the hydraulic stiffness in some conditions thus it make the control law is suitable for real time control. It can also serve as an intuition design at the beginning design stage of a complicated hydraulic system. The strictly theoretical proof and experiments were conducted. The result is being published in the IEEE/ASME Transactions on Mechatronics[8].

A novel hydraulic circuit has been set up and experiments were conducted to valid simulation results. The circuit not only ensures the circuit itself stability, also reserves the high energy efficiency of the traditional circuit. Furthermore, a tracking compensation can be issued by the controller to improve the dynamic response of the cylinder. Part of results culminated to a paper which is accepted by Journal of Dynamic System, Measurement and Control[9].

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

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

Part of result (2) will be presented at an industry conference in March 2011 and results (3) and (4) are now being prepared for journal publications.

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

Four new input modes were added to the excavator simulator. Previously the joysticks could only be used in joint velocity mode, which is the current state of the art. The two new velocity control modes allow the operator to move in either the world frame (a frame fixed to the tracks of the excavator) or in the operator frame (a frame that rotates with the cab). Each of the joystick axes commanded a wrist velocity of the excavator in the direction of the axes of the frame and the fourth degree of freedom of the joysticks commanded the curl of the bucket. An extra feedback loop was added to coordinate the motion of the joints. Also added to this control loop was a block that modified the command if any of the joints reached their limits. When operating at a joint limit, the command was projected onto a plane tangent to the workspace at the current wrist location. The other input modes developed were world and operator frame velocity control modes for the Phantom. The same control module was used, but the commands were read in from the Phantom. The Phantom was programmed to have spring centering force to return the device to a spherical deadband.

New hardware was added on the excavator simulator as well. Donated industrial hand joysticks, the same as on TB1, replaced the finger joysticks after new mounts were machined, which greatly enhanced the realism of the operator workstation. A new handle with hard stops was made for the

Phantom, making it more ergonomic and easier to use. A “traveling” simulator was constructed that can easily be transported and set up on a table top. As part of making this condensed simulator, the software was rewritten to require only two computers while maintaining real time demands. Significant preparatory work has been done on the operator workstation (the cab of an excavator matching TB1) to enable the swing of the cab so that it swings when the operator commands it to, rather than just the on screen simulator swinging. The cab swing should be functional early next year.

In addition to changing the software to reduce the number of computers, many other changes were made to increase the versatility and ease of use of the software. The simulation code was rewritten so that all parameters can be varied before any run. The software can be toggled online between any of the six different control modes. With data from TB1, a fuel map was created that allows the simulator to calculate the fuel consumption of the excavator instantaneously and cumulatively. Previous test, such as the one performed early in 2010, compared the energy consumption of different HMIs. Now a fuel amount can be calculated, and from that a calculated dollar amount of the savings provided by new HMIs. Also, additional code has been added that allows data recorded from TB1 to be read in as either joystick commands or swashplate commands. This enabled the comparison of the simulator to TB1 for model validation. Initial comparisons are promising, although not perfect. More data has been requested from TB1 so that model parameters, such as friction and leakage, can be corrected so that the simulator behavior better aligns with the behavior of the test bed. This data will be sent by the end of the year, so the model can be modified and validated.

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

<u>Biodynamic feedthrough and its alleviation</u> Two types of experiments were performed on a set of five different controllers, three of which were vibration-compensating. First, a set of experiments with a software input were performed, in order to test the controllers’ ability to provide adequate cylinder tracking while minimizing cab vibration, without the variability introduced by a human-in-the-loop. Next, a set of human operator experiments was performed, in order to determine if the controllers with vibration compensation do provide superior tracking performance with the operator in the loop, by reducing biodynamic feedthrough.

For the software input experiments, results showed that two types of passive compensation, an input shaper and a notch filter, were able to significantly reduce cab vibration. However, this compensation comes at the expense of some degradation of tracking performance. The next set of experiments, with the human in the loop, was intended to show that the reduction in biodynamic feedthrough outweighs any degradation in controller performance resulting from vibration compensation.

For the human-in-the-loop experiments, the trend in the results indicated that both the passive input shaper and the active vibration cancellation could reduce cab vibration, as compared with results from similar controllers without vibration compensation. However, only eight subjects were tested, which was not sufficient to obtain statistical significance.

Conference papers were presented at the ASME Dynamic Systems and Control Conference and the Fluid Power Net International Annual Ph.D. Symposium[10]. Another conference paper was submitted for the IEEE International Conference on Robotics and Automation[11]. Further human subject testing is ongoing, which is intended to be published in a journal paper early in the upcoming year.

C. Member company benefits

The most interested and affected companies are the equipment builders in CCEFP. This includes John Deere, Caterpillar, and Bobcat. Caterpillar has attended our webcasts regularly and has a very active industry champion. Deere and Bobcat have donated equipment that has enabled the studies to be as realistic as possible. HUSCO has been invaluable in critiquing the progress on pump displacement control.

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3A.2: Human/Machine Interaction via Passified Pneumatic and Chemo-fluidic control

Research Team

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Other Faculty: Dr. Wayne Book, Georgia Tech, Mechanical Engineering
Graduate Student: Venkat Durbha
Industrial Partners: Festo and Enfield Technologies

1. Statement of Project Goals: The goal of this project is to develop control design methodologies for pneumatic and chemofluidic actuations such that the controlled system can interact safely and stably with a wide range of physical environments, and be controlled intuitively by the human operator. To ensure safety, the energetic passivity property will be enforced. Control oriented modeling frameworks for pneumatic and chemofluidic systems are being developed. Control functionalities being studied are: bilateral haptic tele-operation and human power amplification with the rescue crawler test bed (TB4) as the target application. Future development can be directed towards design of passive controllers for dynamic tasks with time delay such as motivated by the gait motion in TB4 (rescue robot) and TB6 (assistive device).

2. Project Role in Support of Strategic Plan: A major barrier to the use of fluid powered systems for human scale applications is the need for such systems to be safe and intuitive to use. When a fluid power actuated system such as TB4 (rescue crawler) and TB6 (assistive orthosis) interacts physically with humans and unstructured physical environment, the physical interaction can potentially be unstable. By designing control systems such that the closed loop system possesses the energetic passivity property, such instability can be avoided for a broad range of physical environments. The tele-operation and human power amplification functionalities are directly applicable in TB4 to enable haptic control by the human operator and the use of the robot as an assistive device for a person on site. Pneumatics and chemofluidic actuations are being promoted as the primary actuation methodologies for human scale applications. Yet passive control design frameworks for these actuation methodologies have not previously been developed. This project is making pioneering advances in these areas that will enable other human scale fluid power applications.

3. Project Description

A. Description and explanation of research approach

A characteristic of devices such as TB4 and TB6 is that they are in physical contact with the environment or are directly controlled by humans. For such systems, passivity is a useful property as it relates to both safety and ease of control. Roughly speaking, a passive system is one that does not generate energy but only stores, dissipates, and releases it. The amount of energy that a passive system can impart to the environment is limited by the external input and so safety is ensured compared to non-passive systems. This results in the useful property that coupling between a (strictly) passive system and another passive system will remain stable. Such a useful property is not enjoyed by systems that are merely (input/output) stable individually. Since most physical objects are passive, a passive system can safely interact with a broad class of environments without fear of being destabilized. Moreover, because the concept of “power” can be used to plan and execute manipulation tasks, passive systems are potentially more intuitive to use.

Passivity concept has been relatively well developed for hydraulic systems in the past few years by the project leader. Passive control design methods have been developed both for tele-operation and human power amplification. The challenges of developing this framework for pneumatics and chemo-fluidic actuation are: 1) all pneumatic systems are significantly more compressible than hydraulics; 2) in pneumatics and chemo-fluidic systems, significant heating and cooling occur during compression and expansion; so that effect of temperature variation and heat transfer will affect the overall dynamics, and hence passivity; 3) chemo-fluidic systems that involve complex reaction dynamics have not been subjected to passivity analysis.

The research approach is to consider the problem in three stages: a) isothermal/adiabatic pneumatic systems, b) pneumatic systems with finite heat transfer, c) chemo-fluidic actuation. Bond graph and pseudo bond graph modeling, as well as exploitation of similarities with previously known domains (hydraulics and electromechanical) will be essential techniques that are being applied in the research. In addition, since the targeted systems are mobile systems with portable power sources, in our control design efficient use of energy is being considered an important criterion.

B. Achievements

Passive pneumatic actuation with heat transfer

In previous years (Yr1-4), our control development of pneumatic controllers has relied on the assumptions that the thermodynamic process in the actuator was either isothermal or adiabatic where heat transfer is complete or is ignored respectively. With such assumptions, we have successfully developed and experimentally tested passive teleoperation and human power amplifier controllers [1, 4], as well as a method for minimizing energy use [5]. However, in actuality, heat transfer is present and at a finite rate. While simulation studies have indicated that in regular pneumatic actuation, controllers designed based on isothermal or adiabatic assumptions also work well in the presence of finite heat transfer, the effects of heat transfer will be more significant in the case of chemofluidic actuation. Thus, in the past year (Yr 5), we have turned our focus on investigating the effects of finite heat transfer. Specifically, we assume that heat transfer is allowed between the actuator chambers and the constant temperature environment at arbitrary heat transfer coefficient: i.e.

$$\dot{Q} = h(t)A\,(T_0 - T), \qquad \infty \geq h(t)A \geq 0 \tag{1}$$

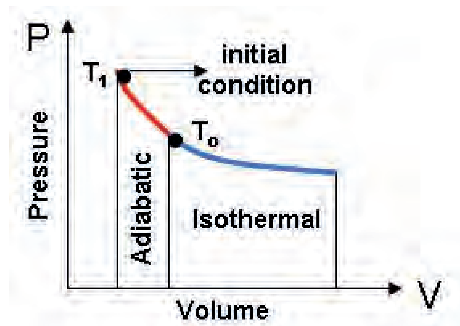

Figure 1: Maximum work output in an expansion process when temperature is greater than the ambient temperature T_o

While the isothermal/adiabatic assumptions allow for quite straight forward definitions of the storage function as the potential energy stored in the compressed gas, it is not the case with finite heat transfer. So a major accomplishment in the past year is an appropriate definition of a storage function that enables passivity analysis and passive control design to be carried out naturally. The storage function is defined as the maximum work output from the actuator, for a given mass, from the current temperature, and volume of air in the actuator to the mechanical and thermal equilibrium state, under any heat transfer scenario in (1).

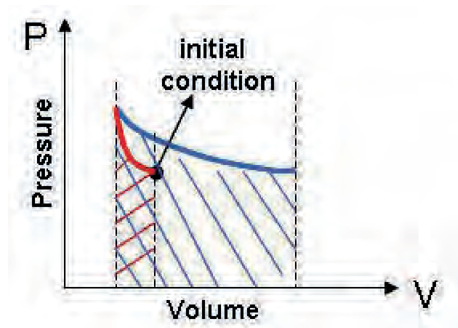

Figure 2: Maximum work output in an expansion process when the air temperature is less than the ambient temperature T_o

This program is carried out by considering the expanding and compressing chambers in the pneumatic actuator separately. It is shown that for any given state, the optimal process to extract the maximum expansion work consists of an adiabatic compression/expansion until the temperature reaches ambient, followed by an isothermal compression/expansion to the equilibrium position. The storage function for the expanding chamber can therefore be defined as,

$$W_1 = m_1 C_v (T_1 - T_o) - m_1 C_v T_o \log\left(\frac{T_o}{T_1}\right) + m_1 R T_o \log\left(\frac{P_1}{P_o}\right) \tag{2}$$

where m_1 is the mass of air in the chamber, C_v is the specific heat of air at constant volume, R is the universal gas constant, and P_o is the ambient pressure. The first term in the above definition is change in internal energy and corresponds to work that can be extracted from an adiabatic process. The second and third term correspond to work that can be extracted from the isothermal process. Note that the above storage function states that, if the initial temperature of air is below the ambient temperature, then maximum work is obtained if the gas is initially compressed to ambient temperature and then expands to provide work. This is illustrated in the schematic in figure 2.

Similarly for the compressing chamber, the minimum work should be done on compressing the air in other chamber. The optimal process is again an adiabatic compression/expansion until the air reaches the ambient temperature followed by an isothermal compression to the equilibrium state. Therefore, the storage function for the chamber being compressed is given by,

$$W_2 = m_2 C_v (T_2 - T_o) - m_2 C_v T_o \log\left(\frac{T_o}{T_2}\right) + m_2 R T_o \log\left(\frac{P_2}{P_o}\right) \tag{3}$$

where m_2 is the mass of air, T_2 and P_2 are the temperature and pressure of air respectively. The first term again corresponds to the adiabatic process and the second and third terms correspond to isothermal process. By combining the storage function for the pneumatic actuator as the sum of the storage functions for the two chambers:

$$W_a = W_1 + W_2 \tag{4}$$

The above storage function gives a supremum of work that can be extracted from the actuator and may not correspond to an actual realizable process.

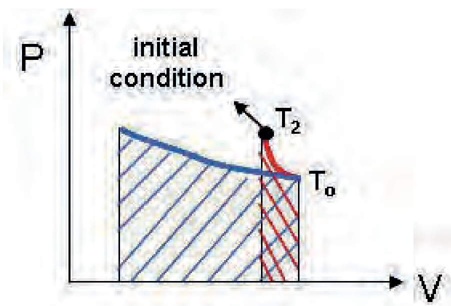

Figure 3: Minimum work input required in an compression process when the air temperature is less than the ambient temperature T_o

On differentiating the storage function in Eq (4), and the process dynamic that includes heat transfer, the rate of change of storage function is obtained as,

$$\dot{W}_a = -F_a \dot{x} + \dot{Q}_1\left(1 - \frac{T_o}{T_1}\right) + \dot{Q}_2\left(1 - \frac{T_o}{T_2}\right) \tag{5}$$

where F_a corresponds to the actuator force, $\dot{x}$ corresponds to the actuator velocity and hence the first term corresponds to the mechanical power extracted from the actuator. The heat transfer rate is defined in (1) for each chamber,

$$\dot{Q}_i = h_i(t) A_i (T_o - T_i) \qquad \infty \geq h_i(t) A_i \geq 0 \tag{6}$$

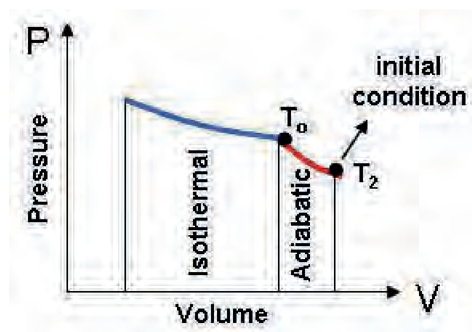

Figure 4: Minimum work input required in an compression process when the air temperature is greater than the ambient temperature T_o

So that:

$$\dot{W}_a = -F_a \dot{x} - \frac{h_1(t) A_1}{T_1}(T_1 - T_0)^2 - \frac{h_2(t) A_2}{T_2}(T_2 - T_0)^2 \tag{7}$$

Note that in equation (6) the terms involving heat transfer are always negative and thus dissipative. Therefore, in the absence of control inputs, the actuator behaves passively even in the presence of heat transfer even with unknown or uncertain heat transfer coefficient. Thus, in case of unstable response of the system, shutting down the inputs will result in dissipation of available energy and should stabilize the operation.

It is interesting to note that the storage function definition in Eq. (4) and its derivative Eq. (6) reduce to the respective items for isothermal and adiabatic processes in [1,4]. Thus, the storage function can truly be considered a generalization of the special cases in [1,4] to the more general case of arbitrary heat transfer to an environment.

When control input (i.e. valve opening) is included, an additional term in (8), say $f(\varphi, u)$, will appear due to control action. It corresponds to power input associated with the control action. If the controller is designed such that it by itself is passive with respect to $-f(\varphi, u)$, then closed loop passivity will also be guaranteed. We are currently completing development of the control design methodologies for teleoperation and human power amplification in the finite heat transfer case by following this line of arguments.

Chemofluidic Actuator

In a chemo-fluidic actuator the gases required for actuation are obtained from catalysis of hydrogen peroxide solution to water vapor and oxygen. The reaction is exothermic in nature, and the products obtained are at a temperature of 450^{o}K. Therefore, chemo-fluidic actuators have higher energy density than pneumatic actuators and are thus more amenable for mobile applications.

Conceptually, a (direct injected) chemofluidic actuator differs form a conventional pneumatic actuator in that the flow of compressed gas is not controlled by a throttling valve, but instead by the control of the generation of hot gas through the chemofluidic peroxide decomposition. Thus, much of the passivity analysis of pneumatic system with finite heat transfer will be application with the additional consideration of the control of chemical reaction dynamics.

In the past year, analytical model of the chemofluidic actuator has been developed. Preliminary control design and simulation studies on achieving force amplification through chemo-fluidic actuators have also been performed. The system model identified and presented in [2] has been used in the simulation studied. Since the experimental setup is the same as the one identified in [2], a high measure of confidence is placed on the parameters identified in [2]. The existing test apparatus at U of Minnesota (donated by Vanderbilt U. and was setup in Yr 4) for chemo-fluidic actuators uses on/off solenoid valves to meter the peroxide solution through the catalyst. While these valves can withstand the high temperature of operation, their discrete nature of operation provides additional challenges in achieving a desired continuous output force from the actuator. The common methods for controlling such systems are to either use nonlinear averaging or direct switching. A direct switching controller has been designed to achieve the desired force amplification.

In lieu with our earlier work [1, 4], the force tracking problem is formulated as a velocity co-ordination problem between the inertia being moved by the actuator and a virtual inertia being acted upon by the desired actuator force. The following Lyapunov function is formulated in terms of the velocity error,

$$V = \frac{1}{2}s^2 \tag{7}$$

where $s = \dot{V}_E + \lambda V_E$, and V_E is the velocity co-ordination error. The objective is then to design the control inputs which will drive the above Lyapunov function to zero. However, as mentioned above, the control inputs to the valve can take only discrete values (1: fully open, 0: fully closed). In direct switching controller, the affect of all inputs on the Lyapunov function is evaluated at each time step, and the input which brings the Lyapunov function closer to zero is selected. The achieved force tracking is as shown in figure 5. The plot shows good tracking results in steady state. In these simulation results, the exhaust valve is also kept completely open or closed even though it is a proportional valve. This will help in lowering the operating pressure on the discharge side and hence can improve the efficiency of operation.

Simulation of the control system indicates that the valve needs to switch on and off rapidly, to achieve the desired smooth force profile. The valves being currently used have a reported time constant of about 20ms, which is not sufficient to achieve a smooth continuous tracking. However, as reported in [3], a spike and hold circuit can be used to improve the time constant to be less than 0.4ms. Therefore, a spike and hold circuit has been built to achieve the desired bandwidth of operation.

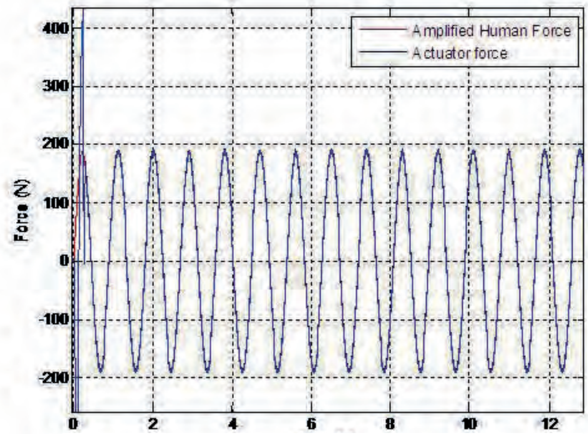

Figure 5: Force tracking result using chemofluidic actuator (simulation)

Current / Future work

For pneumatic actuators, passivity of controllers for actuator operation with finite heat transfer is currently being completed. The resulting controls will be implemented and tested on the 1-DOF setup at the University of Minnesota.

We plan to implement and test the pneumatic passive teleoperation and human power amplification controllers on Test Bed 4 at Georgia Tech in Spring or Summer 2011. Teleoperation mode will refer to the control of the two front legs, while human power amplification will refer to using the robot as an assistive tool directly manipulated by a person on site. Either the isothermal/adiabatic/finite heat transfer version of the controllers will be implemented. While the correct control law design can easily be extended to multi-degree of freedom system, the specific kinematics and dynamics of the robot and haptic input device need to be incorporated. To do so, we plan utilize dynamics derivation and simulation/animation facility in SrLib (a software developed by Seoul National University). At the same time, some actuation and sensing facilities need to be updated on TB4 before implementation.

Once the pneumatic controllers have been completed, we shall extend the passivity control framework to the chemofluidic actuation situation. The current force controller (as shown in Figure 5) does not consider passivity rigorously.

We shall also seek funding from external sources to pursue extending the passivity control framework to the control of gaits and other near cyclic and dynamic tasks, and where the number of degrees of freedom that the system exceeds that of the operator input device.

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

Research Team

Project Leader:	Prof. Steven Jiang, Industrial and Systems Engineering, NCAT
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	Prof. Eui H Park, Industrial and Systems Engineering, NCAT
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Undergraduate Students:	Hoskins, V., Heard, J., Bryant, L.
Industrial Partner:	Bobcat

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

In fluid power systems where human operators interact with the machines, the overall effectiveness of the system depends on the effectiveness of the human operator performance. Modeling human performance has been proven to be a very critical tool in developing/improving systems. However, existing performance modeling tools often concentrate on either cognitive or physical aspect of the operator, failing to take into the consideration the interaction between the two. To better understand operator performance, a new integrated model needs to be developed that addresses this concern. This project proposes a framework to integrate cognitive and physical models of human performance for a fluid power system. A case study using the excavator test bed is underway to validate the integrated model and provide design suggestions for other complex fluid power systems. Specifically, the interaction between operator and the machine will be studied to assess the overall system effectiveness. With regard to any revision or a new design of a fluid power system interface, a user centered design approach is recommended so that end users are involved in the design process from the very early stage and ensures the interface will be easy, comfortable, and safe to use, and consequently, will be more effective.

3. Project Description

A. Description and explanation of research approach

Research efforts in complex fluid power systems where human operators interact with the machines to complete tasks are mainly focused on improving machine performance. For instance, excavators have gone through technological innovations to improve the machine efficiency over the years. However, issues such as high pressure, friction, containment, and constant movement continue to present problems with controllability, leaks, and losses in efficiency in many fluid power systems. Therefore, research is needed to improve machine performance in FP systems. Unfortunately, the side effect of this is that very little attention has been given to operators of those fluid power systems. In fact, many complex fluid power systems are still manually controlled, requiring excessive amounts of energy, intense task concentration, high skill level, and decision-making capabilities. Operators need to interact with machines effectively to accomplish the desired tasks. Unfortunately, complex interactions between the operator and the system due to these requirements can often lead to errors and misunderstandings, and consequently degrade the overall system performance despite the fact the machine performance has advanced. Machines alone simply cannot accomplish complex tasks. Human performance deals with the physical and cognitive limitations of humans and has been widely used in aviation, automobile, military, medicine, and other industries. However, only limited research has been conducted in those complex fluid power systems [1].

Research efforts on human performance often concentrate on either physical or cognitive part of the performance, failing to take into consideration the interaction between those two. This is especially true for the complex fluid power systems [1]. With the development of fluid power technology at CCEFP moves forward, it is critical to assess the impact of those technology have on the interaction between human operators and machines where these technologies will be deployed. For those complex fluid power systems where both physical and cognitive resources of human operators are required, it is even more critical to evaluate the impact on human performance. Therefore, a framework that integrates both physical and cognitive human performance needs to be developed for those complex fluid power systems. We adopted the following sequential approaches:

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

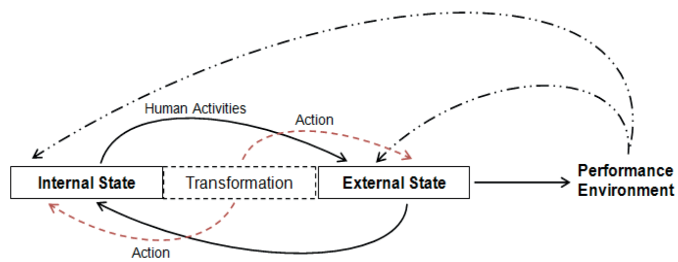

Figure 1. Definition and Relationship of Performance States

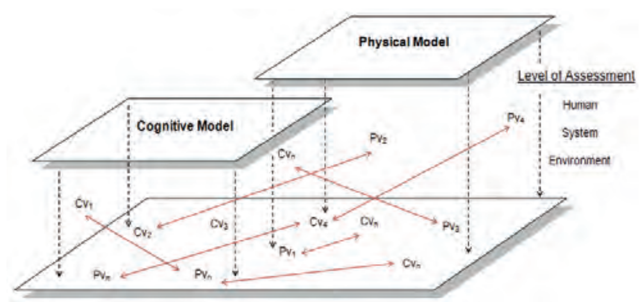

Figure 2. Linking of performance variables

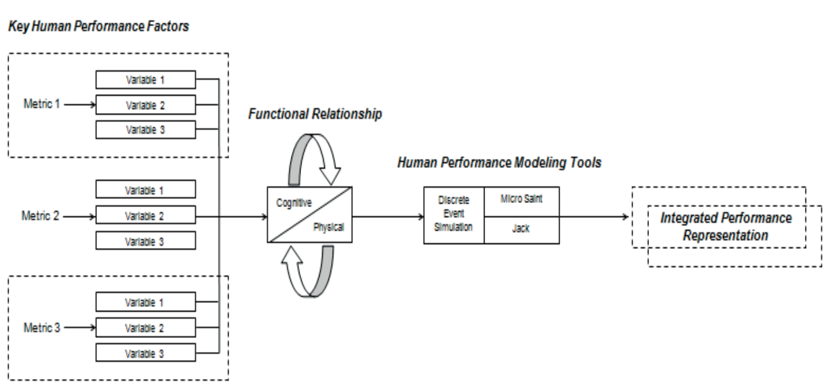

Figure 3. Integrated Human Performance Model Representation.

B. Achievements

- Developed an integrated framework for modeling operator performance in complex FP systems.
  - Findings of the study resulted in one published and one accepted conference proceedings paper [2].
  - A paper will be submitted to the international journal of industrial ergonomics.
- Conducted a pilot study on excavator operator performance with the integrated model.
  - Linking factors were identified for cognitive and physical factors for excavator operators.
  - Simulation models were integrated with the linking factors using Micro Saint and Jack.
  - Experiment data was collected and will be analyzed next month.
- Conducted empirical studies using various developed Jack models (physical model) for the rescue robot operators
  - Assessed the impact of the control device (joystick vs. haptic) and its placement on the operator as measured by low back compression force, forearm twist, and wrist flexion.
  - Findings of this study has been published in the IERC proceedings [7]
  - A manuscript is in preparation to be submitted to the international journal of human factors and ergonomics in manufacturing and service industries.
- Conducted an empirical study using eye tracking to assess the effectiveness of the trust instrument for human robotic interaction
  - Studies were conducted using prototype GUI interface of a rescue robot.
  - Eye tracking data was captured to help assess the effectiveness of the trust instrument.
  - Findings of this research have been published in 2010 industrial engineering research conference proceedings [4].
  - A manuscript is in preparation to be submitted to the international journal of human factors and ergonomics in manufacturing and service industries.
- One graduate student received his MS in Industrial engineering based on his CCEFP research.
- One student joined the doctoral program in the IE department at Virginia Tech.
- Conducted a usability study to evaluate the haptically controlled excavator simulator in Georgia Tech
  - Findings have been published in the 2010 IERC proceedings.
  - Results will be used to help revise the human excavator interface.
- Developed a conceptual model for a user interface suite that interfaces the pneumatic-power ankle-foot orthosis (PPAFO) with clinicians and patients.

Plans for the Next Year

- Conduct a case study on excavators using the integrated operator performance model.
  - Various environmental and system factors will be identified and effects of those factors on operator performance will be investigated.
  - Cognitive and physical models will also be developed independently
  - Operator performance using three different models will be compared and assessed
- Conduct an empirical study to assess the conflict between multiple modalities of excavator operators

- Conduct an empirical study to investigate the effect of haptic force feedback on excavator operator performance.
- Develop quantitative models for multimodal human excavator interface
- Develop (revise) a multimodal human excavator interface
- Investigate alternative ways to assess rescue robot operator workload.
- Interview the clinician population at GA Tech and create user profiles for this population
- Conduct a task analysis on clinicians interacting with the PPAFO
- Develop a prototype for the clinician-PPAFO interface
- Develop protocols for usability evaluations of the prototype

Expected Milestones and Deliverables

- Case study using the excavator test bed to demonstrate the framework to integrate cognitive and physical models that can be used to guide future study of human performance in the FP area.
- A multimodal human excavator interface.
- A testable working prototype for the clinician-PPAFO interface

C. Member company benefits

Even though excavators were chosen in the case study, the integrated human performance model can be expanded to other complex fluid power 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. 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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3B.1: Passive Noise Control in Fluid Power

Research Team

Project Leader:	Prof. Kenneth A. Cunefare, Woodruff School of Mechanical Engineering
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Undergraduate Students:	Leighann Ngo, Michael Walsh, Anthony Crenshaw
Industrial Partners:	Michel Beyer, Eaton Corporation

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

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

The research approach in this project is unique in its application of a voided, engineered, compliant lining to noise control devices for fluid power systems. There are a number of patents for noise control devices that reference voided polymer materials,[1, 2] however, there does not appear to be any product on the market exploiting these patents, nor is there material in the literature. Theoretical models may be found in the literature for annular air silencers[3] and for hydraulic silencers using flexible plates[4] but none currently addresses annular, compliant-lined hydraulic silencers. Other devices such as Helmholtz resonators and Quincke tubes have been studied but are not found in practice as their size is typically too large for practical application. Helmholtz resonators have been studied extensively for air; one notable study for a fibrous-lined resonator was performed by Selamet.[5] A number of studies have evaluated Helmholtz resonators for hydraulic systems, but none have been found that incorporate a lining.[6-9] Devices known as tuning coils act as ¼-wavelength resonators and are common in power steering systems. A patent for a tuning coil was first issued in 1967,[10] and they were studied in the literature in the mid 1990s.[11, 12] Quincke tubes act as ½-wavelength resonators and were evaluated in some of the same literature. Aside from separate noise

control components, fluid-borne noise may be abated by integrated design features. For example, changes to the geometry of axial-piston pumps and the use of relief ports in valve plates.[13-15]
A major barrier in reducing the size of noise control devices for fluid power lies in the properties of the material used in their construction. The material must be significantly more compliant than the working fluid, yet remain compliant while under hydrostatic pressure. Coupled factors include the sound speed and loss factor; a low sound speed is related to reflection losses from the impedance change at the inlet and internal reflections, while the loss factor is the variable governing energy dissipation. In addition, capturing all these factors in a predictive model for a given device is also key to tailoring the material properties and device geometry to a given application. The microvoided urethane used in this research shows significant promise with respect to these aspects.

B. Achievements
Significant experimental accomplishments and improvements to the theoretical development were made with regard to the in-line silencer. Transmission loss measurements were accomplished by changing the architecture of the test rig compared to what was previously known from the literature. A silencer was added to the downstream side to prevent contamination from downstream noise, and a needle valve was installed upstream to generate broadband noise. Measurements of transmission loss were then acquired for the silencer - the experimental results for the prototype silencer with the voided liner, the commercial benchmark silencer, a silencer with an unvoided liner, and the theoretical results for a silencer with no liner are shown in Figure **1**a). The prototype silencer and the commercial benchmark have nearly identical performance below 500 Hz. The benchmark outperforms the prototype between 500 and 1300 Hz by 3-5 dB, above which the prototype performs increasingly better from 1300 to 3000 Hz, with a positive difference of 10 dB at 3000 Hz. The prototype silencer with the voided liner was found to significantly outperform a liner with no voiding. The unvoided silencer results are comparable to the theoretical model for a silencer with no liner at all. The implication is that the voiding is necessary for the performance of the device. Figure **1**b) illustrates the time-domain impact of the prototype silencer with the voided liner on the pressure ripple of the experimental test rig. The peak amplitude is reduced from approximately 80 psi to around 10 psi.

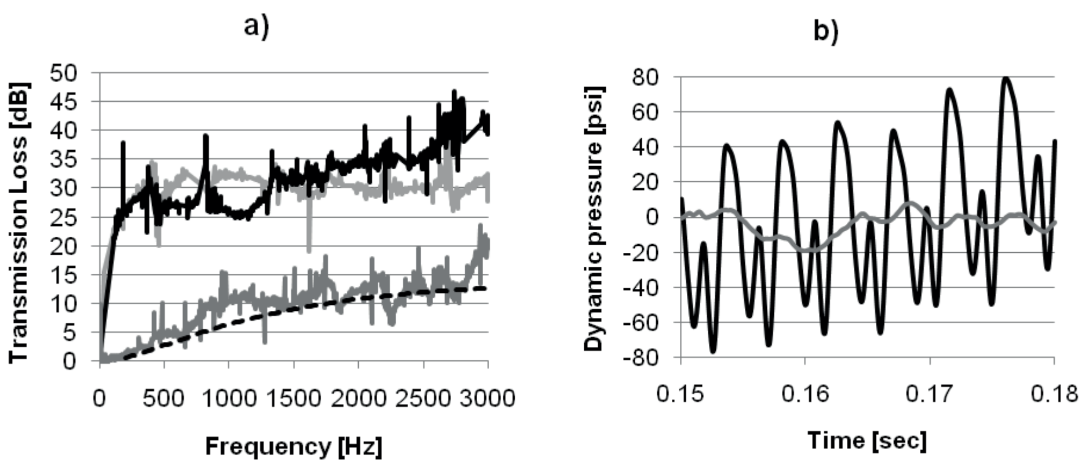

Figure 1: a) In-line silencer at 300 psi: ▬ prototype, ▬ commercial, ▬ unvoided, ▪▪▪ no liner.b) Time-domain dynamic pressure: ▬ without silencer, ▬ with silencer.

With regard to the theoretical modeling, a two-dimensional model was constructed that followed the development of Xu, et al.[3] This model applies appropriate axial velocity and pressure matching conditions at the silencer boundaries. The accuracy of the model depends on knowledge of the material properties. The available material properties of the liner material were only available at a lower temperature and pressure than the experimental conditions, so the projection of these properties to higher pressures are of unknown accuracy. An inverse-design study was performed to estimate the material properties at the pressure of the experiment, based on the results of the experiment. The results of the theoretical model using both the material properties provided by the manufacturer of the material and the material properties that resulted from the inverse-design material-identification analysis are compared to the experimental transmission loss in Figure **2**. The model with the material properties provided by the manufacturer shows good agreement below 400 Hz, and again between 1250-1750 Hz. The obvious issues are the troughs at 1000 and 2000 Hz. The estimated properties from the inverse-design study show better agreement from 200-1700 Hz, after which the results seem to be out-of-phase with the experiment. Obtaining better material property estimates is a topic of future work that will be addressed later in this report.

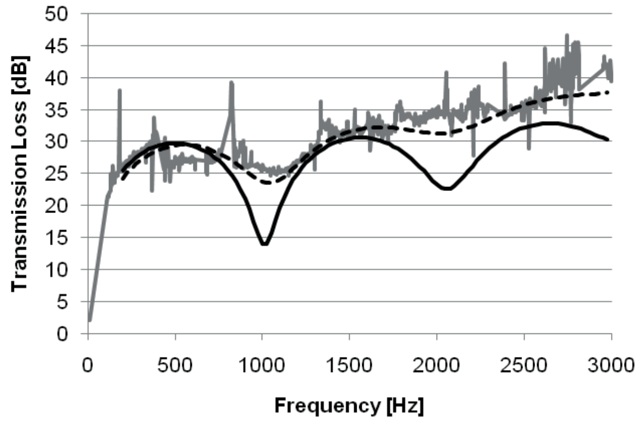

Figure 2: Transmission loss of the prototype in-line silencer at 300 psi: ▬ experiment, ▬ known properties, ▪▪▪▪ estimated properties.

Silencers designed for use in air often incorporate a perforated annulus around the main flow path which, while sometimes helping to hold the liner material in place, also contributes to the acoustic performance of the device. The silencer used in these tests also includes such an annulus; so in an attempt to resolve the performance gaps between the prototype and commercial silencers, two perforated annuli were constructed of different open-area fractions and tested in the prototype silencer. While the effects were either negligible or negative, a consequence of construction of the annuli was the realization that noise control devices could be constructed from the same housing and liner as the in-line silencer. Two non-perforated annuli were constructed to transform the silencer into a prototype tuning coil and Quincke tube. The annuli create an annular space between the annulus and the liner, and have circumferential gaps at one or both ends to create a ¼- or ½-wavelength resonator, respectively. The measured transmission loss for the tuning coil and Quincke tube can be found in Figure **3**. The tuning coil shows strongly periodic behavior, and a transmission loss of 35 dB near 270 Hz. The periodic behavior may be particularly effective for treating the fundamental frequency of a fixed-speed pump and its harmonics. The Quincke tube does not show any obvious periodicity, indicating the dominant effect may be the impedance change at the boundary.

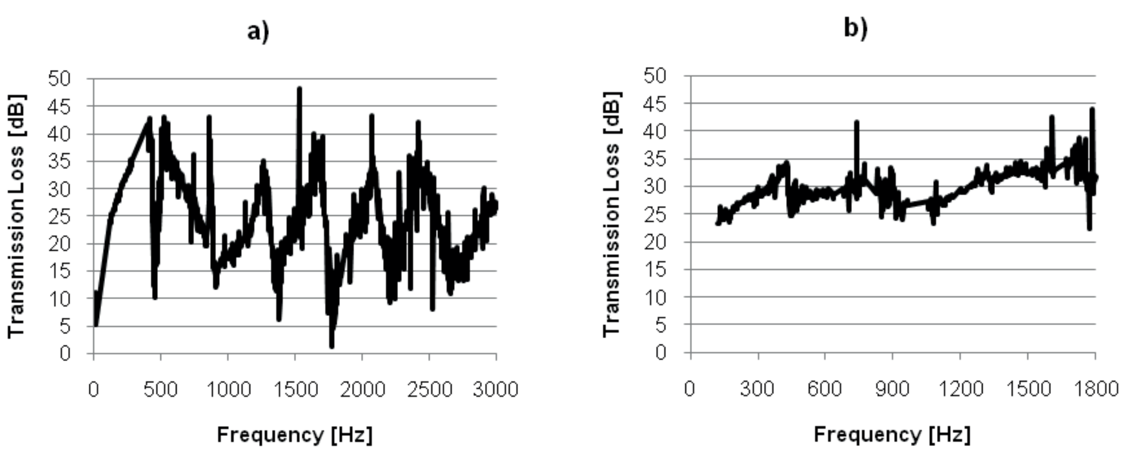

Figure 3: a) Tuning coil at 300 psi. b) Quincke tube at 300 psi.

Additionally, a Helmholtz resonator was developed using the shell and liner from the silencer, and constructing a new end cap and pipe section. A lumped-parameter theoretical model was also developed to predict the performance of the lined resonator. The experimental results from the Helmholtz resonator are particularly promising. The transmission loss for the resonator with both the voided and unvoided liners at 300 psi, as well as the results of the theoretical model using the estimated material properties from the silencer study, is shown in Figure **4**. The resonance frequency of the resonator using the voided liner is approximately 37 Hz, while the resonance frequency using the unvoided liner is approximately 223 Hz. For an unlined Helmholtz resonator with the same neck geometry to have a resonance frequency of 37 Hz, it would need a chamber volume that is two orders of magnitude larger than the prototype presented here. The model using the material properties from the inverse-design material-estimation study of the silencer matches well in amplitude and quality factor, however, it does not match the resonance frequency. Additional work to refine the model is necessary.

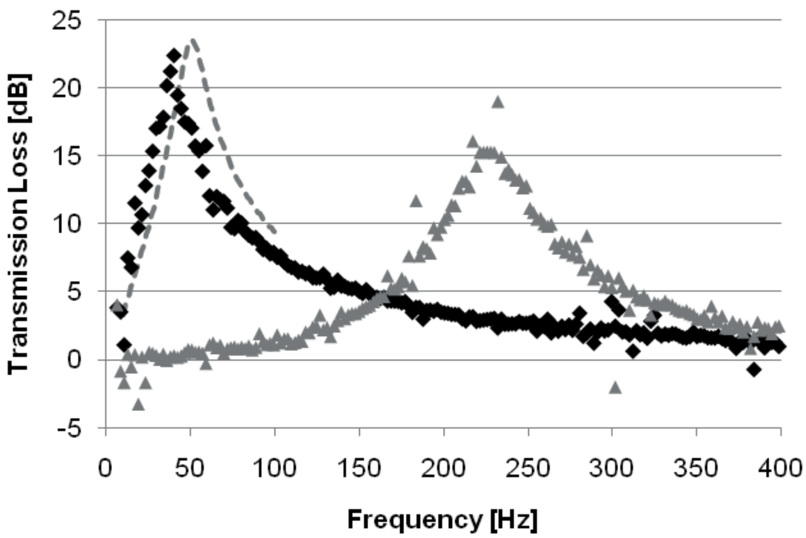

Figure 4: Transmission loss for prototype Helmholtz resonator at 300 psi: ◆ voided, ▲ unvoided, ▪▪▪ model with estimated properties.

