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7th Annual Report
Volume 2

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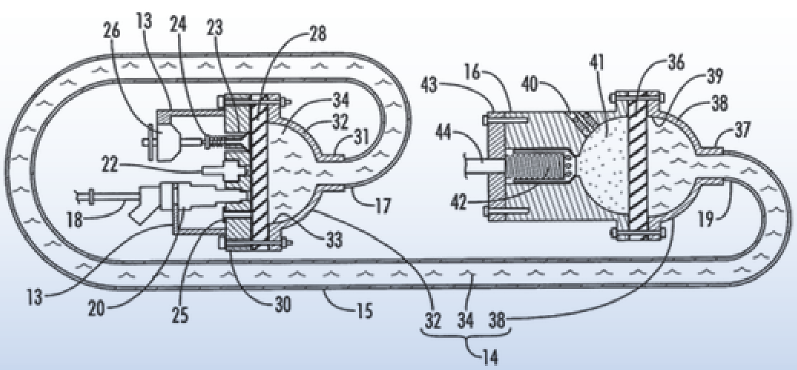

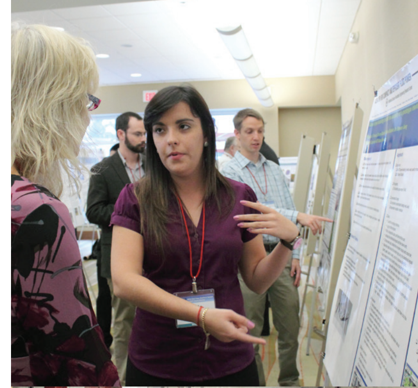

CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

University of Minnesota

Georgia Institute of Technology

Milwaukee School of Engineering

North Carolina Agricultural & Technical State University

Purdue University

University of Illinois at Urbana-Champaign

Vanderbilt University

Dr. Kim Stelson, Director

Dr. Perry Li, Deputy Director

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

RESEARCH PROJECTS

Thrust 1 – Efficiency

Project Name	PI / Institution / Sponsor
1A.1: Technology Transfer Process for Energy Management Systems	Kim Stelson, University of Minnesota; Andrew Alleyne, Univ. of Illinois at Urbana-Champaign
1A.2: Multi-Actuator Hydraulic Hybrid Machine Systems	Monika Ivantysynova, Purdue University
1B.1: New material combinations and surface shapes for the main tribological systems of piston machines	Monika Ivantysynova, Purdue University
1D: MicroTextured Surfaces for Low Friction / Leakage	William King, Purdue University; Eric Loth, Purdue University
1E.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor	Perry Li, University of Minnesota; Thomas Chase, University of Minnesota
1E.3: High Efficiency, High Bandwidth, Actively Controlled Variable Displacement Pump/Motor	John Lumkes, Purdue University; Monika Ivantysynova, Purdue University
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	Perry Li, University of Minnesota; Thomas Chase, University of Minnesota
1E.5: System Configuration & Control Using Hydraulic Transformers	Perry Li, University of Minnesota
1E.6: High Performance Actuation System Enabled by Energy Coupling Mechanism	John Lumkes, Purdue University; Monika Ivantysynova, Purdue University
1F.1: Variable Displacement Gear Machine	Andrea Vacca, Purdue University
1G.1: Energy Efficient Fluids	Paul Michael, Milwaukee School of Engineering
1J.1: Hydraulic Transmissions for Wind Energy	Kim Stelson, University of Minnesota;
Advanced Energy Saving Hydraulic System Architecture for a Wheel Loader	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Advances in External Gear Machines Modeling	Andrea Vacca, Purdue University *Sponsors:* Casappa S.p.A.

Project Name	PI / Institution / Sponsor
Advances in Modeling External Spur Gear Machines and Development of Innovative Solutions	Andrea Vacca, Purdue University *Sponsors:* Casappa S.p.A.
Design of low noise emission internal gear machines	Andrea Vacca, Purdue University *Sponsors:* Confidential
Design of positive displacement machines for SCR automotive applications	Andrea Vacca, Purdue University *Sponsors:* Confidential
Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump	Andrea Vacca *Sponsors*: Confidential
Effect of Various Oils on the Efficiency of a Series Hydraulic Hybrid	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	Perry Li, University of Minnesota Terrence Simon, University of Minnesota *Sponsors:* National Science Foundation
Energy Saving Hydraulic System Architecture Utilizing Displacement	Monika Ivantysynova, Purdue University *Sponsors*: Confidential
Evaluation and Design Improvements for a Hydraulic Pump	Monika Ivantysynova, Purdue University *Sponsors*: Confidential
Evaluation of a Proprietary Gear Pump	Andrea Vacca, Purdue University *Sponsors*: Confidential
Evaluation and Design Improvements for a Hydraulic Pump	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Modeling and Analysis of Axial Piston Pump	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Modeling and Analysis of Swash Plate Type Axial Piston Pump (Interface)	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Modeling of Axial Piston Pumps and Motors	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
PCA Mule- System Implementation and Testing	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Performance Prediction and System Control through Coupled Multi-domain Models: A Comparison Study	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Pump Dynamic Model Development	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Reliable Lightweight Transmission of Off-shore Utility Scale Wind Turbines	Kim Stelson, University of Minnesota Brad Bohlmann, University of Minnesota *Sponsors:* Eaton Corporation, Clipper Wind Power, UMN's Eolos Wind Consortium

Thrust 2 – Compactness

Project Name	PI / Institution / Sponsor
2B.1: Free-Piston Engine Compressor	Eric Barth, Vanderbilt University
2B.2 Miniature HCCI Free-Piston Engine Compressor	David Kittelson, University of Minnesota Will Durfee, University of Minnesota
2B.3: Free Piston Engine Hydraulic Pump	Zongxuan Sun, University of Minnesota
2B.4: Controlled Stirling Thermocompressors	Eric Barth, Vanderbilt University
2C.2: Advanced Strain Energy Accumulator	Eric Barth, Vanderbilt University
2C.3: Flywheel Accumulator for Compact Energy Storage	James D. Van de Ven, University of Minnesota
2D: Multifunctional Fluid Power Components Using Engineered Structures and Materials	Vito Gervasi, Milwaukee School of Engineering Douglas Cook, Milwaukee School of Engineering
2E: Model-Based Systems Engineering for Efficient Fluid Power	Chris Paredis, Georgia Tech
2F: MEMS Proportional Pneumatic Valve	Thomas Chase, University of Minnesota
2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems	Robert Webster, Vanderbilt University Jun Ueda, Georgia Institute of Technology
Functionally Graded Metallic Lattice Components for Advanced Propulsion Components	Vito Gervasi, Milwaukee School of Engineering *Sponsors:* DARPA
Open Accumulator Compressed Air Storage Concept for Wind Power	Perry Li, University of Minnesota Terrence Simon, University of Minnesota *Sponsors:* University of MN; IonE and IREE

Thrust 3 – Effectiveness

Project Name	PI / Institution / Sponsor
3A.1: Teleoperation Efficiency Improvements by Operator Interface	Wayne Book, Georgia Institute of Technology; Steven Jiang, North Carolina A& T State University
3A.3: Human Performance Modeling and User Centered Design	Steven Jiang, North Carolina A&T State University Zongliang Jiang, North Carolina A&T State University
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	Andrea Vacca, Purdue University
3D.1: Leakage/Friction Reduction in Fluid Power Systems	Richard Salant, Georgia Institute of Technology

Project Name	PI / Institution / Sponsor
3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems	Scott Bair, Georgia Institute of Technology
3E.1: Pressure Ripple Energy Harvester	Kenneth A. Cunefare, Georgia Institute of Technology
Adaptive Control for Oscillation Damping	Andrea Vacca, Purdue University *Sponsors:* CHN America, Inc.
Analysis of transmission noise sources	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Development of an Experimental Pressurized Thin-film Couette Viscometer and Consultation	Scott Bair, Georgia Institute of Technology *Sponsors:* Total Oil Company
Evaluation of the High Pressure, High Shear Stress Capability at Georgia Tech	Scott Bair, Georgia Institute of Technology *Sponsors:* Lubrizol Corp.
Multimodal Human-Machine Interface design with Augmented Reality and Ergonomics	Silvanus J. Udoka, North Carolina A&T State University *Sponsors*: Confidential
Optimization of Valve Plate to Reduce Noise and Control Effort for Axial Piston Pump	Monika Ivantysynova, Purdue University *Sponsors*: University of Stuttgart/German Research Foundation
Shaft Pumping by Laser Structured Shafts with Rotary Lip Seals	Richard Salant, Georgia Institute of Technology *Sponsors:* University of Stuttgart/German Research Foundation; The Toro Company
Suppressor System Development	Kenneth Cunefare, Georgia Institute of Technology *Sponsors*: Eaton Corporation
Understanding and Reducing the Adverse Effects of Biodynamic Feedthrough	Wayne Book, Georgia Institute of Technology *Sponsors:* Caterpillar, Inc.; Bobcat; Deere and Company.
CPS: Synergy: Integrated Modeling, Analysis and Synthesis of Miniature Medical Device	Pietro Valdastri, Vanderbilt University *Sponsors*: National Science Foundation

EDUCATION AND OUTREACH PROJECTS

Project Name	PI / Institution / Sponsor
EO A.1 Interactive Exhibits Fluid Power	J. Newlin Jr, Science Museum of Minnesota
EO A.3 Multimedia Educational Materials	Alyssa Burger, University of Minnesota Kim Stelson, University of Minnesota

Project Name	PI / Institution / Sponsor
EO B.1 Research Experiences for Teachers (RET)	Alyssa Burger, University of Minnesota
EO B.3 Hands-on Fluid Power Outreach	Alyssa Burger, University of Minnesota Will Durfee, University of Minnesota
EO B.3a Hands-on Pneumatics Workshop	Will Durfee, University of Minnesota
EO B.3b Portable Fluid Power Demonstrator and Curriculum	John Lumkes, Purdue University Will Durfee, University of Minnesota
EO B.4 gidaa K12 STEAM Programs	Alyssa Burger, University of Minnesota
EO B.4a gidaa K-12 STEAM Camp	Alyssa Burger, University of Minnesota
EO B.4b gidaa odaangiina anaangoog (Shooting for the Stars) Robotics Program	Alyssa Burger, University of Minnesota
EO B.5: BRIDGE Project	Paul Imbertson, University of Minnesota Alyssa Burger, University of Minnesota
EO B.7 NFPA Fluid Power Challenge Competition	Alyssa Burger, University of Minnesota
EO C.1 Research Experiences for Undergraduates (REU)	Alyssa Burger, University of Minnesota
EO C.2 Fluid Power OpenCourseWare	Will Durfee, University of Minnesota James Van de Ven, Univ. of Minnesota
EO C.3 Fluid Power Projects in Capstone Design Courses	James Van de Ven, University of Minnesota Will Durfee, University of Minnesota
EO C.4 Fluid Power in Engineering Courses	James Van de Ven, Univ. of Minnesota Will Durfee, University of Minnesota
EO C.5 giiwed'anang North Star Alliance	Alyssa Burger, University of Minnesota
EO C.6 Fluid Power Simulator	Will Durfee, University of Minnesota Christiaan Paredis, Georgia Institute of Technology
EO C.8 Student Leadership Council	Alyssa Burger, University of Minnesota Kim Stelson, University of Minnesota
EO C.9 Undergraduate Research Diversity Supplement (URDS)	Alyssa Burger, University of Minnesota
EO C.10 Graduate Research Diversity Supplement Program (GRDS)	Alyssa Burger, University of Minnesota Kim Stelson, University of Minnesota
EO C.11: Innovative Engineers	Paul Imbertson, University of Minnesota Alyssa Burger, University of Minnesota
EO D.1 Fluid Power Scholars Program	Alyssa Burger, University of Minnesota Linda Western, University of Minnesota
EO D.2 Industry Student Networking	Alyssa Burger, University of Minnesota
EO D.5 CCEFP Webcast Series	Alyssa Burger, University of Minnesota
EO D.6 Publication	Kim Stelson, University of Minnesota Linda Western, University of Minnesota
EO E.1 Evaluation	Paul Imbertson, University of Minnesota Alyssa Burger, University of Minnesota
EO Assoc Project: Zephyr Wind Power Teaching Training Workshop	Alyssa Burger, University of Minnesota

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

Research Team

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

1. Statement of Project Goals

The goal of this project is to develop and implement a well-defined process for transferring energy management technology developed within the Center to industrial partners supporting the CCEFP. From previous Center-funded work in the study of energy management strategies (EMS), it was concluded that there is no single strategy that is optimal for all applications [1-6]. These algorithms have been successfully implemented on a test setup at the University of Illinois, and this project aims to develop a method to transfer these algorithms to industry partners to be used on industrial applications. We will develop a formal process for transitioning some of the algorithms developed to practitioners as well as develop a software framework for interfacing to the available tools. The project will rely on a small set of companies who will provide the beta test group for the resulting process.

2. Project Role in Support of Strategic Plan

The project addresses a particular aspect of the efficiency barrier by providing a pathway for efficient operation algorithms developed within the Center to be readily implemented up by industrial partners. It will provide an easy interface for the choice of appropriate energy management strategies and will provide results in a format readily usable by practitioners.

As importantly, this project will provide a set of 'best practices' for transitioning the tools from the academic setting to the industrial setting. These can be used by other projects throughout the Center that generate design tools or system models. We feel this will be a good approach to attracting industry support and supporting Center sustainability.

3. Project Description

A. Description and explanation of research approach

This project is the outcome of a request by CCEFP industrial advisory board members to take the CCEFP research results and put them in a form that can be easily adapted by industry members. We propose to create a process for moving a particular CCEFP technology from university to industry. This technology is the energy management strategies developed within the previous project 1A.1. These strategies are essentially control algorithms that use optimization of various levels to manage the power production, energy distribution, energy storage, and potential energy recovery in mobile hydraulic systems while maintaining prescribed levels of performance. The goal is then to create a process with metrics and milestones that one can use to track and guide the maturation of control algorithms to the point where they are in a good position to be readily utilized by industrial practitioners for their own product development.

Multiple energy management strategy (EMS) tools have been created within Project 1A.1 with a motive towards creating a toolbox. The tools within the toolbox will be applied to different problems with the choice of tool depending on the a priori level of knowledge about the duty cycle under which the system will operate and other design attributed of the system. At present, the tools involve Rule Based Controllers based on Deterministic Dynamic Programming results, Model Predictive Controllers, and Stochastic Dynamic Programming; these are given here in the order of increasing knowledge required for effective implementation. The general concept for this approach can be seen in Figure 1.

By understanding the vehicle being designed and the various design attributes, it is possible to choose the most appropriate tool for the EMS. Currently, the role of the Decision Algorithm is filled by CCEFP researcher expertise. It is our goal to make that algorithm into a more user-friendly tool.

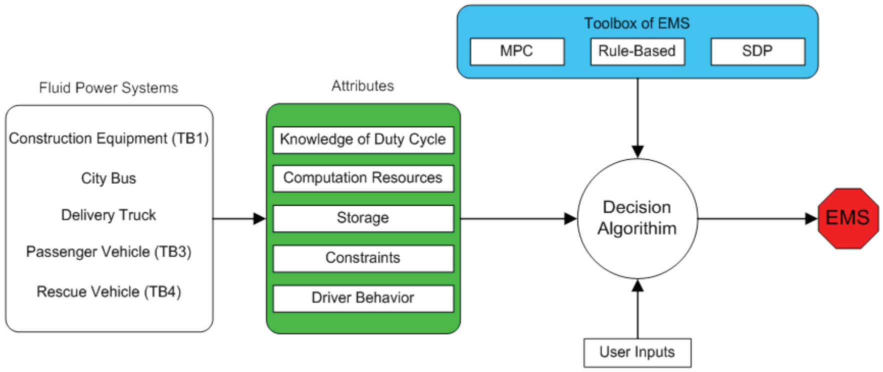

Figure 1: Implementation of the 1A.1 EMS Toolbox

The approach is a five phase process. The first phase is to understand the 'voice of the customer'; in this case, a group of industry participants most likely to utilize the tools. By understanding their goals and constraints, it will be easier to tailor the EMS algorithms and turn these into controllers and decision-making strategies that can be implemented within industrial hardware. The second phase, closely tied to the first, is to define a format for information entry that would be suitable for a large class of users. We may not be able to please all but we would find formats that could be used by several. The third phase is to determine a suitable test platform to work out development issues. This would need to be a system (e.g. wheeled loader) that has attributes common enough to a large segment of our industry partners to allow for framework development having broad applicability. This will allow other systems to be added, either in-house by company engineers or by CCEFP researchers at later dates. The fourth phase, which is the most challenging, is to actually create this framework using readily accessible tools. A Visual Basic or Java-based toolset seems to be very appropriate for incorporating the input and using a decision tree to determine a candidate control approach. The actual control design would then be performed with an adjacent tool, most likely Matlab/Simulink, that would be able to provide the control designer the freedom and flexibility to tune their designs repeatedly. The fifth phase is to implement it on the test platform, evaluate the process utility, and iterate on any gaps in the process. Throughout, the industry test group will be co-developing this tool with us and providing feedback as to what works and what could be improved. They will assist in developing some of the interfaces and decision support tools as well.

B. Achievements

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

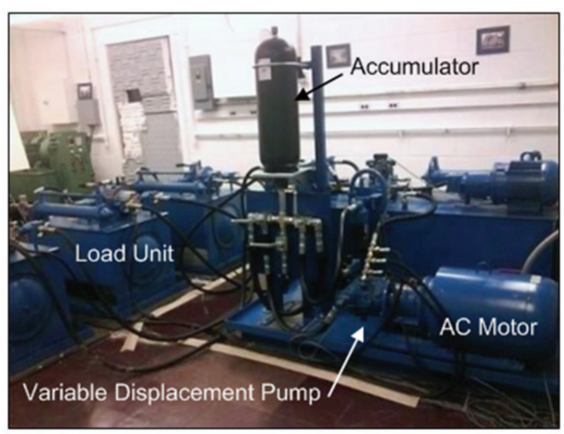

Figure 2: AEVPS System

When implementing the rule-based, model predictive control (MPC), and stochastic dynamic programming (SPD) energy management strategies onto the AEVPS, hardware and computing constraints had to be satisfied. For the rule-based and SDP strategies, a proportional plus integral feedback controller was employed to regulate the valve opening and ensure tracking of the desired hydraulic motor speed. The error signal sent to the controller is the difference between the desired and measured motor speed. Also, due to noise in the motor speed measurement, a first-order low pass filter was applied to the signal before calculating the tracking error. Figure 3 shows a comparison of the simulation and experimental results for the rule-based strategy. The experimental results show spikes in the engine speed which do not appear in the simulation results. This was expected since the simulation from which the rule based strategy was derived did not include the engine dynamics for computation time. The engine speed fluctuations cause slight variation in the accumulator pressure, but the motor speed is still able to track the reference speed. The simulated and experimental fuel consumption results are within 5% of each other, showing good agreement.

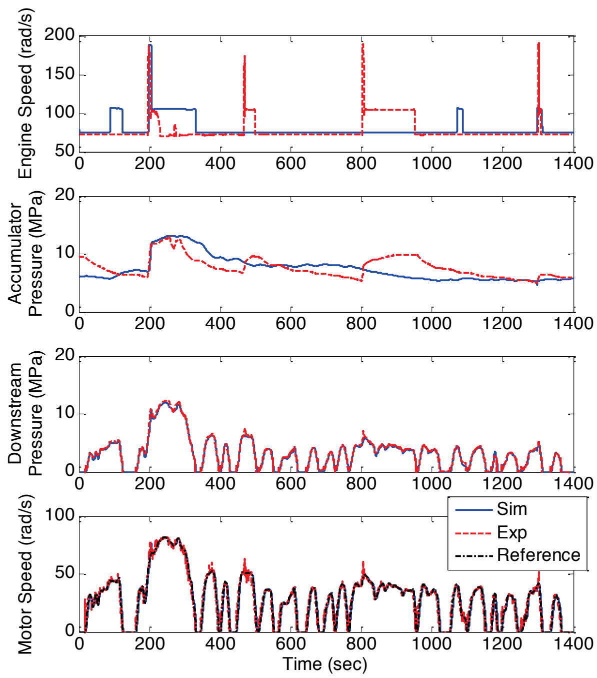

Figure 3: Comparison of simulation and experimental results for rule-based strategy

The MPC strategy was implemented using an update rate of 1Hz and a prediction horizon length of 5 steps. These values allow for real-time execution while balancing the step size against the prediction horizon length. A 10 second dwell time is also incorporated to prevent the high frequency switching between engine idle and engine load. Also, all control signals are passed through a first-order low pass filter to smooth the inputs and prevent exceeding actuation bandwidth limitations. Figure 4 shows the comparison of the simulation and experimental results for the MPC strategy. The response is nearly identical over the UDDS cycle. One difference is the accumulator pressure, which loses charge faster than the simulation results. This is due to un-modeled losses in the accumulator. Like the rule-based strategy, the fuel consumption between the simulation and experiment are within 5% of each other.

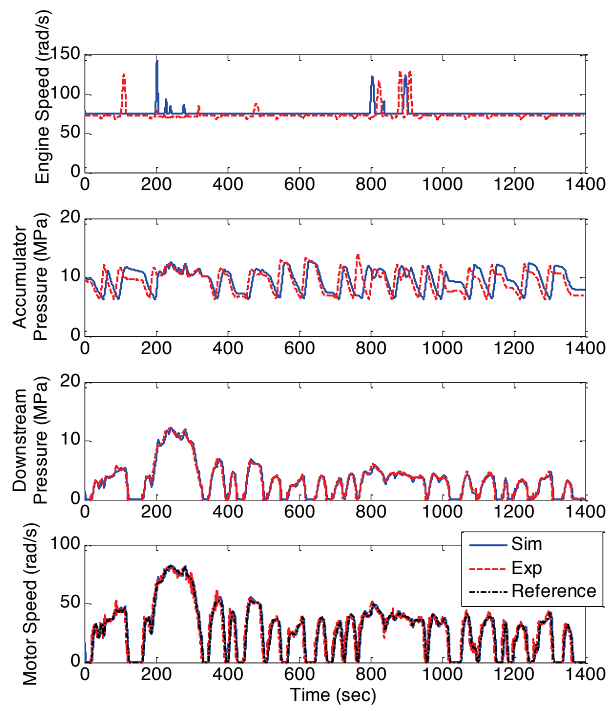

Figure 4: Comparison of simulation and experimental results for MPC strategy

Finally, the SDP strategy was implemented on the hardware with a discrete update rate of 10Hz for the look-up tables to ensure time for the controller to complete the interpolation between update steps. Due to hardware bandwidth limitations of the actuators, the outputs of the look-up tables are passed through a first order low pass filter to prevent the high frequency response given by the SDP solution. Imposing these limitations did affect the tracking performance of the controller, but are necessary for physical implementation. Figure 5 shows the comparison of the simulation and experimental results for the SDP strategy. The most significant different is that the engine speed falls below the idle speed in the experimental case when the motor speed is high. Also, the error in the reference speed tracking, especially at high motor speed, is greater than the previous two cases. However, the fuel consumption between the simulation and experimental results is also with 5% of each other.

Since all three strategies show agreement between the simulation and experimental results, simulation can be used to do further studies for which method works better for different scenarios. Using the transition probabilities developed for the SDP algorithm, 100 random drive cycles with urban driving characteristics were generated. Each of the three strategies was then simulated through each of the drive cycles. To quantify the performance of each strategy, two metrics were considered: the fuel consumption and the tracking error. The fuel consumption for each is normalized with respect to the fuel consumption of a non-hybrid vehicle for the same drive cycle. This provides a reference point to assess the relative improvement of each strategy for all drive cycles. The root mean square tracking error is a measure of how closely the vehicle speed agrees with the desired speed from the drive cycle. Figure 6 shows the mean fuel consumption results relative to a non-hybrid vehicle. The error bars represent ±1 standard deviation from the mean. The SDP approach achieved the greatest improvement in fuel economy with small variance between urban drive cycles. The MPC and rule-based achieved similar performance overall, with the rule-based having a larger variance. This is not surprising since the rule-based approach was tuned for a specific drive cycle so it would be more prone to variance in the drive cycle. Figure 7 compares the tracking error between the three strategies for the same 100 random drive cycles. The rule-based strategy achieved the lowest tracking error while the SDP strategy had the highest error. This is due to the consequence of its sensitivity to errors in the model due to offline optimization, while the rule-based strategy incorporates a proportional-integral controller for tracking the desired speed. Based on these results, the rule-based strategy is the best compromise between fuel improvement and reference tracking.

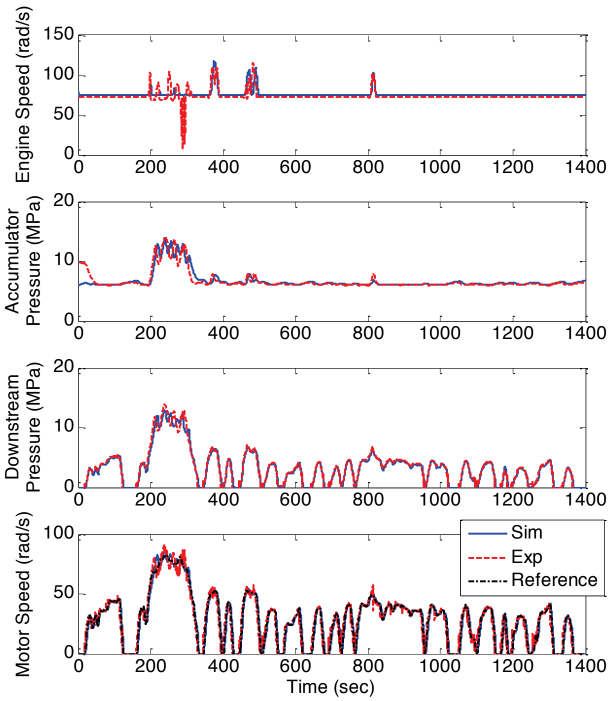

Figure 5: Comparison of simulation and experimental results for SDP strategy

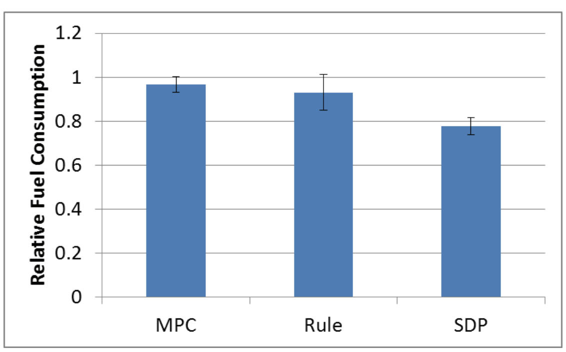

Figure 6: Mean fuel consumption relative to a non-hybrid for urban driving

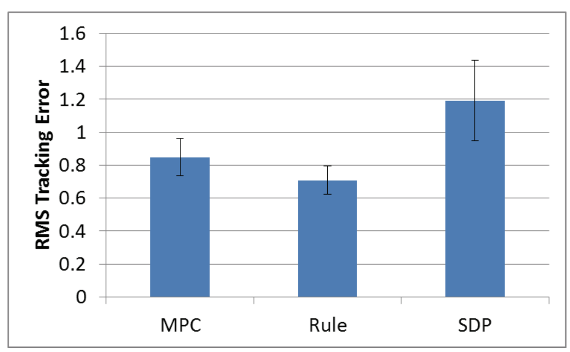

Figure 7: Mean tracking error for urban driving

A similar study was performed using random highway driving cycles. As with the urban driving case, the SDP strategy achieves the lowest average fuel consumption but with the poorest mean tracking performance. The rule-based strategy achieved the worst fuel economy performance with tracking performance nearly as bad as the SDP solution. Finally, the MPC strategy has the best tracking performance and less fuel consumption than the rule-based result. Combining the above observations, the MPC strategy is the most robust and would be best for highly uncertain applications, the SDP strategy is best suited in predictable environments with well-defined models, and the rule-based method is best suited for applications with known trajectories, such as city buses. A journal article for the ASME Journal of Dynamic Systems, Measurement and Control with the above results was submitted and is currently under review.