Due to the numerous developments, seven patent disclosures that pertain to this technology were filed with the Georgia Institute of Technology's Office of Technology and Licensing. The full list of disclosures can be found at the end of this report section. The patent disclosures consist of the compliant-lined tuning coil, Quincke tube, and Helmholtz resonator along with embodiments including actively tuned versions and dispersive/tunable versions. Three conference publications were presented during the reporting period, two at Noise-CON 2010 and one at the 6th FPNI-PhD Symposium.[16-18]

There are two main thrusts for future work with this technology. The first and perhaps primary goal is to arrange testing of the devices at higher pressures. This has been a point of concern with industry members and is a crucial test for the practical application of the technology. Current testing infrastructure may permit 1500 psi, but other arrangements may have to be made to achieve pressures of 3000 psi and higher. A result of higher pressures is better understanding of the material properties, notably how the compliance of the voided liner is affected by higher static pressures. Current material data is only available for up to 260 psi, so projections of this data are currently made to estimate properties at higher pressures. Castings of new liner materials have been acquired that include varying material compliance and density, and testing of these liners is scheduled for January 2011.

A second thrust of future work involves refining the theoretical models for the silencer and Helmholtz resonator, and expanding the application of models to the tuning coil and Quincke tube. The planned testing of the new liner materials as well as testing at higher pressures should provide more insight into the material properties.

Work related to this project, but peripheral to the main thrust of work, includes exploration of the experimental test rig and the related ISO standard. Gaps may exist in the technique for resolving the downstream wave amplitudes and suppressing standing wave modes in the measurements. In addition, construction of an actively-tuned Helmholtz resonator by attempting to mix iron powder into the voided urethane for a magnetorheological elastomer would be a proof-of-concept of yet another variation on the technology. The manufacturing methods of hydraulic hose will be investigated to consider the possibility of mixing microspheres into the elastomeric lining, for both compliance and micro-texturing purposes. The application of a Helmholtz resonator to the suction side of a pump for cavitation reduction has been noted in the literature;[19] this may be a topic to explore with the compact resonator developed in this research.

C. Member company benefits

This project is yielding very positive results that are strongly rooted in practical application and the development of new technology. There are fully functional prototypes for an in-line silencer, Helmholtz resonator, tuning coil, and Quincke tube that have demonstrated performance characteristics. For the Helmholtz resonator, there is a significant improvement in compactness over existing technologies. In addition, should a sponsor company be convinced of the merits of the work, a portfolio of intellectual property is available for investment. Seven patent disclosures were filed with the Georgia Institute of Technology’s Office of Technology and Licensing over the course of the year; their specific titles and reference numbers can be found in the references. The patent disclosures include various embodiments of the technology under development, for example, the compliant-lined Helmholtz resonator and variations including a tuneable version, a filtering network (multi-volume resonator) and an actively tuned resonator. In addition, a supplier is already on-line to provide tailored liner materials with the capability to vary the microsphere size, stiffness, density, and host matrix properties. This project has been identified within the Center as having the highest Technology Readiness Level – the implication being that an interested company would have minimal further development to invest in before market-ready devices are available.

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Project 3C: Simulation of Cavitation and Noise in Fluid Power

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Graduate Students: Kameswararao Anupindi

1. Statement of Project Goals

The problem to be solved is related to cavitation in hydraulic components such as pumps and valves. Computer codes are being developed and applied based on state-of-the-art high-fidelity computational fluid dynamics (CFD) tools to study, predict, and control cavitation noise in fluid power components. The focus is on the large eddy simulation (LES) technique for computing turbulent flows and features the use of high-order numerical methods for solving both the compressible and incompressible Navier-Stokes equations together with a suitable cavitation model. Interactions with industry also feature the use of commercial CFD codes depending on the nature of the problem being addressed. The most recent goal of the project is to develop a new CFD tool capable of high fidelity LES and cavitation for simulating flow through complex geometries of interest to the ERC and industry. This project will be successful if we are able to validate our LES cavitation code against experimental data, simulate flows through industrial geometries, e.g. valves, producing meaningful and useful results, and producing a code that can be used by others in academia and industry.

2. Project Role in Support of Strategic Plan

The goal of compact, efficient, and quiet fluid power systems will most likely result in higher flow rates and rpm's and hence more turbulence and cavitation. In order to optimize such designs to maximize performance but reduce cavitation and noise, CFD clearly has a role to play. As projects within the ERC strive to develop improved piston pumps that avoid cavitation and fast-acting valves that optimize flow forces, an accurate and efficient CFD tool becomes invaluable.

3. Project Description

A. Description and explanation of research approach

In this project we develop state-of-the-art high fidelity computational fluid dynamics (CFD) tools to study, predict, and control cavitation noise in fluid power components. Fluid power components in general feature rotating/reciprocating geometries with transitional/turbulent multiphase flow through them. Off-the-shelf CFD packages employ Reynolds averaged Navier Stokes (RANS), which is a time averaged method and owing to this fact they have difficulty in accurately capturing the unsteady complex flow features of the fluid power components. In order to alleviate this difficulty the tools developed by the current project make use of large eddy simulation method (LES), which is based on spatial filtering of quantities and time accurate in implementation. The CFD tool developed under this project (here after referred to as *WenoHydro*) makes use of higher order spatial and temporal discretization together with an accurate subgrid scale (SGS) model which is a de facto for implementations involving LES. The main challenge of this project lies in efficiently implementing higher order LES solver together with the ability to handle complex geometries. Usage of higher-order spatial discretization is primarily limited to structured grids. The underlying directional grid they provide makes it easier to devise higher-order schemes. At the same time, many of the linear solvers and algorithms can be efficiently implemented on structured grids. Treatment of complex geometries was a difficult task with structured grids until the recent research advances in immersed boundary methods (IBM) (Mittal et al. 2005), and fictitious domain method (FDM) (Khadra et al. 2000). These methods are based on elegantly handling complex geometries with structured meshes using forcing technique to accurately satisfy the boundary conditions on the complex geometries. *WenoHydro* makes use of FDM to handle complex geometries. The innovative idea behind this approach is to make use of efficient structured grid algorithms and yet handle complex geometries with relative ease which is quite suitable for simulating complex fluid power devices. The usage of FDM on structured meshes does not require re-meshing of the grid at each time step unlike their unstructured counterparts which spend most of the time in re-meshing and interpolating the solution variables to the newly generated grid. This is another important advantage of the method at hand. With the aforementioned features and advantages of the method it seems that *WenoHydro* is a successful tool to be used for simulation of fluid power devices.

B. Achievements

Earlier research on this project (Dittakavi et al. 2010) concentrated on developing a fully compressible LES solver for turbulent cavitating flow simulations. In this solver, the fully compressible Favre-filtered Navier-Stokes equations are coupled with a homogeneous equilibrium cavitation model. To close the filtered non-linear convection terms a dynamic Smagorinsky subgrid-scale turbulence model is employed. The equations are numerically integrated in the context of a generalized curvilinear coordinate system to facilitate geometric complexities. A sixth-order compact finite difference scheme is employed for the Navier-Stokes equations with the AUSM+-up scheme to handle convective terms in the presence of large density gradients. The stiffness of the system due to the incompressibility of the liquid phase is addressed through an artificial increase in the Mach number. The capability of this code is demonstrated by simulating a turbulent cavitating flow in a venturi nozzle as reported in Dittakavi, N. et al. 2010. The simulation predicts the formation of a vapor cavity at the venturi throat with an irregular shedding of the small scale vapor structures near the turbulent cavity closure region. The effect of vapor formation on the velocity fluctuations and the effect of cavitation on the vortex stretching term were also analyzed. A spectra of the pressure fluctuations in the far-field downstream region shows an increase in the acoustic noise at high frequencies due to cavitation. The vortical structures and void fraction computed by this fully compressible code are shown in Figure 1. While the simulation results from the aforementioned compressible LES solver highlighted the ability of LES to capture turbulence-cavitation interactions in model geometry, the numerical limitations of using a fully compressible approach and the applicability of the solver only to simple geometries precludes the use of this code for practical fluid power components.

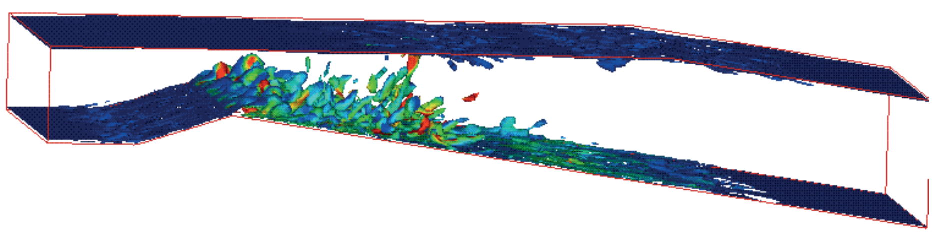

Figure 1: Snapshot showing vortical structures colored by void fraction highlight interaction between cavitation and turbulence in a model venturi.

With a motivation to extend the higher order LES solver to complex geometries, the current research on this project concentrates on developing an incompressible LES solver (*WenoHydro).*
WenoHydro as the name suggests employs 5th order accurate weighted essentially non-oscillatory (WENO) scheme for discretization of convection terms, 4th order accurate spatial discretization for diffusion terms and 3rd order Runge-Kutta time stepping. For performing LES simulations, we use Vreman (2004) SGS model, which is designed for application of LES to fully inhomogeneous flows. The ability to handle complex geometries which is the main motivation behind developing *WenoHydro* solver comes from the FDM implementation. Also, we implemented the cavitation-induced-momentum-defect (CIMD) correction approach of Srinivasan et al. (2008) for simulating cavitating flows through fluid power components. *WenoHydro* solver has been validated for its numerical accuracy, and its ability to accurately simulate turbulent flows as shown in the published results of Shetty et al. (2010). The details of FDM and the CIMD model as implemented in *WenoHydro* solver are discussed here briefly.

Fictitious Domain Method (FDM):

In FDM (Khadra et al. 2000), the first step is to construct a fictitious domain from the original fluid domain and the embedded solids as shown in Figure 2. Next, a single set of global governing equations are formulated over the whole domain (fictitious domain) in order to determine the physical fields in each medium, like velocity, pressure, temperature etc... The methodology of FDM consists in adding a volumetric drag term called Darcy drag to the Navier-Stokes equations which represents the effect of the embedded solid bodies on the flow field. This volumetric drag term is a function of the permeability *K*, whose value tends to infinity in the fluid domain and to zero in the solid domain there by effecting the global governing equations behave as the Navier-Stokes equations for viscous fluid and Brinkman equations in the solid region respectively. The interface boundary condition between the fluid and solid regions is implicitly absorbed into the governing equations through introduction of volumetric control terms. Detailed discussions about the method can be found in the original paper by Khadra, K et al. (2000).

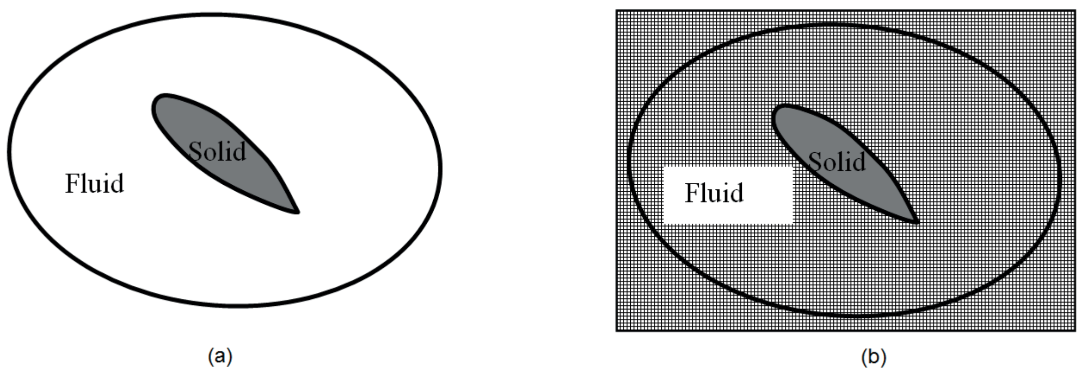

Figure 2: (a) Schematic showing original fluid and solid domains (b) Fictitous domain constructed from the fluid and solid domains and by overlapping a cartesian grid.

In order to demonstrate the capability of the FDM to handle complex geometries we performed various simulations ranging from curved pipe, transitional flow through a pipe with constriction, flow in a model valve etc… The vortical structures obtained from the simulation of the flow through a model valve at a Reynolds number of 500 are shown in Figure 3. The model valve geometry considered here is inspired by the application of *WenoHydro* solver to practical fluid power components.

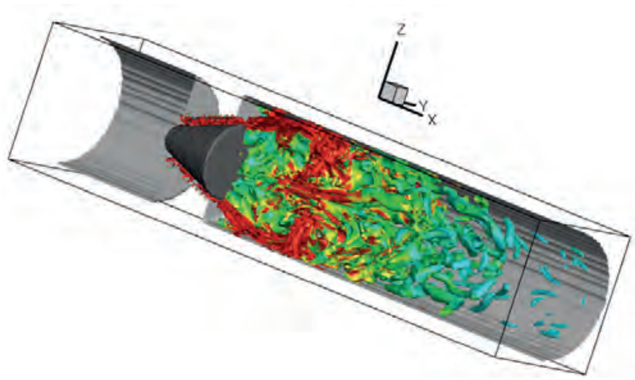

Figure 3: Instantaneous vortical structures visualized by isosurfaces of lambda2 = -2, colored by vorticity magnitude for a Re = 500 in flow through a model valve.

Cavitation-Induced-Momentum-Defect (CIMD) correction method:

CIMD correction methodology (Srinivasan et al. 2008), is an unsteady cavitation event tracking model for predicting vapor dynamics occurring in multi-dimensional viscous incompressible flows. In this procedure, in addition to the Navier-Stokes equations for the liquid phase, vapor transport equation (scalar transport) for the vapor phase is solved at each time step. The CIMD correction methodology accounts for cavitation inception and collapse of events as relevant momentum-source terms in the liquid phase momentum equations. Homogeneous equilibrium model (HEM) assumptions are employed to track cavitation zones and for the consideration of compressibility effects introduced by cavitation. Detailed discussion about this method can be found in the paper by Srinivasan et al. (2008). With the implementation of CIMD correction approach in *WenoHydro* we were able to simulate the same Venturi nozzle problem shown in Figure 1. The contours of z-vorticity are shown plotted in Figure 4 for the 2D Venturi nozzle simulation at a Re 1000. Further, the vapor fraction contours are shown plotted in Figure 5, for various non-dimensional times starting from t = 2 to t = 20. Inception of cavitation at the low pressure throat region can be seen in Figure 5 at earlier times and at later times the cavities are partially shed and convected downstream of the throat region.

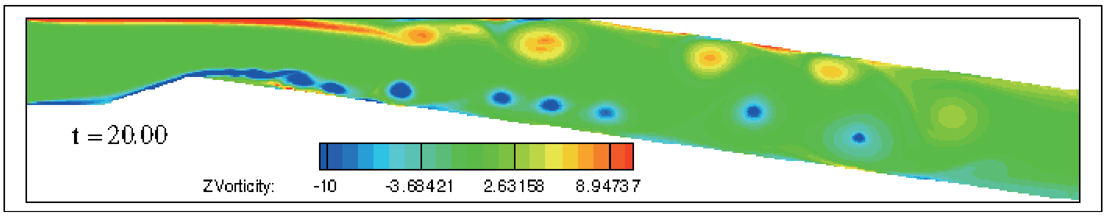

Figure 4: Contours of z-vorticity for flow through a 2D Venturi nozzle at a Re 1000.

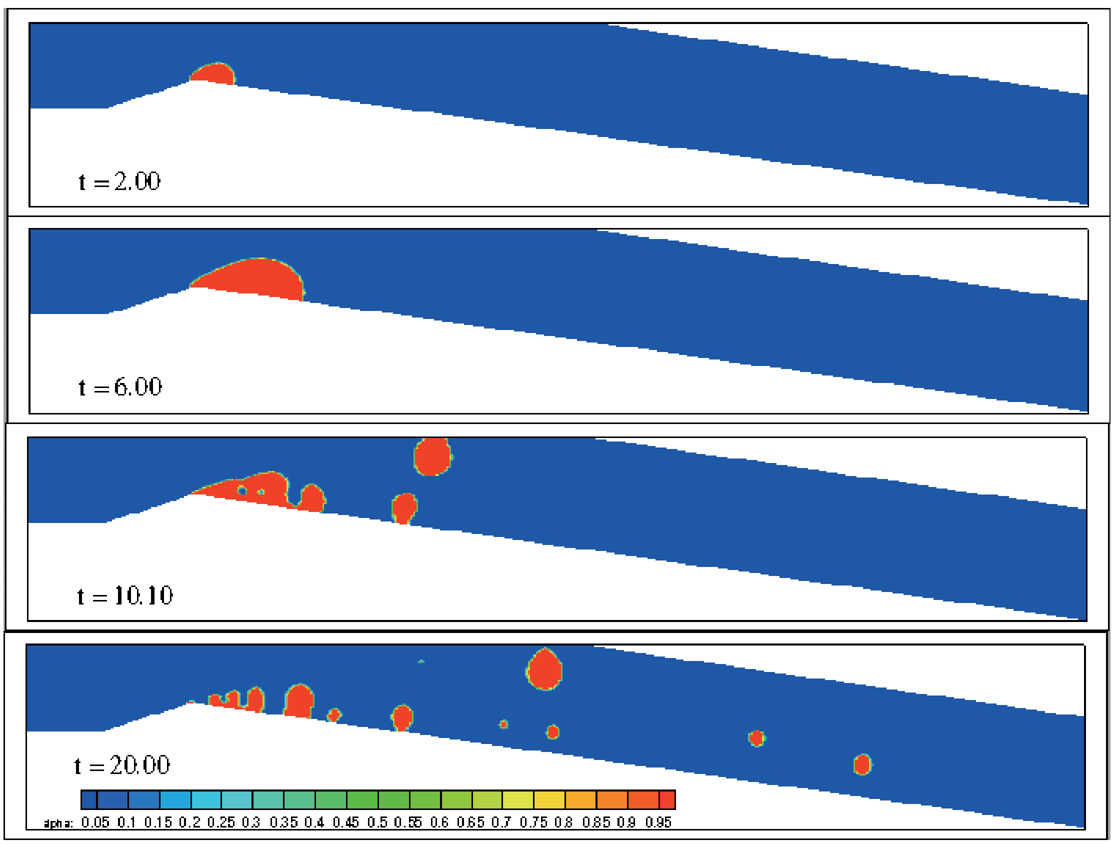

Figure 5: Contours of vapor fraction for flow through a 2D Venturi nozzle at a Re 1000.

Future Work:

Next, we plan to perform 3D Venturi cavitation simulations with *WenoHydro* solver and validate them against the published experimental results of Delghosha, et al. (2003). After successfully validating the code for cavitation we would like to simulate cavitation in industrial fluid power components of interest.

C. Member company benefits

CCEFP member companies interested in (i) cavitating flow simulations through industrial fluid power components or in (ii) fluid – structure interaction of the components, can greatly benefit from *WenoHydro* solver. Simulations in *WenoHydro* can be performed starting from the CAD geometry of the components that companies have and arriving at final solution in a straight forward manner within a reasonable amount of time. In the due course of this research interactions with Moog Inc. and Eaton Corporation for the simulations of their proprietary components are very much appreciated and we look forward to perform more simulations of interest to other CCEFP member companies as well in future with *WenoHydro* solver.

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3D.1 Leakage Reduction in Fluid Power Systems

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Graduate Students: Bo Yang, Azam Thatte, Yuli Huang
Industrial Partners: Trelleborg Sealing Solutions, Evonik, Bosch-Rexroth, John Deere, Caterpillar, Haldex, R. T. Dygert

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

The fluid power industry has recognized that the reduction or elimination of leakage of hydraulic fluid from fluid power systems is a fundamental prerequisite for the expanded use of fluid power. At virtually every major fluid power manufacturer, leakage reduction is at or near the top of the list of urgent technological needs. Leaking rod seals are the most significant sources of environmental pollution in fluid power systems. At the present time, these seals are developed through empirical means, using trial and error techniques, since the fundamental physics of seal operation has been poorly understood.

Rod seals are reciprocating seals. Past research on such seals is described in a recent review paper [1]. Serious studies date back to at least 1964. Since that time many studies have been performed, but these have not had a significant impact on the practical aspects of seal design due to the complexity of modeling the operation of rod seals and the need to make many simplifying assumptions. In particular, both the roughness of the seal surface and mixed lubrication in the seal-rod interface, were generally ignored.

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

The models developed in this project simulate the dominant physical processes governing the behavior of rod seals and take account of mixed lubrication and seal roughness. They include analyses of the fluid mechanics, contact mechanics, thermal processes (in some cases) and deformation mechanics, and an iterative computational procedure. Inputs to the models include the operating conditions, material properties, macro-geometry, and micro-geometry of the sealing surfaces.

Model development involves analyzing the fundamental physics of the various processes, setting up numerical analyses and computational strategies, constructing appropriate algorithms and writing code. Model validation makes use of experimental results obtained from industrial collaborators. As required, simulations of seals suitable for the test bed are performed and, based on the results of the simulations, design recommendations are made for the test bed seals. As the project progresses and more is learned about the physics of seal behavior, that information is transmitted to the test bed projects.

B. Achievements

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

The results of the above simulations have revealed much about the basic physics of rod seal operation. They show that these seals 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.

During the last year, considerable progress was made on the further development and application of the viscoelastic transient seal model, begun during the previous year. The steady-state and transient models discussed above treat the seal as elastic. When viscoelastic effects are taken into account, the behavior of the seal at any instant of time depends not only on current conditions, but also on the entire past history of the seal. This model makes use of the Generalized Maxwell Model constitutive relation with a five term Prony Series. It takes account of the viscoelasticity in both the contact mechanics analysis and the deformation analysis. The development work increased the robustness of the model. Then the model was used to produce a number of simulations.

First an injection molding application was simulated. Viscoelasticity is seen to affect the leakage and friction characteristics of the seal through its effects on the changing fluid pressure and contact pressure distributions as the rod velocity and sealed pressure change during a cycle. Compared to purely elastic behavior, viscoelasticity increases the fluid pressure and the contact pressure significantly in the sealing region closest to the sealed end, shifts the fluid pressure peaks away from the sealed end during the instroke and enhances the cavitation during the outstroke. It results in thicker fluid films and produces a significant increase in the Poiseuille flow during the instroke.

Next, a short stroke, high frequency actuator application was simulated. As in the injection molding application, viscoelasticity is seen to affect leakage, friction, contact pressure and fluid pressure distributions. In addition, except for low frequencies, the various characteristics (leakage, friction, etc.) change from one cycle to the next. The results also emphasize how application-dependent, rod seal behavior is. A seal that is leakless at high frequencies can leak at low frequencies.

The final simulation involved a concept for an electronically controlled rod seal. A seal was designed with several PZT piezoelectric elements, in various configurations, embedded in the elastomer. Preliminary simulations show that by varying the voltage supplied to the elements, the seal macro-geometry and contact pressure distribution, and therefore the fluid pressure distribution, can be varied at will. This has the potential of allowing a seals behavior to be tailored to a particular application. An invention disclosure describing this concept has been filed [10].

Tasks with deliverables and major milestones:

- Task 1: Incorporate rod texture in fluid mechanics and contact mechanics analyses. [months 1-6] Deliverables: Algorithms for Reynolds equation solution, flow factors, contact mechanics solution
- Task 2: Assemble model. [months 4-9] Deliverables: Algorithm and computer program
- Task 3: Simulate a specific application. [months 7-12] Deliverables: Simulation results
- Task 4: Validate with testing at industrial partner. [months 10-15] Deliverables: Test results and analysis

Rod surface texture	QI	Q2	Q3	Q4
1. incorporate texture in analyses	X	X		
2. assemble model		X	X	
3. simulate specific application			X	X
4. validate with testing at industrial partner				X

C. Member company benefits

All publications and computer programs will be available to Center members. The steady-state model has already been transferred to Trelleborg Sealing Solutions.

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

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

1. Statement of Project Goals

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

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

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

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

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

2. Project Role in Support of Strategic Plan

<u>Compactness</u>

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

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

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

<u>Efficiency</u>

Surprisingly, there has been little progress within EHL over the last forty years in explaining the mechanism of mechanical dissipation in full EHL films. In very recent related work [2] using the temperature/pressure correlation devised by this project, the first experimentally validated EHL friction calculation was performed which included thermal-softening and shear-thinning. Fragility has been shown to be the principal property controlling friction. In particular, the results of this project may be used to rank the mechanical energy loss of contacts lubricated by fragile hydraulic oils.

3. Project Description

A. Description and explanation of research approach

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

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

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

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

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

where n is the power-law exponent which in the limit of high shear rate is $n = 1 + \partial \ln\eta / \partial \ln\dot{\gamma}$.

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

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

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

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

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

B. Achievements

PUBLICATIONS

The achievements of this project may best be summarized by a list of resulting publications. Fifteen papers have resulted from the three years of work; nine have been written, submitted or published within the last year alone. They are listed below and referred to later in the progress section in superscript.

1. Kudish, I.I., Kumar, P., Khonsari, M.M. and Bair, S., "Scale Effects in Generalized Newtonian Elastohydrodynamic Films," ASME J. Tribology, Vol.130, 2008, 041504, 8 pages.

2. Roland, C.M., Bogoslovov, R.B., Casalini, R., Ellis, A.R., Bair, S., Rzosca, S.J., Czuprynski, K. and Urban, S., "Thermodynamic Scaling and the Characteristic Relaxation Time at the Phase Transition of Liquid Crystals", J. Chem. Phys., Vol.128, 2008, 224506, pp.1-9. Alan Berman chemistry award winner

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7. Krupka, I., Kumar, P., Bair, S., Khonsari, M.M. and Hartl, M. "The Effect of Load (Pressure) for Quantitative EHL Film Thickness," Tribology Letters, Vol.37, No. 3, 2010, pp.613-622.

8. Martini, A. and Bair, S., "The role of Fragility in EHL Entrapment," Tribology International, Vol. 43, 2010, pp.277–282.

9. Bair, S., "The Dependence of the Dynamic Properties of Elastohydrodynamic Liquids on Temperature and Pressure (Volume)," Proc. I. Mech. E., Part C, Journal of Engineering Science 224(C12), 2010, pp.2568-2576.

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13. Young, A. and Bair, S., "Experimental Investigation of Friction in Entrapped Elastohydrodynamic Contacts," Tribology International 43(9), 2010, pp.1615–1619.

14. Laeseke, A. and Bair, S., "High Pressure Viscosity Measurements of 1,1,1,2-Tetrafluoroethane," in preparation for submission to Int. J. Thermophys.

15. Krupka, I., Kumar, P., Bair, S. Svoboda, P. and Hartl, M., "Mechanical Degradation of the Liquid in an Operating EHL Contact," Accepted Tribology Letters.

PROGRESS DURING THIS PERIOD

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

We have extended our work on the effect of scale[1] on generalized Newtonian EHL film thickness to include the effect of load[7] (pressure). Earlier in this program, we showed through analysis using realistic shear dependent viscosity that the classical Newtonian theory understates the dependence of film thickness on scale[1]. We later experimentally validated this effect by measuring film thickness for various size steel balls against glass discs[6]. For this year further analysis indicted that a similar effect was important to contact pressure and experimental measurements using a WC ball against a sapphire disc validated the theory[7]. We found that the film thickness is reduced due to the shear stress dependence of viscosity for any process which increases the pressure gradient within the inlet zone.

These investigations lead to the observation of measurable molecular degradation in an operating EHL contact[15]. In each case, for shear thinning liquids, experimental film thickness was more sensitive to load and scale than the rheology would suggest[6,7]. Although these were ostensibly pure rolling contacts, the most obvious explanation was molecular degradation from the shear applied to the liquid. To test this hypothesis, time-dependent film thickness measurements[15] between a steel ball and a glass disc were made with the most shear dependent liquid we have studied, a gear oil. The film thinned rapidly after the first revolution of the ball and reached a steady thickness after about ten revolutions. To investigate the effect of stress history on the shear dependence of viscosity, flow curves were generated with a new pressurized Couette viscometer. Viscosity was measured as a function of increasing shear stress to 1.2 MPa and, afterward, as a function of decreasing shear stress[15]. The exposure of the liquid to high stress permanently decreased the viscosity measured at low stress, an indication of molecular scission.

By examining the measured and predicted film thicknesses for very low viscosity liquids, ordinary liquids at very high temperature and water-based solutions, we have developed the first film thickness formula for linear piezoviscous liquids[12]. The new formula predicts that the speed sensitivity will be reduced at high temperatures for many low-viscosity liquids. The formula was then experimentally validated[12].

We developed a framework for transient modeling of sliding EHL including thermal effects[10]. The volume anomaly which occurs as the glass-to-liquid boundary is crossed as the liquid is decompressed was included in the calculation to explain anharmonic variation in film thickness from harmonic variation in entrainment velocity. We concluded that these anomalies cannot be explained by solutions of the Reynolds equation which is only valid when the product of shear stress and local pressure-viscosity coefficient is less than one[10].

We constructed a bench-test for implementing EHL entrapment into a geroller start-up mechanism to provide a means of incorporating the recently discovered[13] effect of entrapment on friction. A lubricated contact which is brought to a rapid stop or has experienced an impact of the two surfaces will often tap a pressurized pocket of liquid. The persistence of this entrapment is dependent upon the fragility of the liquid lubricant. The entrapment can last for seconds or days. We have demonstrated experimentally that the load support offered by an entrapment will substantially reduce the starting friction once sliding resumes.

We have applied the viscosity scaling that was developed earlier in the program[3] to other materials including dimethyl pentane and a volatile refrigerant[14]. The Stickel analysis technique was useful in identifying a second regime of viscosity scaling different from that of ordinary hydraulic oils which are fragile glass-formers having more complex molecules.

In three papers[3,5,9] we have set out a rheological framework for realistic numerical simulations of film and friction behavior in lubricated concentrated contacts. In associated work, see [2], a full EHL simulation of sliding contacts with significant dissipation clearly shows the profound effect of the pressure dependence of the liquid thermal conductivity on friction. This simulation was thoroughly validated experimentally. The relationship between thermal conductivity of a liquid and full-film friction has not been reported previously.

PLANNED PROGRESS

The geroler bench test will be employed to evaluate mechanisms for the generation of EHL entrapments to ease start-up.

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

1. It seems that the speed dependence of the film thickness depends on the piezoviscous strength.
2. Sliding friction in full films can be strongly dependent upon the thermal properties of the liquid. The characterization of the pressure and temperature dependence of thermal conductivity will be a priority.
3. There is presently no single standard definition of "alpha" which characterizes the piezoviscous strength for film-forming for all liquids.
4. It may be possible to simply correct the classical film thickness formulas for the effect of molecular weight on the shear dependence of viscosity. Experimental film measurements will be made with an homologous group of oils of varying molecular weight.

C. Member company benefits

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

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Project 3D.3: Improved Seal Design Based on Adaptive Materials

Research Team
Project Leader: Prof. Barney E. Klamecki, Department of Mechanical Engineering, University of Minnesota
Graduate Student: Daniel Matus

1. Statement of Project Goals
The loss of working fluid from fluid power systems has severe consequences. The visible results of hydraulic fluid leakage are obvious and lead to system acceptability concerns related to working environment degradation. Coupled with environmental concerns are losses in system performance, efficiency and up-time when working fluid and pressure are not adequately contained.

Seal performance breaks down due to changing or unforeseen operating conditions and the effects on seal material properties and behavior. Even if such large scale processes do not occur, seal performance decreases over time in use. Over time in service permanent material deformation grows, contact pressure decreases and high pressure working fluid can move through the now lower contact pressure seal-counterface region.

The goals of this project are to improve seal performance by

- increasing seal life by minimizing the permanent material deformation that develops in elastomeric seals in use
- establish seal design principles that will enable the rationale design of longer-lived seals
- demonstrate improved performance in seals based on the new design concepts
- foster industrial applications of research results

2. Project Role in Support of Strategic Plan
The effectiveness thrust of the Center mission explicitly recognizes the need for fluid power systems to be safe, quiet, clean and easy to use. The technical barriers to producing clean, leak-free operation are limitations in detailed understanding of some of the basic physical processes occurring in the seal system and the degradation of seal performance resulting in limited life of currently available seals. Fundamental studies of the sealing process and development of predictive models of it are being carried out in another Center project. This project, 3D3, is focused on increasing elastomeric seal life through seal material design. The project directly attacks a major technical barrier to wide spread adoption of fluid power systems – producing and assuring leak-free operation over extended time in use.

3. Project Description

A.1 . Research Approach

The development and justification for the seal design concept was based on experimental results summarized in Figure 1(a), Maciejewski et al. [1], Sefkow et al. [2], most of which were developed in this project. In summary, the results indicate the source of permanent material deformation and an approach to controlling it.

In characterizing the driver of permanent deformation resulting in so-called compression set two types of tests were conducted. In one series of experiments cylindrical specimens were cast from the polyurethane material and the specimens wrapped with stiff flat twine to produce various amounts of imposed compression. Specimens were held in the constrained state for varying lengths of time, unwrapped and the amount of deformation measured as percent compression set, i.e.

$$CS = \frac{\textbf{Permanent deformation}}{\textbf{Imposed deformation}} = \frac{d_o - d_f}{d_o - d_c} 100\% \tag{1}$$

with d_o the initial specimen diameter, d_c the diameter under load and d_f the final diameter after release of constraint.

In the other kind of test the load required to produce a specified deformation of wrapped specimens was measured at various times, analogous to the loss of seal-counterface contact pressure over time.

The test results were characterized in several ways with description of them in terms of strain energy being the most useful.

The specimen strain energy was calculated for all specimens and average values for the various imposed deformations are shown in Figure 1(a) along with measured compression set and the change in applied load needed to produce 20% compression.

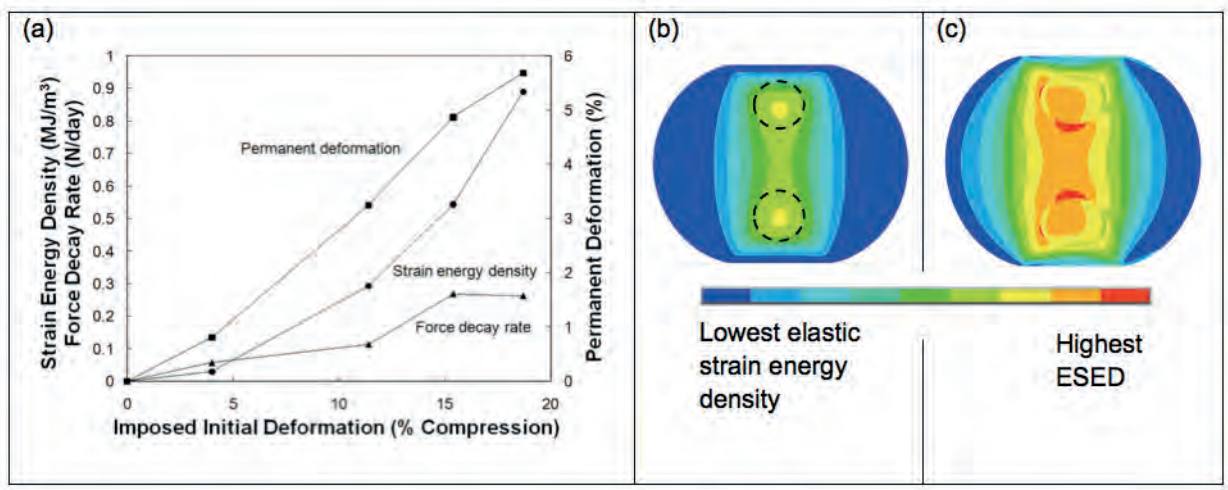

Figure 1: (a) Permanent deformation and change in load required to produce specified compression for test specimens held under various strain energy states for varying lengths of time. Strain energy density for (b) One-material O-ring section, (c) O-ring with a region of different stiffness material.

The correspondence between both permanent deformation and rate of change of mechanical behavior and the material strain energy content led to selecting strain energy as a particularly important dependent seal design variable. Specifically, the design concept is to base seal design on minimizing strain energy and so minimizing the impetus for compression set and loss of sealing contact pressure.

Another set of results is summarized in Figures 1(b) and 1(c) which show calculated strain energy density from finite element models of O-ring sections subjected to displacements in the vertical direction in these pictures. The O-ring section in Figure 1(b) is composed of one material and that in Figure 1(c) contains an inset region of different elastic modulus in the larger section.

The two relevant observations are that the high energy regions are localized in the seal section (circled in Figure 1(b)) and that large changes in the energy level and distribution can be produced by introducing regions of different material behavior into the larger seal section.

A.2 Seal Design Concept

Two observations about initial results shaped the direction of this research. One was the belief that reducing stored elastic strain energy in the seal would decrease permanent material deformation and its deleterious effects on sealing. The other observation was that the high strain energy regions were to be the target for new seal design concepts.

In summary, the design concept pursued was to decrease strain energy in seals by including regions of different material behavior in high strain energy regions of the O-ring section.

B. Achievements

B.1 Elastic Strain Energy

The elastic strain energy density, energy content and seal-gland contact pressure were calculated in numerical models of the baseline, one material, O-ring design and for seal sections with circular cross-section insets of varying elastic modulus, size and location in the larger seal section.

In one design study of many that produced similar results the overall section surrounding the insets had a modulus of elasticity of 13.4 MPa and the inset material elastic modulus was a design variable. The less stiff material insets were located in the larger section with the outer edge of the inset 1 mm below the main O-ring surface. Seal section loading was an imposed displacement of 15% of the O-ring section diameter.

Elastic strain energy content of the O-ring sections was characterized by the maximum value of strain energy density and the total strain energy in the section. Section total strain energy content was defined as the sum of the energy density contents of the individual contours in the plots of elastic strain energy density. The energy content of individual contour regions was calculated as the portion of the section area covered by the contour times the average value of the energy density in that contour. Contour area was measured as the number of pixels in the contour in the strain energy density plots in finite element analyses.

Results regarding the effects of varying material stiffness over the seal section are summarized in Figure 3. The baseline O-ring design was a one-material section with elastic modulus of 13.4 MPa. The modified designs had insets of lower elastic modulus ranging from 10.9 MPa to 5.1 MPa. The overall section diameter was 8.4 mm with 1.8 mm diameter insets. Figure 2 shows the energy content of the finite element solution contours graphically.

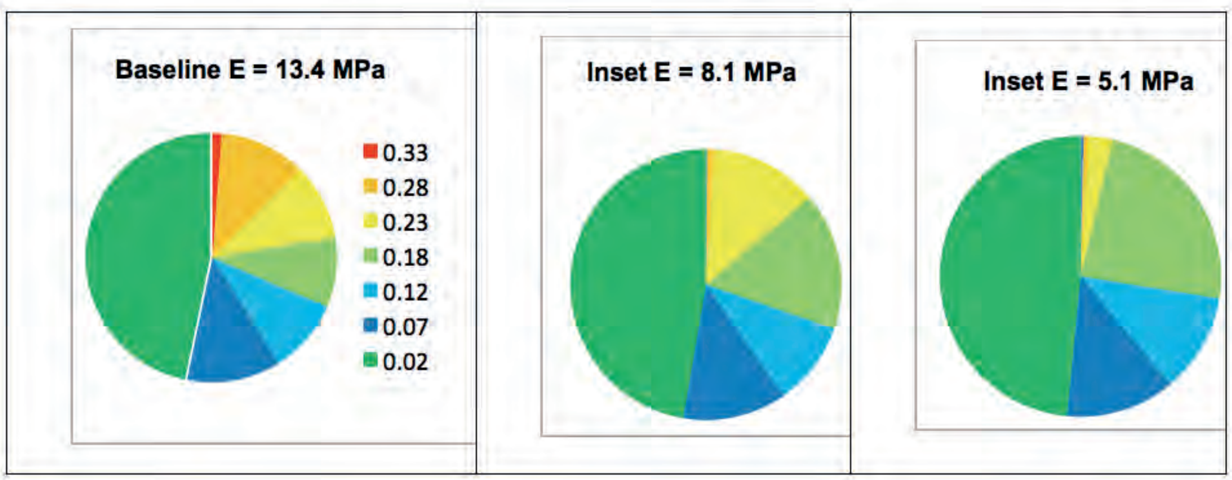

Figure 2: Portions of O-ring sections with particular elastic strain energy content, MJ/m^3.

Including softer material insets in the overall O-ring section decreases the size of the higher energy level regions. As shown in Figure 2 when a softer inset is included in the baseline design and inset elastic modulus is 8.1 MPa, the areas of the three highest energy levels change from {1.2%, 11.2%, 9.9%} to {0.2%, 0.82%, 12.9%} of the total section area. With a 5.1 MPa elastic modulus inset the corresponding areas are reduced further to {0.4%, 0.5%, 2.8%}. The lower energy regions increase slightly in size. The three lowest energy regions cover {9.6%, 12.2% and 46.7%} of the section area in the baseline design compared to {10%, 12.4% and 47.3%} for the 8.1MPa elastic modulus inset design and {11.4%, 12.6% and 48.4%} for the 5.1 MPa elastic modulus inset design.

In summary, the overall section energy content decreases due to significant decreases in the energy in the highest energy regions, with minor increases in the size of lower energy level regions. The implication is that significant changes to seal deformation behavior can be produced with easy to implement changes in a few small regions of the seal.

B.2 Compression Set Measurements

Physical experiments were performed to evaluate new seal design concepts in terms of compression set. The new design O-rings were fabricated by casting an industrial rubber molding compound around commercial O-rings used as the inset component of the overall ring. Three O-ring of the same material and with toroidal diameter of 37-mm were found with cross-section diameters of 2-mm, 3-mm, and 4-mm. It was necessary that the main O-ring cross-section was large enough to accommodate two insets. An O-ring cross-section diameter of 12.7-mm was chosen based on tooling and molding process considerations. The larger overall O-ring sections had average hardness of 89 Shore A and the inset O-ring harness was 72 Shore A.