We have held teleconference meetings with various fluid power companies to gauge their interest and to identify possible industrial applications as test platforms. The two companies that have shown a significant interest are Eaton and Sauer Danfoss. We have held further teleconference meetings with these companies and have determined that a set of linearized state-space equations is the best way to express the models of the physical hardware. The Matlab/Simulink software was also chosen as the best software for the development of the models. We are continuing to work with these companies to obtain the models of their systems in this format and eventually incorporate the EMS strategies on the physical system.

Expected Milestones and Deliverables

- Development of first-draft of toolbox (4/2013)
- Implementation of EMS strategies on industrial applications (5/2013)
- Toolbox refinement (6/2013)
- Validation of toolbox on multiple industry owned systems (1/2014)
- Extension of toolbox to other energy domains (1/2016)

C. Member company benefits

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

D. References

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

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

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

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

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

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

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

Research Team

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

1. Statement of Project Goals

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

Since August 2012, the project has been focused on reducing production costs, further improving system efficiency and introducing effective machine prognostics of highly efficient displacement controlled hydraulic machines. It has been demonstrated that up to 39% of the system energy is lost through pump losses. To achieve lower production costs and higher system efficiencies, pump switching between actuators during machine operation will be analyzed, thus reducing the number of and size of the pumps installed in the hydraulic system and ultimately leading to lower parasitic losses. Such concepts are especially important for large machines where the current design approach requires the installation of large pumps. Preliminary simulations of a single pump, two actuator displacement controlled system have shown that pump switching is a viable solution to reduce production costs of multi-actuator displacement controlled machines and increase system efficiencies. Another goal of the project is the development of effective machine prognostics concepts. These will allow for the prediction of impending failures thereby avoiding expensive machine breakdowns making displacement control a more competitive technology.

2. Project Role in Support of Strategic Plan

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

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

3. Project Description

Description and explanation of research approach

Traditionally in multi-actuator machines using hydraulic actuation, one or two large hydraulic pumps transmit power from the engine. Control valves that are downstream of the pumps, arranged in series or parallel, are responsible for controlling actuator motion according to operator input. Such configurations incur in energy losses since they throttle flow through the valves and additionally, do not allow energy recovery from aiding loads. Alternative system designs, such as displacement control, have already demonstrated improvements in efficiency, as was shown on Test Bed 1.

Hybrid vehicles have been studied for years in the transportation sector and recently there has been increasing interest in hybridizing off-highway applications such as in construction, mining and agricultural machines. This is a result of rising fuel costs and more stringent emission regulations. Much of the focus has been on electric hybrids and Case, Kobelco and Komatsu have released hybrid electric construction equipment to the market. Little focus, however, seems to have been placed on hydraulic hybrid systems. Through project 1A2, hydraulic hybrid configurations for multi-actuator machines have been investigated and combined with displacement controlled actuation for the entire system.

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

Prior to 1A2, optimal control studies that generate dynamically optimal results had not been previously undertaken for off-highway applications. Dynamic programing was utilized to formulate the optimal control problem. This allowed for a method of benchmarking implementable control techniques, and a reference for designing simpler, rule-based techniques.

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

The breakdown of a construction machine at the construction site often involves not only an expensive in-field service; it can disrupt the whole construction site and in the worst cases cause death or serious injury. There has been an increase in interest of machine manufacturers and end users on implementation of condition monitoring allowing flexible maintenance intervals and a reduction of machine breakdowns. More and more off-road vehicles produced today are equipped with sensors to monitor the condition of the fluid and to detect engine and electric system failures. Different methods for a more complex approach of condition monitoring and fault diagnostics of hydraulic systems have been developed [11- 14], but the application on mobile machines until today is mainly focused on monitoring of fluid properties and load cycles.

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

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

- The DC hydraulic system is operational and was demonstrated by video at the CCEFP annual meeting on October 7, 2009 and in person to a delegation from Caterpillar on November 4, 2009.

- 40% fuel savings were demonstrated [16] at a Caterpillar facility in independent side-by-side testing of the prototype DC excavator and the standard Bobcat mini-excavator, in August, 2010 for an aggressive truck-loading cycle with loose soil.
- Through an optimal power management strategy [10], 56% fuel savings were demonstrated over the standard excavator system in September, 2010.
- Feasibility studies for the parallel hybrid excavator architecture were completed showing that more than 50% fuel savings over the standard valve-controlled excavator system, together with 50% engine downsizing, can be achieved without loss of performance of the working functions.
- Novel series-parallel hybrid architectures were proposed, patented and analyzed in simulation demonstrating fuel savings of at-least 20% over the prototype DC system.
- An implementable rule-based strategy which replicates the optimal trends formulated for the hydraulic hybrid using the dynamic programing technique was proposed and analyzed.
- A new methodology was proposed for sizing the pump adjustment system (selection of valve flow gains, control pressure and control cylinder diameter) to satisfy requirements on pump response times, power and pump size for displacement controlled system architectures.
- A complete thermodynamic model has been developed to predict the system and actuator temperature in displacement controlled multi-actuator machines. The model has been verified through temperature measurements of the test bed 1 during standard machine operation [17].

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

Pump Switching Model

Figure 1 shows the proposed basic hydraulic circuit for the simulation of pump switching.

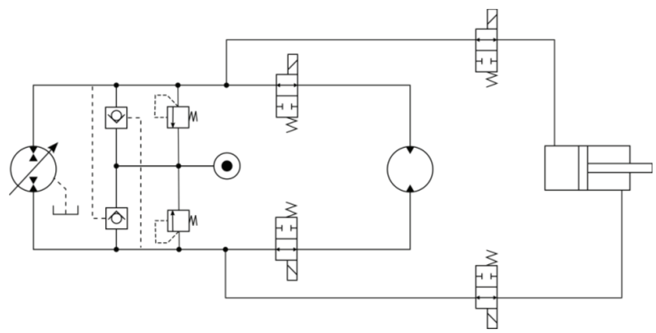

Figure 1: Multiple actuator pump switching model

An iterative approach, which solves for the pressures in the actuator chambers as well as the pump's high and low pressures to then solve for the cartridge valves flow based on the differential pressure and spool position was utilized. The main advantage of utilizing this approach is that, due to the model dependence on pressure difference, the calculation of the valves opening and closing transitions is greatly simplified and stability of the solution is guaranteed. Figures 2-4 show the simulated pump and actuators pressures.

Open flow from pump to motor (no flow to cylinder)
Open flow from pump to cylinder (no flow to motor)

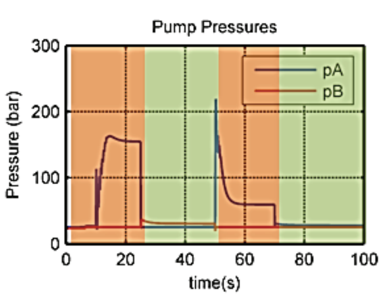

Fig. 2: Simulated pump pressures

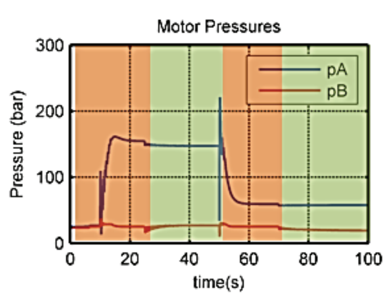

Fig. 3: Simulated motor pressures

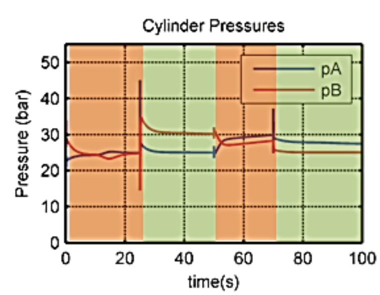

Fig. 4: Simulated cylinder pressures

It can be observed that pressure transients exist; however, the response time, as shown in Fig. 5 and Fig. 6, is adequate as the actuator positions are well tracked. The development of robust controls to eliminate these pressure transients is essential for this technology. It is important to note that for this simulation the control loop is closed using the actuator control. To adapt this technology to mobile systems, the development of actuator open loop controls is crucial.

Open flow from pump to motor (no flow to cylinder)
Open flow from pump to cylinder (no flow to motor)

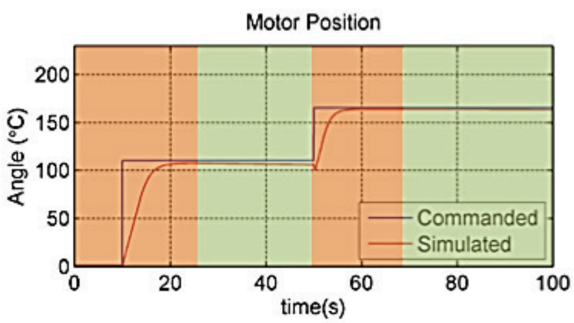

Fig. 5: Motor commanded and simulated positions

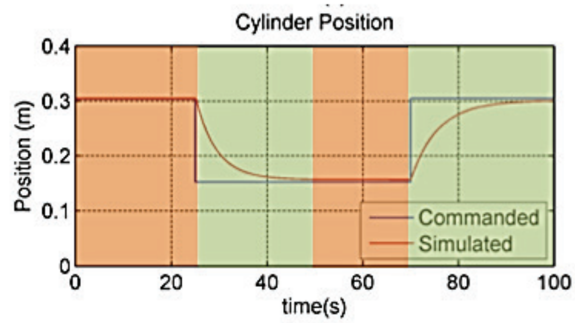

Fig. 6: Cylinder commanded and simulated positions

Test-rig Implementation of Pump Switching

Figure 7 shows the proposed test rig to validate the simulation described above. The primary pump (1), an 18 cc/rev axial piston pump, is already installed in the test rig. The switching block (3) has already been manufactured and installed in the test rig. For this particular case, the addition of a secondary pump (2) on the gear box is required for the compensation of the considerable cross-port leakage inside the vane motor. This pump is a cost-effective solution acting as a brake holding the rotary actuator position when no movement is commanded. In order to do this a second block (4) would need to be added.

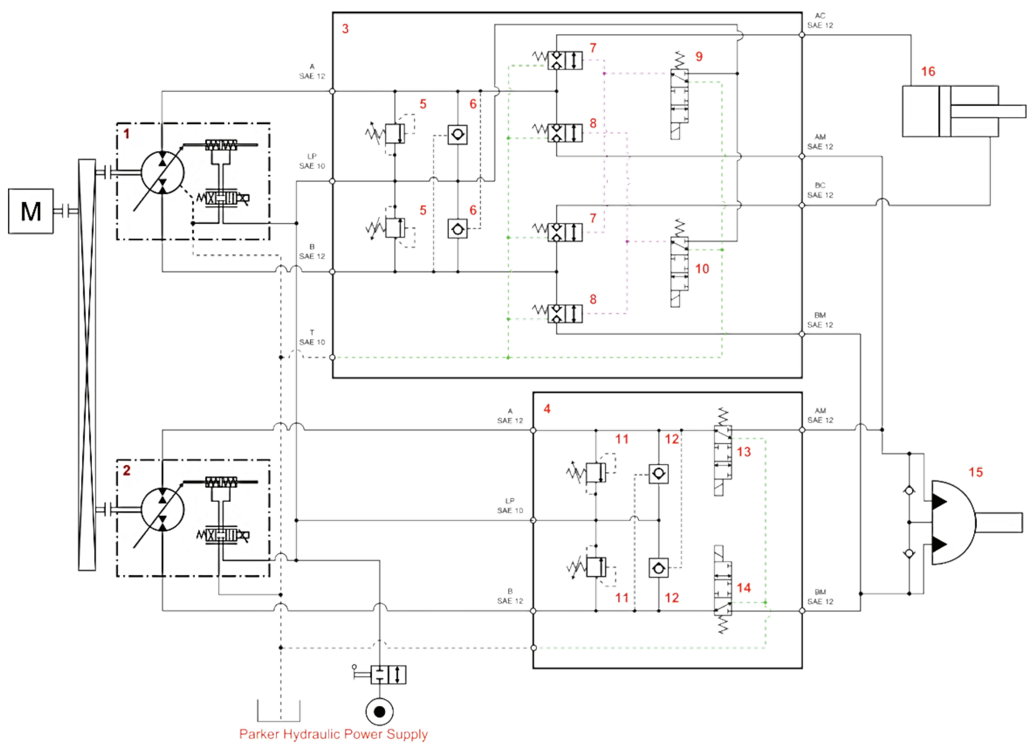

Fig. 7: Proposed test rig for the validation of a single-pump two-actuator basic hydraulic system

Planned Achievements following the reporting period

- Design, modeling, simulation and implementation of a simple pump switching architecture
  - Deliverables
    - Validated model that can be implemented in the development of a displacement controlled excavator such as test-bed 1 [01/03/2013]
- Design, modeling and simulation of both hybrid and non-hybrid multi-actuator displacement-controlled architectures with pump switching
  - Deliverables:
    - Hydraulic circuit schematics with pump switching for 5-ton and 20-ton displacement controlled excavators both hybrid and non-hybrid [01/05/2013]
    - Multi-body dynamic and hydraulic co-simulation models of 5-ton and 20-ton excavators including engine, hydraulics, and machine structure [01/08/2013]
- Develop intelligent controls for handling pump switching transitions
  - Deliverables:
    - Optimal pump controls for pump switching transitions to minimize pressure transients resulting from opening and closing valves [01/06/2013]
- System prognostics design, study, simulation, and implementation
  - Deliverables:
    - Analyze proposed DC system architecture with pump switching in order to identify different system failure modes [01/10/2013]
    - Study the applicability of system diagnostics based on monitoring of thermodynamic system behavior. [01/12/2013]
    - Defined applicable diagnostics and condition monitoring methods [01/12/2012]
    - Simulated machine fault detection [01/06/2014]
    - Simulation results for all proposed prognostic concepts [01/12/2014]
    - Implemented and fully functional system prognostics [01/06/2016]

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

C. Member Company Benefits

The results of project 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 hydraulic actuation systems.
- The results of this project have already shown that up to 40% fuel savings can be achieved, and potentially up to 50% fuel savings have been predicted in simulation over the standard excavator system. This would clearly be a benefit to OEM companies within the center.
- The improved efficiencies and potential for reduced engine power made possible by the technologies being developed in this project will help OEMs meet upcoming emission regulations under the TIER emissions standards.
- The improved efficiencies offered by the technologies developed in this project will reduce the cooling requirements for mobile machines saving cost and space for machine production.
- The work done toward improving swash plate adjustment systems for displacement controlled actuators will aid in reducing the cost of bringing the technology to production.
- The possibility of reducing production costs using pump switching will certainly facilitate the introduction of this technology to the market.