Compression set tests were run using a test apparatus that realistically mimics the actual in-use situation. A compression fixture was designed and fabricated that holds a set of four O-rings between two metal plates that are held apart by spacers sized so as to impose a specified amount of compression. Accelerated aging is a common practice in stress relaxation and compression set testing of elastomers and was implemented in this work. After applying the compression, the test fixture containing the O-rings was placed immediately in an oven pre-heated to 45°C, and left for 70-hours. After removing the test fixture from the oven, the O-ring were removed from the fixture, and placed on a wooden surface, a poor thermal conductor. The samples were untouched and allowed to relax for 30-minutes, and then final section height (diameter) measurements were made and compression set calculated.

Results from two sets of compression set tests at 18.75% compression and results from a 7% compression test are plotted in Figure 3.

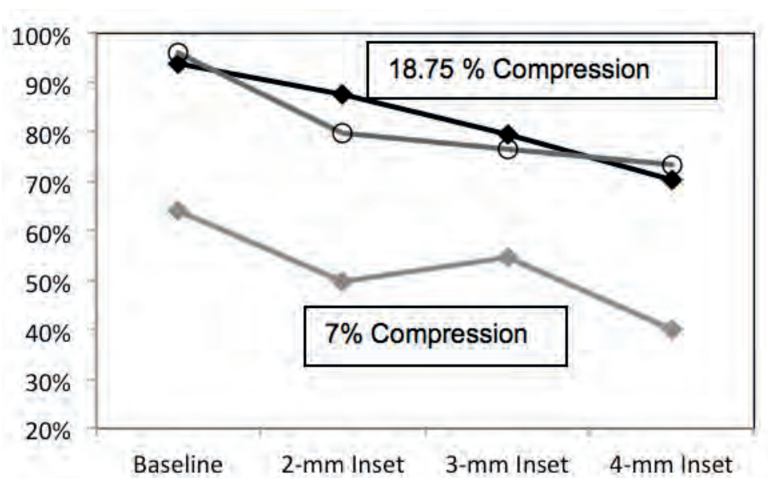

Figure 3: Compression set test results for baseline and O-rings with 2 mm, 3 mm and 4 mm insets.

There are two primary conclusions that can be drawn from these compression set results. Foremost, the decrease in compression set for O-rings with softer material insets in the high elastic strain energy region corresponds to the lower calculated strain energy content. This effect is large, with the baseline O-ring compression set of 95% reduced to 87%, 78% and 67% as the inset diameter was increased from 2 mm, to 3 mm and to 4 mm in the 18.75% imposed compression case. The same kind of result is seen in the less severe situation of 7% imposed compression. This general experimental result corresponds to results expected with regard to the design concept put forward and to the results of numerical design studies.

The second conclusion is that the greater decrease in compression set with increasing inset diameter is presumably due to a larger region of decreased permanent material deformation. Again, this reinforces the design concept of modifying local regions of the O-ring to produce improved performance of the entire structure.

B.3 Stress Relaxation and Contact Pressure

In stress relaxation tests a 7% compression was held on O-rings and the change in compressive force measured continuously over 8 – 10 day periods. The tests were run using 12.7 mm diameter baseline, one-material O-rings and O-rings with softer material insets of 2 mm, 3 mm and 4 mm similar to the O-rings used in compression set measurements. The results of one of these sets of tests are shown in Figure 4.

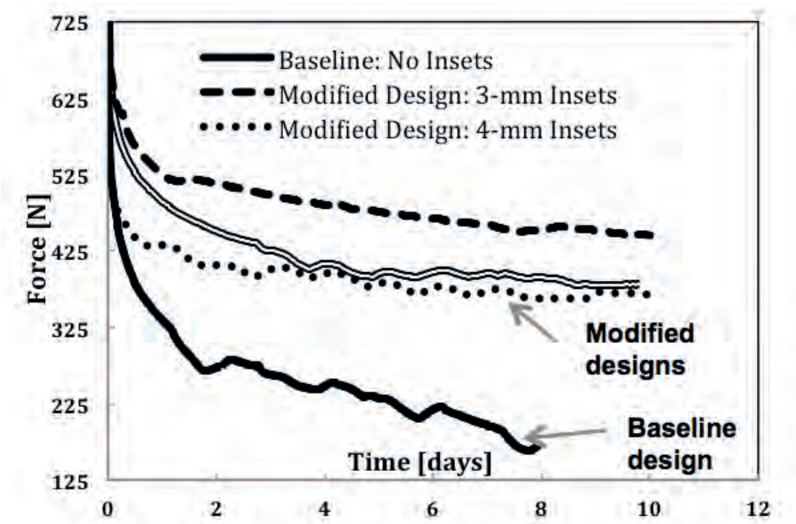

Figure 4. Stress relaxation test results for comparison of new design O-rings to baseline O-ring.

Initial contact pressure was higher for the baseline design (as seen more clearly in Table 1 below) but the rate of contact pressure decay was less for the modified designs.

O-ring Design	*Initial contact pressure (MPa)*	*F(t) = A ln[t] + B*	R^2	*Decay Coefficient, A*	*Change from Baseline*
Baseline	720	-66.8 ln[t] + 330	0.900	-66.8	-
2-mm Insets	680	-48.5 ln[t] + 481	0.928	-48.5	26%
3-mm Insets	660	-39.2 ln[t] + 538	0.962	-39.2	46%
4-mm Insets	550	-30.4 ln[t] + 430	0.922	-30.3	37%

Table 1: Compression Stress Relaxation Curve Fitting

Contact pressure decay rate was described by fitting the data to the logarithmic function listed in Table 1 and the rate of loss of contact pressure described by the coefficient *A* in this model. The inclusion of the softer material insets resulted in a decreases of contact pressure loss of 26%, 46% and 37%.

C. Member Company Benefits

This project ended in May, 2010. At the present time relationships are being developed with member companies to evaluate the concepts and results that can reasonably be pursued for commercialization.

D. References

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3E: User-Centered Human-Machine Interface for an Excavator

Research Team

Project Leader:	Prof. Silvanus J. Udoka, Dept. of Industrial & Systems Engineering, NCAT
Other Faculty:	Prof. Xiaochun Jiang, Dept. of Industrial & Systems Engineering, NCAT
	Prof. Zongliang Jiang, Dept. of Industrial & Systems Engineering, NCAT
	Prof. Eui H. Park, Dept. of Industrial & Systems Engineering, NCAT
	Prof. Wayne Book, Dept. of Mechanical Engineering, Georgia Tech
Graduate Student:	Joseph Akyeampong
Undergraduate Student:	Lashawn Nevins
Industrial Partners:	Caterpillar, John Deere

1. Statement of Project Goals

This project seeks to develop an environment for experimentation to facilitate configuration of an efficient user-interface for test bed 1 (High Efficiency Excavator) using Multimodal Design (MD) and Augmented Reality (AR). An AR environment will be rendered to provide a biologically inspired combination of modalities, providing realistic test environment to inspire effective user interface design. Success will be measured by the ability for the environment developed to capture realism natural operator environment.

2. Project Role in Support of Strategic Plan

The approach to this research sought to identify the critical design activities that will yield the overall goal of an efficient interface. An efficient user interface is one that is user-centered and provides the user with the needed information at any time to achieve their task goals. The critical design activities were identified by exploring the inter-relationship between the three major components of any human-machine interaction, that is, task, user and system. Between the system and task, the design objective was to develop a multimodal interface to provide multiple sensing cues to aid the operator. Between user and system, the design objective was to develop a user-centered interface metaphor. Between task and user, the design objective was system ergonomics.

3. Project Description

A. Description and explanation of research approach

It has been well documented that the traditional design of excavator-operator interface rely primarily on visual and to some extent auditory modalities, which has the tendency to lead to cognitive overload of the operator visual system, thus negatively affecting operator performance. There is thus a need for a structured approach to capture operator usage patterns in an experimental setting that mimics natural human information processing. The goal of this research is to use information obtained through experimentation to highlight barriers to effective human-system interface design current design systems (excavators), and use this knowledge in design of future human-system interface designs to achieve the overall goal of an efficient interface design that utilizes a biologically inspired mix of interface modalities that leads to the best overall operator task performance. Such experimental information has to be synthesized and presented to product designers in a readily usable format to inform their design of next generation products to more effective human-system interaction.

In this research, we develop a mixed reality system that will be used in experimentation, the outcomes of which will provide input to system designers for the design of new generation fluid power systems that promise to be compact and efficient. The mixed-reality environment will be used to conduct studies in a bio-inspired interactive mock-up (Virtual and Augmented) to experimentally characterize multi-modal human system interfaces using multiple sensing and display modalities to achieve operational effectiveness in fluid power systems.

B. Achievements

To this point in the research, the development of human-system interaction test environment has explored the relationship between criteria (User-System-Task) to establish important design activities (or objectives) and constraints that relates to the overall set of design goals. The critical design activities were identified by exploring the inter-relationship between the three major components of any human-machine interaction, that is, task, user and system. Between the system and task, the design objective was to develop a multimodal interface to provide multiple sensing cues to aid the operator. Between user and system, the design objective was to develop a user-centered interface metaphor. Between task and user, the design objective was system ergonomics.

User – Task (Task Analysis/Ergonomics):

- Hughes, K. & Jiang, X. (*Using discrete event simulation to model excavator operator performance*): suggest that designers consider the placement of controls and measures to reduce operator workload for better performance in future systems
  - ***Where are the controls to be placed? – System Ergonomics***

Task – System (Functional/non-functional requirements)

- Which display modalities (visual, audio, haptic) will be used and how can information be presented efficiently across several displays?
  - ***What modalities will be used, how do we rationally integrate them? – Multimodal Design***

System- User (Usability)

- Wickens et al suggest that the design must fit user's mental model system(*13 principles of display-control design*)
- Nezami (User-Centered (UC) GUI Design for GIS): Emphasize the need for a UC interface to have a two-way mapping between system interface and user's mental model of the system.
  - ***What interface metaphor to use?***

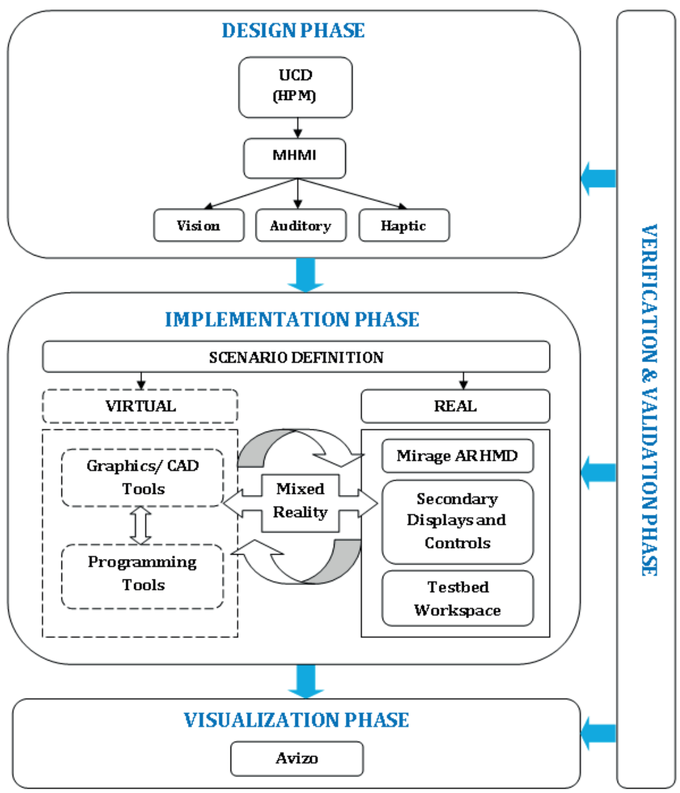


Figure 1: Research Model

2010 Progress:

Critical Design Activities

1. *Multimodal Design*: A 3-dimensional (2^3)design space with visual, auditory and haptic modality dimensions has been developed to assess eight different multimodal interface solutions, each incorporating at least one option (known as elements) of each dimension is

shown in Figure 2. The goal is to evaluate the various modality elements and determine the combination that will contribute to achieving an efficient human-machine interface.

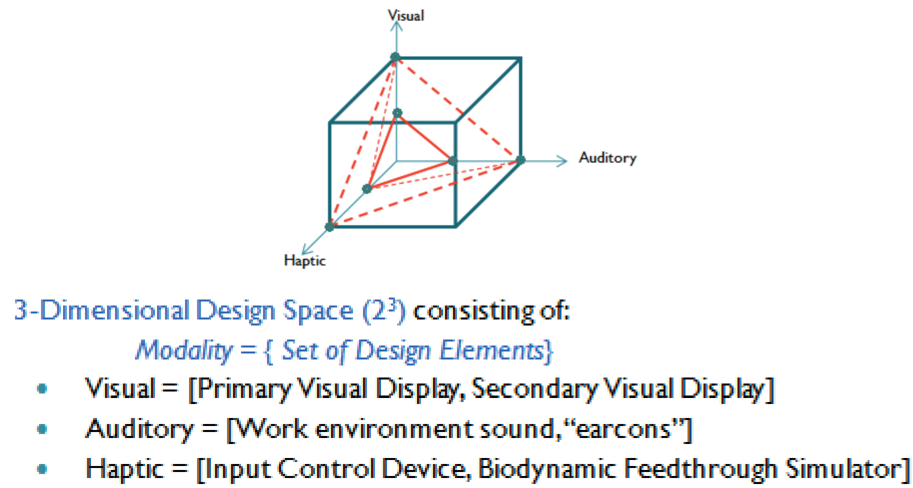


Figure 2: 3-Dimensional Design Space

2. *User-Centered Interface Metaphor:* A cockpit metaphor has been designed for the excavator as shown in Figure 3. This is to be evaluated through a proof of concept, which will take place during the Implementation Phase.

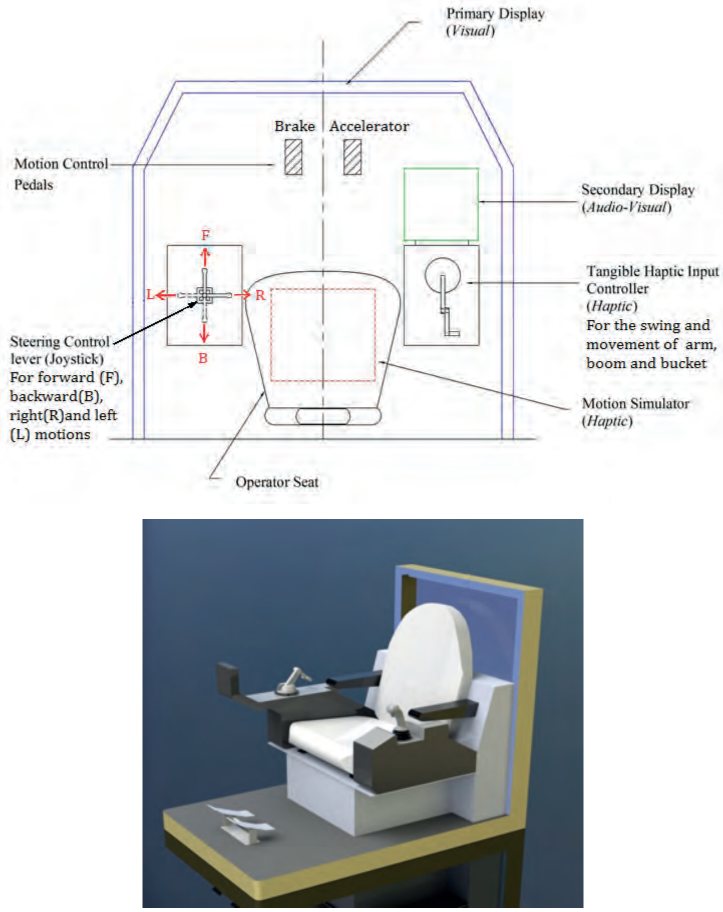
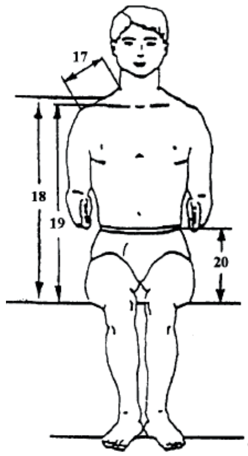


Figure 3: Interface Metaphor (Cockpit Metaphor)

3. *System Ergonomics*: Ergonomic analysis of the operator's work space has been done. Figure 4 shows the dimensions for seating assuming a 95th percentile.



Body Description	Dimensions (inches)
Elbow grip length	15.9
Normal Sitting Height	38.3
Politeal Height	18.7
Elbow Rest Height	11.5
Head Breadth	6.3
Headrest	5.8
Buttocks to Politeal length	20.9
Upper Breadth	24.5
Hip Breadth	16.3

Figure 4: Ergonomic seating dimensions

Major Milestones/Tasks for Next Year

- Development a virtual (mixed reality) simulator
  - Augment the scene
  - Additionally:
  1. User demographics will be verified.
  2. Detailed spatial arrangement of controls and other interface components will be determined.
  3. Interface Metaphor will be verified.

Future Tasks
The following are the major tasks to be performed in the next year:

- Simulator Programming
  - Adding video to scene
  - Secondary visual display of target area to show bucket trajectory (Figure 5)
- Dynamics programming/Simulation

Figure 5: Virtual Simulator

Information Analysis

- Visual Modality: The augmenting information may consist of virtual geometric objects placed into the environment, or a display of non-geometric information about existing real objects (Wang and Dunston 2007).
- Auditory Modality: An audio display that gives warning or directions for allocating attention can also be added to such AR systems.
- Haptic Modality: Haptic feedback (haptic display) will also be provided via mechanical device(s).

Augmentation Strategies

Startup/System Augmentation

- Virtual tags surrounding corresponding real objects. (Visual)
  - Helps especially novice operators to learn/reinforce their knowledge of functions of each object in the instrument cluster.
  - Automatic display of safety information (Audio-Visual)
  - Auditory icons providing reminders such as wearing a hat, checking machine before moving, environment scan verification

Task/Environment Augmentation

- Bucket trajectory display (Visual)
  - Bucket trajectory provides a visual cue indicating that harder digging corresponds to more curl of moving boundary of bucket.
- Force feedback from weight of soil (Haptic)
- Performance alerts using auditory icons (Auditory)
  - For example if dumping ends with too much soil falling outside the target i.e. target missed, the auditory icons will provide warning indicating poor performance

C. Member company benefits

Member companies will benefit by being able to use simulation to develop and optimize operator interfaces more effectively.

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TB1: Heavy Mobile Equipment – Excavator

Research Team

Project Leader:	Prof. Monika Ivantysynova, Purdue University, School of Mechanical Engineering, Dept. of Agricultural & Biological Engineering
Other Faculty:	Prof. Andrew Alleyne, UIUC Prof. Wayne Book, Georgia Tech Prof. Paul Michael, MSOI Prof. Kim Stelson, Minnesota
Test bed manager/staff:	Anthony Franklin, Edat Kaya
Graduate Students:	Josh Zimmerman, Dat Le
Industrial Partner(s):	Bobcat, Caterpillar, Parker Hannifin, Moog, Husco, Sauer Danfoss

1. Statement of Project Goals

Prior to June 2010

The goal of this test bed is to study new system concepts based on throttle-less actuator technology and to demonstrate fuel savings (target of 40%) and improved performance and compactness using this technology for the large sector of construction, agricultural and forestry machinery. The excavator will also be used to study and demonstrate effective control strategies for complex multi actuator systems and robot like machine functions. This will include new human/machine interfaces, including those that provide haptics feedback.

After June 2010

The project focus will be to develop a multi-actuator mobile machine (an excavator in this case) with dramatically improved fuel economy and a significant reduction in engine size that uses displacement controlled hydraulics and hybrid technologies. The machine should be capable of equaling or exceeding the performance capability of the standard version of the machine.

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

Task definition and functional requirements:

- Reduce fuel consumption to 50% of standard excavator
- Reduce engine size by 50% of standard excavator
- Emissions: Meet current TIER emission standards
- Maintain standard machine performance

2. Test Bed Role in Support of Strategic Plan

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

3. Project Description

Description and explanation of research approach

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

The core of the test bed will be based upon the theoretical results from project 1A2 although technologies developed within the scope of several projects throughout the CCEFP will be integrated onto the test bed for demonstration. All contributing project leaders have been contacted and agreed to the timeline for the milestones and deliverables listed in the previous section. The contributions are as follows:

Project 1A2 (Dr. Ivantysynova, Purdue):
- Controls for optimal power management of multi-actuator DC hydraulic system
- Controls for energy based trajectory optimization
- Design and installation of hybrid hydraulic system and downsizing of excavator engine
- Reduction of hydraulic cooling power due to improved system efficiency
- Design and installation of smart pump with integrated electronic pump controls

Project 1B1 (Dr. Ivantysynova, Purdue):
- Development of next generation of highly efficient and smart variable displacement pumps

Project 1E2 (Dr. Lumkes, Purdue):
- Development of virtual variable displacement pump for the excavator low pressure hydraulic system using high speed on-off valves

Project 1E3 (Dr. Lumkes, Purdue):
- Development of a high efficiency, high bandwidth, actively controlled variable displacement pump/motor

Project 1G1 (Dr. Michael, Milwaukee School of Engineering)
- Testing of energy efficient hydraulic fluids

Project 3A1 (Dr. Book, Georgia Tech)
- Tele-operation of the test bed using haptics controls and the Phantom controller

Project 3D3 (Dr. Klamecki, University of Minnesota)
- Improved seal design based on adaptive materials

Achievements prior to the reporting period:
- Four variable displacement pumps were installed on TB1 (compact excavator) along with associated sensors and electronic control hardware. All 8 functions (swing, boom, stick, bucket, track drives, boom offset, and blade) are now displacement controlled.
- Control laws for pump displacement, actuator position and actuator velocity were designed and implemented on TB1.
- The DC hydraulic system is operational and was demonstrated by video at the CCEFP annual meeting on October 7, 2009 and in person to a delegation from Caterpillar on November 4, 2009.
- Performance measurements made on the test bed indicated 50% energy savings compared to original LS valve-controlled hydraulic system for soil digging duty cycle.

Achievements during the reporting period:

Productivity and Fuel Test

The productivity and fuel test for Test bed 1 with DC hydraulics was conducted in cooperation with Caterpillar, Inc. who is a member company of the CCEFP. Two mini excavators were tested: Tested 1 with DC actuators and a standard excavator of the same model. The test site is shown in Figure 1. Measured quantities included the mass of soil loaded, fuel mass consumed, and cycle times. The excavator loaded soil into a 6-ton dump truck, after which the truck was weighed to determine the soil mass. Fuel measurements were obtained by weighing an external fuel tank with a precision scale (5 g resolution). Data was acquired on the DC excavator from all onboard sensors. The standard excavator was not instrumented. All testing was conducted at the same location with the same professional operator on the same day. Identical fuel was used for all tests.

Tables 1 and 2 summarize the results of the test and it can be seen that Test bed 1 consumed 40% less fuel on average than the standard machine while moving the same amount of dirt. This shows that the goal of reducing the energy consumption of the system by 40% was achieved. The results not only show that the fuel consumption was reduced, but the productivity of the machine was increased because on average the Test bed with DC actuators was able to move 16.6% more tons of dirt per hour.

Figure 1: Productivity test site

Machine	Soil loaded (metric ton)	Fuel consumed (kg)	Cycle time (s)
Standard LS	6.85 ±0.43	0.529 ±0.046	11.86 ±0.67
Prototype DC	6.97 ±0.47	0.319 ±0.037	10.32 ±1.09
Difference	+1.73%	-39.7%	-12.9%

Table 1: Excavator productivity test results

Machine	Fuel consumption rate (kg/h)	Productivity (ton/h)	Fuel Efficiency (ton/kg)
Standard LS	8.04	104.3	13.0
Prototype DC	5.57	121.7	21.9
Difference	-30.8%	+16.6%	+68.7%

Table 2: Excavator performance comparison

Machine Power Management

A fuel efficiency test was conducted to evaluate the proposed optimal power management algorithm from Project 1A2. The duty cycle consisted of moving a 250 kg mass suspended from the bucket on a chain. Targets were placed on either side of the excavator. While rotating the cabin 180°, the weight was raised from one target and then lowered onto the other. Each trial consisted of 20 repetitions, after which an external fuel tank was weighed to determine the fuel mass consumed. Five trials each were conducted with and without power management. In the latter case, the engine speed was set to high idle (~2700 rev/min).

Figure 2: Power management fuel test setup

Results are tabulated in Table 3. Mean values are listed along with 95% confidence intervals based on a two sided t-distribution.

	Fuel consumed (g)	Cycle time (s)	Fuel rate (kg/h)
Constant engine speed	270 ±14	15.9 ±0.3	3.030 ±0.116
Power management	118 ±16	15.3 ±1.0	1.383 ±0.114
Difference	-56.4%	-3.5%	-54.4%

Table 3: Power management test results, average of five trials

Using power management, the engine operates at a lower speed and the pumps operate at higher displacement. In this way, the same actuator motion is attained more efficiently. The measured duty cycle was intentionally selected because it requires slow, careful motions to prevent the weight from swinging. The cycle is comparable to pipe laying or other realistic tasks for an excavator. In a more demanding cycle, there would be less opportunity for reducing engine speed and fuel consumption.

DC Hydraulic Hybrid Feasibility Study

Through project 1A2 a feasibility study was done for a DC hydraulic hybrid system on TB1. The simulation model previously created for the DC excavator test bed was modified to include an additional pump/motor (18 cc/rev) and accumulator (5 L) to create a parallel hybrid system. Measurements from the productivity study where an expert operator was performing a truck loading cycle as fast as possible were used to generate actuator trajectories and loads for the cycle. This cycle was selected because it is very aggressive representing the extremes of the power requirements for the DC actuators. As previously stated one of the project goals is to be able to reduce the required engine power of the machine by 50%. To check the feasibility of this goal the simulation was controlled to limit the engine power output to be 50% of the current test bed engine power where power requirements of the cycle above that level would be met by the hydraulic accumulator and the additional pump/motor.

Figure 3 shows the simulated engine power for the non-hybrid and the hybrid DC hydraulic systems during the digging cycle. From the figure it can be seen the hybrid system power was able to be limited to be half of the maximum engine power suggesting that the engine size could be reduced without sacrificing the productivity of the machine for the truck loading cycle.

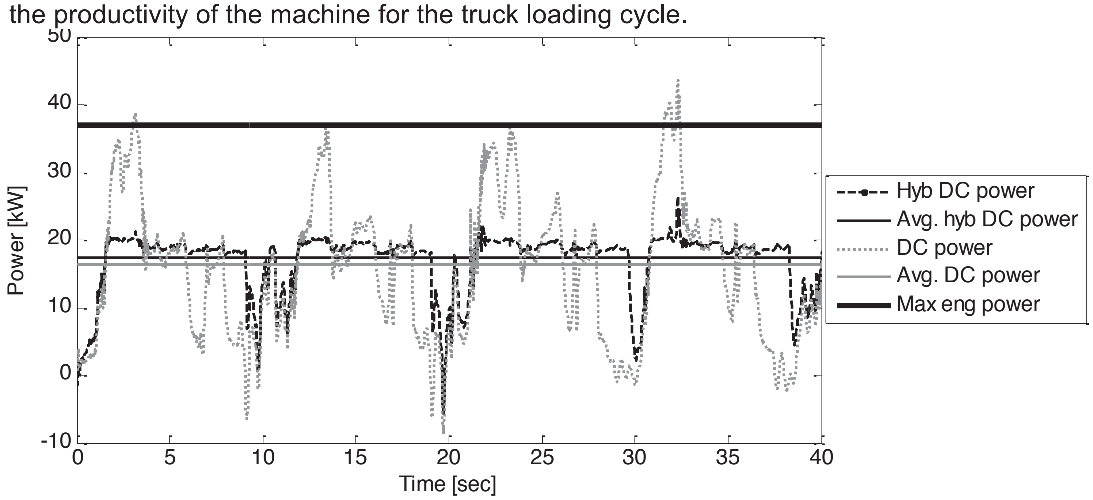

Figure 3: Simulated engine power for non-hybrid and hybrid DC hydraulic systems

Planned Achievements following the reporting period:

- Modification of machine control for haptics tele-operation (from project 3A1 headed by Dr. Book)
    - Deliverables:
        - Installation of controller hardware [06/01/2011]
        - Demonstration of haptics tele-operation [07/01/2011]

- Design, modeling, and simulation of hybrid excavator system
    - Deliverables:
        - Hydraulic schematic and component sizing (accumulator, pump/motor, etc.) for displacement controlled hybrid machine [01/01/2011]
        - Dynamic and energy simulation model in Simulink of hybrid system and energy/fuel consumption predictions [03/01/2011]
        - Thermal model of test bed hydraulic system [06/01/2011]
- Conduct on-vehicle experiments
    - Deliverables:
        - Thermal measurements of hydraulic system and experimental evaluation of reduction in cooling requirements [06/01/2011]
        - Installation of hybrid hydraulics and smaller engine [04/01/2012]
        - Measurements of fuel and performance of hybrid system [06/01/2012]
- Demonstration of technologies from associated projects
    - Deliverables:
        - Installation of next generation smart pump (integrated electronic pump control system from continuation of project 1A2 headed by Dr. Ivantysynova) and demonstration of control of a single actuator [2012]
        - Integration of high speed valves from project 1E2 (headed by Dr. Lumkes) to create a virtual variable displacement pump for low pressure system and measurements or resulting energy savings [2012]
        - Comparison of energy consumption of the test bed using standard hydraulic oil and energy efficient fluids developed in project 1G1 (headed by Paul Michael) [2012]
        - Integration of next generation of efficient pumps (from project 1B1 headed by Dr. Ivantysynova) for control of a single actuator [2013]
        - Demonstration of adaptive material for seals from project 3D3 headed by Dr. Klamecki [2013]
        - Demonstration and energy measurements for digital pump control of a single actuator using a prototype high efficiency, high bandwidth, actively controlled variable displacement pump/motor (from project 1E3) [2013-2014]

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 emission regulations under the TIER emissions standards

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TB3: Hydraulic Hybrid Passenger Vehicle

Research Team

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Industrial Partners:	Bosch-Rexroth, Eaton, Parker, Sauer-Danfoss, Ford Motor Company, and Folsom Technologies International

1. Statement of Project Goals

The overall goal of this project is to realize a hydraulic hybrid power-train with drastic improvement in fuel economy and good performance to be competitive with other technologies such as electric hybrid, for the passenger vehicle segment. 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: fuel economy of 70 mpg under the federal drive cycles; an acceleration rate of 0-60 mph in 8 seconds; the ability to climb a continuous road elevation of 8%; emissions meeting California standards; and size, weight, noise, vibration and harshness comparable to similar passenger vehicles on the market.

2. Project Role in Support of Strategic Plan

Test Bed 3 directly supports goal 2: improving the efficiency of transportation. Efficiency is obtained by utilizing fluid power to create novel hybrid powertrains for passenger vehicles. The powertrains integrate high efficiency components (goal 1), compact energy storage (goal 2) and methodologies for achieving quiet operation (goal 4) from related CCEFP projects.

3. Project Description

A. Description and explanation of research approach

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

Three possible architectures for hybrid drive trains are series, parallel and power split. A series drive transmits all power from the engine to the wheel with hydraulic pumps and motors. This architecture enables running the engine at its most efficient combination of torque and speed; however, it cannot take advantage of the high efficiency of purely mechanical power transmission through a shaft. A parallel architecture augments the engine with a pump/motor. It sends a high percentage of wheel power through the efficient mechanical shaft, but it has less ability to keep the engine at its best operating point. TB3 focuses on power split architectures which are the less studied hydraulic hybrid architectures. Power-splits combine the positive aspects of the series and parallel drive train. In addition, all architectures can be used to regenerate braking energy.

This test bed is currently developing two hydraulic hybrid passenger vehicles, each of which offers unique research benefits. The “Generation 1” vehicle was built in-house using the platform of an off-road all terrain vehicle (a Polaris “Ranger” which was donated to the CCEFP). An *input-coupled* power-split architecture is utilized in this vehicle. The vehicle has been outfitted with a modular power train. This enables experimenting with different pump, motor and energy storage technologies, including those developed in complementary CCEFP projects. However, the first vehicle cannot be driven at speeds higher than about 25 MPH due to concerns about vehicle stability.

The “Generation 2” vehicle is being developed in partnership with Ford and Folsom Technologies International (FTI). It is built on the platform of a F150 pickup truck, which has refined vehicle dynamics capable of highway speeds. Its power-train utilizes a custom-built continuously variable *output-coupled* power-split hydraulic transmission developed by Folsom which will be complemented with hydraulic accumulators for enable hybrid operation. The power-train is attractive in that it is built as a compact, highly integrated, self-contained package. It will be capable of rigorous testing and presents an opportunity for the study of an alternate power-split architecture. Nevertheless, the integrated package prevents changing out the hydraulic pump/motors. Also, since it is not originally designed for hybrid operation, the transmission not necessarily optimally sized and presents some control restrictions when operating in hybrid modes. Therefore, the “Generation 1” vehicle is being continued despite the pending availability of the roadworthy “Generation 2” vehicle.

Our ultimate goal will be a “Generation 3” vehicle with a true passenger vehicle chassis. We expect this development to begin in 2012.

B. Achievements

Achievements for the 2010 year that apply to both the Generation 1 and Generation 2 vehicles are described first. Achievements specific to the Generation 1 vehicle are described next, followed by achievements specific to the Generation 2 vehicle. Plans for the next year are described, where applicable, at the end of each individual achievement. Integrated milestones are summarized at the end of the section.

Achievements and Plans Applicable to Both Vehicles

Three achievements apply to both vehicles: replacement of the controls firmware, a study of input and output coupled hybrid transmission architectures, and a comparison of hydraulic and electric hybrid architectures. These studies utilize the 3 level hierarchical control/analysis approach that was developed in previous years [5]. They are described in order below.

Controls firmware upgrades: The Generation 1 vehicle has previously used “xPC Target” firmware to interface the controller with the powertrain. We are now converting to firmware that is popular for automotive systems, “Micro-Autobox”, to improve both the hardware and software robustness. In addition, the standard system will simplify migration of the controller to the Generation 2 vehicle.

Micro-Autobox utilizes a specialized software, “DSpace”. The control algorithms developed in-house are written in “MATLAB”. Therefore, we are also developing “MATLAB” code capable of communicating with “DSpace”.

The conversion from xPC Target to Micro-Autobox and DSpace will be completed on the Generation 1 vehicle in 2011. Micro-Autobox will be used for all controls implementation on the Generation 2 vehicle. Installation of the controller on the Generation 2 vehicle will be initiated in 2011.

Architecture	Input coupled
Matrix G	$\begin{pmatrix} 1.0175 & 0 \\ 2.0660 & -8.3570 \end{pmatrix}$
P/Ms' size	P/M-T=27.7cc P/M-S=28.8cc
City	78.6 [mpg]
Highway	56.1 [mpg]
Combined	64.2 [mpg]
Architecture	Output coupled
Matrix G	$\begin{pmatrix} 1.2768 & -4.0424 \\ 0 & 4.7239 \end{pmatrix}$
P/Ms' size	P/M-S=23.9cc P/M-T=39.1cc
City	72.7 [mpg]
Highway	54.9 [mpg]
Combined	61.2 [mpg]
Architecture	Compound
Matrix G	$\begin{pmatrix} 0.981 & 0.64 \\ 2.0573 & -8.3764 \end{pmatrix}$
P/Ms' size	P/M-1=24.5cc P/M-2=24.7cc
City	79.5 [mpg]
Highway	56.1 [mpg]
Combined	64.5 [mpg]

Table 1: Preliminary results of the architecture comparison

Input vs. Output Coupled Study: Available power split transmissions can be classified as “input coupled”, “output coupled” and compound. An input coupled transmission utilizes a fixed gear ratio between the engine and one pump/motor, while the second pump/motor is coupled to the wheels with a planetary gear train[1]. An output coupled transmission utilizes a fixed gear ratio between the wheels and one pump/motor, while the second is coupled to the engine with a planetary gear train[2]. A compound transmission is one in which both pump/motors are coupled with planetary gear trains.

A study to determine the most efficient powertrain configuration was performed. This was achieved by defining and optimizing a generalized expression that relates the kinematics of the engine,

[1] The architecture of the rebuilt Generation 1 vehicle, shown in Fig. 2, is input coupled.
[2] The transmission in the Generation 2 vehicle is output coupled.

wheels, and pump/motor units. This expression is referred to as Matrix G. Matrix G takes different degenerate forms for input coupled and output coupled drive trains, as seen in Table 1. However, a general Matrix G can represent a combination of the two. The combined configuration is described as a “compound” drive train.

The elements of Matrix G were optimized for a prescribed drive cycle using all three potential architectures. This approach maximizes the opportunity for improving fuel economy. The optimal size of the hydraulic pump/motors is generated as part of the process. Whereas previous approach to determining the optimal power-split configuration explicitly considers and optimizes each discrete physical configuration [4], our approach of the optimization of the kinematic relation (Matrix G) is more efficient since a Matrix G can be realized by multiple physical configurations with the same performance.

Preliminary results are shown in Table 1. As seen in the table, the fuel economy of the various architectures appears fairly similar: the optimized results are within about ±5%. The component sizing varies slightly, with the compound architecture requiring the overall smallest pump/motors. However, the input and output architectures are competitive. Refined results will be obtained in 2011.

Hydraulic/Electric Hybrid Comparison: A comparison of the efficiency of hydraulic and electric hybrid vehicles was performed in 2010.The initial results indicate that for the light (1000kg) vehicle that was studied, electric and hydraulic hybrids have comparable fuel economy under standard EPA driving cycle without additional acceleration requirements. It is expected with heavier vehicles, more stringent acceleration requirements, and more efficient pump/motor, the advantages of hydraulic hybrids will be accentuated. Improved analysis will be performed to refine this comparison in 2011.

<u>Achievements and Plans for Generation 1 Vehicle</u>

Work on the Generation 1 vehicle in 2010 has focused on redesigning the drive train. In addition, a fuel sensor has been added. These accomplishments are described below, followed by discussion of additional plans for exploiting the availability of the improved vehicle in 2011.

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

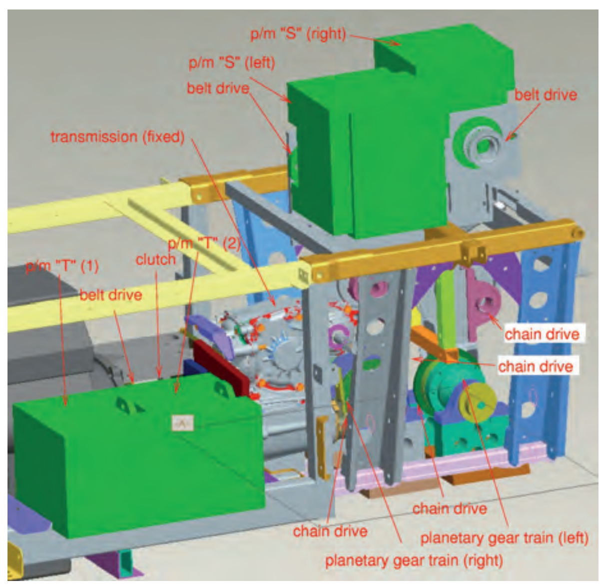

Figure 1: CAD model of original Generation 1 HHPV powertrain

The drive train was completely redesigned in 2010. A CAD representation of the system is shown in Figure 3 and a schematic of the revised system is provided in Figure 2. All of the problems caused by the belts, chains and frame flexion have been eliminated by using gears. The drive train has been simplified by replacing dual rear wheel pump/motors and planetary gear trains with single units driving a stock automotive rear wheel differential. The original axial piston type pump/motors have been replaced with high efficiency bent axis piston units. Gear ratios and pump/motor sizes are chosen to optimize fuel economy under EPA driving cycles and to satisfy the acceleration requirement.

The redesigned drivetrain can operate in four different modes. The first is “HMT” mode, where the engine is engaged with the rest of the system while both P/M “T” and P/M “S” (see **Figure 2**) are hydraulically engaged. The second is parallel mode, where pump/motor “T” is coupled to the engine and

P/M "S" is locked up. The third is "T-only" mode, which is the same as parallel mode except that the engine clutch is disengaged. The last is "S-only" mode, where P/M "S" alone is used to drive the system. The engine is removed from the system by disengaging the engine clutch and the shaft of P/M "T" is locked up. The last two modes are similar to a series transmission where only the motor is operating and powered only by the accumulator charge.

Transmission components are currently in the machining and assembly stages. A fully assembled transmission expected to be ready for testing in March 2011.

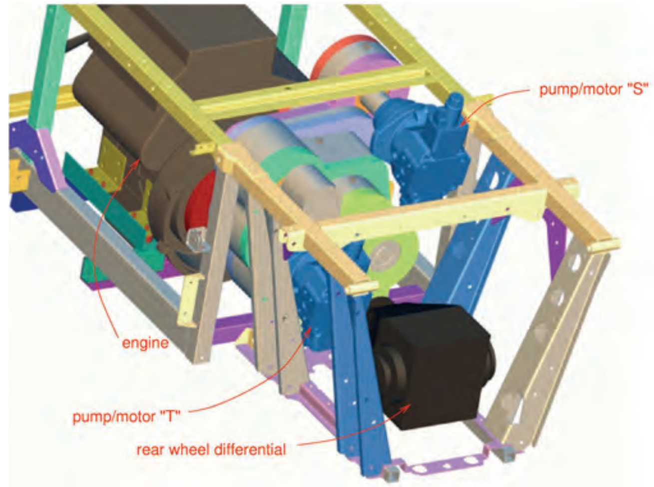

Figure 3: CAD model of redesigned Generation 1 HHPV powertrain

In addition to providing a more robust drivetrain on the vehicle, the transmission is also designed to stand alone. With this new capability, it will be possible to test the transmission on a dynamometer, facilitating efficiency mapping and control development of the vehicle.