- The implementation of advanced prognostic systems will increase machine reliability over traditional systems and will make displacement controlled actuation a more competitive technology.
- Project 1A2 has led to associate projects where multiple sponsors have worked with the Maha Fluid Power Research Center, with a total funding amount of $1,310,000 since June, 2006.

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

Research Team

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

1. Statement of Project Goals

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

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

2. Project Role in Support of Strategic Plan

Piston pumps form the heart of new energy saving displacement controlled hydraulic systems and hydraulic hybrids, both of which are new concepts that have been proposed and developed in the CCEFP. By improving the efficiency of pumps and motors over a wide range of operating conditions, it enables these new system designs to successfully compete with alternative technologies. Therefore, the project primarily addresses the efficiency of these machines. It does this by providing a deeper understanding of the lubricating gap's behavior and enabling digital prototyping of a new generation of pumps and motors. Digital prototyping represents practical design method to create more efficient designs which utilize new technologies for surface shaping, material coatings and other advanced manufacturing technologies.

3. Project/Test Bed Description

A. Description and explanation of research approach

Positive displacement pumps are a critical element of hydraulic systems. Although numerous pump designs exist, swash plate type axial piston machines are widely used today in industry due to their high pressure and variable displacement capabilities, and their cost to efficiency ratio. The hydraulic systems in which these machines are used demand a wide range of pump operating conditions, necessitated by system performance requirements. Unfortunately, axial piston machines reach their peak efficiency only over a limited range of operating conditions near full displacement. The sealing and bearing gaps separating the movable parts of the rotating group (piston, slipper, and cylinder block) form the most critical design element of piston machines. These gaps, as illustrated in Fig. 1, determine in large part the achievable

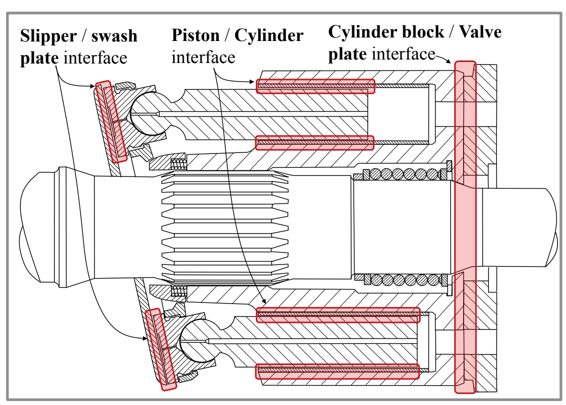

Figure 1: Swashplate axial piston machine cross section and identification of the three lubricating interfaces

machine performance (speed, pressure, and maximum swash plate angle) and overall efficiency.

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

B. Achievements

Achievements prior to the reporting period:

Significant work has been conducted to model the lubrication inside axial piston machines, in large part due to previous CCEFP projects. Numerical models were developed initially that considered most parts to be rigid and undeformable due to hydrostatic or hydrodynamic pressures. Those models were extended to consider solid body pressure deformation starting with the cylinder block – valve plate interface. This model considering cylinder block deformation was used by Baker and Ivantysynova[1] to investigate a circumferential micro-waved pattern on the valve plate surface. The simulation model predicted up to 60% reduction of total power losses associated with the cylinder block interface when a circumferential pattern of 1μm amplitude was introduced. Testing on a prototype showed up to 10% improvement in overall pump efficiency.

Since that work, progress has been made advancing the fidelity of the numerical models for all three lubricating interfaces. This has allowed all the bounding bodies to be considered deformable and included the solid body thermal effects such as temperature surface distribution and thermoelastic deformation. In particular, the work of Pelosi and Ivantysynova [6], [7], [8] has resulted in a numerical model that is able to simulate the piston pump lubrication with excellent accuracy. The model was instrumental in discovering how surface deformations enable high pressure operation of axial piston pumps[4]. Figure 2 shows experimental and simulation comparisons of the lubricant temperature field between the piston and cylinder bore in as measured in a special test rig. (Additional results are reported in [5])

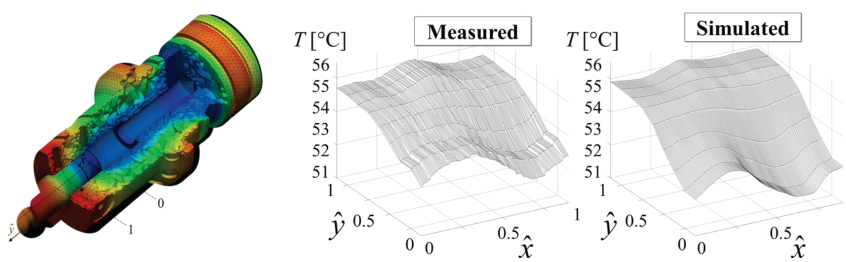

Figure 2: comparison of the measured and simulated temperature field in the lubricating film (EHD test rig).

Achievements during the reporting period:

The piston/cylinder couple, the lubricating interface performance in axial piston machines can be successfully predicted only by including and coupling together different physical phenomena in the analysis[7]. During the reporting period, a multi-domain model for the cylinder block / valve plate interface was completed. Figure 3 illustrates an overview of the model.

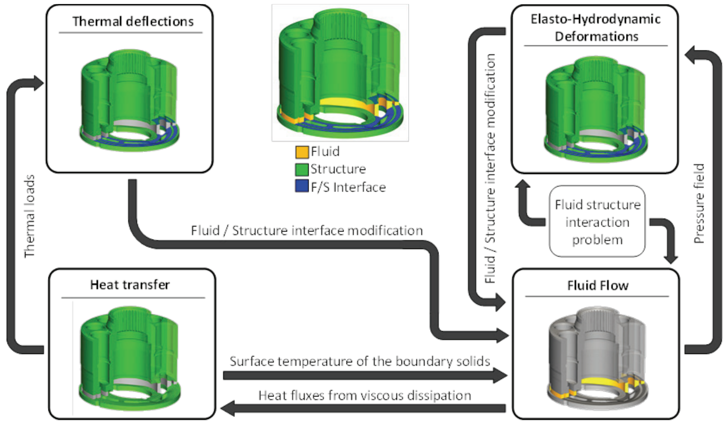

Figure 3: Overview of the multi domain model for the cylinder block / valve plate interface

The model solves different problems in the fluid and structural domains and the solutions are coupled together through the common interface. Each problem is addressed by a specific module, where the most effective solution approach has been pursued and implemented. The fluid flow module considers the fluid film domain, governed by the Reynolds and the Energy equations:

$$\nabla \cdot \left(-\frac{\rho h^3}{12\mu}\nabla p\right) + \left(\frac{\boldsymbol{V}_t + \boldsymbol{V}_b}{2}\right) \cdot \nabla(\rho h) - \rho \boldsymbol{V}_t \cdot \nabla h_t + \rho \boldsymbol{V}_b \cdot \nabla h_b + \rho(w_t - w_b) \quad (1)$$

$$\nabla \cdot \left(\rho \boldsymbol{V} T - \frac{\lambda}{c_p}\nabla T\right) = \frac{\mu}{c_p}\Phi_d \quad (2)$$

In Eq. 1 the subscripts “b” and “t” identify the bottom and the top surface respectively, because the Reynolds equation has been specifically derived to account for any kind of inclination or deformation of both cylinder block and valve plate surface. The velocity of the boundary surfaces along the film was indicated with V and the velocity component across the film with w. It is important to note that viscosity is allowed to change along the film, whereas is assumed to be uniform across the film. A detailed fluid model was implemented that allows viscosity and temperature to be expressed as functions of pressure and density through correlations derived directly from measurements. In the energy equation (Eq. 2) conduction and convection in the film are considered, as well as heat generation (Φ_d) associated with the viscous dissipation which is expressed as a dissipation function for a Newtonian fluid. In the fluid flow module, the equilibrium of the cylinder block body is obtained using a multidimensional root finding algorithm which iteratively changes the squeeze term $\rho(w_t - w_b)$ until force equilibrium is reached.

The Elasto-Hydrodynamic (EHD) module considers the structural domain and calculates the elastic deformation of the solid parts (i.e. cylinder block and valve plate & end case assembly). The structure is loaded with the pressure field in the lubricant and combined with other loads coming from the pressurized fluid present in the displacement chamber and ports. The minimum potential energy formulation of the finite element method is used to solve the problem and an offline approach is used to speed up the computation. The change in the fluid/structure interface due to the elastic deformation is fed back to the fluid flow module for a correction of the fluid film thickness. Pressure, fluid film thickness, and elastic deformation are mutually dependent and therefore a Fluid-Structure Interaction problem arises. A partitioned Fluid-Structure Interaction algorithm with dynamic under-relaxation was introduced for the coupling of fluid flow and EHD modules.

The heat fluxes towards the solid parts, associated with the viscous dissipation in the lubricant are calculated in the fluid flow module. These fluxes represent a boundary condition in the solution of temperature field in the solid parts, calculated in the heat transfer module. The Galerkin formulation of the finite element method is used to solve the conductive form of the energy equation. The temperature field of the solid parts is then used for two purposes: first to improve the temperature boundary condition applied on the fluid structure interface in Eq. 2; second to calculate the temperature induced strains and associated thermal loads of the solid parts, as indicated in Eq. 3.

$$F_{th} = \int_V B^T C \varepsilon_T \tag{3}$$

In Eq. 3, ε_T is the coefficient of linear expansion, C the constitutive matrix of the material and B the strain-displacement matrix. In the Thermal Deflections module, the solid body deflections are calculated again with a finite element analysis and the relative deformations impacting the shape of the fluid/structure interface is fed back to the fluid flow module for further correction of the fluid film thickness.

A first validation of the model was carried out by comparing the predicted valve plate surface temperature field with measurements. Figure 4 illustrates the comparison at one operating condition.

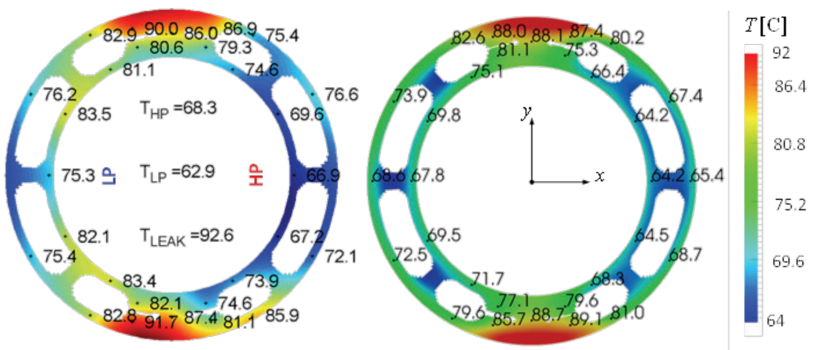

Figure 4: Measurement (left) vs simulation prediction (right) at n=3000 rpm, Δp=300 bar, 100% displacement

The first validation presented showed high accuracy in the prediction of the simulation model both in terms of magnitude and distribution of the surface temperature field. This would suggest a good level of confidence that the predicted film thickness is in good agreement with the actual operational clearance. These results represent significant progress compared to the previous model presented by [9]. However, further experimental validation has been planned for later this year. A different industrial production axial piston pump will be equipped with thermocouples in the valve plate surface and a similar investigation will be carried out for a wider range of operating conditions.

Planned Achievements following the report period

Development underway. Sensor selection and calibration for the new test rig to measure the fluid film thickness between the slipper and swashplate in a specially modified axial piston pump. Further work is required to finalize test rig design and make the required modifications. Once all the components have been machined, the final assembly will require delicate grinding of components to ensure a micron perfect fit. The pump will then be run under a variety of operating conditions and the measured data will be compared to simulation results.

A baseline thermal model was developed to predict the pump discharge and leakage port temperatures. More work is required to allow the model to be expanded to a wide range of operating conditions, different pump sizes, as well as predict other viscous heating inside the pump such as churning losses.

Work on utilizing digital prototyping and optimization techniques will begin soon to investigate various combinations of piston-cylinder material and design combinations using the latest model developed by Pelosi and Ivantysynova. This study will include:

- Deeper simulation study of the thermal waving effect in the piston-cylinder interface using the latest developed numerical models.
- Digital prototyping of new material designs and proposal of best piston cylinder design.

- Physical prototyping of a piston cylinder combination guided by the digital prototyping results and experimental testing. Deliverables include the physically prototyped part and a comparison of measurement results to simulated predictions.

C. Member company benefits

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

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Project 1D: Microtextured Surfaces for Low Friction and Leakage

Research Team

Project Leader:	William King, Mechanical Science and Engineering, UIUC
Other Faculty:	Randy Ewoldt, Mechanical Science and Engineering, UIUC
Graduate Students:	Michael Johnston, Ashwin Ramesh
Industrial Partners:	Trelleborg, Eaton, Caterpillar, John Deere, Hoowaki

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

Our ultimate goal is to enable leak-free components with friction lower than state of the art. Such a technology would overcome current barriers to fluid power systems (efficient components, leak-free) and provide a transformational capability for future fluid power systems (efficient components and systems). The technology will be validated through collaboration with industry and through application to the excavator and orthosis test beds. The work will also improve fundamental understanding critical to fluid power components. Finally, Professor Randy Ewoldt has been brought into the Center, fulfilling the University of Illinois obligation to hire new faculty in support of CCEFP.

3. Project Description

A. Description and explanation of research approach

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

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

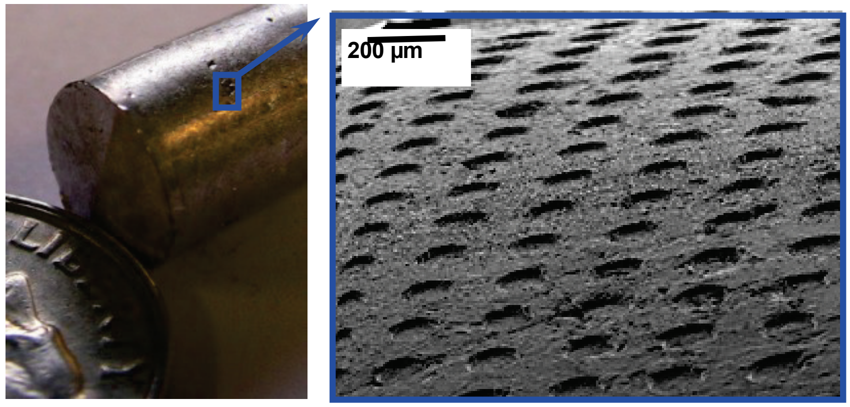

Figure 1: Metal surfaces fabricated with surface micro-textures. This surface is similar to a rod surface we will explore in the proposed research.

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

Now that design rules have been validated for reduction of friction in constant load applications, we are seeking to develop and validate design rules for constant gap applications and to further reduce or eliminate leakage. First, to develop design rules for constant gap applications, a more fundamental understanding of the physical mechanism of the development of normal forces must be achieved. There is disagreement in literature about the exact physical mechanism, but there is some experimental evidence for cavitation being the primary mechanism [11]. This fundamental understanding will be completed by further development of the computational tool used to predict friction reduction and through constant gap experiments on a rotational rheometer. Second, after the design rules have been validated for constant gap applications we will use our computational tool to develop intuition on how to design microtexture shape, orientation and asymmetry along with design of viscoelastic fluid properties to further reduce or eliminate fluid leakage.

B. Achievements:

Microtextured surfaces decrease friction: Computational fluid dynamics (CFD) simulations to model fluid flow and friction between sliding surfaces have been performed. Figure 2 shows the computational regime which consists of two walls in relative motion, one of which is textured and the other is smooth. The velocity, gap thickness, fluid properties, pressure, and texture width, depth, and periodicity can all be defined within the simulation. Figure 2 shows a 2D calculation, although we have also performed 3D simulations and have found the results to be easily scaled from one to the other. The simulations were validated through constant load experiments in a commercial tribometer. The experiments tested textured steel surfaces that were manufactured using the techniques described above. The goal of these experiments was not to mimic fluid power conditions, but to validate the simulation. Figure 2 shows experimental and simulation results at 0.36 m/sec speed, 5.3 MPa pressure, 1.5 Pa-sec viscosity (gear oil) and 30% texture density. Friction reductions as much as 80% lower than untextured surfaces were achieved and results were published in Tribology International [10].

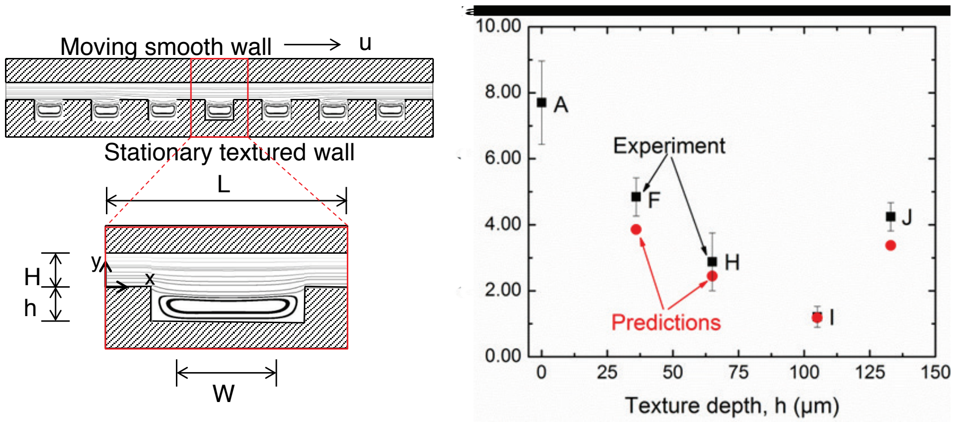

Figure 2: Left: computational regime which consists of two walls in relative motion, along with the key texture dimensions. Right: Computational and experimental results, showing friction force as a function of texture width.

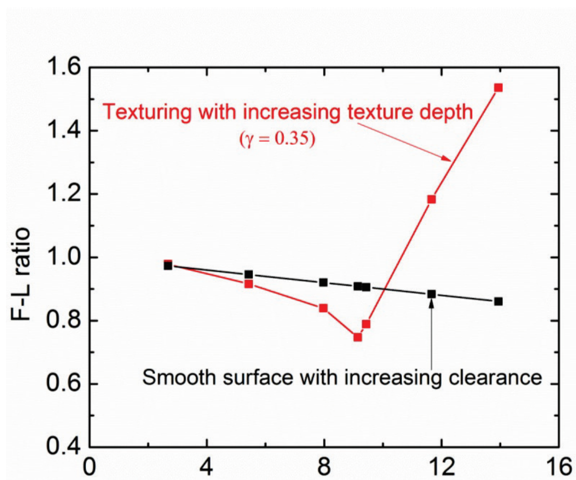

Figure 3: Comparison of the friction and leakage characteristics of smooth and textured surfaces. The F-L ratio is the ratio of friction decrease to leakage increase. For a range of parameters, the microtextured surfaces have clear benefits compared to smooth surfaces.

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

<u>Gerotor roller application</u>: Low efficiency in gerotor motors in the startup regime due to high static friction has been a major concern in the fluid power community. In this collaboration with Project 1.B2, starting friction is being addressed by surface texturing the faces of the gerotor roller. Experimental and numerical work conducted at Purdue University has suggested a static friction

reduction of up to 25% through surface texturing compared to untextured surfaces. The roller has micro-grooves parallel to its axis (Figure 4) and the cylindrical counter bodies have rectangular textures with width 50 µm in 100 µm spacing. These components will be tested for static friction performance in lubricated and unlubricated conditions.

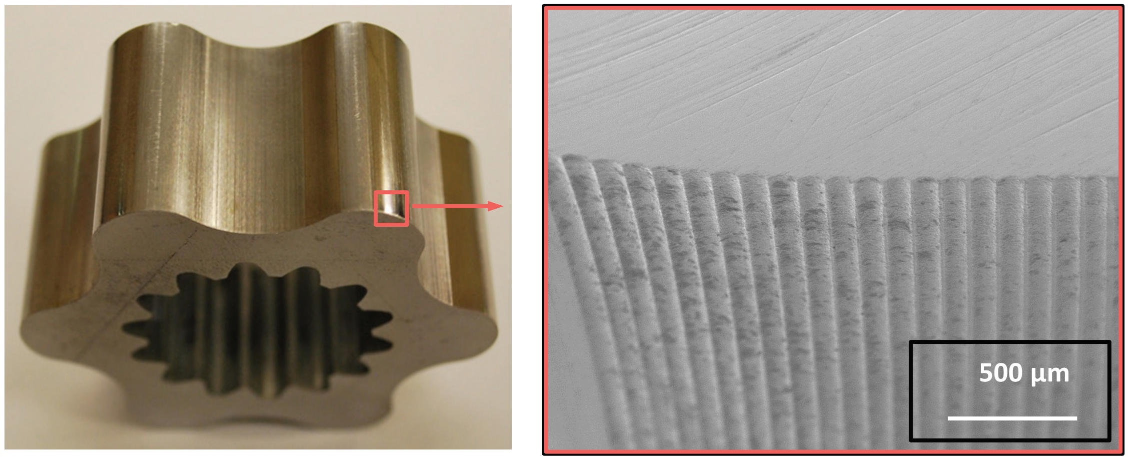

Figure 4: Microtextured gerotor roller (Project 1.B2). SEM image of the textured portion indicates rectangular grooves for reduced start-up friction.

<u>Improved fundamental understanding:</u> To design microtextured surfaces to further reduce or eliminate leakage, we need to fundamentally understand the mechanism by which friction is reduced and normal forces develop. This is being achieved through CFD simulations. We have developed a non-dimensional understanding of how friction reduction and inertial normal forces scale. Figure 6 shows three different microtextures with differing dimensional values that have the same non-dimensional geometry parameters, H*, D*, and W*. Results from simulations show that non-dimensional normal force, P*, and shear stress, T*, are equal for the three microtextures at a given Reynold's number, Re_H. We have also developed understanding of when the system starts to transition from a viscous scaling of normal force, P^*_{vis}, to an inertial scaling, P^*_i. This has enabled design of constant gap microtextures for experimental testing in a rotational rheometer. In conjunction we have started to develop CFD capabilities that will enable us to explore the impact of viscoelastic properties on fluid leakage.

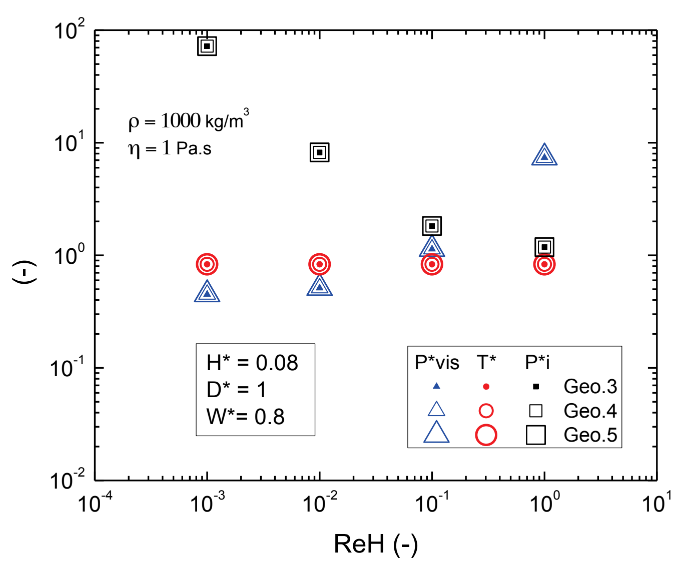

Figure 6: Non-dimensional analysis of reduction in torque (T*), equivalent to friction, and increase in pressure (P*), equivalent to normal force, for given non-dimensional parameters (H*, D*,W*)of microtextures. Dimensional values for each microtexture vary.

Experimental setup for visualization: To validate CFD design tools we have developed an experimental setup that will enable us to vary testing gap while measuring or controlling normal force, velocity and torque (friction). This allows us to test geometries at various non-dimensional values by changing velocity and gap height independently. Along with this robust control we will also be able to visualize the microtextured surfaces and the physical mechanism by which normal force is developed (Figure 7). This is achieved by using a glass bottom plate and mirror. Also shown in Figure 7 are the experimental limits of our instrument. We have validated the “low torque limit” of the instrument with our glass bottom plate setup. This confirms that we have not introduced any new experimental errors due to the custom made setup and conveys the wide experimental range of velocities we can achieve.

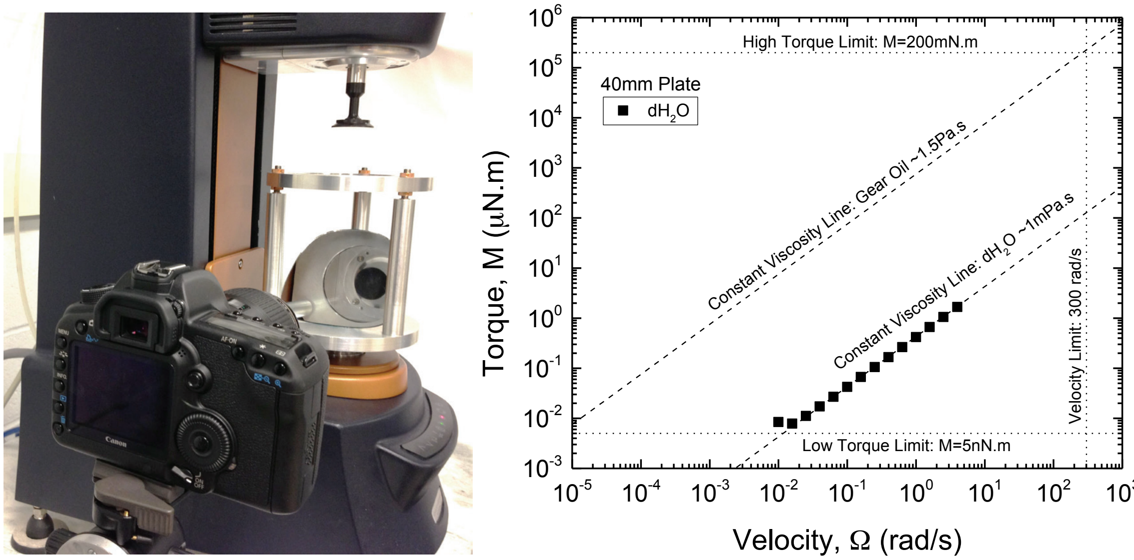

Figure 7: TA Instruments DHR-3 rotational rheometer with experimental glass plate setup and camera. Glass bottom plate is adjustable with sub-micron alignment. Also shown is validation data on the low torque limit with other machine limits.

In year one going forward we expect to complete experimental measurements of friction and normal force on a constant gap rheometer with microtextured surfaces and verify CFD models. Along with that we will design asymmetric microtextures and viscoelastic fluids for leak-free, low-friction seals. We also anticipate initiating fabrication and testing of asymmetric microtextures with viscoelastic fluids. In year two, we are expecting to complete fabrication and testing of asymmetric microtextures with viscoelastic fluids along with testing leak-free, low-friction seals on center test beds.

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 microtexturing echnology shown in Figure 1. Several CCEFP member companies have already purchased microstructured tools from Hoowaki in order to accelerate the insertion of this technology. This CCEFP project aims to develop the design rules for the tools that they are acquiring.