Finally, the modular architecture of the redesigned transmission enables the pump/motors to be changed out. We plan on replacing the bent axis pump/motor used as pump/motor "S" with a pulse width modulated fixed displacement pump/motor designed in Project 1E.1 during 2011. The purpose of this test is to compare the efficiencies of the two approaches. This test will provide demonstration of a real world application for the pulse width modulated pump/motor also.

Low level Control Refinement: System identification experiments have been performed on the existing Generation 1 vehicle. This together with experimentally derived pump/motor maps in [6] provide improved information for refining the low level control algorithm design. However, the basic control architecture presented in [7] was still followed.

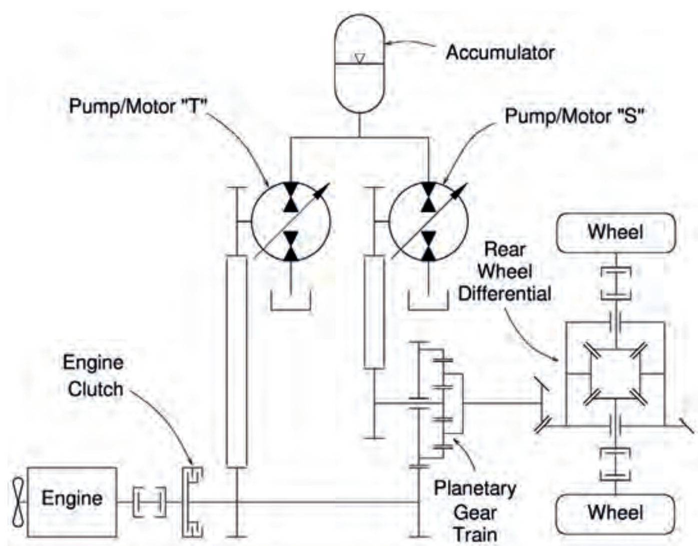

Figure 2: Schematic representation of redesigned Generation 1 HHPV powertrain

Fuel Sensor: An accurate engine efficiency map is crucial to developing controllers capable of minimizing fuel consumption of a hybrid vehicle. Simulations of the Generation 1 vehicle performed to date have utilized a Willans' line [3] approximated engine efficiency map; the engine in the vehicle may deviate substantially from this approximate map. A fuel flow sensor was calibrated and installed on the Generation 1 vehicle, utilizing its original drive train, during 2010 to enable creating an accurate map.

Normally, the engine would be removed from the vehicle and mounted on a dynamometer to obtain the efficiency map. We have instead utilized pump/motor "T" to load the engine. The accuracy of the results is limited by the accuracy of the efficiency map of the pump/motor, which was created using a test stand designed for that purpose during 2009.

Additional Plans for Generation 1 Vehicle During 2011: Experiments will be performed to operate the Generation 1 transmission as a continuously variable transmission (CVT) rather than a full hydraulic hybrid. These experiments have two purposes. First, operation as a CVT serves to prove the effectiveness of the low level control strategy. Second, the fuel economy obtained from operation as a CVT provides a limit for comparing full hydraulic hybrid modes.

Achievements and Plans for Generation 2 Vehicle

Effort on the Generation 2 vehicle in 2010 has focused on returning the FTI transmission to service, creating a test plan for generating the efficiency map of the transmission, and developing enhanced simulations. Each of these efforts is described in detail below. Continuing plans for 2011 are described at the end of each item.

Returning FTI Transmission to Service: Collaboration with Ford Motor Company and FTI was started in spring 2009. Ford donated an F150 truck to the CCEFP. The internals of the FTI transmission to be used in this truck are shown in Figure 4. Testing of the FTI hydro-mechanical transmission was initiated in early winter 2009. The FTI transmission is shown mounted to a 400 HP dynamometer available at the FTI facility in Figure 5.

Problems with the controls on the FTI dynamometer in early 2010 resulted in the transmission being driven at high speed in reverse. Since no lubricant is supplied in this configuration, extensive damage occurred to both mechanical and hydraulic components in the transmission. Ford agreed to fabricate many parts to replace the damaged hydraulic components and new planetary gear sets were procured and modified for the transmission rebuild.

Figure 4: Internal view of FTI power split transmission

Figure 5: FTI Hydro-Mechanical Transmission on the dynamometer test-stand at the FTI site.

Testing resumed in early autumn 2010 and performance problems, particularly poor efficiency and the inability to generate sufficient torque, were noted immediately. It was initially thought that the inability to produce sufficient torque was due to a new clutch assembly that had been installed in place of a clutch pack in the original assembly. However, substitution of the original clutch pack did not produce a measurable torque increase so it was decided that a complete transmission tear-down was in order to determine the root cause of the problem. Examination of the hardware indicated that the stroke of the pistons on the hydraulic motor unit had exceeded the design limit by a margin sufficient to cause the outer piston ring to catch on the end of the cylinder block. This resulted in breakage of six of the seven outer rings and scoring of the bores in the cylinder block. A thrust bearing is being installed between the front face of the cylinder block and the thrust plate in the yoke to limit axial motion of the cylinder block and thus preclude piston ring damage on the next transmission build.

Another significant failure mode was identified in addition to the broken piston rings: The spherical end of all of the motor pistons and the spherical seat of the retainer plate suffered severe fretting and wear. The retainer plate and torque plate were redesigned to incorporate a counter bore for fitment of a bronze retainer ring, thus eliminating the steel/steel contact surface present in the original design. Again, Ford supplied the machining to effect these changes. The transmission is currently being reassembled and is scheduled for resumption of testing in January 2011.

The F150 is expected to be delivered to the University of Minnesota with the FTI transmission installed in Spring 2011.

Efficiency Map Test Plan: FTI has provided a simulated efficiency map with their transmission. However, the transmission was originally intended to be run as a continuously variable transmission rather than a hydraulic hybrid transmission. Therefore, dynamometer tests are being planned to obtain the efficiency map corresponding to hydraulic hybrid operation. This is essential for fuel economy predication and the design the control and energy management system. The test plan, developed by us, will be implemented on the dynamometer available at the FTI site (see **Figure 5**) prior to shipping the transmission to Minnesota.

The tests must be designed to overcome two unique circumstances. First, the two pump/motors in the FTI transmission are intrinsically coupled; therefore, the mechanical and volumetric efficiency of each pump/motor cannot be obtained individually. Second, a hydraulic power supply cannot be utilized for the dynamometer tests at the FTI site.

Both restrictions have been overcome by developing a procedure where flow is measured through a relief valve connected between the high and low pressure ports of the pump/motors. Figure 6 illustrates all combinations in which the combinations of the two pump/motors could operate. Ordinarily, approximately 3600 data points would be required to fully define all portions of this map. In addition, many of these combinations are not feasible with the restriction of the test facility. However, with the assumption that both pump/motor units have similar characteristics, we have devised a means for approximating the entire map by obtaining only 240 data points, which are represented by the stepped red profile in Figure 6. This approach also reduces the risk of operating the relief valve beyond its capacity. Furthermore, regenerative braking scenarios can also be simulated. Data for creating the FTI transmission efficiency map is expected to become available by March 2011.

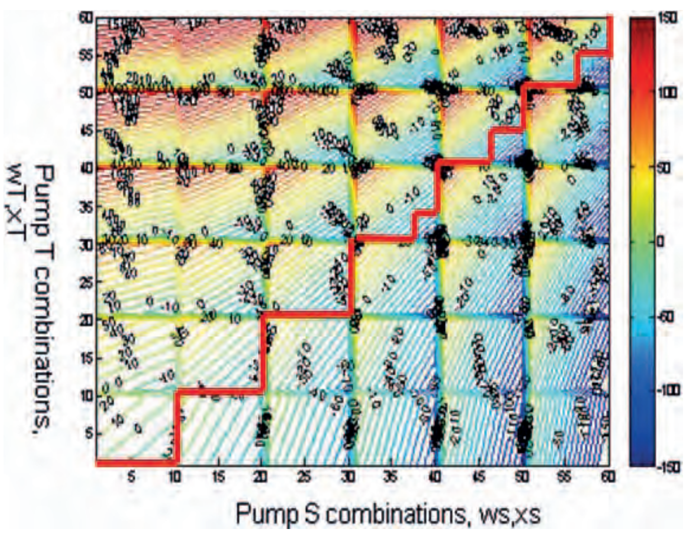

Figure 6: Combinations of test conditions for FTI transmission. Contours represent flowrate through the relief valve.

Development of Enhanced Simulations: Analysis of the FTI transmission utilized in the Generation 2 vehicle was initiated by adapting the "backward facing" simulation tools developed for the Generation 1 vehicle. "Backward facing" means that the drive cycle is known in advance and the transmission components are optimized to provide the prescribed wheel torque while consuming the minimum amount of fuel. Mechanical restrictions imposed by the Generation 2 transmission architecture increase the complexity of the controls strategy development. However, the restrictions appear to have only minor impact on the fuel economy using the backward facing simulation.

In order to further investigate this issue, a "forward facing" dynamic model is being developed and refined. The forward facing model takes driver commands as the input. The forward facing model takes advantage of a MATLAB Simulink model provided by Ford, which includes details of the engine dynamics, auxiliary losses of the vehicle, aerodynamics, temperature variation, and the like. We have enhanced the Ford model by replacing a model of a conventional automatic transmission with a model of the FTI transmission and adding a model of an accumulator. In addition, the model is also being re-structured into a form where the designed controllers can be directly implemented onto the actual vehicle controls hardware. The forward facing model is expected to predict the fuel economy more accurately due to controlling energy management in real time.

Expected Milestones and Deliverables

- Efficiency map of FTI transmission completed – February 2011
- Redesign of powertrain installed in Generation 1 vehicle – March 2011
- Project 1E.1 virtually variable displacement pump/motor installed as Pump/Motor "S" in Generation 1 vehicle – August 2011
- Controller demonstrated in Generation 2 vehicle – October 2011

C. 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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TB4: Compact Rescue Robot

Research Team

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Undergraduate Students:	Allison Byrum, Michael Valente, Michael Baker
Industrial Partner(s):	Bimba, Festo

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

TB4, residing at the top of the three plane chart, will demand inputs from several projects to be successful. Possible compact power supplies are a free piston engine compressor or pump, or a hot gas vane motor. Safe and intuitive tele-operation will be accomplished through multi-modal haptic user interfaces. The current incarnation of TB4 uses pneumatics, as H_2O_2 monopropellant producing 300 psi gas provides is the only source of power in an appropriate package for compact, untethered operation at this time.

B. Achievements

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

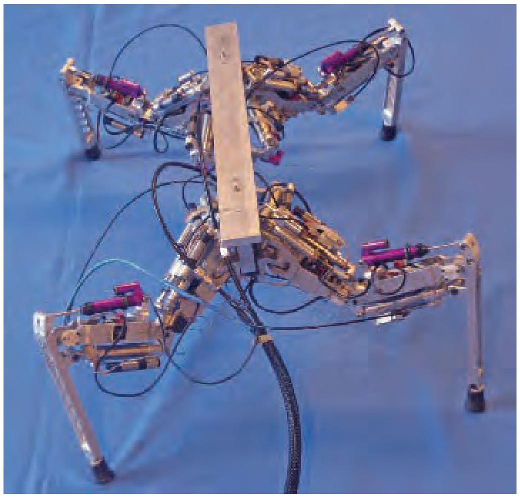

Figure 1: The four legged robot at Vanderbilt.

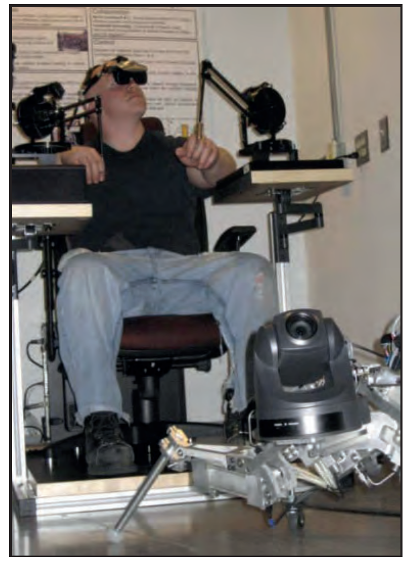

Figure 2: Operator workstation and surrogate robot at Georgia Tech.

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

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

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

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

Georgia Tech has also improved the two-legged testbed, which is used as simulation verification and as a platform for actuator control improvements. Whereas the four-legged testbed couples a damper with a cylinder to make control of the position control joints simpler on a mechanical level, the two-legged testbed employs pressure sensors and Bimba™ cylinders with position feedback. This allows testing of alternate control strategies, such as passive control. In the last year, substantial improvements have been made to this platform. Control was achieved via the operator workstation, using commands from the haptic joysticks to direct motion of the legs. Electronics were reconfigured for a cleaner, more effective, and robust design. The previous custom cylinders were replaced with Bimba hardware, as noted above, actuated by Festo proportional directional valves. An undergraduate researcher, Michael Valente, redesigned the legs to accommodate the different, more compact cylinders. He also enhanced the range of motion of the platform, using increased stroke length and improved design to substantially increase the range of motion of the legs, making them more capable of the desired lifting and motion tasks that the testbed aims to provide. The revised design is also somewhat sleeker and lighter, yet maintains the kinematics used in all previous iterations of the robot (both at GT and at Vanderbilt). This revised design is currently in construction and is expected to be complete by the end of the calendar year.

In the future, the Georgia Tech revised design will be completed and implemented with the new cylinders and improved range of motion. This will be used to test control techniques targeted at precise movement of large loads by pneumatically actuated manipulators.

The Vanderbilt hardware will be completely integrated into the Georgia Tech platform, allowing usage of both the low-level, pre-programmed gaits and the semi-autonomous operator-guided gaits to control the robot. Control techniques similar to the ones used on the two-legged Georgia Tech testbed will be implemented here, too. The robot will also be further equipped with A/V feedback using a pan-and-tilt camera that moves together with operator motions of an associated headset, previously developed at Georgia Tech on the interim testbed.

Testing Environment: While the low-level gaits used on the four-legged crawler have been tested in several outdoor environments, a necessary component to proving the versatility of the designed hardware is the usage of standardized "challenging" terrains. Using the NIST [1] environments as a guide, a modular terrain block was created that can be configured to illustrate several difficult scenarios (Figure 3).

Future plans for this terrain include its use as a way of verifying the capabilities of the robot and simulation.

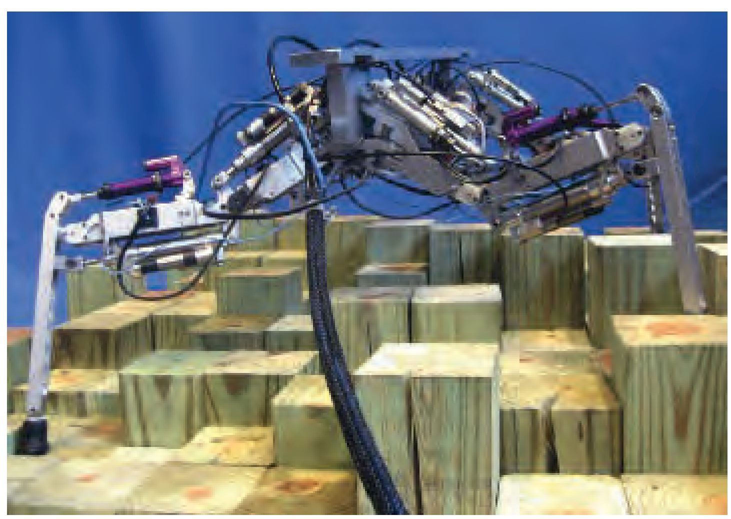

Figure 3: Robot negotiating the modular terrain environment at Georgia Tech.

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

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

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

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

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

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

Education and Outreach: TB4 has consistently provided an array of opportunities for impact and outreach, and the past year has been no different. Because of its interactive set of components, TB4 is ideally situated to provide hands-on demonstrations to audiences from a wide range of backgrounds. This past year, such demonstrations have been given to Atlanta city students visiting campus as part of National Robotics Week, FIRST students from across the country competing in the annual championship in downtown Atlanta, and visitors from a variety of other universities. Additionally, the robot was featured as an example of the future of fluid power at a teaching enhancement session for Atlanta area FIRST students on fluid power, organized in conjunction with Georgia Tech's RoboJackets organization.

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

Finally, work on TB4 has resulted in several papers [4,5,6] on modeling, simulation, and interfaces of fluid-powered technologies, presented or accepted to be presented at conferences both within and outside the fluid power community.

In the future, TB4 will continue to provide compelling demonstrations that benefit from advances in fluid power research and natural appeal among varied audiences. Because of its broad range of components, it will keep serving as an optimal source of research experiences for undergraduates and graduates alike, and will continue to result in publications across the industry.

Upcoming Milestones: To recap, most of the efforts in the upcoming year are targeted at improved performance capabilities of the test bed and associated simulation. Combining such functionalities with fluid-powered energy sources being developed in the associated center projects would truly allow TB4 to showcase the advances it provides to mobile-human scale platforms.

These milestones, as defined by the most recently submitted TB4 proposal, include:

- Robust hardware and software platform for physical testing [January 2011]
- Installation of visual indicators to display state of robot [January 2011]
- Experimental Results regarding FTL effectiveness when combined with stability margins and haptic sensory substitution [March 2011]

  Case II (if alternative design to legged version is decided preferable by end of January) **:** Experimental results regarding effectiveness of sensory feedback and operator workstation in providing improved mobility and manipulative ability when combined with a fluid-powered system [April 2011]
- Paper submission [January 2011]
- Results: Validation of focus on haptics or proof of other more critical sensory modality [May 2011]
- Results regarding mobility and manipulative ability on medium difficulty terrain and with respect to isolated challenges [August 2011]
- Experimental results of improved user interface [March 2012]
- Paper Submission [April 2012]

C. Member company benefits

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

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TB6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses)

Research Team

Project Leader:	Prof. Elizabeth Hsiao-Wecksler, MechSE, University of Illinois (UIUC)
Other Faculty:	Prof. Will Durfee, Mechanical Engineering, University of Minnesota Dr. Geza Kogler, Applied Physiology, Georgia Tech Prof. Tim Bretl, AAE UIUC, MechSE, University of Illionois
Graduate Students:	Alex Shorter, UIUC; David Li, UIUC; Emily Morris, UIUC; Aaron Becker, UIUC; Kathy Braun, UMN; Jicheng Xia, UMN
Undergraduate Students:	Richard Kessler, UIUC (REU); Anastasia Borok, U of Portland (REU)
Industrial Partners:	Trelleborg, Enfield, Festo

1. Statement of Project Goals

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

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

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

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

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

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

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

B. Achievements

In 2010, we continued to advance our first generation portable, powered, ankle-foot orthosis (PPAFO). The Gen1 PPAFO is an improvement over state-of-the-art passive and active systems [4, 5] because it provides subject-specific motion control and torque assistance without tethered power supply or electronics. A U.S. patent application covering the technology embodied by the Gen1 PPAFO was filed [7]. In the current reporting year, a description of the PPAFO system hardware, a characterization of system performance and preliminary results from both healthy and impaired walkers were formally detailed [8]. Subject testing with two impaired individuals demonstrated the PPAFO's ability to provide functional assistance. These subjects were examined because their deficits span the space of impairments that the PPAFO is capable of assisting.

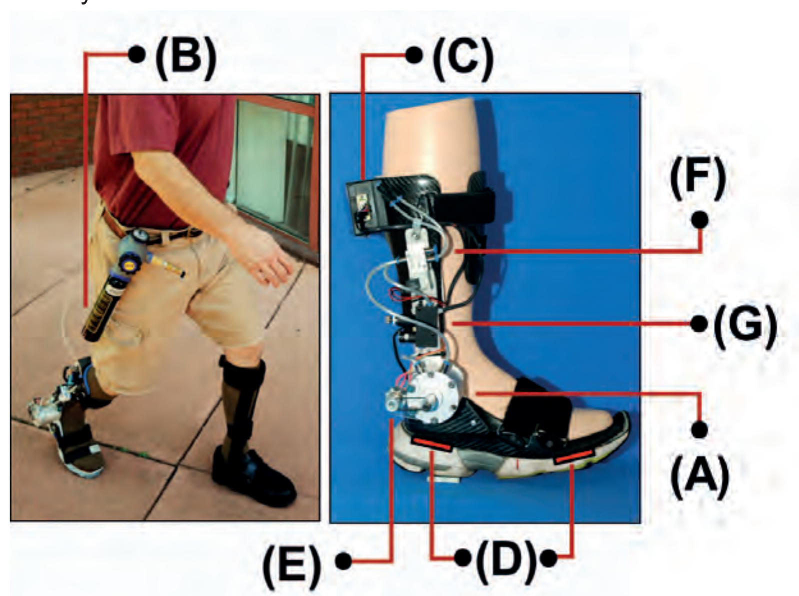

Figure 1: The Gen1 portable powered ankle foot orthosis (PPAFO) shown assisting an impaired walker (Left). The rotary actuator (A) is powered using a compressed CO_2 bottle (B) worn by the subject on the waist. Onboard electronics (C), force sensors (D), and an angle sensor (E) are used to control the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

We analyzed the performance and the efficiency of the Gen1 PPAFO system. The initial low energy efficiency limited the performance of the Gen1 system. Currently, the can run continuously for about 40 min at 30 psig for both plantarflexor and dorsiflexor assistance, falling short of the more than 1 hr of use requirement. To analyze system efficiency, the problem was divided into two parts:

component efficiency and operational efficiency [9]. Component efficiency analysis identified energy loss due to the pressure drop across different components (e.g., line loss, valve loss) as well as backpressure. The operational efficiency analysis identified the energy loss due to how the system was used (e.g., currently energy is wasted when compressed gas is exhausted after an actuation cycle). An overall system efficiency of 19% was calculated from the product of the two efficiencies (component: 50% and operational: 39%). Solutions to improve the overall system efficiency have been proposed and will be investigated in 2011. These include recycling the compressed exhaust gas, eliminating system backpressure and improving the efficiency of the valving. Preliminary analysis indicates that the proposed solutions could raise overall system efficiency to 45%.

We also improved the control of the system. The control problem was divided into two parts: (1) the detection of the gait events during the cycle that determine AFO control objectives, and (2) the implementation of the control. To address the first part of the control problem, we proposed a new cross-correlation based algorithm to accurately estimate events during gait [10]. Gait event detection is essential to the control of the PPAFO because the timing of gait events (heel strike, foot flat and toe off) is used to determine the assistance required by the user. The Gen1 PPAFO uses embedded force sensors with thresholds to identify gait events, but this method lacks the desired accuracy and robustness for the system due to the use of pneumatic power. Experimental results from five healthy subjects walking with the PPAFO were used to verify the performance and highlight the advantages of the cross-correlation algorithm.

We addressed the second part of the control problem through model-based system analysis to facilitate improved control design [11]. The model included the associated pneumatic components of the PPAFO (rotary actuator and valves), and a simplified rigid body model of the human leg (shank and foot). The model was used to evaluate the simulated performance of control schemes and hardware. The results from this work led to adding a proportional valve to the Gen1 system to addresses performance and efficiency limitations of the original binary valves.

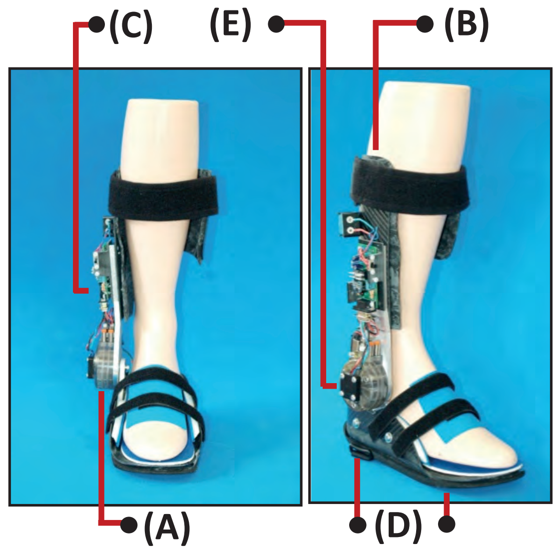

Figure 2: The Gen2 portable powered ankle foot orthosis. A new rotary actuator that was designed by MSOE students and faculty (A) has been integrated into the AFO structure (B) to greatly increase the compactness of the design. Improved onboard electronics (C), along with force sensors (D) and a more compact angle sensor (E) are used to control the solenoid valves that are now integrated into the actuator.

Work continued on developing the Gen2 PPAFO. Several CCEFP projects are contributing to the testbed to improve subsystem performance given target specifications. For the Gen2 design, work at MSOE (Project 2D) resulted in significant compactness and performance gains in the actuator and valve subsystem. The MSOE actuator was bench tested and integrated into the Gen2 PPAFO structure (Figure 2). The compactness of the new actuator was enhanced by integrating the valves, silencers, and sensors directly into the actuator housing and including the actuator directly into the structural subassembly. Additionally, center technologies are being used to address other subsystem limitations, including an integrated shell with vibration and noise abatement (Project 2D), a miniature HCCI air compressor power supply (Project 2B2), passive noise control (Project 3B1), improved human-machine interface (Project 3A3), and a new class of pneumatic MEMS valves to improve compactness (Project 2F).

Last year we identified high pressure hydraulics as a promising technology path for tiny fluid power systems suitable for applications such as the untethered AFO. During the past year theoretical analysis of tiny hydraulic systems was conducted to understand their limits. For example, to understand small-scale hydraulic cylinder efficiency, four configurations of including or omitting seals were analyzed [15]. The key result is shown in Figure 3, which indicates that removing the piston seal improves cylinder efficiency if the clearance between piston and cylinder wall is small. The improvement becomes significant as cylinder bore becomes smaller.

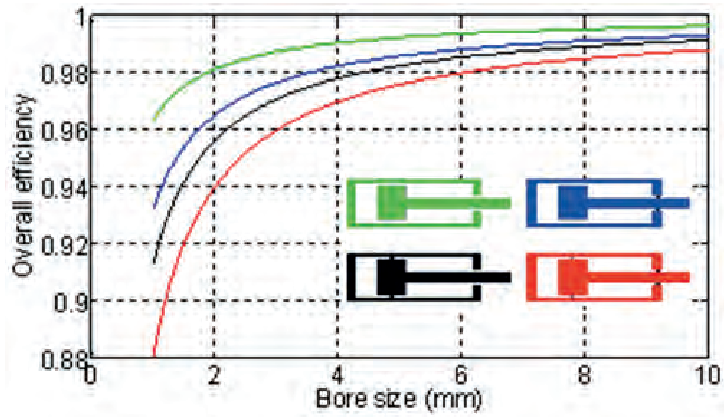

Figure 3: Cylinder efficiency versus bore size

A compact fluid power EHA system was assembled with LiPoly battery, Maxxon motor, Oildyne cartridge pump and Bimba hydraulic cylinder, to demonstrate the capabilities and limits of using off-the-shelf components. The Oildyne pump is the smallest commercially available pump and can output more than 300 Watts of power, more than required for the orthosis. For the custom system we are developing, the vane pump was selected because it is the most compact among all pump types for a given displacement. Preliminary analysis of vane pumps showed that a smaller rotor results in higher pump efficiency. The results also showed that high efficiency is theoretically achievable for small-scale pumps. We will continue this path with further analysis and prototype hardware next year.

During 2010, the TB6 team held a 2-day workshop to discuss systems engineering ideas and the SysML tool (MagicDraw). The workshop was led by Prof. Chris Paredis and his students from Georgia Tech. Participants were students and faculty from UIUC, UMN, and MSOE who work on projects affiliated with TB6. The workshop output included modeling the requirements and some system architectures for the PPAFO designs, which will be used to guide further PPAFO development.

Plans, Milestones and Deliverables for Next Year

- Experimental validation of PPAFO system models (February 2011)
- Implementation of proposed efficiency improvements (March 2011)
- Integration of improved valve technology (proportional) with PPAFO Gen1 (March 2011)
- Construction and bench testing of custom, tiny hydraulic systems (Spring-Fall 2011)
- Gen 2 PPAFO subject testing (Summer-Fall 2011)
- Integration of HCCI engine prototype into the PPAFO (Summer 2011)
- Improved PPAFO control algorithms for different locomotion modes (standing, ramp walking, stairs) (Fall 2011)

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.

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CENTER FOR COMPACT AND EFFICIENT FLUID POWER
A National Science Foundation Engineering Research Center

The Education and Outreach Program Portfolio of the Engineering Research Center for Compact and Efficient Fluid Power (CCEFP)

Education and Outreach Program at a Glance

PROJECT	UNIVERSITY EDUCATION	PRE-COLLEGE OUTREACH	INDUSTRY
Thrust A: Public Outreach			
Bringing the message of fluid power to the general public			
A.1 Interactive Exhibits	x	x	x
A.3 Fluid Power Video	x	x	x
Thrust B: Pre-College Education			
Bringing fluid power education to K-12 students, with a focus on middle and high school			
B.1 Research Experiences for Teachers (RET)		x	
B.2 Project Lead The Way		x	
B.3 Hands-on Fluid Power Workshops	x	x	
B.4 gidaa STEM Programs		x	
B.5 High School Research Opportunity Program (in development)	x	x	x
Thrust C: College Education			
Bringing fluid power education to undergraduate and graduate students			
C.1 Research Experiences for Undergraduates (REU)	x		
C.2 Fluid Power OpenCourseWare	x		x
C.3 Fluid Power Projects in Capstone Design Courses	x		x
C.4 Fluid Power Courses	x		
C.5 giiwed'anang North Star Alliance	x		
C.6 Fluid Power Simulation Application (in development)	x	x	x
Thrust D: Industry			
Making connections between CCEFP and industry			
D.1 Fluid Power Scholars/Interns	x		x
D.2 CCEFP Network	x		x
D.3 Advanced Fluid Power Engineering Workshops	x		x
D.5 CCEFP Webcasts	x		x
D.6 Publications	x	x	x
Thrust E: Evaluation			
Measuring to determine if CCEFP programs are effective			
E.1 External Evaluation of E&O Programs	x	x	x

Introduction

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

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

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

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

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

Diversity: The CCEFP is striving to change the face of fluid power by providing opportunities for a diverse population to become involved in fluid power, including women, underrepresented minorities and those with disabilities. The CCEFP is committed to recruiting and retaining a diverse community of faculty, graduate students, REU students, summer interns, RET teachers and others to participate in all its activities. Some of these efforts are conducted through each university's own offices and programs, others are realized through the work of the Center's affiliated organizations, including LSAMP and AGEP institutions and still others are coordinated by the CCEFP itself.

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 purpose of this project is to create interactive exhibits that demonstrate basic attributes of fluid power and highlight CCEFP research. Prototypes and working exhibits have been and are continuing to be developed by and field-tested at the Science Museum of Minnesota (SMM). SMM prototypers have produced two finished exhibits that are now on display on the museum floor: a hydraulic variable torque transmission with accumulator-based energy storage and a working cut-away variable-displacement axial piston pump arranged to pump tall streams of clear hydraulic fluid. SMM is currently completing a "Hydraulics Lab" that allows museum visitors to set up their own fluid power demonstrations and experiments. Efforts are underway to replicate and distribute these and additional exhibits to other museums and to corporate venues, using NFPA to facilitate through its industry member network. [Project Leader: J Newlin, SMM]

Project A.3 Fluid Power Video

The CCEFP continues to reach out to audiences outside academic communities through several approaches including continuing dissemination of its “Discovering Fluid Power” 30-minute television documentary produced by Twin Cities Public Television and CCEFP,). [Project Leaders: Kim Stelson and Linda Western, CCEFP]

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)

RET is an NSF program whose purpose is to improve science, technology, engineering and mathematics (STEM) education in schools by funding high school teachers to spend the summer in a university research lab. The teacher completes a research project and develops curriculum to be used in their class. Every summer the CCEFP hosts at least eight RET teachers at CCEFP universities. A special CCEFP RET focus is recruiting teachers from area high schools participating in the PLTW program. [Project Leader: Will Durfee, UMN]

Project B.2 Project Lead The Way

The National Fluid Power Association (NFPA) and Project Lead The Way (PLTW) are affiliated organizations within the CCEFP. NFPA funded Project Lead The Way to include fluid power in several of its high school and middle school curriculum modules. 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 the PLTW curriculum. In addition, PLTW teachers participate in the CCEFP RET program. This project also reports to the NFPA Board. [Project Leader: Linda Western, CCEFP]

Project B.3 Hands-On Fluid Power Workshops

Fluid power is most easily understood by students of all ages when accompanied by hands-on experiments. This project develops hands-on apparatus to demonstrate principles of fluid power, creates student and instructor guides appropriate for the targeted education level, and disseminates to the target population of instructors.

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

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

B.3c Workshops: The goal of this project is to create and disseminate hands-on workshops based on the apparatus and curriculum developed in projects B.2a and B.2b, as well as incorporating other fluid power hands-on activities. A special focus is creating instructor guides. The target audiences for workshop instructors include CCEFP faculty, CCEFP graduate students, SMM staff and CCEFP industry member engineers. Classroom teachers are also a targeted audience. [Project Leader: Alyssa Burger, UMN]

Project B.4 gidaa STEM Programs

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

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

B.4b gidaa odaangiina anaangoog (Shooting for the Stars) Robotics Program: Under the gidaa STEM Program umbrella, staff and teachers have introduced K-12 robotics day and after-school curricula using Lego Wedo-Webots, NXT Kits, Vex Kits and Textrix kits and software.

Project B.5 High School Research Opportunity Program (HSROP)

This project is under development.

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)

REU is an NSF program whose purpose is to provide undergraduate STEM students with a summer experience in a university research lab. An objective of the program is to increase the number of top students applying to graduate school in STEM areas. Every summer the CCEFP hosts at least 14 REU students, a minimum of two per university site. The CCEFP REU students begin the summer with an orientation to and instruction in fluid power technology, its applications and the research activities of the CCEFP. Continuing interaction among CCEFP REU students at the seven sites occurs twice during the summer. The CCEFP actively recruits women, students with disabilities and underrepresented minority students for its REU program. [Project Leader: Will Durfee, UMN]

Project C.2 Fluid Power OpenCourseWare

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

Project C.3 Fluid Power Projects in Capstone Design Courses

All ABET accredited undergraduate engineering degree programs have a capstone design experience where fourth-year students work in teams for one or two semesters on a practical design project. The objective of this project is to work with fluid power companies to sponsor and actively engage with students in capstone design projects with fluid power content. This is a collaborative project with the National Fluid Power Association (NFPA). [Project Leader: Will Durfee, UMN]

Project C.4 Fluid Power 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: All CCEFP faculty]

Project C.5 giiwed'anang North Star Alliance

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

Project C.6 Fluid Power Simulator

For undergraduate mechanical, aerospace and agriculture engineering students, high-school students in a PLTW program and professionals new to fluid power, the CCEFP fluid power simulator (FPS) will be a medium-fidelity, essential-capability, easy-to-use, freeware simulator of fluid power systems. Unlike existing commercial simulators, the CCEFP FPS will be targeted towards the education market, but will maintain technical rigor. *This project is under development.*

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-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. Up to ten undergraduate students will be selected to participate in the 2011 program through the cooperative efforts of faculty, industry representatives and CCEFP staff. The Scholars/Interns Program is open to undergraduates who have successfull completed at least two years in an accredited engineering program in the United States. [Project Leader: Linda Western, CCEFP]

Project D.2 CCEFP Network

Using an array of technological tools, the goal of the CCEFP Network is to connect the people of the Center—faculty; undergraduate, graduate and post-doctoral students, REUs, RETs, advisory board members and industry supporters—in mutually advantageous ways. [Project Leader: Alyssa Burger, UMN]

D.2a Database: This database contains all of the demographic and contact information needed by the Center and by NSF.

D.2b Resume Bank: All of the Center's undergraduate, graduate and post-doctoral students are invited to post their resumes at a secured section of the CCEFP website. This site is available to CCEFP member companies for their use in recruiting of CCEFP students for entry-level job placement. This resume bank is also useful as the Center's industry members seek out candidates—both undergraduates and graduates—for industry internships.

D.2c Boarding Pass: New participants in the CCEFP are welcomed through a boarding pass process.

D.2d Alumni Society: Upon graduation or conclusion of a program-specific role within the Center, all CCEFP participants automatically become members of the CCEFP Alumni Society. An exit interview, given when the participants complete their formal CCEFP affiliation, is designed to gather information on Center experiences as well as follow-up contact information, The interview will be followed over time with ongoing outreach as the Center tracks career and interest paths as a way of evaluating program impact. Meanwhile, as members of the Society, participants will receive periodic newsletters highlighting CCEFP developments, will have access to contact information for other alumni, and will have access to other key areas of the CCEFP website.

Project D.3 Advanced Fluid Power Engineering Workshops

The objective of this project is to facilitate knowledge transfer between CCEFP faculty and degreed engineers in design and manufacturing positions in fluid power companies as well as Center faculty and 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 will be launched in conjunction with two key industry trades shows in March 2011. Subsequently, workshops will be taught primarily through half-day and longer e-Learning courses to minimize travel time and costs for the intended audiences. An e-Learning short course could be as simple as a webcast, but eventually our goal is to incorporate the emerging principles of e-Learning pedagogy to deliver high-quality courses. [Project Leader: CCEFP Industrial Liaison Officer, UMN]

Project D.5 CCEFP Webcasts

The CCEFP hosts bi-weekly webcasts, each with two to three presenters describing either research projects or discussing Center-wide programs such as education an outreach projects, strategic planning initiatives, special topics, or project evaluation. The webcasts are open to all CCEFP students and faculty and to all CCEFP member companies. The webcasts are an important means for Center-wide communication and knowledge transfer. [Project Leader: Alyssa Burger, UMN]

Project D.6 Publications

Publications included here include press releases and articles detailing results of research and education/outreach projects. Targeted publications for the publications include those intended for industry-specific audiences, as well as the engineer and educator communities. [Project Leader: Linda Western, UMN]

D.6a Press Releases and Articles: The Center works with the editorial staffs of these publications, providing material of general interest based on the Center's research, education and outreach activities. (Formerly Project A.3b which focused on industry, this project has been broadened to include journals of professional organizations.

D6.b Academic Journal Special Issues: Subject-specific, issue-length coverage of issues/initiatives central to CCEFP research.

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.

Each PI of an EO project completes a project update report in the same four-up format as the research project updates. Project progress is evaluated by a committee whose members include the Education Program Co-Directors, the Education Outreach Director, The Center Director, and the Industrial Liaison Officer. In addition, four education advisors, selected for their expertise and varying perspectives, evaluate the EO program as well as provide guidance on E & O strategy and direction. Further evaluation of selected programs is carried out by the Center for Applied Research and Educational Improvement (CAREI). See Project E.1.

Project E.1 External Evaluation of Education and Outreach Programs

These ongoing evaluation activities, led by the Center for Applied Research and Educational Improvement (CAREI), determine if projects within the Education and Outreach program are meeting the Center's goals of (1) increasing awareness of and education in fluid power at the pre-college, college and professional level, and (2) increasing the number of women and under-represented minorities in engineering and specifically in fluid power. Each year a subset of the EO program portfolio is selected for evaluation by CAREI. The Fluid Power Interns, REU and RET programs were evaluated by CAREI in 2009. [Project Leader: CAREI, UMN]

Associated Projects

TRIBES-E: Teaching Relevant Inquiry-Based Environmental Science and Engineering

Administration of the EO Program

The EO Program is headed by Education Program Co-Directors Linda Western and Will Durfee. The Co-Directors report to Center Director Kim Stelson. Education Outreach Director Alyssa Burger is responsible for program implementation. The Education and Outreach Network (EON) has one representative from each of the seven universities. The EON facilitates communication among the CCEFP sites and is a core working group for a number of the EO initiatives. Education Advisors provide guidance, recommendations and oversight for the EO Program.

Responsibility for fluid power education and outreach rests with every CCEFP participant. Each research and test bed project in the Center has an EO component. The EO activities of individual research projects are reported in the project update reports.

Project A.1: Interactive Exhibits

Project Team

Project Leader: J. Newlin, Director of Physical Sciences & Technology
Science Museum of Minnesota

Other Personnel: Peder Thompson & Forrest Price, prototypers
Cliff Athorn, Director of Production, Science Museum of Minnesota

1. Project Goals

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. How Project Supports 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,
- Building display prototypes in SMM's exhibit shop.

Capstone Projects: In 2007 and again in 2008, small teams of University of Minnesota seniors developed exhibits as part of their capstone design courses. One was an exhibit about a hydraulic hybrid scheme for regenerative braking in vehicles. Another 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. A third 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 last was a prototype of a water-based fluid power experiment lab for use by museum visitors. The first of these exhibits is on display at the museum (Figure 1). Another inspired the hydraulics lab exhibit now being completed by museum staff.

Figure 1: Hydraulic Hybrid Car

High School Project: In 2008, an SMM prototyper (Price) worked as 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 put it on display (Figure 2).

Figure 2: Supermileage Car

Museum Projects: SMM prototypers have produced two finished exhibits that are now on display on the museum floor. One of these is a hydraulic variable torque transmission with accumulator-based energy storage (Figure 3). The second is a working cut-away variable-displacement axial piston pump arranged to pump tall streams of clear hydraulic fluid (Figure 4).

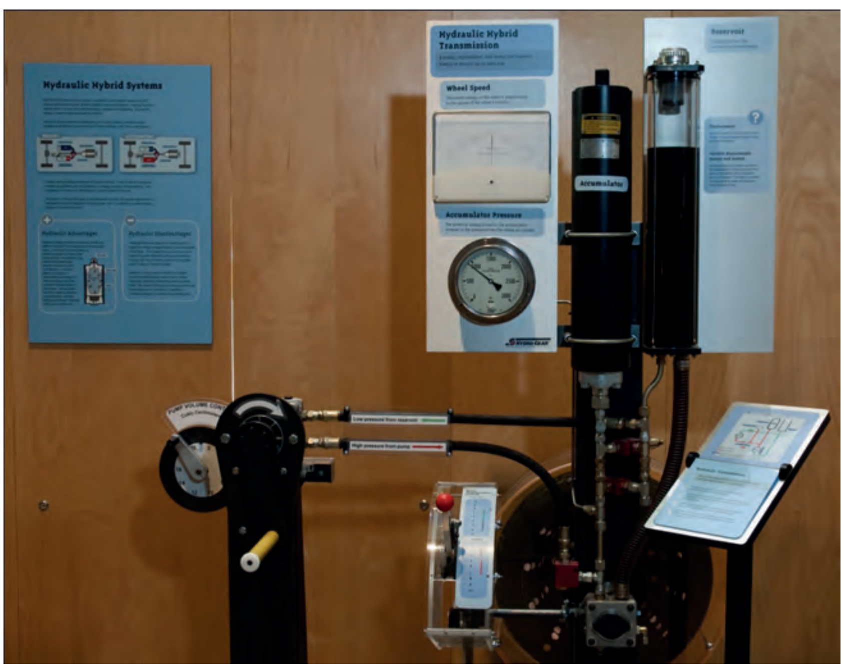


Figure 3: Hydraulic Transmission

Figure 4: Axial Piston Pump

SMM has also completed a **Hydraulics Lab** (Figure 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.

Figure 5: Hydraulics Lab

There has been an expanding group of Fluid Power exhibits on display at the Science Museum of Minnesota since 2008. They now include **Axial Piston Pump**, **Hydraulic Hybrid Car**, **Hydraulic Transmission**, **Supermileage Car**, and the **Hydraulics Lab**. In Fall, 2010 SMM reinstalled these exhibits, placing the Hydraulics lab inside a low-walled “corral” and including a set of four simple exhibits about simple hydraulic circuits.

1. In **Hydraulic Crane**, visitors employ two different sized pistons connected by a clear hydraulic line to lift a weight on a movable arm.
2. In **Hydraulic Circuit**, visitors pump water out of a reservoir, through a check valve, into and out of a piston pump, through a second check valve, and back into the reservoir.
3. In **Accumulator**, visitors use a piston pump to force water from a reservoir through a spool valve into an accumulator. By changing the spool valve, they allow the pressurized water to flow through a flow meter back into the reservoir.
4. In **Double Acting Cylinder**, visitors pump water from a reservoir through a four-port spool valve into a double acting cylinder, forcing it to move a piston that rings a bell. By changing the spool valve, they pump the piston back again.

SMM has refurbished and installed an exhibit that uses a pneumatic bearing to support a large **Double-weight Pendulum**. This consists of a granite spherical cap supported by air flowing into a spherically-ground concave base. A rod extends vertically from the center of the cap on which visitors may adjust a weight to change the vibration frequency of this double weight pendulum.

SMM has also developed a fluid power activity kit that volunteer staff 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, SMM joined Eric Lanke of the National Fluid Power Association in a presentation and discussion of fluid power exhibit ideas at Milwaukee's Discovery World science center.

4. Plans
SMM is currently reworking labels and graphics for the new installation. Once these are complete, the exhibit group will be evaluated (see below).

Winter/Spring 2011
SMM staff is working with ME Capstone Design Students on a new project that will result in prototype exhibits that communicate to museum visitors basic ideas about compact and efficient use of fluid power in the area of the Testbed project on human orthoses. Once rough versions of these exhibits are developed by students, SMM staff will refine them so they can live on the museum floor.

Summer/Fall 2011
SMM will work with senior CCEFP staff to indentify appropriate exhibit topics that will strengthen the engineering aspects of its fluid power exhibit programming. These topics will be developed to complement SMM's development of a major permanent exhibition on engineering innovation called *Engineering Studio*, which has been funded by 3M. A small pilot version of this project was mounted on SMM's exhibit floor in August, 2010. The full exhibition is planned to open in late 2013.

SMM will develop a new fluid power engineering exhibit that allows younger visitors to create their own fluid-powered ball run, illustrating how fluid power mechanics can be incorporated into innovative, artistic, useful, and whimsical personal projects.

SMM will add the revised and new exhibits to the Exhibit Brochure and make it available to museums and science centers that are neighbors of CCEFP academic and industrial partners.

5. Evaluation
Once the labels and graphics fluid power exhibits are installed, SMM's evaluation group will conduct a remedial evaluation of the exhibits, looking particularly at attractiveness, ease of use, and effectiveness at communicating basic fluid power concepts.

6. Member Company Benefits
Exhibits developed by SMM are useful to introduce public audiences to the capability and advantages of fluid power. Such exhibits could be replicated for other museums, for student centers at technical universities, or for lobbies at fluid power industries.

Project A.3: Fluid Power Video

Project Team

Project Leader:	Kim Stelson, CCEFP Director
Other Personnel:	Linda Western and Don Haney
Industrial partners:	Eric Lanke, National Fluid Power Association; Twin Cities Public Television, Tom Trow
Video Cast:	*Center students*: Serena Tyson and Caleb Sancken (and others in bit roles) *Faculty members*: Kim Stelson, Perry Li, Andrew Alleyne, Wayne Book and Monika Ivantysynova *Industry representatives including*: Jeff Herrin (Sauer-Danfoss), Ed Howe (Enfield Technologies), Dennis Harvey (MTS), Astrid Mozes (Eaton), Eric Lanke (NFPA) and others.

1. Project Goals

Though applications of this technology are commonplace in everyday life, this technology is little known to most pre-college students and adults. *Discovering Fluid Power* addresses the lack of awareness of fluid power's ubiquity. This 25-minute documentary offers a basic introduction to fluid power technology and features footage, with accompanying narratives, that highlight the many applications of hydraulics and pneumatics.

2. How Project Supports the EO Program Strategy

The production and distribution of *Discovering Fluid Power* is an excellent example of CCEFP strategy—seeking out strong partners to help and support the Center's education and outreach program. Produced in collaboration with the National Fluid Power Association (NFPA is an affiliate organization of the CCEFP) and Twin Cities Public Television (TPT), *Discovering Fluid Power* is a companion to NFPA's video, *Fluid Power: A Force for Change,* which focuses on careers in fluid power. Much of the application footage in both videos was contributed by the Center's industry supporters and by fluid power trade associations around the world. Students and faculty of the CCEFP as well as industry representatives provide the narratives for both videos. *Discovering Fluid Power* and *Fluid Power: A Force for Change* are appropriate for upper elementary, middle and high school students as well as for adult audiences.

3. Achievements

Since its full release in 2008, *Discovering Fluid Power* has been broadcast nationwide. Airings in Los Angeles, Milwaukee, Madison, Denver, Minneapolis/St. Paul, and Kent (Ohio) are confirmed. It is also repeatedly viewed through a PBS network (six stations) in Minnesota. It is likely that the video also has been aired on other stations; however, it is difficult to keep this information complete and current. While no new promotional efforts have been launched in 2010, the following summary of promotions and successes, as reported in our 2009 Annual Report, continues to be current:

The video is broadcast through the Research Channel--on broadcast rotation in many communities as well as on-demand. NFPA is continuing its efforts to market the two videos: to additional public television stations nationwide, to its sister trade associations worldwide, and to its network of technical college and university members. Several of these schools have volunteered that *Discovering Fluid Power* offers a useful and entertaining introduction to hydraulics and pneumatics. TPT is a partner in promoting the video, too, through its magazine (85,000 readers) and e-blasts (45,000 viewers). The Internet provides an important distribution channel beyond e-blasts. *Discovering Fluid Power* can be viewed at no cost at the Center's website (www.ccefp.org), at Project Lead The Way's Virtual Academy (an online resource site for PLTW teachers), and at www.nfpa.org. Excerpts are available on YouTube. CCEFP as well as NFPA staffs have mailed copies worldwide to schools, universities, businesses and individuals.

The Center's university and industry networks also have access to the video and report using it in classes and for student on-campus visits as well as for employee orientations.
Copies are being included with the hands-on workshops discussed at B.3.

4. Plans
During production, TPT producers along with industry and Center reviewers, took special care to insure as long a "shelf life" as possible for the video. With that said, the video will soon be four years old and following this year, active promotions will taper off. While the video will continue to be available to many audiences through the above channels, active efforts will focus on getting as many copies as possible into classrooms. In doing so, the CCEFP will capitalize on links to industry and educational websites; promote the video as a learning tool to middle school, high school, technical college and university educators; and engage the Center's universities and other partners in using their networks to promote and distribute the video.

5. Milestones and Deliverables
The CCEFP will periodically refresh clips from the video posted on YouTube. There are now three. The video will be available soon for download at iTunes U. Two hundred institutions are affiliated with this site. Every member of the CCEFP will have seen--and own--a copy of the video.

6. Member Company Benefits
The video is a promotional as well as an educational tool for the fluid power industry and for the Center. The cooperative efforts between industry, NFPA and the CCEFP in preparing both videos combine to tell their own success story. Now, industry leaders as well as everyone in the Center have every reason to continue to cooperate in distributing both videos to as many audiences as possible.

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

Project Team

Project Leader: Will Durfee (UMN)

Other Personnel: Alyssa Burger (UMN), Program Coordinator
Stacy Klein Gardner, Vanderbilt University
CCEFP faculty advisors.

1. Project Goals

The CCEFP's RET program enables teachers in pre-college schools to introduce fluid power to their students, drawing on their experiences in CCEFP research labs. In this six-week summer program, teachers learn first-hand about fluid power basics and are engaged in research because of their work in the Center's university network. With these experiences as a foundation, teachers develop research-inspired curriculum modules to bring back to their classroom. Special efforts are made to recruit Project Lead The Way (PLTW) teachers to this program in geographic locations where the Center's RET program is hosted and where PLTW has a presence.

2. How Project Supports the EO Program Strategy

The RET program is an example of the CCEFP's strategy to maximize program impact: one teacher reaches many students; many teachers reach many classrooms. And, in sharing the curriculum modules they develop, RET teachers support another key CCEFP strategy—development of projects that can be replicated and/or adapted by other educators for new audiences. The work of RETs can be used by a host of teachers who have not participated in the RET program.

3. Achievements

- Six teachers participated in summer 2010, the fourth year of the CCEFP RET program: two at the University of Minnesota, two at Vanderbilt and two at Purdue University.
- Three of the six 2010 teachers are Project Lead The Way (PLTW) teachers. PLTW assists by recruiting PLTW teachers for the CCEFP RET program.
- The CCEFP held its Annual Meeting in June 2010 at Purdue University in West Lafeyette, IN . All RET teachers attended the meeting which included an program orientation led by Prof. Stacy Klein-Gardner from Vanderbilt University.
- The Center for Applied Research and Educational Improvement (CAREI) formally evaluated the 2010 program. (See E.1 for details.) CAREI also evaluated the CCEFP's 2008 and 2009 programs.
- Twelve teachers participated in summer 2009, the third year of the CCEFP RET program: five at the University of Minnesota, two at Vanderbilt, two at North Carolina A&T, and two at Milwaukee School of Engineering. The three teachers from the University of Minnesota from the 2008 program returned for a second summer and leveraged their previous experience in mentoring the new participants as well as getting a head start on their project.
- Seven of the 2009 RETs attended the Vanderbilt RET Boot Camp in Nashville. This helped cross-collaboration among the teachers, as well as renewed some previous acquaintances as several teachers had participated in PLTW teacher trainings in the past.
- 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. Note that at three of the four schools, pairs (one trio) of teachers were hired together in order help all maximize their learning experiences.
- The 2008 program was the first to bridge with another NSF program by fostering cross-collaboration with the NSF RET VaNTH Site at Vanderbilt University. A total of ten of the 2008

and 2009 teachers have attended the three-day RET orientation there hosted by Dr. Stacy Klein Gardner. In addition to providing a good introduction to the RET program, the event enabled teachers at different CCEFP sites to make connections and begin networking. During the RET "boot camp," participants learned to translate research into a curriculum module and also learned strategies to connect current content with new content. Not only are their lesson plans to be designed around state education standards, but Dr. Klein Gardner also encourages curriculum writing surrounding The Legacy Cycle. Teachers are required to modify their curricula to meet the standards of the NSF-sponsored TeachEngineering.com, an on-line repository of tools for K-12 teachers.

Portable Fluid Power Demonstrator (PFPD) Project

2009 and 2010 RET Project at Purdue University conducted by **Brian Bettag** and **Gary Werner**, both PLTW Teachers.

During the summer of 2010, RET participants Brian Bettag and Gary Werner designed and built a fluid power kiosk that allows children and adults alike to learn more about the world of fluid power. The kiosk highlights the principles of fluid power, how it is used in the world around us, and the current research that is being done at the CCEFP. The simple design and use of the touch screen allows users to learn at their own pace and watch animations and videos, provided by the NFPA and CCEFP, to create a captivating platform to spread the word about fluid power. The kiosk is currently deployed in a local science and technology center in Lafayette and will be moved back to the ABE department at Purdue during the summer for the department tours.

4. 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.

5. Plans

- Though the CCEFP will not pursue an NSF RET Site Award, the Center will host a strong and effective RET program in 2011 and beyond.
- The Center will promote the newly developed fluid power curriculum modules at its website, on TeachEngineering.com, and through other channels.
- The Center will continue to leverage the Project Lead The Way (PLTW) teacher network for recruiting.
- The model of multi-year RET participation proved to be success at UMN in years 2008 and 2009. The CCEFP will encourage this model wherever possible and will engage the RETs throughout the year on their curriculum and implementation.
- A challenge is to remain connected to the teacher once the summer session is over as well as remaining in contact in the years following the RET experience. The CCEFP aims to encourage faculty advisors to communicate regularly with the teacher participants and inquire as to the status of the curriculum implementation and development.

6. Milestones and Deliverables

- In 2011, the CCEFP commits to hosting between six-eight teachers within its university network.
- The RET participants across the CCEFP will post their curricula on TeachEngineering.com, the CCEFP website, Youtube, TeacherTube, and other relevant sites.
- The CCEFP will continue to enable access to this curricula through its OpenCourseWare project (see C.2).

7. Member Company Benefits

Following their RET experiences, teachers can bring their experiences in university research as well as their expanded understanding of fluid power concepts to their classrooms. New curricula stemming from these experiences should inspire and motivate a next generation of leaders in the engineering, corporate and/or academic arena.

Project B.2: Project Lead The Way (PLTW)

Project Team

Project Leader:	Linda Western, Education Co-Director, CCEFP
Other Personnel:	DWill Durfee, Education Co-Director; Alyssa Burger, Outreach Director; John Lumkes, Purdue University; Kim Stelson, CCEFP Director
PLTW:	Richard Grimsley, Vice President for Programs; Sam Cox, Director of Curriculum for Engineering; Bryan Kind, Associate Director of Curriculum for Engineering
Industry Partners:	Volunteers from the membership of the National Fluid Power Association's Education Committee

1. Project Goals

Project Lead The Way (PLTW) is a not-for-profit national program dedicated to developing STEM-relevant courses for middle and high school students. An affiliate organization of the CCEFP, PLTW is a strong and growing partner in the Center’s outreach efforts to help teenage students and their teachers better understand fluid power technology, its applications, and the research that is shaping the industry's future.

2. How Project Supports the EO Program Strategy

Seeking out partnerships with highly regarded and broadly distributed education and outreach networks in order to maximize program impact is central to CCEFP strategy. The Center's affiliation with PLTW does just that. The PLTW network currently involves 350,000 students in all 50 states. More than a half million students reportedly have taken at least one PLTW class.* As another of its core strategies, the CCEFP seeks to leverage and coordinate the accomplishments of individual Education and Outreach projects in facilitating the progress and successes of other E & O projects. Implementation of this strategy is very evident here as other E & O projects (e.g., A.3 and B.3) interface with the PLTW initiative.

3. Achievements

- The National Fluid Power Association (NFPA), also a CCEFP Affiliated Outreach Institution, provided funding to develop the revision and addition of fluid power content in several PLTW courses. With the launch of the CCEFP, the Center joined in this partnership for curriculum development. Writing high quality project-based curricular material is a challenge made more difficult here since fluid power technology is not widely understood. The three-way CCEFP/PLTW/NFPA partnership provides a solution since CCEFP personnel and industry volunteers are subject matter experts. What began with focused editing of prepared curricula with fluid power content has grown into a broader role for the CCEFP and industry. Along with volunteers from NFPA, CCEFP faculty have advised and contributed to curriculum content and project design for PLTW's *Gateway to Technology*, *Introduction to Engineering Design*, *Principles of Engineering* and *Computer Integrated Manufacturing* courses. Fluid power-related projects are also an option for students in *Engineering Design and Developm*ent, a class in which teams of students, guided by community mentors, work together to research, design and construct a solution to an engineering problem.
- Following a successful pilot at one university in 2008, the Center involved teachers associated with PLTW in both the CCEFP's 2009 and 2010 Research Experiences for Teachers (RET) program. Consequently, PLTW teachers have developed course material based on their experiences in Center labs, sharing them with their students and colleagues through the Center and PLTW networks as well as on TeachEngineering.com.
- A hands-on workshop designed to introduce students to pneumatics was developed by CCEFP faculty at the University of Minnesota. This workshop is scheduled to be included in the Gateway Academy, a summer camp program sponsored by PLTW and the Society of Manufacturing Engineers. This far-reaching program, with its 700 camps, is aimed at interesting middle school children in STEM fields.

- Another hands-on workshop, this one based on the construction of a mini-excavator, was designed by faculty at Purdue with assistance from Center graduate students, REUs and two RETs who are also Project Lead The Way teachers. One PLTW/RET produced an accompanying curriculum matched to Indiana education outcomes, developed web-based material for other high schools (now available at www.ccefp.org).. Several high schools are now constructing their own mini-excavators and using the curricular materials as a result of this exposure.
- PLTW volunteered to link CCEFP's video, *Discovering Fluid Power*, at its Virtual Academy website (see project A.3). PLTW teachers can view the video at this website, and can also request free copies from CCEFP headquarters.
- In spring 2010, CCEFP faculty member Professor Will Durfee (University of Minnesota) developed a tutorial for use by PLTW teachers on fluid power basics. The purpose of the tutorial is to help these teachers better understand fluid power so that they, in turn, can help their students to learn about hydraulics and pneumatics--why and how these technologies are used.
- As a new dimension of the unique three-way partnership between PLTW, NFPA, and CCEFP, representatives of all three groups began a series of regularly scheduled conference calls in the summer of 2010. The purpose of these calls, now held approximately every two months, is to seek out ways in which projects can be initiated and strengthened through cooperative efforts.
- Faculty at MSOE participated in a PLTW Teacher Training Institute during the summer of 2010, presenting ERC research to PLTW teachers and providing a hands-on demonstration of a hydraulic excavator tool.

4. Plans

- Given successful involvement of PLTW teachers in the Center's RET programs in 2008, 2009 and 2010, the CCEFP will continue to focus efforts in recruiting PLTW teachers for its 2011 RET program and beyond. PLTW has agreed to continue its help in this recruitment.
- As an outgrowth of the three-way conference calls noted above, exploratory work has just begun on the development of a fluid power simulator. This is envisioned as a medium-fidelity, essential-capability, easy-to-use freeware simulator of fluid power systems. This project, only in an early stage of development, involves faculty from the University of Minnesota, Georgia Tech and Purdue. As a next step, is a these initial explorations may become the subject of a Capstone Design project. (See C.3)
- CCEFP and PLTW are moving forward in identifying ways to integrate the hands-on kits and teaching strategies, developed in additional CCEFP projects under B.3. This work is facilitated through the involvement of PLTW/RETs working at Purdue university.
- At this writing, PLTW has just announced a number of additions to its curricular plans, teaching materials, delivery mechanisms, etc. As one example, PLTW has announced a new partnership with VEX Robotics. There may be opportunities for the Center-related activities here, too, though it is premature to be specific.PLTW has contracted with the Northwest Evaluation Association in developing and administering pre- and -post course assessments. The CCEFP and NFPA plan to gather information from PLTW, based on these new evaluations, about the effectiveness of new fluid power content in the classroom.

5. Milestones and Deliverables:
The CCEFP is striving to assure that every teacher of Project Lead The Way's *Principles of Engineering*, *Gateway to Technology* and *Computer Integrated Manufacturing* will have received fluid power material from CCEFP and will use it in their course delivery before the end of Year 6.

CCEFP faculty will continue to serve as a resource and as reviewers as PLTW moves toward a new course revision schedule.

6. Member Benefits

All industry members of the CCEFP join other stakeholders in the fluid power industry in their concern about the adequacy of current pre-college science, technology, engineering-related and mathematics (STEM) education. The cooperative efforts of the CCEFP with PLTW (often involving NFPA, too) respond to this concern given PLTW's goal of increasing the number, quality and diversity of a new generation of engineers. PLTW's evolving curricula engages students in hands-on experiences, applying STEM-relevant concepts to solving real-life problems.

* Note that not all PLTW students and teachers engage in the units, lessons and projects with fluid power content developed through this project.

A Project Lead The Way Teacher, also an RET at Purdue University, works on the Portable Water Hydraulics Demonstrator under the guidance of Professor John Lumkes.

Project B.3a: Hands-On Pneumatics Workshops

Project team:

Project Leader:	Prof. Will Durfee, University of Minnesota, Education Co-Director, CCEFP
Other personnel:	Prof. Chris Paredis, Georgia Tech
	David Cook, student, University of Minnesota

1. Project Goals
The goal of this project is to create curricular material and portable lab kits for use in hands-on workshops about pneumatics. The target audiences for workshops include high school students participating in FIRST Robotics, CCEFP RET teachers and their students, teachers and students engaged in the fluid power curriculum embedded in Project Lead The Way (PLTW) pre-engineering courses, and CCEFP pre-college outreach workshops. The curriculum for the workshop will eventually include: (1) a basic hands-on tutorial, (2) an advanced workshop tailored to experienced FIRST Robotics teams, (3) web-based self-learning material, and (4) a module for PLTW teacher training workshops and for PLTW courses.

2. How Project Supports the EO Program Strategy
Pneumatics is easy to understand, easy to work with, and relatively inexpensive to demonstrate through hands-on activities. Workshops based on pneumatics serve to broaden an awareness of fluid power among pre-college students and their teachers. The strategy for the CCEFP EO program is to leverage existing networks. The kits are used to train FIRST Robotics teams in pneumatics and there are currently approximately 1,500 FIRST teams involving over 30,000 students. Workshop contents could be used in the PLTW program, another large network connected to CCEFP. The workshops are also used by CCEFP RET teachers, who in turn reach their students. Reaching only a fraction of this motivated audience serves to bring fluid power to the target audience.

3. Achievements

- Additional kits were constructed and distributed to CCEFP sites and CCEFP RET teachers .
- Instructors guide was revised.
- Dozens of FIRST Robotics students participated in the pneumatics workshops sponsored by the University of Minnesota at the FIRST Splash event in December, 2010 and the workshops sponsored by Georgia Tech in Fall 2010. Over a half dozen other workshops were conducted through the College of Science and Engineering’s Office for Diversity and Outreach in 2010.
- Undergraduate David Cook (UMN) developed an advanced pneumatics workshop targeted to FIRST Robotics teams. The workshop covers pneumatics in more depth than the introductory workshop and includes materials on controlling pneumatics with the FIRST Compact RIO microcontroller. The workshop was delivered at the Minnesota FIRST Splash event.
- A 20 minute video training guide was created, targeted at PLTW instructors needing assistance with the fluid power lesson plans in the PLTW curriculum. The video covers a few of the basic principles of fluid power and provides suggestions for hands-on learning materials, including pneumatics. Video was published on YouTube (three parts) and linked under the education resources section of the CCEFP web site.

4. Plans

- Continue to revise and improve the materials. For example, now that the kits have been in operation for three years, wear and usability weaknesses have become apparent. Design modifications will correct the weaknesses.
- Revise the curriculum and instructors guide to include experiments that can be conducted with the kits. The curriculum will show how the experiments are relevant to practical issues in fluid power.

- Develop a version of the workshop for professionals with a target market of employees in engineering, marketing and sales at fluid power companies who are new to fluid power. The workshop would be intended for company in-service training.
- Develop a computer-controlled option of the workshop using the low-cost Arduino board.
- Explore the potential for pneumatics workshops for college-level education. For example, one path is to add digital pressure, temperature and length sensors to the cylinders, coupled with a low cost data acquisition system (e.g. built around an Arduino board) so that thermodynamic measures, including efficiencies can be analyzed for a cylinder cycle.
- Continue discussions with PLTW curriculum writers on hands-on pneumatics experiments for the PLTW fluid power course modules.

5. Milestones and Deliverables

- Increase the number of workshops
- Increase the number of kit distributed
- Curriculum and instructors guide 2.0
- Professional workshop for in-service training.
- Incorporate kits and/or pneumatics experiments into PLTW curriculum

6. Member Company Benefits
Increased awareness of fluid power by a growing number of pre-college students.

Portable Fluid Power Demonstrator

Pneumatics Kit

Project B3.b: Portable Fluid Power Demonstrator and Curriculum

Project Team

Project Leader:	Prof. John Lumkes, Purdue University
Other Personnel:	Jose Garcia, Micah Olson and Luke Mishler, Purdue University, Staff from the Minnesota Science Museum and the National Fluid Power Association, staff and teachers from Project Lead The Way
Industry Partners:	Clippard Instrument Laboratory, Inc., Vex Robotics

1. Project Goals

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 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. A Robotic Ping Pong Ball Launcher (PPBL) was developed as a much lower cost item that could serve to teach more advanced robotics and simple pneumatics.

2. How Project Supports 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 specifically targets the fifth component of the ERC's vision for education, to "increase public and K-12 student awareness of the importance of fluid power, and the excitement and possibilities that new technologies of the Center will bring".

3. Achievements

PFPD (Portable Fluid Power Demonstrator) Development, Design, and Outreach

Undergraduate level students from Purdue were recruited for independent study classes to help design the PFPD kit and curriculum. An REU student participated in the design phase during 2008. This process was guided by an ad-hoc committee on project parameters including representatives from academia, FIRST, FPEF, NFPA, PLTW, and the Minnesota Science Museum. During 2009 the base design of a kit was finished and curriculum activities posted on the CCEFP website. In 2010 additional electronic control options, various microcontrollers, and new arm options were designed and tested. Multiple outreach programs were offered to pre-college and early-college students.

For approximately $800 USD a complete working micro-excavator using water hydraulics or pneumatics can be built and implemented in classrooms or hands-on displays. The kit includes a case, water pump, necessary power supplies, hardware (nuts, bolts, etc.), cylinders, valves, tubing, fittings, and excavator arm. It is possible to completely build the demonstrator using only common shop tools (wrenches, screwdrivers, hacksaw, and drill). This design was revised and a construction manual was published on the CCEFP website along with an accompanying curriculum guide.

In early 2010, a new, electronically controlled PFPD was designed and about a dozen generation III, electrically controlled PFPDs were constructed at Purdue and utilized in various K-12 outreach programs, museums, high schools, conferences, and distributed to CCEFP member universities.

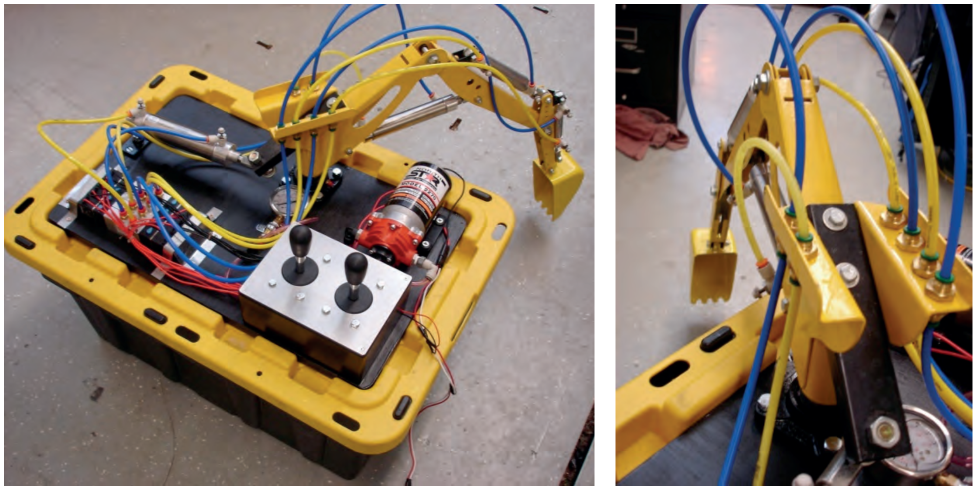


Figure 1: Generation III Electrically Controlled Portable Fluid Power Demonstrator

Much of the work in 2010 was dedicated to investigating a wide verity of robotic control possibilities for the PFPD. The motivation behind this investigation was to offer a robotically controlled version as a simple upgrade so that the PFPDs can be used to show additional aspects of fluid power systems, specifically, electrohydraulics and robotics. The robotic interest was demonstrated when a local high school received one of the new prototypes on loan for several weeks and proceeded to use a VEX controller and software to operate the PFPD remotely with a control box. The local newspaper also ran an article about the project with a front page picture of the students working with the PFPD.

During 2010, the arm originally used for the PFPD became much more expensive to acquire, so a Summer Undergraduate Research Fellowship student designed a new arm for the PFPD that is built from stock and bolts for about $30, as opposed to the new price of the originally purchased arm nearly $200.

With each model pictures were taken during the construction and a set of instructions were developed including the new arm and an appendix describing a variety of tested robotic control options. These pictures and instructions were compiled in a new assembly manual and bill of materials that will be available to download from the CCEFP website in PDF format.

Two schools in Indiana have used the PFPD to teach fluid power principles to high school students. Both of these schools have built their own models using the assembly manual and have provided with valuable feedback about assembly and handouts.

Summary of PFPD outreach activities to date

- In 2010 Purdue offered eleven pre-college outreach programs. There were 262 participants, of which 147 were female, 109 were female, and 62 were from under-represented ethnic groups.
- In total, Purdue has offered over 20 programs, reaching over 500 students with over 50% of the participants being female and/or from under-represented groups.
- Since the project's 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.
- Two PFPD kits were built by CCEFP students at the Fall conference in Chicago. The kits were subsequently used at the University of Minnesota's booth at the Minnesota state fair.
- 4-H, FFA, High school, and other groups have participated in programs at Purdue and PFPDs have been used at a variety of community events around the nation.
- A variety or models have been designed to offer an ideal configuration for whatever skill set is to be taught.

PPBL (Ping Pong Ball Launcher) Development and Design

Many high schools have expressed interest in the PFPD but expressed concern that it is still too expensive to have in every class room. Thus a challenge was presented to students to design a new kit with similar teaching capabilities as the PFPD. The parameters for this kit were set as: complete ticket of $300 or less, portable, must include robotic/mechatronic components, must include fluid power components, must be fun for students, and, of course, must be educational.

After discussion with high school students and high school teachers, the kit decided upon was a robotic ping pong ball launcher. The system would meet all the requirements and exceed all expectations in the “fun for students” category. The PPBL was designed and simplified so that its final total cost is only about $100, including hardware, electronics, and software. Furthermore, the PPBL uses standard hobby servos and can be adapted to use many available microcontrollers (these are typically already available in many high schools). It is possible to construct the entire project for as little as $50 if a microcontroller already exists. A construction instruction manual was written and will be made available to as soon as it is finalized.

The PPBL allows students to program a microcontroller to aim the launcher by controlling the rotation and elevation. Once the device is aimed the controller activates a solenoid valve to use compressed air to launch the balls. The speeds are intentionally constrained by the design for safe operation and it is expected that one of the “design challenges” offered will be to have small teams of students compete to see who can program their launcher to successful make three (or some other number) of baskets in the shortest amount of time. The “baskets” (cardboard boxes, plastic tub, pails, etc.) can be placed at various distances (the range is typically limited to 15 feet) requiring the students to plan for various rotation angles and elevations. In the future advanced groups could make approximations of the trajectory and predict the target location with the team hitting closest the target earning the most points.

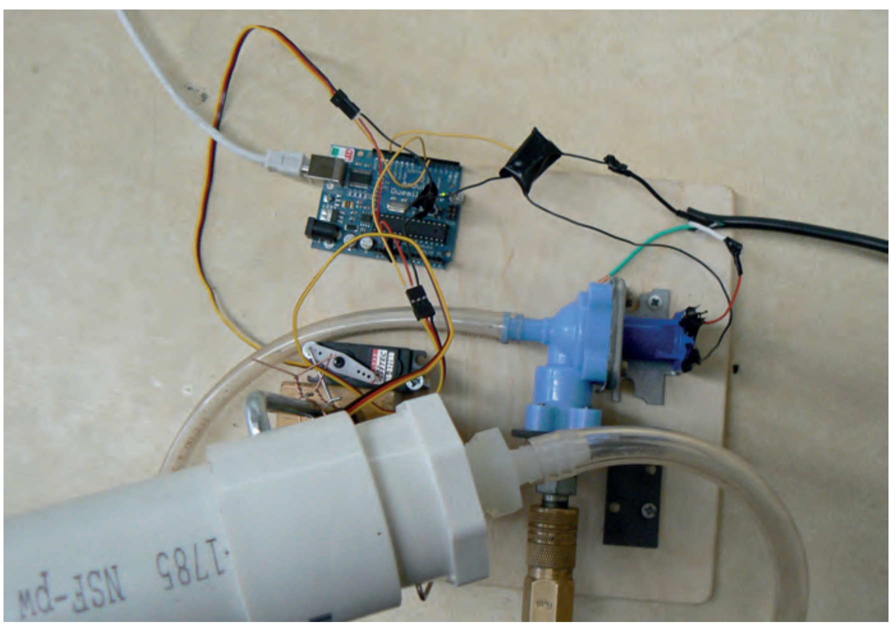


Figure 2: Robotic Ping Pong Ball Launcher

Other Relevant Work

Other relevant work is underway within the Center through the coordinated efforts the Education Outreach Network of the Center, through similar educational outreach activities at other Engineering Research Centers in the United States, at several industrial partners who have training programs, and at various Universities around the world where Engineering education research is underway. Partnerships are being fostered with existing organizations (PLTW, FIRST, Science Museum) to leverage this project for maximum impact. Representatives from these organizations are also providing valuable input during the design and construction, and will continue this support with the development of curriculum.

4. Plans

- The near term goals for the project include the completion of the assembly manual for the PPBL, distribution of this manual and the manual for the new electrohydraulic version of the PFPD kit, a strengthening of the relationships with local high schools that have used or expressed interest in using the kits, and continuing the development of a new outreach tools.
- Long term goals include the continued development of a strong partnership with PLTW to have the kits and curriculum become available through their large network of participating schools. Successfully fostering this plan would lead to national impact and exposure for fluid power.
- The core concepts of the PFPD can be applied to various expansion platforms for different applications with the design of add on kits (for example, instead of an excavator, an airplane flight control system).
- New theories for assessing student learning (moving beyond student perceptions and grades) are constantly being discussed and this project can draw upon the excellent engineering education programs and learning programs at member and partner universities to develop an appropriate assessment tool for this project, both on the project level and for individual students exposed to the learning kit.
- Finally, new outreach practices and innovative ideas are continually being discussed (and when able, tested) for possible expansion in future years. The demonstrator kits program has provided a variety of research and design positions for high school students. From the students that worked in a classroom setting to design the first VEX controlled robotic PFPD, to the other students building and using excavators in their classrooms, to two local high school students involved on campus through a work field experience program at their school for one semester, to a high school student that has worked part time on the project for nearly a year, deep involvement of high school students promises more lasting effects and could be expanded to create a more focused outreach program that will have a more significant and lasting impact.

5. Milestones and Deliverables

- May 2011: Completion of microcontroller add-on kits for the PFPD with accompanying assembly and operation instructions.
- July 2011: Completion of Generation 1 PPBL with bill of materials, example code and applications, and handouts.
- May 2012: Integration of kits into PLTW curriculum.
- 2012-2015: Development of new applications and curriculum modules for both earlier students (K-8) and post high-school students (technical colleges and engineering programs).

6. Member Company Benefits

This project will directly benefit member companies involved in fluid power by providing a methodology and demonstration kits to capture the imagination of future engineers, their future workforce. All reports and publications will be available to Center members.

Project B.3c: Fluid Power Workshops

Project Team

Project Leader:	William K. Durfee, Education Co-Director
Other Personnel:	Alyssa A. Burger, Education Outreach Director
	CCEFP Faculty
	CCEFP Graduate Students
Industry Partners:	Donaldson, Bimba Manufacturing Company

1. Project Goals

Through this project, curricular material and portable lab kits have been developed (and continue to be enhanced) for use in hands-on workshops about hydraulics and pneumatics. These workshops benefit many audiences: high school students (including those participating in FIRST Robotics and in Project Lead The Way Courses); RETs and other teachers interested in learning about and teaching fluid power; fluid power manufacturers and distributors; and participants in outreach activities sponsored by museums, technical colleges and universities. All the materials and kits developed under this project's umbrella are designed for use in reaching key CCEFP goals: developing research-inspired, industry practice-directed awareness of and education about fluid power for pre-college, university and practitioner students as well as for the general public.

2. How Project Supports the EO Program Strategy

This project supports EO Program Strategy in several ways. Our work with strong partners (as examples, PLTW, industry donors, and FIRST) optimizes both distribution and use. The ease with which these projects can be replicated maximizes opportunities for use by many workshop leaders in many settings--another EO strategic priority. And, reflecting yet another priority of EO strategy, this project supports other EO projects: B.1, RET program, B.2 - Project Lead The Way, and B.4 - gidaa STEM Programs.

3. Achievements

- Four targeted curriculum modules are being developed for the pneumatics kit (B.3a): 1) a basic hands-on tutorial, 2) an advanced workshop tailored to experienced FIRST Robotics teams, 3) web-based self-learning material, and 4) use by Project Lead The Way in its Gateway Academy program and other of its curricular activities.
- Directions for and curriculum accompanying the water hydraulics project Project B.3b, Portable Water Hydraulics Demonstrator and Curriculum, are posted at the CCEFP website and are available for free download.
- Industry support of pneumatics kit components: received grants of $15,000 from Donaldson (2009) and $3,000 from Bimba Manufacturing Company (2010)
- Hired a part-time undergraduate engineering student from the giiwed'anang Northstar Alliance to assemble the pneumatics kits.
- Several Purdue graduate students as well as a Purdue RET (summer 2010) have participating in the fabrication of the Hydraulic Demonstrator and the development of its accompanying curriculum.
- All participants of the CCEFP Student Retreat were able to build and assemble both the Hydraulic Demonstrator and a Pneumatic Kit, Chicago, 2009.
- CCEFP Pneumatics Workshops
    - Over 20 annual outreach events at the CCEFP partner institutions, 2008 - 2011
    - African-Americans Day in Science at the Science Museum of Minnesota, 2010, 2011
    - American Indians Day in Science at the Science Museum of Minnesota, 2010, 2011
    - Big Brothers / Big Sisters, Minneapolis, 2010
    - St. Paul Minority Education Program, 2010

- Minnesota Splash FIRST Robotics, Minnesota, 2009, 2010
- Minnesota State Fair, 2009
- Robojackets Orientation Event, GA Tech, Atlanta, Fall 2009
- TRIBES-E Teacher Enrichment Program, Bemidji, Minnesota, 2009
- Kit was tested and piloted at the Project Lead The Way Gateway Teacher Training Institute, Minneapolis, MN, 2008 and 2009
- Kit was tested and piloted at the Student Leadership Retreat, 2008

- CCEFP Portable Water Hydraulic Demonstrator Workshops
  - Over 20 annual outreach events at the CCEFP partner institutions, 2008 - 2011
  - Minnesota State Fair, 2009
  - Society of Automotive Engineers (SAE) Conference, October 2009
  - NFPA Industry Economic Outlook Conference, Chicago, Summer 2009
  - NFPA-CCEFP Fluid Power Challenge Competition, Fall 2009

Pneumatics Kit

Portable Fluid Power Demonstrator

4. Plans

- External evaluators (CAREI) will engage in a formal study to assess the impact of the project. With that input as well as with what is learned during ongoing experiences with teachers and students, the CCEFP will continue to refine and evaluate accompanying curricular materials.
- With company support, the Center will expand its efforts to assemble and distribute kits through its industry and academic networks.
- The CCEFP will set a workshop schedule in place across all seven participating universities led, in part, by the Student Leadership Council and other student volunteers as well as outreach outfits across the CCEFP.
- PLTW will include the pneumatics workshop in its Gateway Academy, a STEM-focused summer camp program for middle school students. The Society of Manufacturing Engineers is a program co-sponsor. Implementation is scheduled for 2011.
- All 54 FIRST teams in the 2009 Minnesota Regional were surveyed in order to better understand attitudes towards pneumatics. Twenty one teams used pneumatics (39%) and 33 did not. The reasons for not using pneumatics included “Past teams used electric—so that’s what we did,” “Not familiar with pneumatics,” and “Not enough time to learn.” The reasons for using pneumatics included “Pneumo: simple, compact” and “Pneumatics is pricey but small.” In Spring 2010, FIRST

teams in the Milwaukee, Atlanta, West Lafayette and Minneapolis areas will be queried with a similar survey. Survey replies affirm the opportunities for expanding learning experiences in pneumatics and will guide further development of appropriate instructional approaches.

5. Milestones and Deliverables

- At least two K-12 workshops per semester will be organized and led by faculty/students at each of the Center's seven universities in 2011.
- The CCEFP will help industry supporters in conducting at least five workshops per year.