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

Research Team

Project Leader: Perry Y. Li, University of Minnesota, Mechanical Engineering
Other Faculty: Thomas R. Chase, University of Minnesota, Mechanical Engineering
Graduate Students: Ed Sandberg, 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 efficient, high performance control of hydraulic power using on/off valves in a throttle-less manner. This goal will be met through the development of critical enabling technologies such as novel high speed rotary on/off valves that will be integrated into virtually variable displacement pump/motors (VVDPM) 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 was conceived to improve valve efficiency at high pressure and high bandwidth operation by simplifying the valve flow path while simultaneously reduce the internal compressible volume. Prototype targets include 21-35MPa operating pressure, system bandwidth in excess of 10Hz and hydraulic valve efficiency greater than 85% at 50% displacement.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

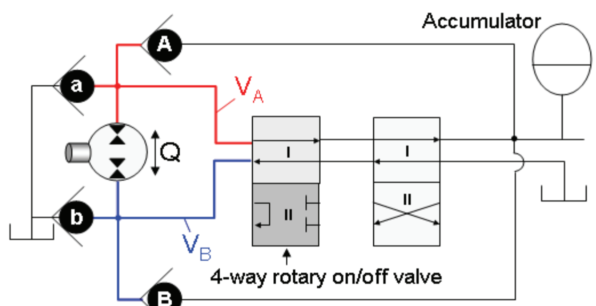

Figure 1: Hydraulic schematic of a VVDPM using a 4-way tandem rotary on/off valve. Check valves a and b prevent cavitation while check valves A and B reduce pressure spikes during transition.

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

The lack of high-flow, 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 and have fast transitions to reduce the time when the valve is partially open. In addition, 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 that must be accelerated and decelerated rapidly for PWM control. This requires large actuators since power input is proportional to the cube of the PWM frequency.

The approach used in Project 1E.1 is to develop novel on/off valves that use continuous rotary motion to generate on/off switching [10]. These rotary valves do not need to start and stop; therefore, the only power required is to overcome friction (proportional to frequency squared). 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 valves found in the literature [2, 3] are compared to the prototype rotary valve in Fig. 2.

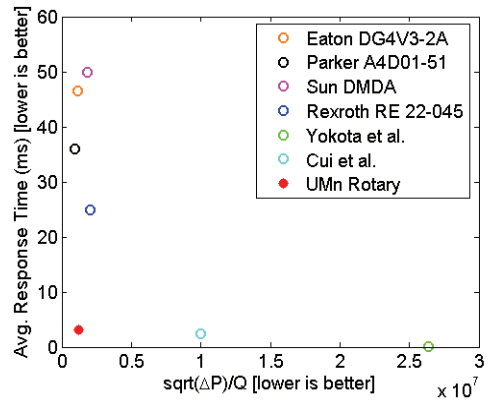

Figure 2: Effective flow area and response times of existing on/off valves

B. Achievements

The goal of this project is to develop two rotary valve prototypes that will be integrated into VVDPMs for demonstration on Test Bed 3, the hydraulic hybrid passenger vehicle. The plan is to replace the speeder pump/motor of the vehicle, which is used for decoupling the engine speed from the wheel speed [11]. The first prototype is based on the spool valve architecture that has been under development since the inception of the CCEFP [10,17]. This architecture has evolved from a 3-way self-spinning design for the control of fixed displacement pumps to a 4-way tandem design for the control of pump/motors [13,16]. The second prototype is based on a novel ring valve that was proposed with the goals of improving valve efficiency in VVDPMs during high pressure, high PWM frequency operation.

Rotary 4-way spool valve prototype

Achievements over the past year include: fabrication of all prototype components, successful modification of the fixed displacement pump/motor with a custom housing for integration with the rotary valve, and preliminary testing of the prototype valve,. These achievements are described in order below.
A major achievement in the past year was successful fabrication of all of the prototype 4-way rotary valve components. Finding a shop to cast and machine the custom pump/motor housing, required for reducing the internal switched volume of the VVDPM, was a significant challenge which led to several design iterations. The custom pump housing, along with the prototype rotary valve spool, sleeve, and sleeve housing, are shown in Fig. 3.

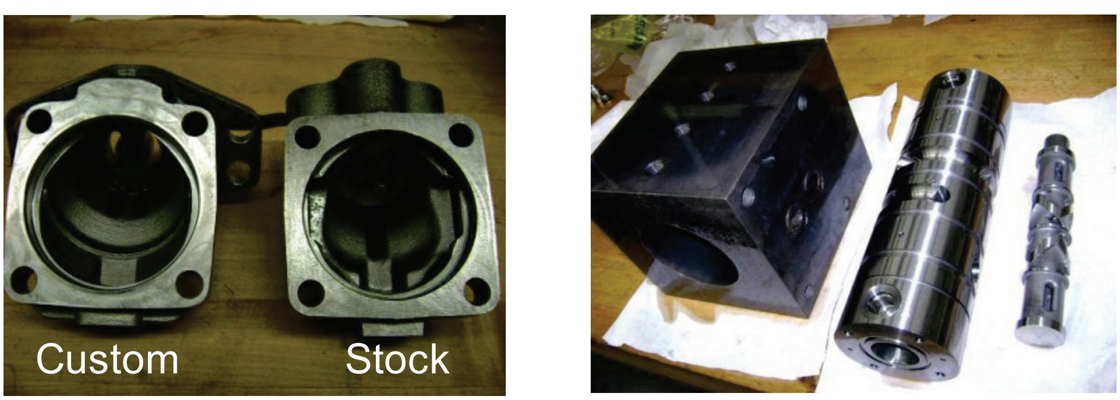

Figure 3: The image on the left shows a comparison of the custom and stock pump housings. The image on the right shows the valve spool (right), sleeve (middle) and sleeve housing (left).

Another noteworthy achievement was the successful modification of the fixed displacement pump/motor, which required considerable disassembly of the stock unit to insure proper timing between the shaft and cylinder barrel. After modification the pump/motor was run and tested at pressure. The measured case flow at 21MPa (3000psi) was within the manufacturer's specifications, indicating that the unit was functioning properly.

The fully assembled prototype rotary valve, shown in Fig. 5, was an additional milestone. The valve exhibited unusual behavior during initial bench-top testing that was later attributed to internal leakage. Disassembling the valve revealed voids in the spool body that were due to casting defects (see Fig. 6). 3M acrylic adhesive was used to seal the internal voids. Static testing at 14MPa (2000psi) verified that the repair was successful. Further testing validated the new magnetic linear encoder axial sensor as well as the functionality of the rotary valve at low pressure and PWM frequencies up to 40Hz. In the horizontal orientation shown in Fig. 5 with the pump/motor attached to the valve via hoses, the system was run at 40Hz PWM frequency for minutes at a time without issue, with the longest run on the order of 10 minutes.

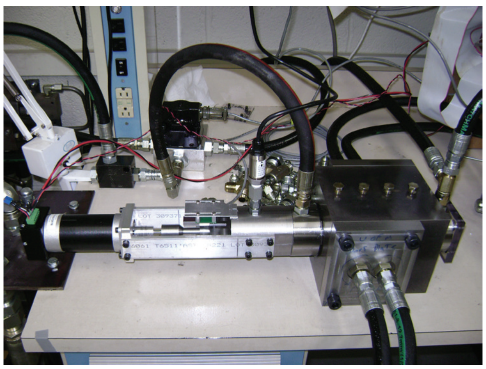

Figure 5: Fully assembled prototype rotary valve including external driving mechanism and axial sensor.

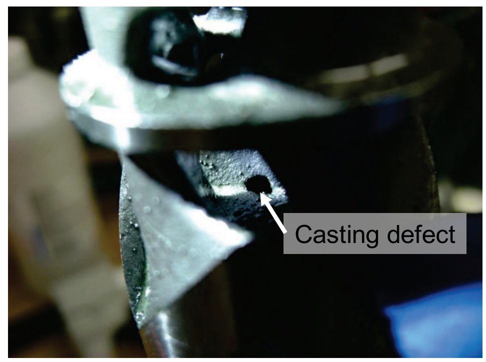

Figure 6: Casting defects within the spool resulted in internal leakage in the rotary valve. The spool was repaired with 3M acrylic adhesive.

Once preliminary bench testing was complete, the prototype valve was transported to Sauer-Danfoss in Ames, IA for more rigorous testing. The test circuit illustrated in Fig. 7 was set up in one of their test cells (see Fig. 8). Initial testing consisted of characterizing the fixed displacement pump/motor in pump mode to establish a baseline of the modified unit. Baseline testing was completed successfully with speed and pressure maps recorded. Unfortunately, testing with the rotary valve mounted to the pump/motor was plagued by seizing. Less than 5 seconds of rotary run time was managed despite numerous attempts to clean and repair the valve. A scanning electron microscope (SEM) was used to analyze particles found after filtering a sample of solvent that was used to clean the prototype components. The SEM detected PTFE, 8620 steel, stainless steel, zinc, and plain carbon steel, as shown in Fig. 9. The valve was completely disassembled, the critical diameters of the spool and sleeve honed, and all of the parts thoroughly cleaned with solvent. The test stand was completely flushed and filters were installed in all upstream lines. Upon reassembly, the spool seized almost immediately as testing resumed.

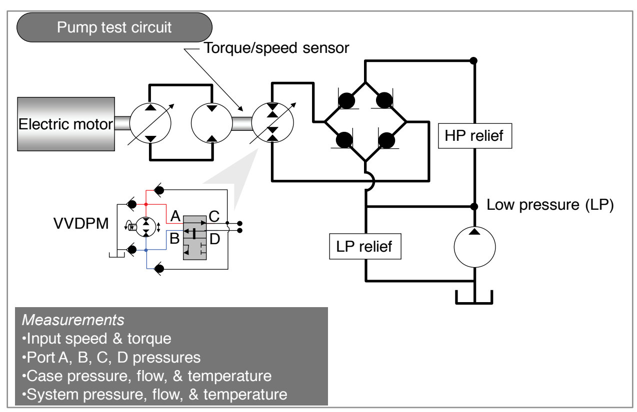

Figure 7: VVDPM pump test circuit used in test cell at Sauer-Danfoss in Ames, IA. The 4-way check allows testing both shaft directions of the pump without the need to reconfigure the circuit.

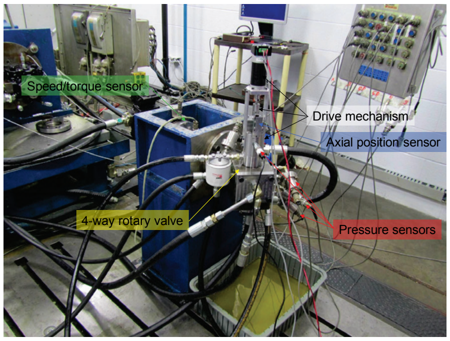

Figure 8: Prototype VVDPM in test cell at Sauer-Danfoss in Ames, IA.

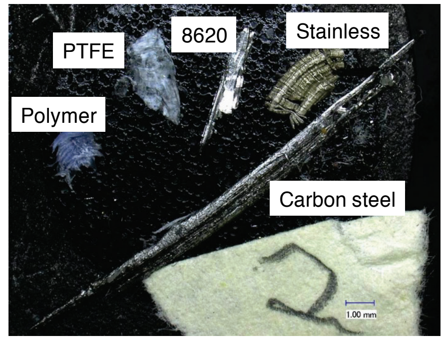

Figure 9: Scanning electron microscope (SEM) analysis of filtered solvent used to clean the prototype valve revealed numerous contaminants.

The setup was returned to Minnesota for further investigation. A new student, Ed Sandberg, was brought onboard for this task and to complete the testing. The device was disassembled and cleaned. Significant scratches and scorings were observed on the outer diameter of the spool and on the inner diameter of the sleeve. The inner diameter of the valve sleeve was then honed to polish the surface, and the edges of the port openings were slightly rounded to reduce interaction between the spool and sleeve during both axial translation and rotation of the spool. Conditions under which seizing occur were systematically identified. Specifically, seizing appears to occur when the sleeve ports interact with certain parts of the helical regions of the spool. This occurs even when pressure is not applied but is exacerbated by the application of pressure and in the presence of flow through the valve.

Further investigation is in progress to determine the cause of the seizing and to correct it when the next spool is manufactured.

Rotary 4-way ring valve based design

The final achievement over the last year was completion of a preliminary comparison via simulation of the 4-way rotary spool valve with the next generation 3-way ring valve. Preliminary geometry, pressure drops from computational fluid dynamics analysis (CFD), and analytical power loss study are compared in Table 1. Internal switched volumes of the valve (V_A and V_B) are reduced by over 50% in the ring valve. Full open pressure drops are predicted to be less as well. While the ring valve is predicted to experience higher friction and leakage due to its structure, the compressibility losses as well as full open throttling losses are significantly reduced. Fig.10 compares motoring efficiency maps between the two valves that includes the effects of compressibility, leakage, throttling, and actuation (friction) losses. The ring valve exhibits a flatter efficiency curve with respect to shaft speed indicating that the ring valve is capable of higher flow rates. There is roughly a 5% improvement in efficiency across the entire map.

	4-way	Ring
N	3	3
D (mm)	30	60
Ar (mm^2)	35.1	35.2
V_A (cc)	25.5	9.4
V_B (cc)	42.4	20.5
ΔP_{ON} (psi)	88.1	62.7
ΔP_{OFF} (psi)	88.1	20.1
$\pi_{friction}$ (W)	16.2	43.1
π_{leak} (W)	62.2	121.6
π_{comp} (W)	339.5	74.8
$\pi_{open,ON}$ (W)	827.3	588.7
$\pi_{open,OFF}$ (W)	827.3	188.9

Table 1: Geometry and power loss comparison between 4-way spool valve and 3-way ring valve.

Current and Future work

Once the 4-way rotary spool seizing issue is corrected, performance characterization rotary spool based VVDPM will continue. The VVDPM will then be installed and demonstrated on Test Bed 3 as a replacement of the current off-the-shelf S(peeder)-pump/motor.

Expected Milestones and Deliverables

Bench testing of the prototype 4-way tandem externally driven spool valve is targeted for completion by June 2013. Implementation onto Test Bed 3 will begin during the summer of 2013.

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

Research Team

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

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

Two test beds within the Center will 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 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 are more likely to be successful than past attempts because of several reasons 1) electronic and sensing capabilities have progressed significantly in the past decade, 2) new fundamental knowledge has been gained in the area of pump/motor design [6, 11] and can be used in this project, 3) computational power and simulation tools are allowing for coupled multi-domain system models to be optimized, 4) the high cost of energy is making component efficiency an important consideration, 5) previous and ongoing research on high speed on/off valves is providing the enabling technology, and 6) the CCEFP provides a unique critical mass of researchers, industry, and resources to successfully overcome the barriers.

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

B. Achievements

Important progress was made in several key areas. There has been continuing and valuable collaboration with Project 1B on understanding the internal losses within the pump and with Project 1E.2 on high-speed valves and there is currently collaboration with project 1E.6 on high performance valves enabled by energy storage and transfer.

Other researchers and companies (Artemis) have focused on digital pump/motors with using sequential flow-diverting to vary the displacement. This work had introduced three other methods to achieve variable displacement with the digital pump/motor technology by utilizing two high-speed on/off valves for each chamber. Although proposed in literature, flow-limited operation of a digital pump/motor had not yet been realized in practice, nor had it been analytically or experimentally characterized. Similarly, this work is the first to explore the full range in techniques to vary the effective displacement of a digital pump/motor.

A comprehensive multi-piston pump/motor model was developed using Matlab/Simscape. This model, shown in Figure 1, enabled the development of the four different operating methods of a digital pump/motor. The derived valve timing of the four operating strategies was established utilizing the simulation model.

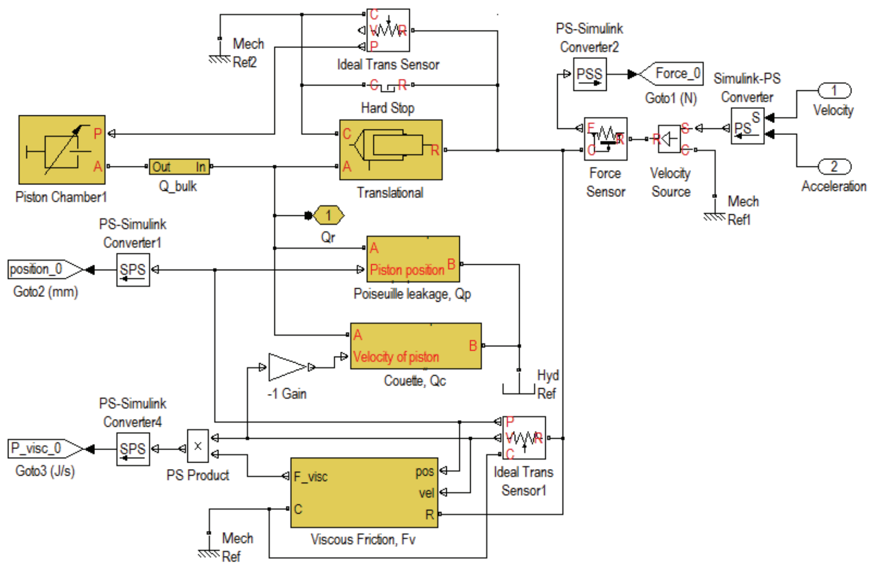

Figure 1: Matlab's Simscape model of digital pump/motor

A digital pump/motor test stand was designed and built to validate the variable displacement capability of the digital pump/motor. A real-time controller enables operation of the digital pump/motor, control of test conditions, and data acquisition through implementation of a Simulink model. Operational algorithms were established for variable displacement operation with flow-diverting and flow-limited operating strategies for both pumping and motoring. The field-programmable gate array enables accurate execution of model outputs. The test stand, complete with control system, power electronics, and valve power supplies, is shown in Figure 2.

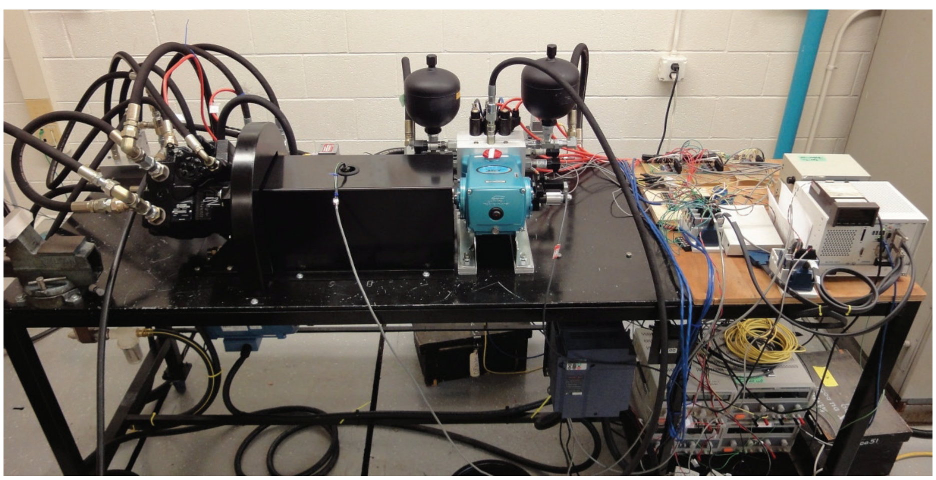

Figure 2: Test Stand

The overall efficiency of the digital pump/motor over the range of tested displacements for partial and sequenced flow-diverting and flow-limited operation at 500 rpm and 103 bar differential pressure are presented in Figure 3. Before the actively controlled digital valves were implemented on the CAT Model 660 three piston pump, the base unit was characterized for full displacement benchmark efficiency. It was found that the efficiency of the base unit at this operating point was 90%, and is included in figure 2. The variable displacement digital pump/motor was then tested. The overall efficiency of the unit is greatest when operating with sequential displacement control because valve transitions occur at low piston velocity. The overall efficiency of the unit is similar between sequential flow-limited and sequential flow-diverting operation. This is logical, considering the slower speeds achieved by the unit. Greater separation would likely be observed between these operating strategies if smaller valves were installed, leading to greater power losses due to pressure drop across the valves. With sequential flow-limited and flow-diverting operation, efficiency near that of the base unit is maintained until 50% displacement. These are encouraging results.

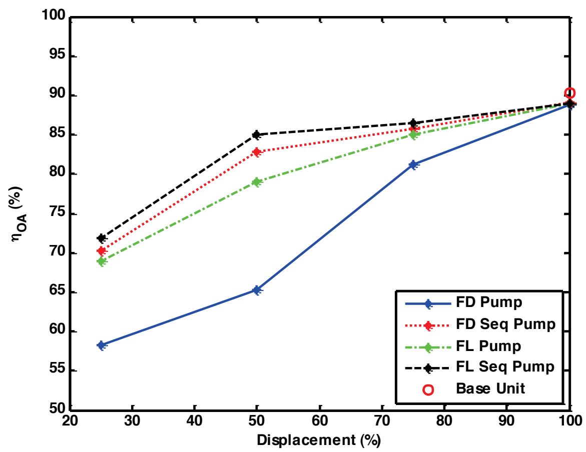

Figure 3: Overal efficiencies as a function of displacement for different pumping modes

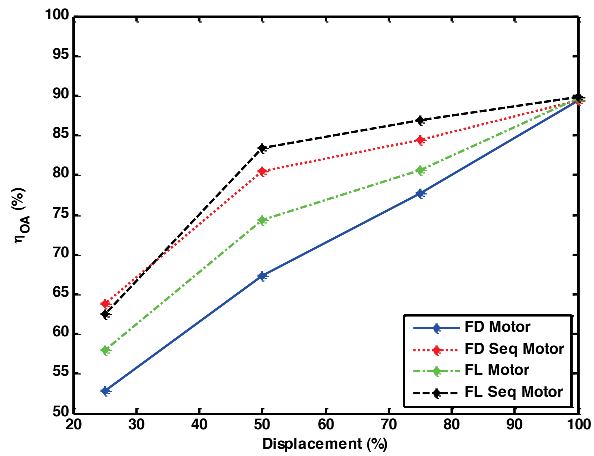

Figure 4: Overall efficiencies as a function of displacement for different Motoring modes

When operating as a motor, the overall efficiency is the ratio of delivered shaft power to the input fluid power. As shown in ***Figure 4***, overall efficiency trends in motoring are very similar to that of pumping at 500 rpm and 103 bar differential pressure. Since the base unit could only operate in a full displacement (check-valve) pumping mode, there is not a base unit efficiency included in Figure 4.

The simulation and measured results of partial flow-diverting (F-D) and partial flow-limiting (F-L) are compared against each other when operating at 700 rpm and 103 bar. ***Figure 5*** shows the percentage loss with respect to theoretical power at 50% displacement, 700 rpm, and 103 bar. The partial flow operating strategies have significant valve throttling losses due to switching at high piston velocity and also having a slow valve results in extra throttling losses due to compressibility of the fluid. Partial F-L has half the valve throttling loss that the partial F-D operating strategy experienced. This is evident by the almost 20% better measured efficiency of the partial F-L strategy than the partial F-D strategy at 50% displacement as seen in ***Figure 5***.

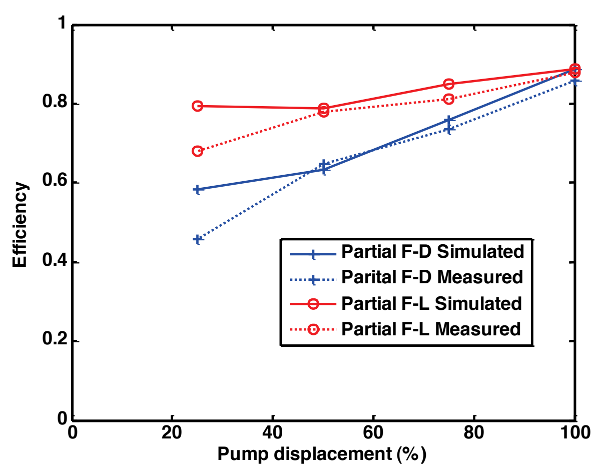

Figure 5: Simulation versus measured results

The future work for project 1E.3 includes implementing higher-speed and flow on/off valves, which remain key enablers for the digital pump/motor. Thus, current collaboration with project 1E.6 will likely yield the most significant gains in terms of efficiency. With the results from the multi-piston pump/motor test stand, implementation on Test Bed 1 (Excavator) and/or Test Bed 3 (Hydraulic Hybrid Vehicle) with a properly sized pump/motor is being planned. This will demonstrate 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. 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, to build (or supply from existing) the various components and sub-assemblies (pumps, valves, sensors, etc.) and help with the fabrication and testing.

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Project 1E4: Piston-by-piston control of pumps and motors using mechanical methods

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Industrial Partner(s): Sauer-Danfoss

1. Statement of Project Goals

The goal of this project is to develop simple and efficient strategies for controlling hydraulic power transformation machines (i.e. pumps, motors or transformers) on a piston-by-piston basis. The project will focus on creating a variable displacement pump/motor that can meet or exceed existing designs in peak efficiency and demonstrate a shallower drop off in efficiency as the displacement is decreased. By utilizing a 2 degree of freedom rotary valve, the expected efficiency benefits of piston-by-piston control will be achieved with a control mechanism that is simpler and more cost effective than competing research approaches.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

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

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

In project 1E.4, piston-by-piston displacement variation will be achieved with a single control input, in the form of a two degree of freedom rotary on/off valve. This project leverages knowledge gained in the design of a similar rotary valve for CCEFP project 1E.1 [5-11]. With this approach, a rotary spool valve that can translate axially will enable or disable the desired number of pistons to vary the displacement of the machine.

Using a mechanical control method offers many advantages. The first is simplicity: only a single control input, the axial position of the rotary valve, is needed. The second and third are robustness and cost: the pump-motor does not require solenoids and wires and current drivers for each piston. The fourth is low actuation power: the rotary valve does not need to be accelerated and decelerated. The fifth is repeatability: the valve is mechanically coupled to the drive shaft, thereby ensuring repeatable timing. The sixth is contamination resistance: significant torque is available to spin the valve through contaminated oil. The approach does also suffer one disadvantage: control flexibility is reduced as a result of replacing flexible electric controls with fixed mechanical controls. However, this is anticipated to have only a slight effect on the overall efficiency.

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

B. Achievements

The initial phase of this project, completed in 2011, was to examine how the losses in a variable displacement pump/motor scale with displacement, in both conventional and piston-by-piston approaches. The goal of this phase was to demonstrate the feasibility of the approach and define the magnitude of the potential energy savings. The results of this analysis are shown in Fig. 1.

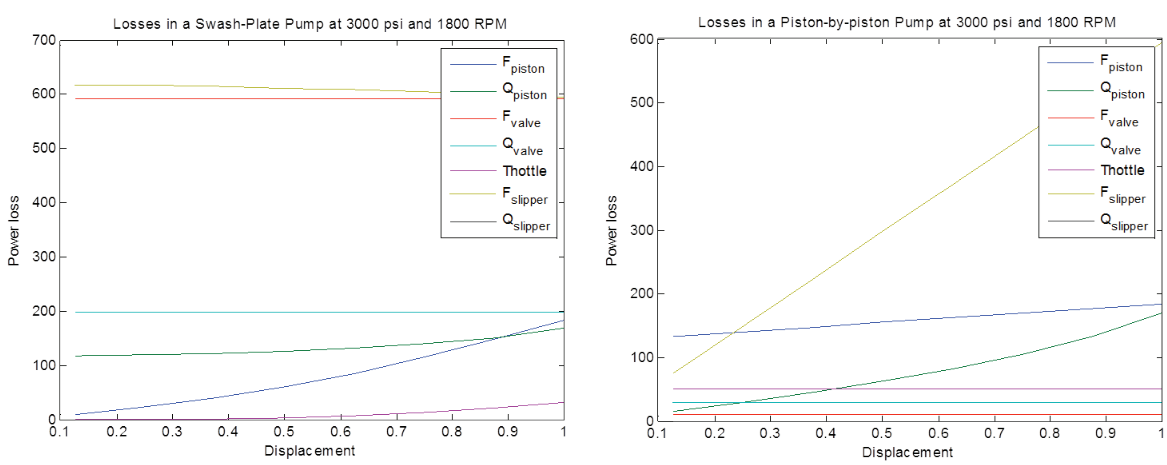

Figure 1: Losses in a swash plate (left) and piston-by-piston (right) pump

The models used to generate this comparison were designed for a pump the size of the expected prototype (52 cc) and are based on a combination of first-principles modeling and measurements of physical parameters from literature or existing components. This was not intended to be a high-fidelity study of the losses in a pump/motor, which is a project unto itself [12]. However, the trends of the losses with displacement are clear. The key benefits of the piston-by-piston approach are the reduction of swashplate friction with displacement and the reduction in valve plate friction and leakage by using valves to control each piston. This removes the tradeoff between sealing and load bearing that exists in a typical valve plate. The combination of the losses in Fig. 1 is shown in Fig. 2.