6. Member Company Benefits

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

Project B.4: *gidaa* STEM Programs

Project Team

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

Other Personnel: Holly Pellerin, *gidaa* Coordinator
Diana Dalbotten, National Center for Earth-surface Dynamics (NCED)
Lowana Greensky, Director of American Indian Education in St. Louis County Schools

1. Project Goals

The Center for Compact and Efficient Fluid Power, together with the National Center for Earth-surface Dynamics (NCED) and the Fond du Lac Tribal and Community College (FDLTCC), organize Native American Education Immersion Programs in the Cloquet, Minnesota region, which is also home to the Fond du Lac Indian Reservation. Camps for K-12 Native students, originally known as *gidakiimanaaniwigamig* (Our Earth Lodge, in Anishinaabe), have been held on a regular seasonal basis since 2003. Since then the "*gidaa*" program has taken on a life of its own to include other educational outreach programs that bridge several federally funded organizations.

gidakiimanaaniwigamig is committed to engaging Native American students as they work towards their high school graduation and prepare for post-secondary education in the areas of Science, Engineering, Technology and Math (STEM). CCEFP and NCED have sponsored this ongoing program through professional and financial support of seasonal camps, science fairs, and robotics day and after-school programs. *gidaa* is also committed to training teachers using strategies that help them integrate STEM into their classrooms across curricula. Progressive models such as eSTREAM, standards outlined in the Atlas of Science Literacy (AAAS), and organizations like the American Indian Science and Engineering Society (AISES) continue to educate and provide enrichment.

The relationship between the University of Minnesota (including CCEFP as well as other centers and programs in the University) and *gidaa* continues to grow and develop as new areas of study and opportunities become available. Students attending *gidaa* come from many Minnesota communities including Crookston, Carlton, Cass Lake, Cloquet, Duluth, Fond du Lac Reservation, Greenway, Leech Lake Reservation, Minneapolis, Saginaw, Tower, Walker and Wrenshall.

The projects and activities known as ***gidaa* STEM Program** include:

- *gidaa* STEM Camps (CCEFP Project B.4a)
- *gidaa* odaangiina anaangoog (Shooting for the Stars) Robotics Program (CCEFP Project B.4b)
- giiwed'anang North Star Alliance (CCEFP Project C.5)
- TRIBES-E Teacher Enrichment Program (CCEFP Affiliated Project with NCED)
- Robotics Undergraduate and Pre-Engineering Curriculum (FDLTCC and MN NASA Space Grant Consortium)
- Annual local, regional and national science fairs (NCED, CCEFP, *gidaa*)
- *gidaa* manoomin (Wild Rice) Project (NCED, LaCore, Geology - UMN)
- Earthscapes: The Youth Science Center at the Science Museum of Minnesota (NCED)
- Science and Technology Institute Summer Camp (Inst. of Transportation Studies – UMN)

2. How Project Supports the EO Program Strategy

Essential elements of the CCEFP strategic plan include promoting diversity in science, technology, engineering, and math (STEM) fields and preparing Native American youths for STEM careers. The EO program also seeks out strong partners with whom to work in assuring success. All of the initiatives under the *gidaa* "umbrella" represent implementations of these strategies.

3. Achievements

The *gidaa* STEM program is the "umbrella" of Native American educational/outreach activities in northern Minnesota, with a network that spans several cities and counties in the region. It is a well established program, with a solid core group of teachers, curricula aligned with national standards, and regular visits by research scientists from the University of Minnesota and other institutions all in place. The most critical challenges moving forward include: 1) establishing programs at the undergraduate level at the University of Minnesota and FDLTCC and surrounding regions that will meet the needs of Native American students as they graduate from high-school and transition into the next phases of their education, 2) maintaining and extending the partnerships with other institutions that enrich the program, 3) continuing to incorporate national and state standards in new curricula. These challenges will be met by utilizing the *gidaa* Circle of Learning which promotes good communication between all partners and participants in the program, mediating between the (at times) contradictory goals and visions of stakeholders and helping them instead to seek out the shared goals that will drive the program's strategic plan.

gidaa continues to expand with new programs and cultivate the partnerships that have allowed the project to establish a complete pipeline from kindergarten to college and beyond. Its network of teachers, leaders, staff and students continues to grow, too.

- *gidaa* is in its second year of the odaangiina anaangoog (Shooting for the Stars) Robotics Program. The *gidaa* feeder schools such as Albrook School and the Ojibwe School currently host the robotics activities. This program includes day and after-school robotics courses, CCEFP Project B.4a.
- In 2009, *gidaa* was awarded an NSF Opportunities for Expanding Diversity in the Geosciences grant titled "The manoomin (wild rice) project" which provides $1.5M over 5 years. This funding will support the *gidaa* program as well as an associated research project that involves evaluating the past, present and future effects of the environment on the wild rice lakes on the Fond du Lac Tribal Reservation in Cloquet, MN.
- A former *gidaa* participant received a special invitation in the Fall of 2010 to visit the President of the United States. She and other bright young scientists from across the nation gathered in Washington D.C. to share their science, engineering, or mathematics research with President Obama during the White House Science Fair. The student was recommended to attend the fair and present her research to the President by the American Indian Science and Engineering Society (AISES). Through CCEFP and NCED sponsorship, she had attended the AISES national science fair over the past four years and each year was one of the top Grand Awards winners at the event.
- The CCEFP supports these initiatives, working most directly with *gidaa* STEM Camps, *gidaa* Robotics Program, and the giiwed'anang North Star Alliance.

4. Plans

Through cooperative efforts between the Fond du Lac Tribal and Community College (FDLTCC), the University of Minnesota's College of Science and Engineering, the National Center for Earth-surface Dynamics (NCED) and the Center for Compact and Efficient Fluid Power, plans are in place to continue to support these efforts. The leadership of the *gidaa* program will continue to apply for funding in order to duplicate *gidaa* in geographic locations where there is a critical mass of Native American communities. The manoomin Project is a good example of the type of funding *gidaa* is seeking. Whenever possible, the two (or more) *gidaa* programs can bridge events and activities to create a stronger network of Native American students learning about STEM. Program Directors will continue to submit for support for a second *gidaa* site in the Bemidji, MN area. Currently, all evaluation and assessment is carried out by the National Center for Earth-surface Dynamics.

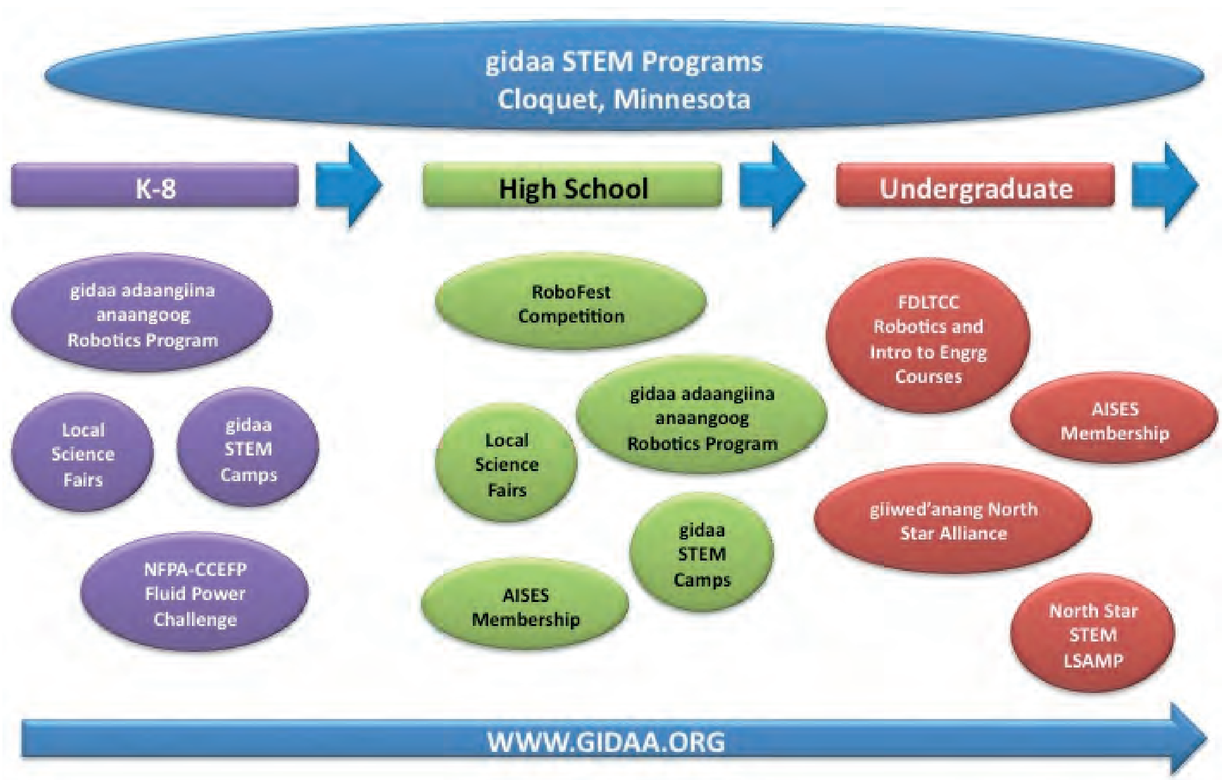
5. Milestones and Deliverables

- 200 students per year participating in program camps and related programs.
- Greater interest among these students in science, technology, engineering and mathematics.

- A majority of *gidaa* participants choosing to attend college, with a significant number majoring in science, math, engineering or technology.

6. Member Company Benefits

Several students from the *gidaa* program have begun taking classes at the FDLTCC as part of the Minnesota Post-secondary Education Option, which allows students to take college courses without charge while still in high school. These students will begin transferring to 4-year programs. We also have introduced the CCEFP to students who are current undergraduates at FDLTCC. These students will be encouraged to job-shadow at local corporations as part of the North Star STEM LSAMP Alliance. We expect this program will help in matching students with the Center's member companies for internships as they begin transferring into 4-year programs.



Project B.4a: gidaa STEM Camp

Project Team

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

Other Personnel: Holly Pellerin, Camp Coordinator
Diana Dalbotten, National Center for Earth-surface Dynamics
Lowana Greensky, Director of American Indian Education in St. Louis County Schools

1. Statement of Project Goals

The Center for Compact and Efficient Fluid Power, together with the National Center for Earth-surface Dynamics (NCED) and the Fond du Lac Tribal and Community College (FDLTCC), organizes camps known as *gidakiimanaaniwigamig* (Our Earth Lodge, in Anishinaabe), for students in grades 3 through 10. Offered monthly throughout the year, these camps provide students with a mix of lab and field science experiences selected to coincide with current science education standards as well as culturally relevant study. Program elements include both an introduction to the scientific method and a focus on Native American culture. This program illustrates the CCEFP's commitment to increasing the diversity of students and practitioners in STEM-related fields.

2. How Project Supports the EO Program Strategy

Essential to the CCEFP's strategic plan is its work with strong partners in order to assure program success. As partners, NCED and FDLTCC are key in helping to organize and deliver program content.

3. Achievements

- General
  - To date, more than 400 students have participated in gidaa. Over 50% of these participants have attended more than one camp.
  - 10 out of 12 gidaa high school graduates are attending college and 5 other high school students are attending Fond du Lac Tribal Community College where they are enrolled in PSEO courses.
  - The gidaa STEM programs continuously update its website: **www.gidaa.org**.

- 2010
  - In 2010, eight weekend camps and 2 week-long camps including a week at the University of Minnesota and a extended trip to Montana for an experience at the Salish Kootenai Tribal College. A fluid power activity is demonstrated in each camp, tied to the camp's theme.
  - In 2010, the CCEFP supported two high school students to attend the NAISEF Science Fair in Albuquerque, NM.

- 2009
  - In 2009, ten camps and/or associated activities have been held in connection with gidaa. In addition to seven gidaa camps, associated activities include the National American Indian Science and Engineering Fair in March 2009, FIRST Robotics Competition in April 2009 and Valleyfair Physics Fun Day in July 2009.
  - In the fall of 2009, following the manoomin Project (NSF Opportunities for Enhancing Diversity in the Geosciences) award, gidaa initiated monthly weekend camps that begin with a community Friday Forum. (Note: The manoomin project provides partial funding and partial programming for gidaa programs like this one.The grant also funds evaluations of the past, present and future effects of the environment on the wild rice lakes on the Fond du Lac Tribal Reservation in Cloquet, MN. High school and

undergraduate students are involved in these research efforts.) See the new manoomin website: **www.gidaamanoomin.ning.com**

- Two high school gidaa students presented their science fair posters at the AISES National Conference in Portland, Oregon, October 2009. One student received the Best Poster Award for a high school student.
- In 2009, 27 students presented posters or science fair projects at the NAISEF Science Fair in Minneapolis, Minnesota. Students brought home over 30 medals and awards, including a NASA award, two Women in Science and Engineering awards and two Grand Awards.

Fall 2010 gidaa STEM Camp

Winter 2010 gidaa STEM Camp

Other Relevant Work

- Partners in the gidakiimanaaniwigamig program are working in conjunction with the University of Minnesota-led North Star Louis Stokes Alliance for Minority Participation to create a Minnesota state alliance of American Indian Science and Engineering Society student chapters (CCEFP Project C.5 giiwed'anang North Star Alliance). The North Star STEM LSAMP Alliance is an NSF-funded alliance of Minnesota colleges and universities, promoting diversity in STEM fields.
- The gidaa STEM Programs also include the gidaa Robotics Program (CCEFP Project B.4b). The coordinators of the gidaa STEM Programs are key facilitators in promoting the high school and undergraduate level robotics as well as introduction to engineering courses at Albrook School in Saginaw, Minnesota, and the Fond du Lac Tribal and Community College in Cloquet, Minnesota.
- CCEFP and NCED sponsored the the Minnesota-based TRIBES-E (Teaching Relevant-Inquiry-Based Environmental Science and Engineering) Teacher Enrichment Program, headquartered in the Bemidji, Minnesota area. See CCEFP Affiliated Projects.

4. Plans

- Continue to engage Native American students in gidaa camps and related programs, encourage their graduation from high school and support their interests in post high school studies, including those in STEM related fields. Plans are in place to continue support of these efforts through the ongoing cooperation of the Fond du Lac Tribal and Community College (FDLTCC), the University of Minnesota's Institute of Technology, the National Center for Earth-surface Dynamics (NCED) and the Center for Compact and Efficient Fluid Power. But there are challenges. (For example, NCED is in year 8 of its NSF funding.) However, as noted above, with new funding from an OEDG grant (the manoomin project), support will be available for the next five years
- The program coordinators have determined that the gidaa STEM program participants enjoy the weekend-stay camps. Consequently in upcoming years there will be a combination of both day-camps and weekend-stay camps. gidaa will have residential camps during the winter months and day camps for the remainder of the year. A year-round schedule is very important. It is crucial for the student participants to be regularly mentored by gidaa staff and teachers. It is also crucial that they are in and among their peers who have the same interests in science, technology, engineering and mathematics.
- gidaa will begin to work with teachers from the Bemidji, MN area, in collaboration with the TRIBES-E Project (Teaching Relevant-Inquiry Based Environmental Science and Engineering).

5. Milestones and Deliverables

- Increase the number of K12 Native American students in gidaa programs.
- Participants return year after year.
- Participants graduate high school and enter college.
- Additional funding sources to support growing program.

6. Member Company Benefits

This program is closely aligned with industry's hope for and support of efforts that prepare for a talented and diverse pool of leaders in academia and in our future workforce.

Project B.4b: gidaa odaangiina anaangoog (Shooting for the Stars) Robotics Program

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director, CCEFP
Other Personnel:	Cameron Lindner, gidaa odaangiina anaangoog Robotics Program teacher
	TJ Ray, gidaa odaangiina anaangoog Robotics Program teacher
	Richard Rhoades, gidaa odaangiina anaangoog Robotics Program teacher
	Lowana Greensky, St. Louis County American Indian Ed Program Director
	Holly Pellerin, gidaa Coordinator

1. Project Goals

The goal of the gidaa odaangiina anaangoog Robotics Program is to to interest and prepare Native American youths for STEM careers. This effort is closely aligned with the Center's goal of developing research inspired, industry relevant education for students of all ages. As the successful FIRST Robotics program attests, robotics is an effective channel for introducing children to basic principles of engineering and related disciplines. Under the gidaa STEM Program umbrella, staff and teachers have drawn on lessons learned through FIRST and introduced K-12 robotics day and after-school curricula using Lego Wedo-Webots, NXT Kits, Vex Kits and Textrix kits and software.

2. How Project Supports the EO Program Strategy

An essential part of the CCEFP strategic plan is to promote diversity in science, technology, engineering, and math (STEM) fields. The Shooting for the Stars Robotics Program enables Native American students in and around Cloquet, Minnesota to use concrete learning experiences with robotics to better understand physics concepts; develop mathematical thinking, problem solving, and programming skills; and participate in team-building through hands-on construction engineering. Ideally, graduates of gidaa and the gidaa odaangiina anaangoog Robotics Program will continue their education either at a community college or a four-year university, joining the giiwed'anang North Star Alliance (Project C.5) there as active undergraduate members. This program currently engages students at the elementary, middle and high school levels. A college-level robotics course at Fond du Lac Tribal and Community College is in its third year.

3. Accomplishments

- 2010
  - Teachers at the Albrook School in Saginaw, MN, are leading the effort to implement the robotics activity both in the day-time and after-school programs. Following a start-up year, the following activities continue:
    - Fall Semester in school course: 30 students working on robotics, setting the stage and gaining interest in particpating in the 2nd Annual Robofest Competition (to be held March 2011).
    - Spring semester in school program: 30 students working on engineering. Examples of projects: 2 litter water rockets, and fluid power mouse trap racers.
    - The Albrook School is in transition as it is less than one year away from its new building where a lab area has been reserved for an engineering / robotics classroom with sufficient space for computers, equipment and storage just for this purpose and program.
    - Afterschool: 20+ students participate in learning about robotics in preparation for the Robofest Competition, March 2011. Students will receive a robotic challenge in which they compete against other robots in a local competition with other teams across Northern Minnesota. This will be the second year of Robofest. Both the Albrook School, gidaa, and the CCEFP sponsor this event.
    - Albrook is the model for a successful robotics program. The Center will continue to support these activities in all interested schools in this district.

        - Through robotics, gidaa has expanded its recruitment of more technology teachers from the area, some of whom have become experts in the robotics curriculum. gidaa program students are graduating. Through robotics, gidaa is reaching out to students who would not otherwise have had exposure to robotics and the larger lessons it teaches. The enrollment demonstrates the interest.
    - Some robotic activity exists at the Ojibwe School on the Fond du Lac Indian Reservation near Cloquet and Saginaw, MN school district, however, changes in personnel has limited the impact and resources in this current year. A new teacher, interested in robotics has recently been hired. The same is true for the Cloquet Middle and High School.
    - Albrook School will host the RoboFest Competition for up to 6 other local school districts. Undergraduate students of the Robotics course at Fond du Lac Tribal and Community College will serve as judges.
- 2009
    - Following the 2009 FIRST Robotics season, gidaa program directors determined that FIRST was not the appropriate medium to introduce robotics to the community. Instead, they decided to leverage available resources to build a sustainable day and after-school robotics curriculum in the region, including competition in the Lawrence Technological University's Robofest (www.robofest.net).

RoboFest participants

    - The Albrook School (gidaa K12 partner) is the only Minnesota site host of Robofest (March 2010). gidaa plans to pioneer the Robofest program in Minnesota. This locally-hosted competition will allow greater number of students to participate.
    - The CCEFP helped to support over 100 students in grades 3 - 12 in various robotics day and after school programs at the Albrook School, Ojibwe School and Cloquet Middle and High Schools including a college-level Robotics course at Fond du Lac Tribal and Community College.
    - FIRST Robotics Competition -- 2009: 27th place.
- 2008:
    - The Center supported the first Minnesota Native American FIRST Robotics Team *anishinaageb ogichidaag*, Team Number 2510. This team has received two $10,000 grants from the University of Minnesota Foundation to join the competition.

- FIRST Robotics Competition -- 2008: 14th place.
- In 2008 and 2009, two teachers attended the Carnegie Mellon Robo Academy.
- In 2008, another teacher attended Art & Code conference.

4. Plans
The CCEFP will continue to foster the growth of the academic and educational programs that have been initiated through gidaa. While most of the curriculum development and implementation will happen at the local level, the Center plays a key role in providing the subject matter expertise, resources and encouragement needed to help these students succeed in school and in STEM.

- The program will recruit new and interested teachers in teaching robotics activities in the Cloquet and Saginaw and Fond du Lac Indian Reservation geographic area.
- gidaa will affect change in STEM curriculum across the local school districts. For example, in the fall of 2010, the first Robotics Course was offered as an elective at the Albrook School, grades 9-12. Albrook School will serve as an engineering feeder school to a pre-engineering program at Fond du Lac Tribal Community College.
- As teachers learn, the Ojibwe school will expand its STEM-relevant curriculum and course development. Although there will be limitations, teachers anticipate the participation will increase in day class enrollment, which will, in turn, generate college level interest.

Expanding Lawrence Technological University's Robofest Competition across Minnesota. Efforts will include working with CCEFP teacher networks: RETs and teachers from the TRIBES teacher-enrichment program in Bemidji, Minnesota.

gidaa will consider loaning Robotics materials to youth in the Bemidji, Minnesota area, under the guidance of the TRIBES teachers.

Relationships with other tribal colleges will continue to grow.

Related Projects
This project is closely aligned with several of the Center's initiatives, in cooperation with the Fond du Lac Indian Reservation and the local area schools in Cloquet, Minnesota, that focus on fostering and mentoring the K-14 students of the reservation as well as in creating programs to help bridge transitions from middle school to high school to college. This all illustrates a very important recipe in making these programs successful: repetition, relationships, trust, a support structure within the community and ongoing support from dedicated partners: the Center for Compact and Efficient Fluid Power, the National Center for Earth-surface Dynamics, the North Star STEM LSAMP Alliance, the University of Minnesota and the Fond du Lac Tribal and Community College.

5. Milestones and Deliverables

- Increase number of participants and expand the robotics activity to other local K12 institutions
- Continue current support and seek additional funding for the program
- Promote the RoboFest to other local K12 institutions, including those in the TRIBES-E teacher network in Bemidji, MN
- Increase the number of teachers participating in robotics activities
- Demonstrate the effectiveness by identifying students who continue in the robotics program, and who decide to pursue STEM after high school graduation.

6. Member Company Benefits
This program is closely aligned with industry's hope for and support of efforts that prepare for a talented and diverse pool of leaders in academia and in our future workforce.

Project C.1: Research Experiences for Undergraduates (REU)

Project Team

Project Leader: Prof. Will Durfee, University of Minnesota, Education Co-Director, CCEFP
Other Personnel: Alyssa A Burger, Education Outreach Director
CCEFP faculty advisors
CCEFP graduate student mentors

1. Project Goals

The REU program is aligned with several CCEFP goals: developing research inspired, industry practice directed education; facilitating knowledge transfer; integrating research findings into education; and increasing the diversity of students and practitioners in fluid power research and industry. Through its REU program, undergraduate engineering students from schools nationwide participate in cutting edge research under the mentorship of Center faculty. The program also provides professional development activities for these students.

2. How Project Supports the EO Program Strategy

REU students learn through the expertise of faculty mentors--an example of knowledge transfer. After completing their summer-long programs, REU engineering students are ofte 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

- Twenty-three REU students participated in summer 2010, the fourth year of the program: five at the University of Minnesota, three at the University of Illinois, seven at Purdue, two at MSOE, one at North Carolina A&T, three at Georgia Tech and two at Vanderbilt University. None of these REU students had previous CCEFP REU experience. Twelve of the 23 were recruited from outside the CCEFP's core institutions, while several REU students from CCEFP schools participated in the research projects of other universities within the Center network.
- The CCEFP held its Annual Meeting in June 2010 at Purdue University in West Lafeyette, IN and all REU students attended. Events included an REU orientation that enabled the REUs across the seven Center institutions to meet each other. This was the first time the Center was able to bring all REU students together in person. At the end of the summer, 11 REU students attended the CCEFP Student Retreat, held at the University of Minnesota. At the retreat, REUs presented their summer research projects to faculty and graduate students and went on tours of two CCEFP industry members, MTS and Eaton Corporation, both in Eden Prairie, MN. Additional poster presentations were made on REUs' respective campuses.

The 2010 CCEFP REU Participants at CCEFP Annual Meeting at Purdue University, June 2010.

- The Center submitted an NSF REU Site Proposal, Fall 2010. If funded, the Center will host 20 REU students in summer 2011 in a program that includes an in-depth orientation to fluid power, led by faculty at the Milwaukee School of Engineering (MSOE). REUs will present summaries of their research projects at the National Fluid Power Association's (NFPA) Economic Outlook Conference, a 1-1/2 day industry meeting focused on economics, market forecasts, and supply chain management, that will also feature a poster session led by the Center's graduate, undergraduate and REU students. The 2011 CCEFP Student Retreat will be held in conjunction with this meeting.
- In 2010, CAREI evaluated the REU program. Results of the program evaluation are in the CAREI project report. CAREI also evaluated the 2008 and 2009 REU program.
- In 2010, CCEFP staff surveyed REU advisors for reactions and recommendations for the REU program. In 2009, CAREI conducted a survey among REU advisors.
- The Center expanded its recruiting database from over 500 schools to 750 schools with multiple contacts at each school, paying particular attention to minority-serving institutions and recent war veterans.
- A former CCEFP 2008 REU student from UIUC was hired at an industrial member company due to his connections to the CCEFP and his REU project.
- Twenty-four REU students participated in summer 2009, the third year of the CCEFP REU program: five at the University of Minnesota, three at the University of Illinois, six at Purdue, two at MSOE, three at North Carolina A&T, two at Georgia Tech and three at Vanderbilt University. One REU student returned from a previous CCEFP REU experience; the others had no prior CCEFP experience. Only eight of the twenty-four were recruited from within the CCEFP's core institutions.

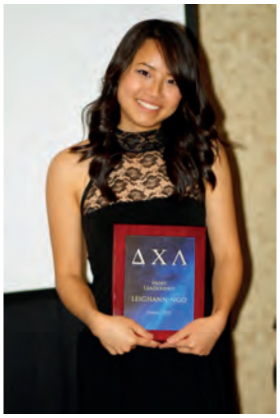
2010 Research Experiences for Undergraduates

Number of Students	23
Males	16
Female	7
Percentage of students from underrepresented groups 1) racial minority 2) gender minority 3) disability	1) 31% 2) 31% 3) 1%

2010 REU Participants

Mr. Kane Smith, Ms. Leighann Ngo and Mr. Xavier Harville will be guests of the CCEFP at the Year 5 CCEFP-NSF Site Visit in Las Vegas, March 2011.

	**Kane Smith**, University of Cincinnati **REU Site**: University of Minnesota **Project**: FES Hybrid Energy Storing Orthosis **Problem**: Is there a pneumatic system that optimizes power and weight that can be applied to human powered machines, more specifically gait restoration devices?

	**Leighann Ngo**, University of Arizona **REU Site**: Georgia Institute of Technology **Project**: Passive Noise Control: HCCI Noise Control **Problem**: Determine the noise and vibration signatures of small IC engines. The CCEFP anticipates the use of a small IC engine for power generation for compact wearable devices; the use of such engines in this application presents challenges with respect to noise and vibration. This project experimentally explored some of the issues associated with silencing and vibration isolating such engines. characteristics.
	**Xavier Harville**, North Carolina State University **REU Site**: Milwaukee School of Engineering **Project**: Compatability Testing of Biodegradable Hydraulic Fluids **Problem**: To create a better understanding of fluid compatibility and the requirements for conversion of petroleum based fluid power systems to biodegradable fluids. Due to advantages in renewability and environmental acceptability, bio-sourced and biodegradable hydraulic fluids are increasingly used in fluid power applications. Conversion from mineral oil based fluids to biodegradable fluids can be expensive because hydraulic systems often must be drained and flushed several times during the conversion process. The goal of this research is to develop a test method for determining the compatibility of hydraulic fluids in order to quantify the extent of flushing required during the conversion process.
	**Loren Bryant**, North Carolina A&T State University **REU Site**: North Carolina A&T State University **Project**: Human Performance Modeling for Fluid Power Systems **Problem**: Since fluid power is an alternative approach, little research has been done on the effectiveness and impact the change a fluid powered rescue crawler will have on operator performance. This is a challenge because collecting a sufficient amount of data from a rescue operator in a catastrophic disaster is impractical also because the complexity and dynamicity predicting operator performance in a specific environment is hard. The discrete simulation tool allows researchers to predict how well the operator will perform using the fluid powered rescue crawler in a specified environment. Questions to be answered: How will haptic control affect operator performance? How will expertise affect operator performance?

4. Plans

- If the Center's recent NSF REU Site Proposal is funded, the Center plans to host 20 REU students in a program that includes an in-depth orientation to fluid power, led by faculty at the Milwaukee School of Engineering (MSOE). Further, REUs will present summaries of their research projects at the National Fluid Power Association's (NFPA) Economic Outlook Conference, a 1-1/2 day industry meeting focused on economics, market forecasts, and supply chain management, that will also feature a poster session led by the Center's graduate, undergraduate and REU students. The 2011 CCEFP Student Retreat will be held in conjunction with this meeting.with a Fluid Power Bootcamp at the Milwaukee School of Engineering (MSOE) and will present research projects at the National Fluid Power Association's (NFPA) Economic Outlook Conference (in conjunction with the 2011 CCEFP Student Retreat) where faculty, students and industry will come together for a 3-day meeting which will host a variety of keynote speakers, breakout sessions and a poster session hosting the Center's graduate, undergraduate and REU students.

- If the CCEFP does not receive additional funding through the REU Site award, the program will remain the same; however the number of students participants will be reduced to 15.
- The Center will continue to encourage education focused research topics and will also serve to recruit and retain women, racially underrepresented students, those with disabilities and recent war veterans.
- The Center will hold an REU Advisor orientation webcast prior to the start of the program.
- The Center will continue to work with local REU programs to create a strong network of students at the local level, but will host activities on-line that foster collaboration and a sense of a greater community outside the walls of the hosting institution. Students will realize the greater network that extends into six other participating colleges as well as the nationwide scope of the overall REU program.
- Social networking sites will continue to be used personal connections among the Center's REU participants.

5. Milestones and Deliverables

- In 2011, the Center will fund two or three students at each university in its network (the number of students from outside must be greater than the number from within. Some sites will host more than three students due to leveraged funding from other sources.
- At least three webcasts will be held for REUs through the summer in order to facilitate knowledge transfer and build a sense of "community."
- The Center will increase the number of underrepresented groups in its REU pool. This will include expanding its recruiting network to include recent war veterans.
- If not funded for the 2010 submission, the Center will submit for another REU Site Proposal during the next solicitation.

6. Member Company Benefits

Member companies can participate in REU projects through the industry champions program. Here, member companies get a first look at a bright, diverse pool of students trained in fluid power who may become future intern or permanent employees. More generally, the REU program contributes to the building of an informed and motivated student group—future leaders for industry and academia.

Project C.2: Fluid Power OpenCourseWare

Project Team

Project Leader:	Prof. Will Durfee, University of Minnesota, Education Co-Director, CCEFP
Other personnel:	Prof. Paul Michaels, Milwaukee School of Engineering
	Prof. Zongxuan Sun, University of Minnesota
	Prof. Eric Barth, Vanderbilt University
	Prof. Andrea Vacca, Purdue University

1. Project Goals

The purpose of the Fluid Power OpenCourseWare (FPOCW) project is to create, digitally publish, disseminate and use high quality college level teaching materials in fluid power. The material can be used in fluid power elective courses, but more importantly can be inserted into core engineering courses taken by all students. Materials exist in the lecture notes, problem sets and lab exercises of CCEFP faculty, as well as faculty outside the center. A small number of engineering undergraduate students nationwide will take fluid power elective courses, but all students in mechanical and related engineering ABET accredited degree programs take required courses in fluid mechanics, thermodynamics, system dynamics and machine elements. These courses cover topics that form the core of fluid power yet currently do not contain fluid power applications. The FPOCW materials can also be used as training materials for BS level engineers at fluid power companies.

Opencourseware is a concept that is gaining traction (www.ocwconsortium.org), and recently popularized by MIT (ocw.mit.edu). We are doing the same for fluid power education. Education materials that are part of the FPOCW collection are under a Creative Commons intellectual property license which essentially allows unlimited use, with attribution for non-commercial purposes. This includes use at companies so long as the FPOCW education materials are not sold for profit.

2. How Project Supports the EO Program Strategy

New departments or four-year majors in fluid power are unlikely. Insertion of fluid power into standard engineering courses is not only achievable but also the most direct route towards increasing the number of engineering students trained in the basics of fluid power.

3. Achievements

- The FPOCW site was launched as the central repository for opencourseware in fluid power. http://sites.google.com/site/fluidpoweropencourseware/

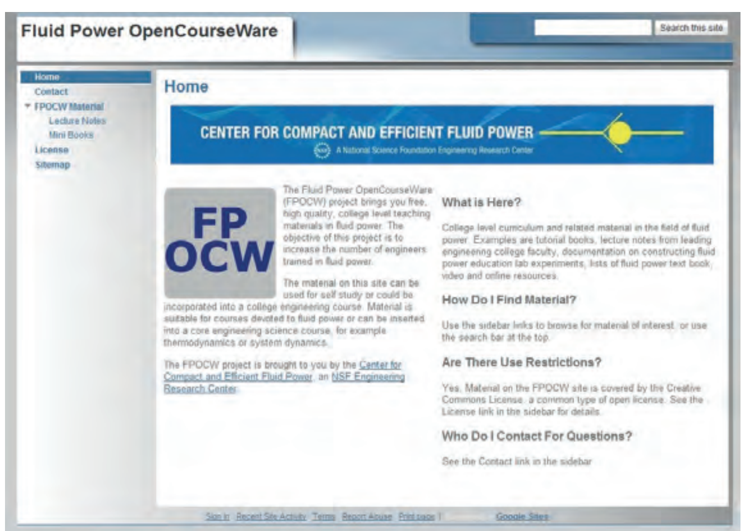


Figure 1: Opencourseware web site

- Lecture notes from three fluid power courses posted to the site. Two mini-books posted to the site.
- Fluid Power in Fluid Mechanics project under the direction of Prof. Andrea Vacca, Purdue University, launched as a sub-project. Report from this project is appended.

4. Plans
Gather additional college-level fluid power training material from CCEFP faculty and disseminate by posting to the site. Create mini-book on modeling and system dynamics of pneumatics. Complete mini-book on fluid power in fluid mechanics and mini-book on hydraulic fluids.

5. Member Company Benefits
Member companies can use the FPOCW repository for internal training, or sales forces can use to educate customers. Member companies also benefit as more engineering students receive training in fluid power.

Project C.2 Appendix: Fluid Power in Fluid Mechanics

Project Team

Project Leader:	Andrea Vacca (Assistant Professor, ABE/ME, Purdue University)
Other Personnel:	Davide Cristofori (PhD, ABE – Purdue University), Massimo Dall'Asta (MS, University of Parma, Italy), Andrew O' Bannon (CCEFP SURF student, summer 2010), Kewen Han, Purdue University

1. Project Goals

The goal of this project is to develop a model to infuse the fluid power discipline into traditional mechanical engineering curriculum through the creation of educational material specifically targeted to introduce fluid power concepts in the introductory classes on fluid mechanics. The project aims to establish an intriguing methodology to provide challenging learning to teachers and students, and it is based on the development of:

- a mini-book titled "Fluid Power in Fluid Mechanics" containing examples aimed to accompany the students in the learning of the main features of hydraulic systems during their completion of the required fluid mechanics introductory class. The examples support the description of basic physical laws of fluid mechanics allowing the comprehension of basic fluid power concepts at the same time.
- demonstration high pressure water hydraulic test rig and the accompanying documentation suitable to present both basic and advanced concepts of fluid mechanics, measurement systems and fluid power.

The two products will widen the educational sources developed or currently under development by the CCEFP, avoiding any overlap of contents.

2. How Project Supports the EO Program Strategy

The project supports the CCEFP education strategic plan, in particular the mission "to develop research inspired, industry practice, directed education for pre-college, university and practitioner student; to integrate research findings into education; to educate the general public; and through active recruiting and retention, to increase the diversity of student and practitioners in the fluid power research and industry". The project specifically addresses college education, providing a model to expand the fluid power discipline to larger undergraduate and graduate engineering student audiences.

3. Achievements

The project started in August 2010, immediately after a preliminary study performed by an REU student supervised by Project Leader. The REU (Andrew O'Bannon) focused his work on the design of a water hydraulic demonstrator, developing a preliminary and simplified version of the test rig that will be realized. O'Bannon's project was awarded as "Best Research Talk" among the 200 undergraduate summer research projects presented at Purdue University.

The project activities have been focused on both goals: the water hydraulic test rig and the mini-book. The accomplishments pertinent to the period August 2010 – December 2010 can be summarized as follows:

a. Mini Book

Different examples have been identified under the idea of developing a mini-book suitable to describe basic concepts of both fluid power and fluid mechanics disciplines. Differently from existing fluid power textbooks, the purpose of the examples reported in the mini-book is to describe the fluid power applications of the fundamental laws of the fluid mechanics. In the mini-book, each physical law is explained in the context of the fluid power problem presented. In this way, through a number of different examples, the student will become familiar with fluid power and will potentially become more attracted to this engineering topic in future choices of elective classes and research projects. The examples and associated fluid power concepts illustrated in the following table.

Fluid Mechanics laws examples	**Fluid Power concepts described**
• bulk compressibility modulus for liquids • shear stress equation • vapor and gas cavitation • conservation of mass • first law of thermodynamics • momentum equation • Bernoulli equation • dimensional analysis • laminar and turbulent flow • flow in pipes and ducts • calculation of friction losses • flow measurement • hydraulic power • machines to extracting/doing work (power) from/on a fluid • calculation of the operating point in fluid systems • positive displacement machines	• symbology of fluid power systems; • components used in fluid power systems (pumps, motors, valves, cylinders, ducts, accumulators): typologies, main features and basic modeling equations; • open loop and closed loop circuits; • basic elements of hydrostatic drives.

A preliminary section will introduce the fluid power discipline, limiting to the concepts necessary for understanding the examples.

b. Water Hydraulics Test Rig

A high pressure water hydraulic system with the necessary instrumentation has been designed with the aim of integrating class activities related to fluid power with experiments and hands-on experiences. The set of experiences permitted by the apparatus are specifically conceived for the introduction of fluid power concepts to students taking introductory fluid mechanics classes. However, more advanced experiences are also permitted.

Although the system can be replicated with standard mineral oil as the pressure medium, tap water was selected for following reasons:

- Water is clean, environmental friendly, non-toxic and does not introduce fire and explosion risks. These features are a plus for a hydraulic system conceived for the use in educational laboratories.
- Water hydraulics is an emerging technology in fluid power. Elements designed for the operation with water at high pressure have to face problems such as corrosion, flow erosion, difficult lubrication of internal parts, high leakages and further sources of contamination (bacteria and fungi contamination) not common for standard hydraulic components. The description of these challenges during the presentation of the various experiments with the accompanying fluid power

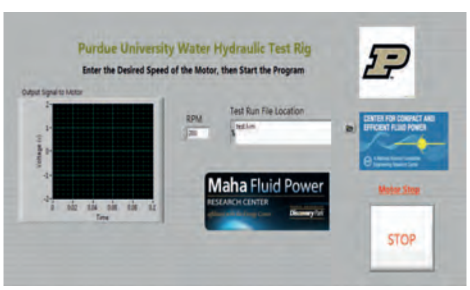
principles can better stimulate the attention of the students and captivate their interest for future activities related to fluid power

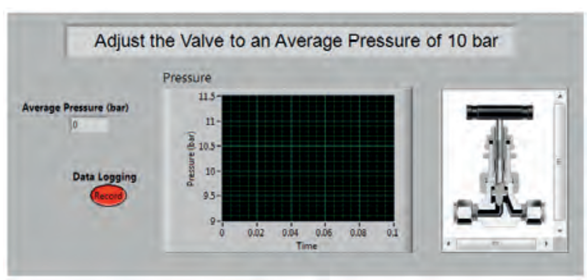
- Water hydraulic components from past research project at Purdue are available for this project. Components for water hydraulics are expensive and this will lower the cost of the project.

The system layout has been conceived with a modular structure to permit tests at different levels according to the following table.

Configuration	**Experiments**
basic	• basic measurements of fluid pressure, temperature, flow rate and power • pump steady state characteristics • pressure relief valve steady state characteristics • restrictor characteristics
advanced	• characterization of a fan drive system: verification of motor steady state characteristics (a), regulation of the fan speed with different methodologies (b) • energy accumulation and measurement of the accumulator charge/discharge processes • effect of the accumulator on flow pulsations

A prototype test rig has been implemented and tested in the basic configuration at Maha Fluid Power Research Center of Purdue University. A LabView application was developed to guide the execution of the experiments allowed by the test rig during Lab experiences (see screenshots below). A simulation model of the system, utilizing the multi domain AMESim® simulation platform was realized. The simulation model permitted tthe final design of the advanced configuration that is now being implemented. Moreover, simulation results in both basic and advanced configurations will be used to complete the accompanying documentation reporting the description of all tests that can be performed with the developed test rig.





The Fluid Power in Fluid Mechanics project was approved by the School of Mechanical Engineering in 2010 for its introduction in ME309 (Fluid Mechanics) in Fall 2011. The average annual enrollment of

ME309 is about 400 students. This will reach the learning objective of incorporating elements of fluid power in the mechanical engineering curriculum at Purdue. The Project Leader will teach the Fluid Mechanics class (ME309). For this reason, particular attention was paid during the design process to the safety requirements necessary for the installation of the test rig in the lab. Moreover, aesthetic of the apparatus was taken as important requirement to realize a structure captivating for the ME Fluid Mechanics Lab general visitors.

4. Plans

The near term goal for the project is to complete the realization of the described educational material (mini-book and water hydraulic test rig) to permit its first use in ME309 class of Purdue University in Fall 2011. The assessment of the students and the instructors' feedback will serve as the first evaluation of the project. On the basis of this result, the material will be refined for its successive utilization. A significant increment of the number of students requesting credits in Fluid Power activities (for design projects as well as for elective fluid power classes) is expected as mid-term goal.

Despite the expected high utilization of the equipment (ME309 is offered in both fall and spring semesters) the mid-term goal is the use of the apparatus for experiences in specific fluid power courses offered in ME and ABE programs, such as ME597/ABE591 Design and Modeling of Fluid Power Systems, about 10 students/year, graduate class and ABE435 Hydraulic Control Systems, about 30 students/year.

As long term goal, the project aims to be become a model adopted by other universities for introducing elements of fluid power in standard mechanical engineering curriculum through introductory courses in fluid mechanics. This will be achieved by disseminating the project details and results within the CCEFP participating universities and through the presentation of the education model at fluid power conferences. The mini-book will be published on the Fluid Power OpenCourseWare site.

5. Member Company Benefits

The Fluid Power in Fluid Mechanics mini-book will be available to member companies. Its content can be used for internal training or to educate costumers. Another benefit is that companies will see increased numbers of engineering students educated in fluid power.

Project C.3: Fluid Power Projects in Capstone Design Courses

Project Team

Project Leader: Prof. Will Durfee, University of Minnesota, Education Co-Director, CCEFP
Other personnel: All CCEFP faculty
Industry partners: NFPA member companies sponsoring projects

1. Project Goals

The objective of this project is to work with fluid power companies to sponsor and actively engage with students in capstone design projects with fluid power content. This is a collaborative project with the National Fluid Power Association (NFPA).

2. How Project Supports the EO Program Strategy

Engagement in these projects provides undergraduate engineering design students with a hands-on experience in fluid power design and development, reinforcing communications with CCEFP and NFPA member companies. These cooperative efforts are directly in line with the CCEFP's goal of fostering knowledge transfer between industry and universities.

3. Achievements

With the assistance of CCEFP, NFPA took substantial steps to promote capstone design projects to its member companies http://www.nfpa.com/education/capstone_design_project.asp . NFPA board members committed to each sponsoring a capstone project. Board member companies were matched to nearby ABET engineering programs. A process was developed where CCEFP faculty would facilitate matching NFPA companies with an interest in sponsoring a project to the appropriate engineering program. Results from this NFPA + CCEFP effort should be apparent in the coming year.

A compilation of recent fluid power capstone projects at Center schools is shown in Figure 1.

University	Year	Sponsor	Project Title
MSOE	Spring 2010	CCEFP	An Investigation of the Tribological Conditions and Lubrication Mechanisms Within a Hydraulic Geroler Motor
MSOE	Spring 2010	CCEFP	Fluid Power Actuator for use in Active Ankle Foot Orthotics
PU	Spring 2010	CCEFP	Skid Loader Boom Extension
UMN	Fall 2010	Tennant	Tile Marking Mechanism
UMN	Spring 2011	Eaton	Hydromechanical transmission
UMN	Spring 2011	Science Museum of Minnesota	Fluid Power Ankle Orthosis Exhibit
GT	Spring 2011	CCEFP	An Educational Simulation Tool for Hydraulic Systems

Figure 1: Recent fluid power capstone projects

4. Plans

New fluid power capstone design projects every year. Continue to work with NFPA on the process of connecting CCEFP member companies to their local college or university to sponsor a capstone design project.

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.

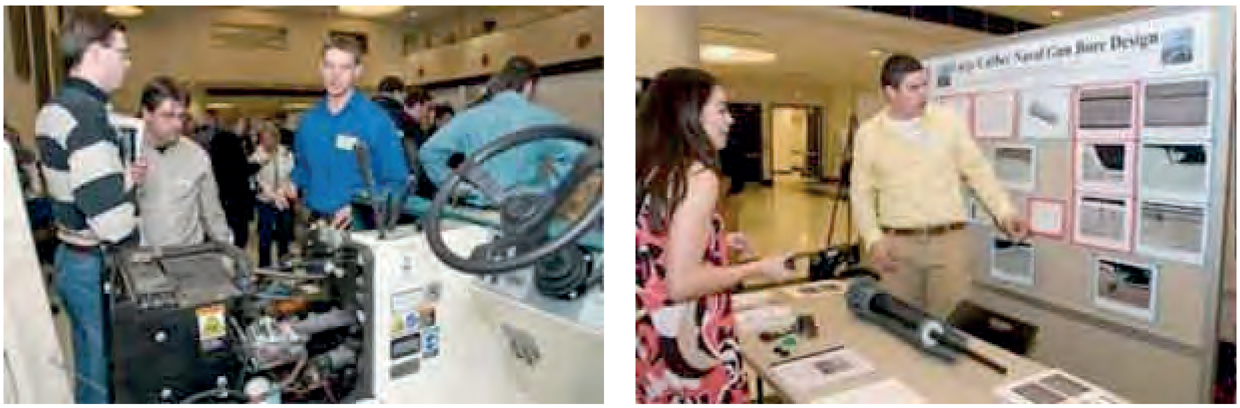


Figure 2: Students presenting their fluid power capstone project results

Project C.4: Fluid Power Courses

Project Team

Project Leader: 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

- 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.
- ME8287 Passivity & Control of Interactive Mechanical and Fluid Power Systems is a new graduate course at UMN, created and taught by Professor Li. First offering Spring, 2011.
- Design and Control of Automotive Powertrains, graduate course at UMN created and taught by Professor Sun. Significant content on hydromechanical systems and modeling and control of hydraulic hybrid vehicles CCEFP.
- Several courses at NCAT modified to include CCEFP research: INEN 371 Human Factors Engineering, INEN 665 Human Machine Systems, INEN 735 Human-Computer Interface.
- ME 597 /ABE 591 Design and Modeling of Fluid Power Systems and ME 697/ABE 691 Hydraulic Power Trains and Hybrid Systems, graduate courses at Purdue, taught by Professor Ivantysynova, have substantial content from CCEFP research.
- ME 4232 Fluid Power Control Laboratory at UMN, taught by Professors Li and Stelson, includes CCEFP research and guest lectures by engineers from CCEFP member companies.
- ME 3015 System Dynamics and Control at GT ME, taught by Professor Ueda, used a pneumatic pressure control system as a class project.
- ME 4803 / ISyE4803 Model-Based Systems Engineering at GT, taught by Professor Paredis, includes modeling of fluid power components and systems.
- ME234 System Dynamics at VU, taught by Professor Webster, includes CCEFP research results and guest lectures by CCEFP graduate student researchers.
- ME309 Fluid Mechanics at PU, taught by Professor Vacca, in Fall 2011 will include fluid power content based on the mini-book under development by Vacca (see project C.2)

4. Plans

Continue to encourage the incorporation of fluid power content into existing courses and to develop new lecture and lab courses in fluid power. The Fluid Power OpenCourseWare project (Project C.2) makes it easier for instructors to include college-level fluid power material in their courses.

5. Member Company Benefits

Graduate and undergraduate students who are learning fluid power through their courses. These educated students become the new employees of the companies.

Project C.5: giiwed'anang North Star Alliance

Project Team

Project Leader: Alyssa A. Burger, Education Outreach Director

Other Personnel: Diana Dalbotten, National Center for Earth-surface Dynamics
Anne Hornickle, North Star STEM LSAMP

Participating Colleges / Universities / Community or Tribal Colleges:

Minnesota Institutions:
University of Minnesota
University of Minnesota-Duluth
University of Minnesota-Morris
Fond du Lac Tribal and Community College
Saint Cloud State University
Leech Lake Tribal College
Bemidji State University
Minneapolis Community Technical College
Century College

Outside Minnesota:
Lac Courte Oreilles Ojibwe Community College (WI)
Salith Kootinah Tribal College (MO)
University of North Dakota (ND)

1. Project Goals

The American Indians in Science and Engineering Society (AISES) and The Advancement of Chicano/Latino and Native Americans in Science (SACNAS) are national organizations with a shared goal: to increase the number of Native American college students in STEM fields. In conjunction with the UMN National Center for Earth Dynamics (NCED), the UMN Institute of Technology Office of Diversity and Outreach, and the North Star (LSAMP) STEM Alliance, the CCEFP is coordinating, sponsoring and hosting all activities of the giiwed'anang North Star Alliance. Goals of the Alliance include: 1) engaging students in STEM-related activities, 2) encouraging students to pursue their education in STEM-related fields at two-year and/or four-year schools and universities, 3) developing a Minnesota student cohort network, 4) increasing the number of AISES and SACNAS chapters.

This alliance aims to form a partnership between the AISES and newly formed SACNAS chapters in Minnesota and to provide tools and resources to assist the students that participate in Minnesota's student chapters. The goals of the giiwed'anang North Star Alliance include forming relationships between Minnesota AISES and SACNAS chapters; providing educational opportunities, academic guidance and opening research doors to Native American students; and bridging the gap between high school, pre- and post-secondary education and industry in STEM fields. By networking with Minnesota corporations and educational institutions, this alliance fosters both fund-raising capabilities and professional support which should lead to an increase in the number of professional student chapters in Minnesota. In turn, the increased number and activities of these chapters should should encourage a larger representation of American Indians in STEM fields and disciplines.

Figure 1: giiwed'anang North Star AISES Alliance Logo

2. How Project Supports the EO Program Strategy
This program is designed to build interest in and prepare under-represented students for STEM careers, a key goal of the CCEFP's Education and Outreach program. Our work with strong and committed partners in reaching this goal illustrates a basic E&O strategy.

3. Achievements

- **2010**
  - The Alliance has helped to initiate an AISES Chapter with St. Cloud State University (SCSU).
  - The Alliance received funding from the Minnesota NASA Space Grant to sponsor a UMN Rocket Competition Team to participate in the All-Nations Launch, a rocket competition for students in AISES.
  - The Alliance has extended its partnerships to actively include the University of Minnesota - Morris who has a very strong AISES Chapter.
  - The Alliance has visited and attended AISES Meetings of over 6 partner institutions in the Fall of 2010.
  - The Alliance hosted a Native Skywatchers event and dinner at SCSU in November 2010, with 18 faculty and students in attendance (Figure 2).

Figure 2: Native Skywatchers Presentation hosted by giiwed'anang Alliance

  - The Alliance co-sponsored a dinner at the AISES National Meeting in Albuquerque, NM, November 2010 for over 40 students associated with the Alliance. Other sponsors include the Northstar STEM (LSAMP) Alliance and the US Nuclear Regulatory Commission, as a former Alliance student now is an employee with USNRC and was serving as an exhibitor at the conference.
  - The Alliance helped to launch the revitalization of the AISES Professional Chapter in the state of Minnesota, which now has over 30 professional members who will serve as mentors to students in the giiwed'anang Alliance.
  - The Alliance supported 9 undergraduate students to attend the Regional AISES Meeting in Fargo, North Dakota, March 2010.
  - The Alliance is determining the most effect social networking tool, leveraging Facebook or a Blog type of internet based tool.
- **2009**
  - The Alliance continues to work with St. Cloud State University and Leech Lake Tribal College on initiating AISES student chapters at those schools.
  - The Alliance has grown from eight participants at the first retreat to nearly 45 students across Minnesota as well as in North Dakota and Wisconsin. (While this project is still focused in Minnesota, some of our students have subsequently transferred to schools outstate. We continue to promote their academic careers and invite them to participate in the program.)

- In the third year of this program, the CCEFP hired an Alliance undergraduate student to work on building the pneumatic kits, part of CCEFP Education Project B.3a.
- Alyssa A. Burger is now the student chapter AISES advisor at the University of Minnesota.
- The giiwed'anang Northstar Alliance is directly responsible for the re-initiation of the Professional AISES Chapter in Minnesota. The Professional Chapter has held three meetings since it's revitalization in late 2009.
- Alyssa A. Burger presented on "How to Start a State-wide Alliance" at the National AISES Conference in Portland, Oregon, in November 2009.
- Since the inception of the giiwed'anang North Star Alliance, the program has received permanent and partial funding for this program from the North Star STEM LSAMP Alliance headquartered at the University of Minnesota as one of its official undergraduate programs.
- The Alliance has held seven giiwed'anang retreats where students gather, network, share academic and career goals, set the agenda and purpose for the Alliance and work to build a greater network of undergraduate Native American students in STEM across Minnesota.
- The Alliance supported 12 undergraduate students to attend the AISES National Conference in Portland, Oregon in November 2009.
- The Alliance co-sponsored and co-hosted the Regional AISES Meeting in Minneapolis, MN in April 2009.
- The Alliance members served as judges at the National American Indian Science and Engineering Fair (NAISEF) hosted at the Science Museum of Minnesota in March of 2009.

- **2008**
  - The Alliance supported 12 giiwed'anang students to attend the AISES National Conference in Anaheim, California in November 2008.
  - The Alliance supported 13 students to attend the Regional AISES Meeting in Rapids City, South Dakota in April 2008.
  - In the first and second year of this program (2008 and 2009), June Sayers from St. Cloud State University was hired as an REU student at the National Center for Earth-surface Dynamics at the University of Minnesota. The giiwed'anang Alliance also contributed to the creation of an AISES Chapter at the Cloquet Middle School in Cloquet, Minnesota as well as St. Cloud State University in St. Cloud, Minnesota.
  - While the Alliance is still in its infancy, we continue to gain exposure and create partnerships across the state of Minnesota. We have a solid base of students in four core schools and have formed a significant network of contacts across the Native American community. However, there continues to be the challenge of establishing a "critical mass" at additional schools. To date, we have received commitments of participation from schools that have not yet participated in the giiwed'anang retreats.
  - An example of collaboration of several gidaa STEM programs is evident in a recap of a giiwed'anang North Star Alliance Retreat , held February 13 – 14, 2009 in Cloquet, Minnesota. The program participants met with representatives of faculty and staff from FDLTCC, UMN, CCEFP, North Star STEM LSAMP Alliance, NCED, and the Fond du Lac Indian Reservation. Following dinner, giiwed held a meeting that included presentations from the North Star STEM LSAMP, the local planning coordinator for the NAISEF Science Fair to be held in St. Paul, MN, a Native Professor from FDLTCC, and a planning group for the AISES Region V Meeting held at the University of Minnesota campus in April 2009. The second day of the retreat, giiwed'anang students attended the gidaa STEM Camp held at the Fond du Lac Tribal and Community College in Cloquet and served as mentors for the participants of the camp as they engaged in STEM learning alongside the students, teachers and community participants. Later in the day, the

giiwed'anang students were given a three-hour block of time to search the Internet and apply for REU positions, scholarships or internships within their field. Subsequently, two of these students were offered research experiences during this academic year and the following summer.

Other Relevant Work

This project is closely aligned with several of the Center's initiatives with the Fond du Lac Indian Reservation, a tribal and community college and the local area schools in Cloquet, Minnesota that foster and mentor the K-14 students of the reservation as well as create programs to bridge middle school to high school to college. The high school students who participate in the gidaa Robotics Program (CCEFP Education Project B.4b) will serve as mentors to the gidaa STEM Camps and the gidaa Robotics day and after-school programs as well as the Robofest teams. Ideally, our graduates of gidaa and gidaa Robotics will continue their education either at a community college or a four-year University and subsequently join the giiwed'anang North Star AISES Alliance and be active undergraduate members of this organization. As noted above, this progressive involvement is illustrative of a very important recipe in making these programs successful: repetition, relationships, trust and a support structure within the community as well as with the Center for Compact and Efficient Fluid Power, the National Center for Earth-surface Dynamics, the North Star STEM LSAMP Alliance, the University of Minnesota and the Fond du Lac Tribal and Community College.

4. Plans

- The North Star STEM LSAMP Alliance will continue to serve as the partial funding source for this program, enabling the Alliance to host three retreats per year and sponsor and/or support student travel to professional conferences, leadership meetings, or academic events.
- The Alliance will provide information for educational opportunities such as research experiences for undergraduates, industry internships, mentorships, outreach opportunities, etc.
- The Co-Directors of the Alliance will continue to be sources of support and mentorship as giiwed'anang students work towards their undergraduate degrees in STEM.
- The program is now in the stages of longitudinally tracking the students who have been supported or mentored in some way. A system is to be designed to maintain the relationships established through the Alliance and to encourage those students to continue participation at the Professional Chapter level.
- The Alliance intends on ensuring that all participating students graduate from their respective schools. In turn, this success will increase the number of students in AISES Chapters in Minnesota as well as increase the number of chapters. We expect to see an increase in transfers from 2-year to 4-year institutions and see the number of students participating in the North Star STEM LSAMP increase to include a greater number of Native American students. By creating a strong network of Native undergraduate students, the Alliance will promote Native education in Minnesota by providing a tool that enables students to complete their education and earn their undergraduate degrees. The Alliance will promote graduate school for participants' respective degrees.

5. Milestones and Deliverables

- Increase the number of participants and institutions in the North Star Alliance.
- Find additional funding for the Alliance and expand its program options.
- Expand the Alliance network at the community and industry levels.
- Increase the number of AISES Chapters in Minnesota.
- Promote the Alliance framework to other states.
- Increase the number of students participating in research experiences or internships.

6. Member Company Benefits

Several students from the giiwed'anang program have begun taking classes at the FDLTCC as part of the Minnesota Post-secondary Education Option, which allows students to take college courses without charge while still in high school. These students will begin transferring to 4-year programs. We also have introduced our Center to students who are current undergraduates at FDLTCC. These students will be encouraged to job-shadow at local corporations as part of the North Star STEM LSAMP Alliance. We expect this program will help us match students to our member companies for internships as they begin transferring into 4-year programs. This Alliance will continue to foster STEM education and in turn that will be a direct benefit to society as a whole.

Project D.1: Fluid Power Scholars/Interns Program

Project Team:

Project Leader:	Linda Western, Education Co-Director, CCEFP
Other Personnel:	Prof. Will Durfee, University of Minnesota, CCEFP Education Co-Director; Alyssa Burger, CCEFP Outreach Director
Industry partners:	Members of the CCEFP Industrial Advisory Board; Education Advisors; members of the National Fluid Power Association's Board of Directors and Education Committee; volunteers from the ranks of the Center's industry supporters.

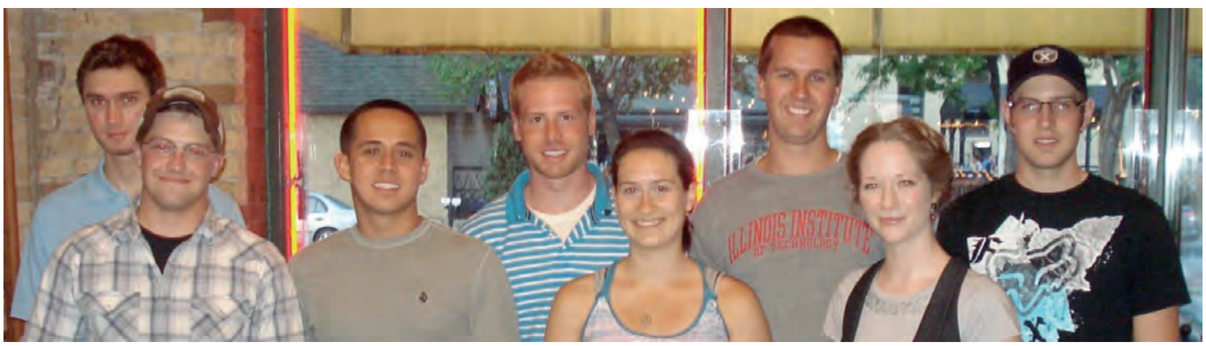
1. Project Goals
As interns, students gain hands-on experience in fluid power technology. Companies hosting interns benefit, too, as students bring fresh insights learned in the classroom. Recognizing these benefits, the CCEFP has enhanced the traditional internship model by adding an intensive orientation to fluid power at the outset of the internship experience in order to expedite knowledge transfer while enabling student interns to make more immediate and effective contributions to their host companies.

2. How Project Supports the EO Program Strategy
Cultivating cooperative efforts is key to CCEFP education and outreach program strategy. The Fluid Power Scholars/Interns Program—informed by and of benefit to both academia and industry—rests on partnerships between industry, the Center, and engineering students nationwide.

3. Achievements
Establishing an effective internship program--one that draws top engineering students to work in the fluid power industry--was a priority of the CCEFP even at its proposal stage. The appeal of the program rests on the promise of shared benefits. As interns, students learn about hydraulics and pneumatics through hands-on experiences while companies with whom they work (perhaps their future employers?) learn about them. Though the benefits to everyone were clearly apparent, developing a successful internship program through the CCEFP proved to be very difficult. For some companies, Center intervention wasn't necessary; they already had established internship programs. For others, the Center's help was welcomed, but within this group there were (still are) a myriad of differences: facility location, start times and internship duration, preferences for where interns should be in their programs (undergraduates or graduate students, students from Center schools or elsewhere), etc. With the benefit of all these lessons learned, the following steps were taken in order to create an appealing and workable plan:

- 2010 program launch and execution:
    - Beginning in October, every supporting company of the CCEFP learned about the 2010 Fluid Power Scholars/Interns program through an ambitious communications campaign led by CCEFP staff. Multiple channels—in print, e-mail, telephone, and website—were employed in this campaign. The campaign was successful. Seven companies offered to support eight scholars in the summer of 2010: Caterpillar, Deltrol Fluid Products, John Deere, Enfield Technologies, Parker Hannifin Corporation, Sun Hydraulics, and Tennant Corporation. Their internship positions were posted at the Fluid Power Scholars section of the Center website.
    - Student recruitment: An equally ambitious student recruitment effort, organized by CCEFP staff, resulted in over 40 student applications. Students representing universities within and outside of the Center applied through an on-line process at the Center website. (Note that the Scholars/Interns Program is open to undergraduate students who have successfully completed at least two years in an accredited engineering program anywhere in the United States.)

- Matching process: All sponsoring companies had access to a secured section of the CCEFP website where student applications were posted. Company personnel studied these applications and selected their top choices for the internships they had posted. While they informed CCEFP staff of these choices, companies were solely responsible for contacting students to set up and conduct telephone interviews and to subsequently make internship offers. 2010 scholars/interns represented Carnegie Mellon (1), Illinois Institute of Technology (1), Montana State University (2), University of Michigan (1), University of Minnesota (2), and University of South Florida (1). (The "myriad of differences" in company choices, noted above, was manifested in the selection process. In only one instance did companies name the same student as their top choice.)
- Fluid power orientation at the Milwaukee School of Engineering: Internal evaluations by MSOE and evaluations led by the Center for Applied Research for Education Improvement (CAREI) indicated high student satisfaction with this element of the Scholar/Intern Program. In fact, several of the students recommended that it be lengthened from three days to perhaps as long as a week.
- End-of-program evaluations: All corporate sponsors of the 2010 fluid power scholars/interns indicated their satisfaction with the program and indicated their willingness to participate in 2011. With one exception, students also indicated their strong satisfaction.
- One of the 2010 scholars, from a school outside of the CCEFP network and who also was an REU at UIUC in 2009, has elected to begin graduate studies at UMN. Dr. Perry Li, CCEFP Deputy Director, will be his advisor.



2010 Fluid Power Scholars

- 2009: The worldwide economic downturn profoundly affected the fluid power industry and the Fluid Power Scholar/Intern program was placed on hold.
- 2008: Center staff together with a task force of industry members explored why the Center's intern program had stumbled, and looked for ways to create something better—a program that would appeal to many companies regardless of where they stood on internships, one that would draw on assets unique to the Center. The Fluid Power Scholars/Interns Program is the product of this group's design. In order to make this program stand out to students and companies alike, participants on the planning team agreed that it should be unique, drawing on resources that set the Center apart. They determined that up to ten Fluid Power Scholars would be named in early spring, each matched through a competitive application process with a corporate supporter of the CCEFP who agreed to be a program sponsor. Sponsors would provide a paid internship and also cover the costs (travel, room and board) that their scholar would incur in attending a three-day intensive orientation to fluid power taught by faculty at the Milwaukee School of Engineering's Fluid Power Institute. The CCEFP would cover costs of instruction. Company internships would begin following the orientation.
- Ongoing evaluations: CAREI has designed and carried out ongoing evaluations directly relevant to the Scholars/Interns program over the past three years. Results of these surveys were

important as the Center's intern program was reconstructed and the Fluid Power Scholars program was designed. They continue to be important now that the program is underway.

- 2008: Telephone interviews conducted by CAREI staff among 2008 interns,
- 2008: Telephone interviews conducted by CAREI staff with companies hosting interns in 2008 (those interns placed with the help of the CCEFP),
- 2008: An electronic survey for all companies supporting the CCEFP concerning their experiences with, views of and plans for internships in the future.
- 2010: Surveys and telephone interviews of the 2010 Scholars/Interns and their corporate sponsors.

2010 Fluid Power Scholars

Number of Students	8
Males	6
Female	2
Percentage of students from underrepresented groups	
1) racial minority	13%
2) gender minority	25%
3) disability	0%

Other relevant work:
Support of other internship programs: Many successful internship programs are already in place and the Center's help isn't needed to implement them. However, the CCEFP can and is helping to spread word of these opportunities to a vast pool of students by providing links to companies with internship programs at http://www.ccefp.org/get-involved/internships. Though complementary to Center goals, these internship programs are independent of the Scholars/Interns Program.

4. Plans
As of this writing, company and student recruitment for the 2011 Fluid Power Scholars/Interns Program is already underway. Other than moving up the timing of the recruitment processes, all other program logistics and processes will be duplicates of the 2010 program.

- A 2010 Fluid Power Scholar will serve as a guest speaker and poster presenter at the CCEFP's Site Visit/Annual Meeting at IFPE in Las Vegas, March 2011.
- The CCEFP's website page that provides links to internships within the fluid power industry outside of the Scholars Program will be maintained.
- A thorough evaluation of the Scholars/Interns Program will be conducted at the launch and at the end of summer 2011 with the help of CAREI. New data, along with comparisons with the old, will help to shape the Fluid Power Scholars/Interns Program going forward.
- CAREI will also be enlisted for long-term follow-up. Did the scholars/interns program have any lasting impact on students' interests? Careers?

5. Milestones and Deliverables

- Nine-ten scholars/interns will participate in the 2011 program (assuming an economy robust enough to enable companies to offer positions).
- The number of scholars/interns will increase steadily in subsequent years. In order to sustain this growth, all sponsoring companies will be encouraged to help in the recruitment effort by sharing their program success stories with non-participating companies.

6. 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.

Project D.2: CCEFP Network

Project Team

Project Leaders:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	Lisa Wissbaum, Administrative Director
	Donald Haney, Communications Director

1. Project Goals

Using an array of technological tools, the goal of the CCEFP Network is to connect the people of the Center—faculty, undergraduate, graduate and post-doctoral students, REUs, RETs, advisory board members and industry supporters—in mutually advantageous ways. In reaching this goal, the Center is pursuing four distinct yet inter-related projects:

Project D.2a CCEFP Database: The Center defines its membership by one of several criteria. ***Academic Membership*** includes any student at the undergraduate or graduate level enrolled in one of the Center's partner institutions who is working on a core or associated project. ***Industrial Membership*** includes representatives of the Center's Industry Member Sponsors. ***Affiliated Membership*** includes any student who is enrolled in the REU program, Fluid Power Scholars Program, any teacher enrolled in the RET program or an individual who is a program participant of the Center's education and/or outreach activities. This database is designed to collect all of the contact, demographic and academic information needed by the Center and by NSF in identifying these many audiences.

Project D.2b Resume Bank / Booklet: All of the Center's undergraduate, graduate and post-doctoral students are invited to post their resumes at a secured section of the CCEFP website. This site is available to CCEFP member companies for their use in recruiting of CCEFP students for entry-level job placement. This resume bank is also useful as the Center's industry members seek out candidates—both undergraduates and graduates—for industry internships. The Center will be creating a Resume Booklet at the 2011 CCEFP Site Visit / Annual Meeting at the International Fluid Power Expo, in Las Vegas, March 2011.

Project D.2c Boarding Pass All CCEFP members, including faculty, undergraduate and graduate students, post-docs, REUs, RETs, education/outreach program participants, industrial members, advisory board members and outreach institutions are welcomed into the Center by way of a CCEFP Boarding Pass. A CCEFP Boarding Pass is given to every participant when they start their formal affiliation with the Center. The Boarding Pass provides resources and materials relevant to success as a CCEFP member. Membership includes access to research, education, advisory board or committee work spaces using Google, the selected collaborative on-line tool; access to current and archived webcasts; availability of all CCEFP-related policies and procedures including patent submissions, intellectual property, new project and budget requests, and the CCEFP calendar; internships and job opportunities; and access to the database of CCEFP students who are interested in becoming part of industry.

Project D.2d CCEFP Alumni Society*:* Upon graduation or conclusion of a program-specific role within the Center, all CCEFP participants automatically become members of the CCEFP Alumni Society. CCEFP Alumni Society Members will receive a De-boarding Pass as well as an exit interview. The Pass will provide additional resources on ways to continue to be part of the Center under the auspices of the Society. The Alumni Society database will be used for follow up when evaluating program impact. The interview will be followed over time with ongoing outreach as the Center tracks career and interest paths in its assessment of long-term program impact. Meanwhile, as members of the Society, participants will receive periodic newsletters highlighting CCEFP developments, will have access to contact information for other alumni, and will have access to other key areas of the CCEFP website. To ensure continued cooperation, the Center will work with the internal processes at each institution to ensure the cohesiveness of the Center.

2. How Project Supports the EO Program Strategy
The use of the CCEFP Network database and resume bank by the undergraduate and graduate students as well as the industry members of the CCEFP supports the Center's strategic plan of facilitating communication between the fluid power industry, newly educated engineers, and their faculty. The network will also help the Center in tracking the participants of its programs.

3. Achievements

- The Center staff maintained and improved its internal Filemaker-based database, all the while looking for a better alternative. Staff believe that it has found that alternative in the recently designed and beta-tested ERC-Personnel-Database (see below).
- An enhanced Center website, www.ccefp.org, was launched in March 2009 and continues to be updated on a regular basis.
- In relationship to the Resume Bank, the CCEFP conducted surveys among students of the Center to determine their interest in providing information, for the purposes of recruitment.
- The Center has implemented an array of web-based "marketing" and social networking technologies. The Center has used on-line technology to conduct student, industry and Center-wide surveys; updated our listserve capabilities using Mailchimp; added a social networking feature using Facebook; facilitated data collection and archival methods using Freedback Forms; employed on-line collaborative tools such as Google-Groups; devised the newly created, but privately managed CCEFP-Intranet; and created an on-line photo repository PhotoAlbum.

4. Plans

- The Center will employ a recently designed, created and beta-tested ERC-Personnel-Database Tool to be integrated into the current Drupal website.
- The CCEFP Network is a 2011 priority. The goal is to have a comprehensive data management tool that will make collecting, archiving and maintaining data more efficient and effective for CCEFP Members and Center leadership and administration. In addition to better data management, the boarding process can facilitate the gathering of additional information across the spectrum of the people and activities of the Center. By the end of 2011, the Center plans to have its ideal database management system in place.

5. Milestones and Deliverables

- Employ the new ERC Personnel Database beta tested by June 2011
- Fully functional electronic database by end of 2011

6. Member Company Benefits

Industrial members will have better access to students who are seeking employment and/or internship openings. Students will have easier access to information about companies who are looking for employees and or interns.

Project D.3: Advanced Fluid Power Engineering Workshops

Project Team

Project Leader:	Prof. Kim Stelson, University of Minnesota, CCEFP Director
Other Personnel:	Thrust leaders and faculty investigators of the CCEFP, members of the Center's E&O Team
Industry Partners:	Members of the CCEFP Industrial Advisory Board (IAB) Staff of the National Fluid Power Association and the Association of Equipment Manufacturers, IFPE show owners

1. Project Goals

These workshops are designed to 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 and applications.The goal in organizing and implementing these workshops is to facilitate knowledge transfer between CCEFP faculty and degreed engineers in design and manufacturing positions in fluid power companies as well as with Center faculty and their students.

2. How Project Supports the EO Program Strategy

Whenever possible, the CCEFP seeks to leverage and coordinate the strengths of individual Center programs and participants in order to insure the success of other programs. The Center also seeks out strong partners to help in building program success. Advanced Fluid Power Engineering Workshops are aligned with both of these strategies. This project draws on the strength of the CCEFP faculty who, in many cases, are world-renowned experts in their fields. Their expertise in a wide variety of subject areas has been developed over years of study. This project taps into that knowledge by enabling these experts to share their knowledge with students and faculty outside of their own classrooms and institutions as well as with practicing engineers who could not access this information as easily or completely from any other source. The Association of Equipment Manufacturers (AEM) and the National Fluid Power Association (NFPA is an affiliate organization of the Center) will be valued partners in the launch of the project, playing pivotal roles in promotion of the initial workshop.

3. Achievements:

- It is difficult to launch a new program in the challenging economy we have faced over the last few years. Earlier workshops were deliberately postponed until the economic climate improved. However, an ideal launch opportunity has presented itself. Every three years the International Exposition for Power Transmission (IFPE), and CONEXPO-CON/AGG co-locate in Las Vegas, Nevada, drawing huge crowds: 140,000+ to CONEXPO-CON/AGG and 25,000+ to IFPE. The co-located shows are scheduled for March 22-26, 2011 and CCEFP's first workshop will be offered in conjunction with them. Some in these audiences, particularly IFPE but certainly some from the larger show, too, will be interested in Center-led workshops targeted to the construction and aggregate markets as well as to their fluid power suppliers. The CCEFP staff played a leading role in organizing and recruiting the presenters for the four IFPE workshops: Noise in Fluid Power Systems; Design, Modeling and Control of Hybrid Vehicles, Hydraulic Fluids and Their Application, and Basic Lubrication. Zongzuan Sun, UMN and Center researcher, will present the workshop on hybrid vehicles. (See www.ifpe.com and www.conexpoconagg.com for more show information).
- The shows' primary owners, the National Fluid Power Association and the Association of Equipment Manufacturers, have agreed to include the Center-led workshop(s) as part of the larger promotional efforts for both shows--campaigns that are far reaching and multi-faceted. Given awareness campaigns of this magnitude and a launch that is almost

certain to be successful at the shows themselves, something of a "workshop brand" will be established, thus making it much easier to follow up with additional CCEFP workshops taught primarily through e-Learning short course--something as simple as a webcast, as well as half-day and longer e-Learning courses. Eventually our goal is to incorporate the emerging principles of e-Learning pedagogy to deliver more extensive high-quality courses.

4. Plans

- The initial CCEFP-led workshop will be offered in conjunction with IFPE and CONEXPO-CON/AGG. A planning committee composed of show management, industry volunteers, and the CCEFP's Industrial Liaison Officer have met regularly to decide on promotion and organizational issues associated with this and the other three CCEFP-organized workshops that will be held in conjunction with the show.
- The Center for Applied Research and Educational Improvement (CAREI) will prepare a concise questionnaire for workshop attendees. The CCEFP will use results of this questionnaire to bring their plans for future Center-led workshops into sharper focus.
- Additional Center-led workshops will be offered in the fall of 2011 and spring of 2112, shaped by lessons learned from this launch and the questionnaire as well as from other organizations that have already demonstrated highly successful working models for workshops and classes. Whenever appropriate, the Center will use these models as its develops its own course offerings. (For example, the Society of Automotive Engineers [SAE] has a particularly impressive program. And MSOE has a highly-regarded industry-training model that Center workshops will complement; the programs will not be competitive.) In sum, plans call for increasingly ambitious agenda—in scope and delivery, based on best practice in e-learning delivery.

5. Milestones and Deliverables

- Working with the questionnaire developed by CAREI, the CCEFP staff will learn from 2011 IFPE workshop attendees about preferences for topics and formats for subsequent workshops.
- The Center's first stand-alone workshop, featuring one of its researchers as presenter, will be organized as a webcast in the fall of 2011.
- Based on insights (topics, formats, etc.) gained from the planning and execution of the fall workshop, CCEFP staff will organize another workshop during the spring of 2012.

6. Member Company Benefits

Many of the Center’s faculty investigators are recognized experts in their fields of study. Together, they offer interdisciplinary perspectives on fluid power research and applications as well as on related fields. Most practicing engineers do not have ready access to this wealth of knowledge and would benefit from opportunities to learn through this unique resource.

Project D.5: CCEFP Webcasts

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	CCEFP staff
	SLC President and Vice President
	CCEFP graduate students
	Invited speakers outside the CCEFP network
Industrial Partners:	All CCEFP Industry Members

1. Project Goals

The goal of the webcast series is to maintain a consistent means of technology transfer throughout the Center—students, faculty and industry supporters. On a regular basis, the CCEFP hosts a webcast featuring two presentations, each discussing either research projects or other Center-wide programs (e.g., special topics, strategic planning, education and outreach, project evaluation, etc.). These webcasts are open to all CCEFP students and faculty and to all CCEFP member companies. The webcasts are presentation based, with audio and visual capabilities. The audience is welcome to interact with the presenters during the question and answer session following each presentation. Each webcast is recorded and archived for retrieval and is posted and available on a secured section of the Center's web site.

2. How Project Supports the EO Program Strategy

This program aligns well with the mission, vision and strategy of the CCEFP by creating widespread awareness of its research and education projects as well as the Center's administrative and evaluative work. Since many of the webcast presentations are made by Center students, participation in this project fosters professional development as they "learn by doing" how best to communicate—describing their work and also responding to and benefiting from the input of faculty, their peers and industry.

3. Achievements

- The Center estimates between 35 - 50 participants per webcast on a regular basis. Participants include industry, faculty, staff and students. Note that we realize that the Center's seven universities as well as industry often arrange for a conference call and meeting space for multiple listeners.In addition to including an audio feedback component, the Center has greatly improved its efficiency and effectiveness with the CCEFP webcasts. The Student Leadership Council members emcee each webcast, creating seamless transitions between each presenter.
- Webcasts now include more special topics, education outreach presentations and "State of the CCEFP" discussions presented by Center Leadership.
- In 2011, the webcasts will continue to feature Special Topics which include invited talks from Industry as well as from experts on matters such as intellectual property, patents, ethics, etc.
- Presentations are not just project-specific information; they also include information on how each project is aligned with the Center's strategic plan. For research, presentations describe how work is demonstrated on the Center's test beds, how current research aligns with what has been done previously as well as how it is breaking new ground, etc. These inclusions have added important new dimensions to the webcasts and have provided another avenue where students, faculty and Center leadership can continue to strategize on the direction of the research projects across the Center.
- The Center evaluated the options for software and costs associated with the webcasts and selected Adobe Presentation software in which the University of Minnesota has a site license to use. There was a steep learning curve in using this software, and while the initial stages of the webcasts were cumbersome, the curve has now leveled off and the

presentations run smoothly. In an effort to satisfy the need for real-time question and answer feedback, the Center opted to incorporate a conference call service in collaboration with the web presentation software. This has greatly improved the level of compatibility between the Center's seven institutions and the many industry representatives participating in the webcasts.

- The Center initiated the CCEFP Web casts in June 2007 with a bi-weekly schedule of presentations given by the graduate students working on their respective projects. Based on the success of these webcasts, the Center introduced weekly webcasts during the fall of 2008. In the early 2009, the Student Leadership Council conducted a survey among identified webcast participants, collecting information regarding preferences for the frequency of the webcasts, the quality, the technology and any additional recommendations. Survey results were very helpful in planning for future webcast series. While the Center clearly has enough information to share on a weekly basis, the Center received internal, external and advisory board recommendations to return to a bi-weekly schedule.

4. Plans

- The CCEFP will continue to host the webcasts which are a proven success, popular within the Center network and among its industrial members. As the Center matures, so will the research and education outreach projects, and the webcasts will reflect the impact of these initiatives. The CCEFP will launch another survey in 2011 to measure the value and effectiveness of the presentations.
- As technology advances, the Center will continue to evaluate the effectiveness of the tools and software available for webcasts and will explore options for improvement. Costs will be a factor, too. Because the webcasts have become so popular, the Center finds it necessary to create a budget line for this program. As the number of participants increase, so does the cost to host the audio component of the webcast.
- Every effort will be made to expand participation among all audiences. The Center will continue to gather input from current and potential participants as we seek out ways to enhance this key Center project.

5. Milestones and Deliverables

- Include professional development topics to the presentation schedule in 2011 as well as in subsequent years (e.g., "effective presentation skills").
- Conduct a participants' survey in 2011 as a part of the Center's continuous improvement efforts.

6. Member Company Benefits

All Center participants—faculty, students, industry and staff—have opportunities to get first-hand updates on research, education and management level activities from project leaders. Webcasts also foster a sense of "community" throughout the Center network as all constituents regularly have opportunities to hear and learn from each other.

Project D.6: Publications

Project Team

Project Leaders: Prof. Kim Stelson, University of Minnesota, CCEFP Director
Linda Western, Education Co-Director, CCEFP

Other Personnel: All CCEFP researchers and staff

Industry partners: Any industry representative contacted by a publication's staff for inclusion in a given article.

1. Project Goals

The CCEFP is committed to encouraging and enabling knowledge transfer. The Center's interactions with the trade press and academic journal create powerful channels for just that to happen--informing engineering researchers and educators in academia along with practicing engineers across a wide spectrum of industries about CCEFP research as well as its education and outreach programs.

2. How Project Supports the EO Program Strategy

The CCEFP seeks to capitalize on broadly distributed networks in order to maximize program impact. Publications that can be categorized under the trade press umbrella, specifically those whose readers have an interest in some aspect of fluid power, form a far-reaching network. Their circulations range from approximately 25,000 to 100,000 readers. When articles about the CCEFP are carried in these publications, the Center is extending its network, reaching engineers and technicians in the fluid power industry and the industries it serves. Similarly, publications read within the engineering and engineering education community provide a forum for the exchange of information and ideas relevant not only to Center research, but also to its efforts in promoting STEM- and fluid power-relevant education

3. Achievements:

- In the four and one-half years since its launch, ten trade press publications have covered news of the Center (*Design News, Design World, Diesel Progress, Engineering News (South Africa), Fluid Power Journal, Hydraulics and Pneumatics, Lubes-n-Grease, Machine Design, OEM Off-Highway, Today's Fluid Power*). Though it is impossible to know how many have actually read these articles, it is safe to say that hundreds of thousands have had the opportunity to learn about the Center's work (Figure 1). Now, these articles are available--either in pdf format or as links--under the News Desk tab at www.ccefp.org.

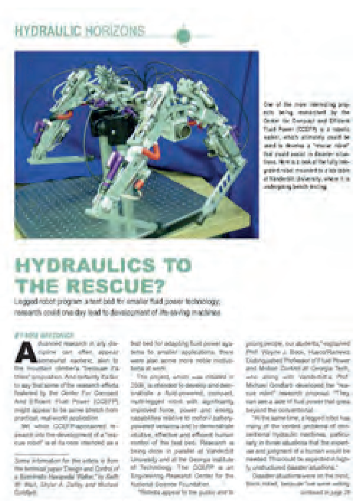


Figure 1: Examples of fluid power articles

- In 2010 alone, ten new articles carrying CCEFP news have appeared in the trade press.
- The CCEFP continues to use the editorial guidelines it has developed and shared within its own network as well as with editors of the trade press on subjects that include lead-time, exclusivity, confidentiality, authorship and reviewing/editing rights. The guidelines have proven to be very helpful, answering inevitable questions from all sides early on in the writing/editing process.
- Though technically not considered a part of the trade press, publications of trade associations also reach key audiences. For example, the National Fluid Power Association features an ongoing column on the CCEFP in *The Reporter,* its monthly on-line publication. *The Reporter* has a readership of over 2,000 manufacturers, suppliers and distributors in the fluid power industry.

4. Plans

- The CCEFP is becoming more ambitious in the broadening the range of publications it seeks out--academic journals (here, articles focusing on overall Center activities to complement the many current technical publications based on individual researcher's work) as well as the trade press. Its work with the trade press will continue in its current vein, though plans call to ramp up the pace and number of articles. Further, CCEFP faculty have now set their sights on developing special issues/articles in journals such as *Mechanical Engineering (*journal of the American Society of Mechanical Engineers), *ASEE Prism,* etc.
- In addition to developing articles based on CCEFP-generated press releases, a growing number of articles about the Center are now initiated by editors who call for information about the work underway. The CCEFP plans to cultivate this enthusiasm, encouraging an increasing number of editors (and publications) to initiate contacts with the Center.

5. Milestones and Deliverables

- Increase the number of articles published in the next year in the trade press by five over this year's total of ten. (Approximately thirty-three articles about the Center have been published in the trade press since June 2006.)
- Add at least two more publications to the list of trade press publications currently covering the Center. One new publication was added in 2010.Maintain reciprocal website links between the Center and publications carrying these articles.
- Continue a newly-launched press release program; the current program focuses primarily on the CCEFP's upcoming participation in IFPE, March 22-26, 2011. (The CCEFP's fifth annual meeting and its NSF Site Visit will be held in conjunction with this event.)
- Publish three articles per year in academic journals about the Center's work over the life of the CCEFP.

6. Member Company Benefits

Articles about the Center's work inform readers about the potential for fluid power. This information is a powerful tool, not only for the CCEFP's corporate members, but also for the entire industry in reaching its marketplace. In short, news about the Center appearing in the trade press is helpful to all parties.

Project E.1: External Evaluation of Selected Education and Outreach Activities

Project Team

Project Leader:	Michael Michlin, Center for Applied Research and Educational Improvement (CAREI)
Other Personnel:	Delia Kundin, Center for Applied Research and Educational Improvement (CAREI)

1. Project Goals
The Center for Applied Research and Educational Improvement (CAREI) in the College of Education and Human Development at the University of Minnesota is the external evaluator of Education and Outreach projects. The evaluation activities include assessment of the overall program goals as well as of individual projects. Each year CAREI undertakes evaluation activities of selected CCEFP programs. Generally selection of the programs for that year's evaluation is based on the importance and timeliness of the evaluation information for the Education and Outreach leadership.

The goals of the external evaluation are, first and formatively, to provide critical information about progress toward achieving the overall program goals as well as about the development, functioning, and efficacy of specific Education and Outreach projects. Second and summatively, the goal is to provide CCEFP with information about the achievement of the overall program goals and the effects, outcomes, and impact of specific Education and Outreach projects.

2. How Project Supports the EO Program Strategy
The external evaluation supports CCEFP efforts by providing formative evaluation data and findings that allow the Education and Outreach leadership to revise projects and redeploy resources as they are warranted in order to make mid-course corrections. Further, summative evaluation data and findings lead to judgments about the achievement of the overall program goals.

3. Achievements
For this the third year of the external evaluation, CAREI continued the evaluation of both the REU and RET programs, which included the data gathering of pre and post-program questionnaires of participants. CAREI evaluators also undertook a questionnaire focused on the Fluid Power Scholars Program interns and interviews of the interns' industry mentors in the CCEFP's industry partner companies. As a first step in a summative evaluation, CAREI worked to identify measurable objectives for the portfolio of Education and Outreach projects.

REU: The REU summer program does affect how students rate their knowledge of engineering technologies. As in previous years, results show that when students participate in the summer REU program, their knowledge of hydraulic and pneumatic technology as well as fluid power applications increases. The effect sizes were large.

From the questionnaire, we find that through their participation in the program, REUs primarily want to learn about fluid power and enhance their research and hands-on experiences. Interest in exploring career options and particular project topics are mentioned less often, and even less often are remarks about preparation for graduate school or a program's reputation or location. Interestingly, after completing the REU program, students were a bit less confident that fluid power was a good match for them and less confident that laboratory experience was essential. The effect sizes were moderate.

Seventy-three percent of the REUs plan to attend graduate school. The top five preferred graduate schools mentioned most often by REUs were Stanford, Purdue, Georgia Institute of Technology, Massachusetts Institute of Technology, and the University of California. Those REUs not planning to attend graduate school do plan to pursue occupations in engineering. The companies these students preferred as employers include NASA, the EPA, Toyota, Third Wave Systems, and Case IH.

CAREI evaluators also asked students to describe how they envisioned using their experiences to enhance their future career plans. REUs plan to continue fluid power research in graduate school, to pursue work in fluid power, to use technology advancements in school and work, and to improve their networking and computer skills.

Ninety-five percent of the REUs reported that overall they were satisfied with their REU experiences. This included satisfaction with the materials, the orientation they received prior to beginning their program, and their relationships with the mentors and professors. The opportunity to interact and discuss their projects with others was important to 90% of the student participants. As three REUs put it:

- *Amazing experience. I don't see how anyone could engage in an opportunity like this without having at least one life changing experience, if not more. A huge thank you to all who were involved.*
- *I enjoyed it immensely and it was a great experience for factors other than just our research. I feel like being pulled into an event like this with other students in my age group and academic path provided a very worthwhile experience for both academic and personal development. This was probably the best summer experience I've had in college and think it is well worth funding.*
- *It was a great experience and has opened a lot of doors for me. It was quite a struggle, but in the end it helped me grow as an individual and pushed me to reach my potential. I hope to see the REU program continue its presence here at the Tech campus.*

RET*:* In general, at both pre and postprogram, the majority of RETs agreed with statements about teaching fluid power, engineering, and technology. Preprogram and postprogram, RETs agreed or strongly agreed that they are confident that they can teach fluid power technology and its applications in their high school classes, that using fluid power in high school classes is a useful tool for motivating students to engage in STEM subjects, that experiences with engineering technologies are important to their students' overall STEM education, and that teaching about fluid power in their classes is a good match for their schools' curriculum standards.

Pre and postprogram, they also agreed or strongly agreed that their experiences as an RET in a university engineering research laboratory are likely to impact their classroom teaching, that students understand STEM subjects more when they design and implement their own scientific investigations, that they can make a difference in the lives of their students in terms of their continuing STEM education beyond high school, and that they consider themselves subject matter experts in what they teach.

The effect sizes in comparing pre-program with post-program questionnaire responses were generally small or moderate with none large, but two were trivial. No pre-program questionnaire responses compared with post-program responses were statistically significant.

RETs' self-ratings of their knowledge of hydraulics, pneumatics, and fluid power applications were generally rated "fair" on the pre-program questionnaire and rose to almost "good" at post-program time. The effect sizes here were all moderate. These increases were not statistically significant, but we are only talking about four teachers (pre) versus five (post).

RETs were interested in the program to enhance their engineering experiences. They expected to conduct research, to expand their experiences in classrooms, to interact with others, and to learn. The RETs expected to benefit from the program by expanding their knowledge of the field, making higher education connections, broadening their knowledge of fluid power, and increasing their hands-on activities in classrooms. Teachers developed devices and lesson plans, and created models they planned to incorporate in their classes.

All the RETs were satisfied with their 2010 RET experiences. They were satisfied with the materials, the availability of resources and equipment, and the orientation they received prior to beginning their program. They were also satisfied with their relationships with professors and other staff and students and with the opportunity to interact and discuss their research projects with others. Bottom line, all of the teachers would recommend the RET program to their colleagues.

In sum, REUs and RETs were satisfied with their summer program experiences. REUs experienced significant increases in their level of knowledge about fluid power applications in engineering. While REUs' knowledge of hydraulic and pneumatic technologies increases significantly, this was not the case for RETs. One explanation for these differences may be that teachers were confident in their teaching before beginning the program. For example, all four teachers consider themselves subject matter experts in what they teach, and they are confident that they can teach fluid power technology and its applications in their classes.

REUs were less confident that fluid power is a good match for them post-program and less confident that laboratory experience was essential for their careers.

Recommendations for program improvements suggested by REUs and RETs focused on CCEFP providing more structure to the programs, and opportunities for students to interact across program sites.

Fluid Power Scholars Program*:* Prior to beginning the fluid power orientation program at the Milwaukee School of Engineering, the eight scholars were confident in themselves and had high hopes for beneficial gains from their coming internship experiences. In the post-internship questionnaire, we found greater variation among the scholars' responses, and means appeared a bit smaller compared with the pre-questionnaire. But statistically, shifts pre versus post were not significant.

After the internship, all or most agreed that completing the application process was easy and that the orientation program prepared them to undertake their internship. Further, focusing on fluid power was a good match for their career interests, and completing an internship in fluid power would motivate them to continue their engineering education beyond their bachelor's degree. Having hands-on experience with fluid power technologies was critical for their overall career preparation, and completing an internship would provide them with new understanding of fluid power technology and its applications. Finally, because of their career preparation, they believed they would make a significant contribution to the field of engineering in the future.

The scholars' reports of their knowledge of hydraulics, pneumatics, and fluid power applications clearly increased pre to post-internship. The effect sizes for hydraulics and fluid power applications were large, and the effect size for pneumatics was moderate. Knowledge was increasing, and the major take home from the internship was knowledge – knowledge of fluid power specifically; knowledge of the design process; and knowledge of the amount of work, resources, and people it takes to take a design from concept to production.

Industry mentors of the Fluid Power Scholars. Mentors expressed their satisfaction with the fluid power orientation classes held for the scholars at the Milwaukee School of Engineering. Two mentors suggested that the time students spend in orientation classes be increased to give students even more exposure to fluid power concepts. Other mentors placed less emphasis on the need for students to have much knowledge about fluid power prior to an internship and more emphasis on other areas. In selecting interns, the engineering companies were concerned about the engineering classes students had completed, previous hands-on work experiences, common sense, and mechanical skills. Mentors were clear that the intent of the internships was to teach students about how to work in fluid power.

When asked how Fluid Power Scholars Program interns compared with other interns, mentors indicated these interns were better prepared when it came to previous work experience. In one case, a student was less prepared technically than previous interns. In another case, a student was hired by the company after completing the Fluid Power Scholars Program internship. All the mentors were clear about the positive contributions interns made to their companies. Overall, the mentors were satisfied with their internship experiences and were interested in participating in the program again next summer.

Developing measurable objectives for the portfolio of Education and Outreach projects*.*

All the initiatives under Education and Outreach's umbrella are instrumental in helping the CCEFP reach its goal: developing research inspired, industry-practice-directed awareness of and education in fluid power for pre-college, university, and practitioner students as well as for the general public. CAREI evaluators took the first steps toward summative evaluation of Education and Outreach's progress to their goal. Evaluators began with a study of the 25 or so projects spread among four Education and Outreach thrusts.

What evaluators learned was that almost none of the projects that could and should have measurable objectives had them in place. Almost all the projects describe actions they propose to undertake but not outcomes per se. The Education and Outreach leadership team then wrote a revised draft of their E&O Project Plan in which they drafted measurable objectives (outcomes) for many of the projects. They shared this draft with the evaluators in early November. Their draft was a good start on what was needed to develop benchmarks to measure progress. As a next step, the Education and Outreach team will meet with CAREI evaluators early in 2011 in order to review the draft, sharpen the statements of measurable objectives as necessary, and incorporate the finalized versions into the Center's E&O Project Plan.

4. Plans

To date only the most preliminary conversation has occurred about the next year's evaluation. Likely areas include

- Advanced Fluid Power Engineering Workshops. CAREI evaluators are scheduled to design a course exit questionnaire to be administered at the end of every fluid power engineering workshop offered in the IFPE and CONEXPO-CON/AGG trade shows in Las Vegas in March 2011.

- Standard evaluation of REU with focus on changes in fluid power knowledge and attitudes. Technical report due October 2011. Also, CAREI evaluators are scheduled to conduct a questionnaire follow up with the 2008 and 2009 REU cohorts in mid-September 2011. The emphasis will be on the impact of their university engineering research laboratory experiences on their academic progress as undergraduate and/or graduate students and/or their experience moving into the engineering profession.

- Standard evaluation of RET with focus on changes in fluid power knowledge and attitudes and changes in classroom pedagogy as a result of RET participation. Technical report of survey results due October 2011; technical report of results of interviews with 2010 participating teachers on changes in classroom pedagogy due in June 2011. CAREI evaluators are scheduled to conduct a questionnaire follow up with the 2008, 2009, and 2010 RET cohorts in mid-May 2011. The emphasis will be on the impact of their university engineering research laboratory experiences on their high school classes, and thus the degree to which teachers have integrated fluid power content, technology, and hands-on activities in their classes as well as their efforts to disseminate their fluid power materials, instructional units, lesson plans, and so on.

- Continue evaluation of undergraduate experiences in fluid power capstone projects. Technical report due January 2012 (for December completers) and June 2012 (for May completers). Currently there are no fluid power capstone projects at the University of Minnesota. Ongoing future evaluation of capstone design courses include tracking the numbers of fluid power capstone projects and student involved in the seven CCEFP schools, interviewing the fluid power students, interviewing students' advisors/mentors, and interviewing industry partners.

- Continue evaluation of pre-college fluid power workshops. Further expand the evaluation efforts across the seven CCEFP sites. Technical report due June 2011. [Data on pre-college fluid power workshops are not yet available.]

- Develop assessment of CCEFP efforts to increase attention to fluid power in the undergraduate curriculum with the use of open source fluid power curricula in undergraduate courses.

- Develop measurable objectives for the portfolio of Education and Outreach projects in collaboration with the Education and Outreach leadership team and the leadership of each project.

- Exploration for future evaluation efforts: Shooting for the Stars Robotics Program

5. Member Company Benefits
CAREI's evaluation efforts with CCEFP indirectly benefit member companies and the entire industry as CCEFP works to increase the numbers and diversity of new engineers in fluid power. The main point of all the evaluation efforts is to assist CCEFP to work smarter and achieve their goals.

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Associated Project Abstracts: Research

Thrust 1 – Efficiency

Acquiring Vehicle Drive Cycle with Fleet Data
Project Leader: Monika Ivantysynova, Purdue University
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Advanced Energy Saving Hydraulic System Architecture
Project Leader: Monika Ivantysynova, Purdue University
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Advances in external gear machines modeling
Project Leader: Andrea Vacca
Sponsors: Casappa SpA

Abstract: This research aim to develop A novel approach to couple a Lumped Parameter model and a CFD model to accurately model External Gear machines. The tool consists of a lumped parameter fluid dynamic model to simulate the flow through the unit, an accurate description of the geometry of the components (i.e. tooth profile, design of sliding elements) and the movements of the gears' axes of rotation resulting from the forces exerted on both gears. The CFD model under development is an automatic pre-processor and a finite volume numerical solver of the Reynolds Equation. This enables a calculation of the pressure distribution in the lateral lubricating gaps between the gears and the sliding bushings of the external gear machines considering full hydrodynamic lubrication.

This combined approach allows a very detailed description of the effects of the lateral and radial lubricating gaps on the operation of the machine.

Design, Simulation, and Control of Hydraulic System Topographies with Integrated Energy Recovery
Project Leader: John Lumkes
Sponsors: National Fluid Power Association

Abstract: This project is developing a new hydraulic system topology with improved efficiency and effectiveness. The goals of the project are to develop efficient hydraulic systems based on innovative topologies and to maximize the effectiveness of these topologies through the development of adaptive control strategies including fault detection and self-healing capabilities. This project uses a network of simple valves configured in such a way that electronically (and in real time) the hydraulic system can operate with characteristics of load-sensing (multi-level), displacement control, independent metering, energy recovery, and energy storage (if an accumulator is added). These operating modes can often co-exist depending on which mode provides the best combination of overall efficiency and effectiveness for the given application and load cycle. The system Topography with Integrated Energy Recovery, or TIER, includes the capability to re-route power in the event of component failure. A prototype system on a small backhoe has been installed and is undergoing testing at Purdue University.

Development of Drive Train Control Concepts for Power Split Hybrid
Project Leader: Monika Ivantysynova, Purdue University
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Displacement controlled actuator for mobile application
Project Leader: Monika Ivantysynova, Purdue University
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Displacement controlled Hex productivity/controllability study
Project Leader: Monika Ivantysynova, Purdue University
Sponsors: **Caterpillar**

Abstract: Unavailable due to confidentiality of project.

Hybrid power train for special truck applications
Project Leader: Monika Ivantysynova, Purdue University
Sponsors: **confidential**
Abstract: Unavailable due to confidentiality of project.

Mechanical Implementation of Waved Surface and Waved Piston Technologies
Project Leader: Monika Ivantysynova, Purdue University
Sponsors: Purdue Research Park Trask funds

Abstract: Different production technologies for waved valve plate surfaces will be studied and prototype plates tested in the Maha lab. Work in progress is a power mdal study to manufacture waved valve plates in co-operation with Netshape Inc.

Modeling and Analysis of Swash Plate Type Axial Piston Pump Piston/Cylinder and Slipper/Swash Plate Interface
Project Leader: Monika Ivantysynova, Purdue University
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Performance Prediction and System Control through Coupled Multi-domain Models - A Comparison Study
Project Leader: Monika Ivantysynova, Purdue University
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Prototype Design of a Hydraulic Hybrid Powertrain
Project Leader: Monika Ivantysynova, Purdue University
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

SGER: Green Energy via Control-Based Design of Free-Piston Stirling Engines
Project Leader: Eric Barth, Vanderbilt University
Sponsors: National Science Foundation

Abstract: The research objective of this work is to apply linear and nonlinear dynamical systems and control design tools to formulate a systematic design methodology for free-piston Stirling engines, which have been traditionally designed from a purely thermodynamic point of view. Historically, the design of Stirling engines has progressed from its original purely kinematic arrangement, where the motion of the displacer and the piston are kinematically constrained, toward a purely dynamic arrangement – such engines are called “free-piston” Stirling engines. Unfortunately, this shift toward a dynamic engine has not seen a commensurate development in the tools needed to realize their design. In this research, free-piston Stirling engines are recast and reinterpreted from a dynamic systems and controls perspective by viewing the interacting dynamic system elements in the context of designing a feedback loop. The design methodology is twofold: 1) apply linear control design tools to design parameter groups of the system as feedback gains, and 2) apply nonlinear dynamical systems analysis tools to verify and refine the design with regard to the full nonlinear system.

Thrust 2 – Compactness

Architecture Models for Fluid-Power Systems

Project Leader: Chris Paredis

Sponsors: Deere and Company

Abstract: The long-term goal of this project is to develop more formal, model-based representations of system architectures from both a descriptive and an analysis perspective. In year 4, the emphasis is on model-based interface definitions. Using models, the interface definitions are represented in a formal, semantically rich and computer-interpretable fashion. The approach leverages the Systems Modeling Language (OMG SysML™) to develop a set of modeling constructs that are suited for modeling the multi-disciplinary system interfaces of interest to Deere. Traditionally, interfaces have been defined using Interface Control Documents (ICDs). Such ICDs have been used most commonly to specify the interfaces to software systems or communication systems. In SysML, the modeling constructs for interface definition are ports — locations on the boundary of a system where an interaction takes place. The project develops best practices for how these existing SysML constructs can be used to define all the types of interactions that can be found in typical system interfaces relevant to Deere, including mechanical interactions (e.g., power transfer through drive shafts, or load interactions between a tractor and a tool attachment), electrical interactions (e.g., power to external electrical drives), and controls and communication interactions (e.g., a communication bus for sharing sensor and control signals between a main controller and an auxiliary unit). In cases where the existing SysML constructs are not sufficiently expressive, we extend the SysML language, as needed, using SysML stereotypes.

Control Based Design of Free Piston Stirling Engines

Project Leader: Eric Barth, Vanderbilt University

Sponsors: Vanderbilt University

Abstract: In this work, Stirling engines are recast and reinterpreted from a dynamic systems and controls perspective. This interpretation offers the use of well-understood control design tools as a constructive design approach for free-piston Stirling engines. The basic idea is to view the interacting dynamic system elements of a Stirling engine in the context of designing a feedback loop. The feedback will be shown to be physical in nature with groups of designable system parameters representing the “gains” of the feedback system. These control design tools for physical feedback systems will fill the current gap in design methods for free-piston Stirling engines and will provide the understanding and insight necessary to take their designs to the next level of power density, efficiency and elegance. Prototype engines will be designed, constructed and experimentally evaluated to both demonstrate the proposed design techniques and lend experimental data to verify the theoretical results. The inclusion of new materials, such as elastic diaphragms or flexure mechanisms, new configurations, such as trapped liquid pistons, and new dynamic elements and effects will result in realizing the full potential of the free-piston Stirling concept.

EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage

Project Leaders: Perry Li, Terrence Simon, J. Van de Ven, Eric Loth & S. Crane

Sponsor: National Science Foundation

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 Storing Orthosis
Project Leader: William Durfee
Sponsors: NIH

Abstract: A system to restore walking in the vicinity of a wheelchair for people with paraplegia resulting from spinal cord injury is under development. The approach combines single channel surface electrical stimulation of the paralyzed muscle with an orthosis. The orthosis is spring loaded and contains a pneumatic system that stores energy during knee extension caused by quadriceps muscle stimulation and transfers it to hip joint for hip extension. A laboratory version of the prototype of the gait system has been fabricated and engineering bench tests performed. The system has been evaluated on one subject with a second subject planned in the coming year.

Functionally Graded Metallic Lattice Components (FGMLC) for Advanced Propulsion Components
Project Leader: Vito Gervasi
Sponsors: DARPA

Abstract: Research on a new associated project titled, "Functionally Graded Metallic Lattice Components (FGMLC) for Advanced Propulsion Components," began in October of 2010. This effort is related to project 2D, "Multi-Functional Fluid-Power Components Using Engineered Structures and Materials" and allows MSOE's efforts on functionally graded composites to expand. The project is funded by the Defense Advanced Research Projects Agency (DARPA) with a duration of two years. Orbital Technologies Corporation of Madison and MSOE are the collaborators on the Phase II SBIR project. The goal of the ongoing research is to develop a new class of materials by leveraging a new approach to composites developed at MSOE. By combining two or more materials in a controlled manner (by employing two intertwined lattice structures) objects with remarkable properties can be produced. To form the component with properties out-of-reach for a single material one-of-two (or more) materials are designed to be present at any location in the component (where those properties are necessary). Conversely, unfavorable properties of both materials can be absent at any region in the component by controlling the internal composition. A number of material combinations are being investigated and system models are being developed to ultimately test several harsh-environment components. The anticipated outcome of this work is a new class of advanced composites which can be "tuned" to their application as needed. Several potential commercial products have been identified and are expected to be launched during the two year program.

Open Accumulator Compressed Air Storage Concept for Wind Power
Project Leaders: Perry Li, Terrence Simon
Sponsors: University of Minnesota's Institute on the Environment – Initiative for Renewable Energy and the Environment

Abstract: The goal of this project is to determine appropriate methods to achieve adequate heat transfer in the air compressor/expander in the open accumulator energy storage concept for use in wind power.

Optimization Environment for the Architecting of Micro-grids in Ultra Low Energy Communities
Project Leader: Chris Paredis
Sponsors: United Technologies Research Center

Abstract: The goal of this project is to develop a software tool to explore different architectures for electrical micro-grids efficiently and effectively. Micro-grids are small grids with high reliability and availability that have the potential to be isolated from the rest of the grid. To achieve this, they rely on renewable sources (wind, solar) and small traditional generation units. The efficiency of the traditional generation units is improved by locating them in areas where the waste-heat can be reused. Within the research team, Georgia Tech is responsible for provide expertise in modeling and methodologies for the automated composition and evaluation of system architectures. This leverages ideas and capabilities being developed for architecture exploration of fluid-power systems within the CCEFP.

Precision Pneumatic MRI Compatible Robotic Surgery
Project Leader: Eric Barth
Sponsors: The Martin Companies

Abstract: The objective of the proposed work is to design and fabricate a pneumatically actuated robotic platform that is capable of performing precision intra-operative MRI guided surgical procedures. The work will emphasize the design of a highly functional and marketable system.

Thrust 3 – Effectiveness

A Characterization of the Pressure-Viscosity Response of Two Fomblin Oils
Project Leader: Scott Bair
Sponsors: Oak Ridge National Laboratory

Abstract: The limiting-low-shear viscosity of two Fomblin Oils was measured with falling cylinder viscometers using various sinkers which apply shear stress of less than 100 Pa. Viscosities were be measured at temperature and pressure conditions specified by ORNL.

Construction of a High-Pressure Viscometer
Project Leader: Scott Bair
Sponsors: The Timken Company

Abstract: A falling body viscometer was constructed and delivered to Timken and training in the operation of the instrument was provided. This viscometer is based upon several instruments already in use in the Georgia Tech Center for High Pressure Rheology. These instruments have demonstrated good repeatability and reliability over twenty years of use to 1.0 GPa pressure and to 180˚C temperature. This instrument differs from others of similar capability in that the pressure vessel is not disassembled to access the vessel chamber. Instead, a threaded plug provides easy access to the viscometer cartridge that resides within the pressure vessel. The viscometer incorporates some design changes as a result of experience gained from use of the original versions.

Construction of a High-Pressure Viscometer
Project Leader: Scott Bair
Sponsors: Laboratoire de Mécanique des Contacts et des Structures, INSA de Lyon

Abstract: The limiting low-shear viscosity of organic liquids at high pressures is of interest to the fields of elastohydrodynamic lubrication. The pressure-viscosity behavior of liquids is essential for the calculation of film thickness and traction in lubricated concentrated contacts. Fine details of chemical structure can produce significant differences in viscosity at gigaPascal pressure. Operating specifications for the proposed instrument are as follows:

Pressure to 0.80 GPa. A commercial pressure transducer with digital readout will provide measurement with estimated accuracy of ± 3 MPa with resolution of 1 MPa. Pressure will be generated in the pressurizing medium (dioctyl sebacate) with an intensifier and hand pump. In a departure from previous viscometers for >0.4GPa, a venting plug will be provided so that pressure may be returned to atmospheric following a measurement at elevated pressure.

Temperature to 160˚C. Temperature will be measured with a type J or K thermocouple. The accuracy of measurement of sample temperature is believed to be ± 0.5˚C. Temperature of the viscometer is maintained and controlled by passing heated air through passages in the vessel.

Viscosity from 5×10^{-4} to 10^{5} Pa•s. The accuracy of the viscosity measurement for normal viscosities is believed to be ± 3%, although repeatability of fall times may be as good as 1%. Three sinkers will be provided to cover this range of viscosity.

Development of an Experimental Pressurized Thin-Film Couette Viscometer and Consultation
Project Leader: Scott Bair
Sponsors: TOTAL Oil Company, Solaise

Abstract: The shear-dependent viscosity of organic liquids at high pressures is of intense interest to the fields of hydrodynamic and elastohydrodynamic lubrication. Many lubricants, however, do not display shear-dependency until the applied shear stress is quite large-greater than 0.3 MPa. For a valid measurement to be made the flow must be essentially isothermal. That is to say, the temperature increase during the experiment must not result in a decrease in the viscosity which would obscure the shear induced change in the viscosity. Capillary viscometers, to a large extent, control the viscous heating by the use of a short capillary to limit the time during which the viscous power is applied to the liquid. With a length of about 10-4 m, a capillary, under some conditions, will provide a satisfactory measurement to a stress of about 0.3 MPa. The circular Couette viscometer may achieve much greater stress without thermal effect by the removal of heat from micron scale films by conduction into high-conductivity cylinders. The Center for High Pressure Rheology at Georgia Tech has gained experience from the development of six different pressurized, thin-film Couette viscometers of increasing capability. These instruments are not routine viscometers; they are experimental devices for which mechanical and electrical failures may be unforeseen and may occur often.

We proposed the construction of a pressurized, thin-film Couette viscometer very similar to one in use in the Center for High Pressure Rheology at the George W. Woodruff School of Mechanical Engineering of Georgia Institute of Technology. Design of this instrument has begun.

MRI-R2: Development of a Precise and High Speed Hydrostatic Dynamometer System for Research and Education in Automotive Propulsion Systems

Project Leaders: Zongxuan Sun, David Kittelson, Kim Stelson

Sponsor: National Science Foundation

Abstract: The objective of this project is to build a state-of-the-art, precise and highly flexible instrument for testing and measuring the fuel efficiency, emissions and performance of automotive propulsion systems. The centerpiece of the instrument is a precise and high-speed hydrostatic dynamometer, which “absorbs” (or “provides”) torques from (or to) the engine/powertrain so that the engine or powertrain can follow any desired rotational speed and acceleration profile. The proposed hydrostatic dynamometer is utilized to experimentally mimic the hybrid drive train, vehicle load, and the hybrid power sources in coordination with an engine control system and a hardware-in-the-loop vehicle driveline emulator. This instrument will allow all aspects of the vehicle propulsion system such as the engine, hybrid transmission, hybrid power sources, energy storage systems, emission control systems and driveline system to be tested or simulated in a real-world driving scenario without actually building the complete physical system. As a shared research infrastructure, the instrument will encourage the interaction and research collaboration of users from multiple departments at the University of Minnesota. Furthermore, it will help to prepare the next generation instrumentalists, researchers and engineers to design and build clean and efficient automotive propulsion systems. The proposed instrument will also be integrated into core mechanical engineering curriculum for both undergraduate and graduate education. It will also enhance collaborations with industrial partners and help to disseminate research results to communities at large.

Shaft Pumping by Laser Structured Shafts with Rotary Lip Seals

Project Leader: Richard Salant

Sponsor: University of Stuttgart/ Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)

Abstract: A simulation model to predict pumping by shafts with various surface finishes, in combination with a rotary lip seal, has been developed and validated by experiment. The model consists of a fluid mechanics analysis of the flow in the sealing zone coupled with a deformation analysis of the seal. The experimental validation consists of pumping measurements with shafts whose surface structures contain laser generated oblique grooves. Plots of pumping rate versus various parameters show good agreement between the model and experiment. Plots of torque vs. speed, as well, show good agreement between the model and experiment.

Associated Project Abstracts: Education and 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.

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, May 2011. In tandem, Dr. Khalil is working to develop the new lab manual to make a smooth transition from the old to the new trainers.

CCEFP role: The Center provided the seed funding for this project in Years 2 and 3.

Purdue University - SURF REU Program
Sponsor: Purdue University
Funding: $16,000 in SURF REU Supplement (recurring)

Abstract: The SURF program provides students across all engineering, science and technology disciplines with an intensive research experience, allowing them to work closely with graduate students and professors in their respective schools. The interdisciplinary aspect 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 and 2010, the CCEFP hosted six REUs at Purdue; two were sponsored by SURF.

The Electrohydraulic Servovalve Coloring Book
Lead Personnel: Rosamond L. Dolid, MTS System Corporation
Sponsor: MTS System Corporation
Funding: Time of R. Dolid at no cost to the Center

Abstract: An electrohydraulic servovalve is a device that takes an electrical current and turns it into hydraulic flow which can then create linear, rotational, uni-directional or reciprocating mechanical motion. The purpose of the coloring book is to facilitate understanding of this complex device, which is not well understood even by those working in the fluid power industry. The inspiration to use coloring as a way of understanding complex ideas is drawn from *The Anatomy Coloring Book* (W. Kapit and L. Elson, third ed., 2002), long used by medical school students to deepen their understanding of how the human body works. Likewise, this book rests on the act of coloring as a means for better understanding just how a servovalve works. It is the first in a planned series of coloring books about fluid power components. College students and degreed engineers working in the fluid power industry are the targeted audiences for the series. Versions of this book have been used to train newly hired engineers at MTS Systems Corporation since 2007.

CCEFP role: Center faculty serve as subject matter experts, and university-level classes provide field testing sites. The book is currently used in course ME4232, Fluid Power Laboratory, at the University of Minnesota.

TRIBES-E: Teaching-Relevant Inquiry-Based Environmental Science and Engineering
Lead Personnel: Dwight Gourneau, NamTech Inc.
Sponsor: CCEFP and National Center for Earth-surface Dynamics (NCED)
Funding: $10,000 (NSF Supplement to CCEFP), $40,000 (NCED)

Abstract: The TRIBES-E project offers professional development opportunities for teachers serving American Indian students in grades 5-12 in Minnesota. The program is aimed at improving student achievement in science by enhancing teaching strategies and teachers' content knowledge in science and engineering. TRIBES-E also integrates indigenous and scientific ways of knowing through an inquiry-based study of ecosystems and related sciences in order to support a regionally relevant, culturally responsive, holistic approach to learning.

A cohort of 25 teachers was selected for the 2010 program which was sponsored by the University of Minnesota's NCED and CCEFP. The program was designed to nurture the seeds of knowledge and respect sewn between Native and non-Native teachers. That knowledge and respect, essential parts of the TRIBE-E community, are the tools that are needed to tackle many of the tough issues facing science educators in Native communities. The centerpiece of the 2010 program was a 5-day summer intensive professional development institute. Thoughout the program, the key focus was on developing access to quality science instruction through culturally responsive teaching. The emphasis of the institute was on issues relevant to the context of Native education, developed through a variety of hands-on experiences that integrated science, technology, engineering, and math as well as a field trip to a Native-owned business.

The contributions of Native specialists, woven throughout the program, were an essential and vital part of the outcome. Three themes that represent the culturally responsive goals/arc of the program are: 1) science as journey, 2) finding common ground, and 3) inviting culture into our class. Science as journey represents the idea that coming to know anything involves a personal journey of discovery. For Native children this means helping them develop a rich set of experiential connections to nature. For teachers it means stepping away from abstract and linear teaching practices that fail to build on the acquired skills, values and knowledge of Native students. It means developing cultural responsive forms of instruction that are grounded in experiences that honor the journey that is science.

CCEFP role: Funded 1/5 of the 2010 program costs. Integrated fluid power curriculum, kits and workshops into the seminar. A 2010 CCEFP REU from Purdue instructed the fluid power segments.

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.

giiwed'anang Northstar Alliance and MN Space Grant
Lead Personnel: Alyssa Burger, CCEFP
Grant: Minnesota NASA Space Grant Consortium
Funding: $1,000

Abstract: The Minnesota NASA Space Grant Consortium will co-sponsor an AISES Rocket Team at the University of Minnesota and Fond du Lac Tribal Community College to compete in the 2011 All Nations Rocket Launch, a program specifically designed for Native American students (through AISES) in STEM fields or students attending tribal and community colleges in Wisconsin and Minnesota.

CCEFP role: The Center is the lead organizer of the giiwed'anang Northstar Alliance (see EO Project C.5). giiwed'anang Northstar Alliance will co-sponsor the rocket teams as well. The program has already sponsored three students to attend a Rocket workshop in Green Bay, WI, December 2010.

NSF ERC Recruiting Project
Lead Personnel: Alyssa Burger, CCEFP
Grant: NSF ERC Program
Funding: $5,000

Abstract: This project is in progress. Preliminary, plans are to build an ERC tradeshow booth for all Center's to share at recruiting events at national conferences such as AISES (American Indians in Science and Engineering Society), SACNAS (Society for Advancing Chicano/Latino and Native Americans in Science), NSBE (National Society for Black Engineers), SHPE (Society for Hispanic Professional Engineers), SWE (Society of Women Engineers) etc. A verbal commitment from NSF has indicated a willingness to support the design and creation of such a such an apparatus.

CCEFP role: The Center will serve as the primary coordinator of this endeavor.

FIRST Robotics Team
Lead Personnel: Will Durfee, CCEFP
Sponsor: FIRST Robotics
Funding: $20,000, University of Minnesota Foundation

Abstract: The goal of this project is to assist in the launching of new Minnesota FIRST Robotics teams. The FIRST Robotics program is successful as an effective channel for introducing children to basic principles of engineering and related disciplines.

CCEFP role: Through academic, outreach and industrial networks, the CCEFP has been key in promoting the FIRST Robotics program to schools in the greater Minnesota region as well as partnering with industry members who serve as mentors and judges at the robotics competitions.

National Center for Earth-surface Dynamics (NCED)
Lead Personnel: Diana Dalbotten, Diversity Director, NCED
Grant: NSF Science and Technology Center, Diversity Programs
Funding: $250,000

Abstract: NCED is a partnership of research and educational institutions, government agencies, and industry that pursues its goal of predictive Earth-surface science by integrating physical, biological, and social sciences. NCED achieves research synthesis by focusing on a fundamental component of the Earth-surface system--channel networks and their surroundings--that recurs in varying but fundamentally related forms across a wide range of environments and scales. NCED collaborates with applied partners to identify knowledge gaps and develop tools to forecast landscape evolution and guide landscape management, restore river systems, find and develop subsurface resources, and promote environmental awareness. NCED shares the excitement of landscape science with a diverse community, exchanging perspectives through partnering, nurturing, and interacting in formal and informal education settings.

CCEFP role: The CCEFP serves as a partner to NCED in the gidaa STEM Programs and gidaa STEM Camps. The CCEFP shares in supporting all efforts of the gidaa STEM Programs, including science fairs, camps and robotics programs. NCED was recently awarded the manoomin (Wild Rice) Project from NSF (see below).

gidaa: The *manoomin* (Wild Rice) Project
Lead Personnel: Diana Dalbotten, Diversity Director, NCED
Sponsor: NCED, LacCore, Department of Geology at University of Minnesota, FDLTCC
Grant: NSF Opportunities for Enhancing Diversity in the Geosciences
Funding: Approximately $300,000 / year

Abstract: The *manoomin* project is designed to investigate the past, present, and future conditions of wild rice lakes on the Fond du Lac Band of Lake Superior Chippewa Reservation. Wild rice *(manoomin; Zizania palustris)* is at the center of Chippewa culture and identity. Some lakes on the Fond du Lac Reservation (FDL) are no longer hospitable to *Z. palustris.* However, the conditions necessary for its growth, its historical habitats, and the causes of recent changes are not well understood. The members of the Reservation are passionate about understanding historical conditions for wild rice growth, current challenges for restoring and enhancing its habitat, and ensuring future production. The answers to these questions will be sought as a collaborative effort between Fond du Lac Tribal Community College (FDLTCC), middle and high school student researchers, and the University of Minnesota (UMN) through the multiproxy analysis of multiple sediment cores from six lakes on the reservation, combined with geophysical profiling, remote sensing and visualization, and historical research. These efforts supplement FDL Resource Management Center's (FDLRMC) long-term modern lake sampling and monitoring program. We propose to build upon the successful science camps *gidakiimanaaniwigamig* (Our Earth Lodge, hereafter "*gidaa*"), for Fond du Lac middle and high school students that have been running as a collaboration between FDLTCC and UMN for the past five years. Students from grades 5-12 and undergraduates will participate in the proposed research through monthly meetings, internships, and pre REU programs. We will support students in their significant transitions: middle to high school, high school to college, and tribal college to 4-year college. The college to graduate school transition will be supported through cooperation with the existing Purdue OEDG program.

CCEFP role: The CCEFP serves as a partner to NCED in the gidaa STEM Programs and gidaa STEM Camps and contributes to the support of all efforts of the gidaa STEM Programs including science fairs, camps and robotics programs. In addition to the research noted above, funds from the *manoomin* (Wild Rice) Project are nearly sufficient to fully support the gidaa STEM Camps. While this funding is key, it is important to note that the *manoomin* project is just one component of the overall gidaa STEM Program/Camp.

Publications

Thrust 1- Efficiency

Bayer, I., A. Steele, P.F. Martorana and E. Loth "Fabrication of superhydrophobic polyurethane/layered silicate nano-structured composites from cyclomethicone-in-water emulsions." Applied Surface Science , pp. 823-826, Vol. 257, (2010).

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