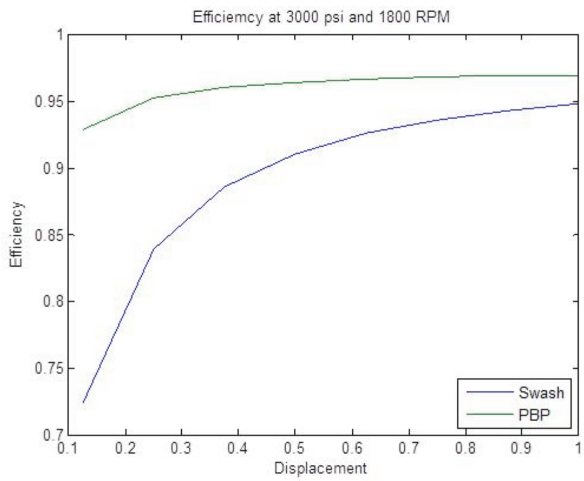

Figure 2: Efficiency comparison between a swashplate and a piston-by-piston pump

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

In the past year, the initial design concept has been developed into a detailed prototype design that is ready to manufacture. The selected on/off valve concept has been designed to fit into a custom pump housing for a wobble-plate pump-motor. The design incorporates elements from a donated pump prototype, along with 25 custom designed parts. The current status of the design is that a small number of design drawings need to be completed. A final prototype design review with industry partner engineers is planned to be completed within the next month. Once the design review is complete and the concerns raised have been addressed, the parts will be sent out for fabrication. After the prototype is built, a final test will be completed to validate the efficiency improvement of the concept. We expect to complete this test in Q2 of 2013.

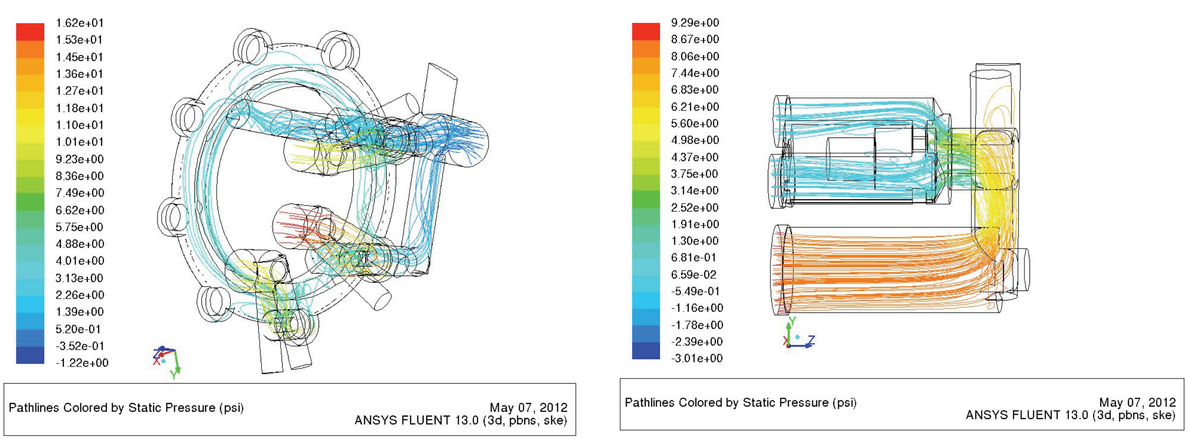

Figure 3: CFD analysis of the high (left) and low (right) pressure flow paths

The detailed design of the pump/motor components was an iterative process that included dynamic modeling as well as CFD analysis (Fig.3). We set a design goal of less than 1 bar pressure drop at peak piston flow (34 lpm). However, CFD analysis predicted our initial design would have a 2.67 bar pressure drop on the high pressure side. The low pressure side was much better, with a predicted pressure drop of 0.59 bar. After three design iterations, the supply side pressure drop was reduced to 1.05 bar at peak flow, which was close to our initial goal. We determined though our loss model that attempts to reduce the throttling loss further could increase the power loss due to leakage.

In addition to CFD, a dynamic model of the valve mechanism was used to predict the power loss. This model was used to analyze tradeoffs as the prototype was being designed. The model includes the valve transition profile and a compressible fluid equation to estimate transition throttling and compressibility losses. Figure 4 shows a combination of the losses predicted in the dynamic model, including valve throttling, fluid compressibility, leakage, and pilot valve actuation power.

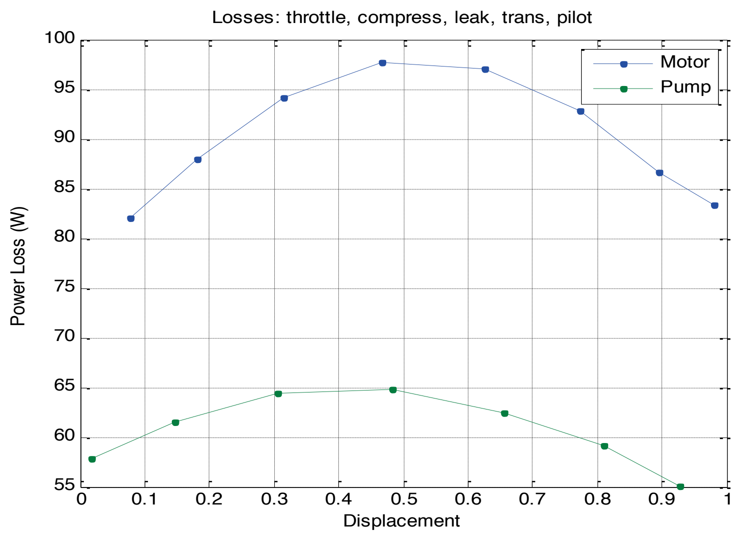

Figure 4: Losses predicted by dynamic model.

Due to fluid compressibility, the power loss in motoring mode is much higher than in the pumping mode. However, our original goal was to have losses less than 125 W per piston, which would result in less power loss than those estimated for a valve plate. The motor case is well below the design goal, and the pumping case is roughly half of the goal.

In order to reduce the losses in the motor case, a method of mechanically adjusting the valve timing in the motor case was developed. Efficiency is gained by allowing limited pre-compression of the oil at the beginning of the motoring stroke. Since shifting the start of the pumping stroke is detrimental to efficiency, this approach will only apply to the motoring case. We developed a mechanism that will satisfy these requirements and reduce the losses in the motoring case.

The prototype will be tested for efficiency and dynamic performance, and if the results are promising it will be demonstrated on Test Bed 3, the Hydraulic Hybrid Passenger Vehicle. At that point, the original project plan will be complete. If the efficiency tests are promising, the next step will be to contact member companies to gauge the interest in further developing the technology. A logical next step for this research is to investigate whether the approach can be extended to a piston-by-piston transformer.

Milestones

- Analyze piston disabling strategies (complete)
- Determine how swash plate and piston-by-piston losses scale with displacement (complete)
- Generate and analyze valve architectures (complete)
- Model selected mechanism to predict losses and dynamic performance (complete)
- Complete mechanical design of the pump/motor (complete)
- Analyze flow paths using Computational Fluid Dynamics (complete)
- Construct prototype (4/13)
- Test efficiency of the pump/motor (7/13)

C. Member company benefits

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

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Project 1E.5: System Configuration & Control Using Hydraulic Transformers

Research Team

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Industrial Partner:	Eaton, Case New Holland, Takako Industries, iRobot

1. Statement of Project Goals

This project will investigate how a hydraulic motion control system can best make use of hydraulic transformers to achieve both efficiency and control performance. Different transformer configurations and connections will be modeled, analyzed and evaluated. New configurations may be discovered as a consequence. The effects of dynamic and efficiency characteristics of the underlying devices and component sizing on system performance will be considered. Control approaches that take into account both efficiency and precision will be developed and demonstrated. These approaches will be conducted in case studies with scenarios taken from CCEFP testbeds 1 & 4, heavy machinery and robotics applications.

2. Project Role in Support of Strategic Plan

Metering valves in current hydraulic system incur significant throttling losses. These could be replaced by efficient hydraulic transformers powered by a single pressure source without sacrificing control performance. Transformers may be amenable to compact integration with actuators. Efficient and high performance control of actuators with appropriate form factors can expand the use of hydraulics for human scale robotic applications. The research focuses on applications with multiple actuators and opportunities for energy regeneration. While future demonstration in the new testbed 4 – patient mover is targeted, hydraulic transformers can also be used in hydraulic hybrid vehicles, excavators, renewable energy, and for small scale human wearable devices.

3. Project/Test Bed Description

A. Description and explanation of research approach

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

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

One aim of this project to gain understanding of how the intrinsic properties of the transformer impact overall system performance and provide guideline for the future design and optimization of transformer devices. Innas has introduced a transformer that uses a rotatable 3 ported port plate and a single rotating piston group (as in a swash plate pump/motor) [1, 6]; and Digital Hydraulics has introduced a transformer based on a linear displacer with discretely selectable areas [5]; a PWM switched inertance transformer was proposed in [7]; the switched model hydraulic transformer as a hydraulic equivalence of switched mode electronic power converter was proposed in [8]. In each of these configurations, elements that perform the function of the pump, the motor, the connecting inertia, and varying the pump and motor displacements can be discerned. While there has been a number of researches performed for Innas Hydraulic Transformer (IHT) [2, 3, 4,15, 16], there has been little research performed in making accurate comparison between IHT and the basic hydraulic transformer concept – a mechanically coupled pump and motor. Even for the case with a combination of discrete pump and motor, there can be many combinations to form a transformer. Through modeling and generalizations, existing transformer implementations will be compared.

The second aim of this project is to develop control strategies and control algorithms for hydraulic transformer-based systems for efficient and precise control. While most rigorously developed advanced hydraulic control concepts are based on flow control (e.g. via control of valves and pump displacements at relatively constant speeds) [10-13], transformers are pressure control devices. Moreover, it needs to be ensured that the internal dynamics of the transformer are well-behaved. Therefore, control strategies and method for analysis will be quite different from the more conventional hydraulic systems.

The third aim of this project is to understand how to best store and regenerate energy – either internally using flywheel or externally with an accumulator. This will be done through extensive simulations and case studies.

Finally, effective and precise control using transformers will be demonstrated experimentally. To do so, a transformer will be created by modifying off-the-shelf components. Implementation on a testbed, such as the new TB4, will be targeted towards the latter part of the project.

B. Achievements

The two most typical hydraulic transformer configurations are 1) Innas Hydraulic Transformer (IHT) with a rotatable 3-ported port plate (Figs. 2 and 3), and 2) the traditional hydraulic transformer concept with two mechanically coupled variable displacement pump/motors (PM Transformer) (Fig. 1). During the first 6 months of the project, extensive modeling, analysis and comparisons of these two configurations were performed.

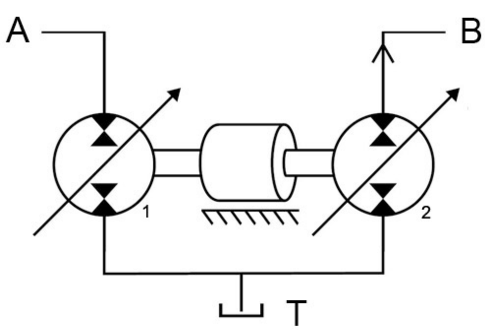


Figure 1: PM Transformer

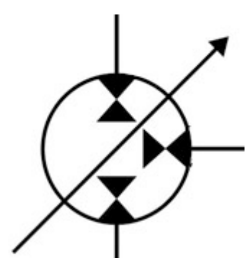


Figure 2: IHT

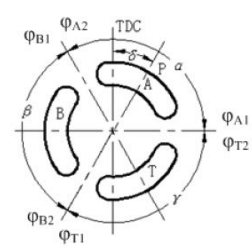
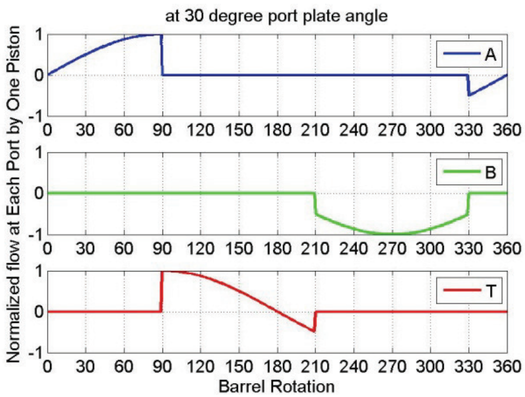


Figure 3: Rotatable port plate

<u>Average models and transformation ratios</u> By considering the net port flows of the transformers over a revolution, average dynamic models have been developed for both the IHT and PM configurations. Fig. 4 shows, for the IHT, the flow profile to each port by one piston over one cycle at one port plate angle. The port flows add up to a sinusoidal profile and the transition points are determined by the port plate angle. The net port flows are then obtained by integrating the port flow rates. At different port plate angles, the flow partitions and the relative flows change correspondingly. The models relate the rotational speed with the port flows, and the port pressures with the net torque, at different port plate angles (for the IHT) and different displacements (for the PM). The flow ratio between the input and output ports also determines the ideal pressure transformation ratio in the steady state. For the PM case, the transformation ratio is simply the ratio of the displacements; whereas for the IHT case, the transformation ratio is a function of the port plate angle and is shown in Fig. 5. The transformation ratio is 1 when the port plate angle is at 60deg.



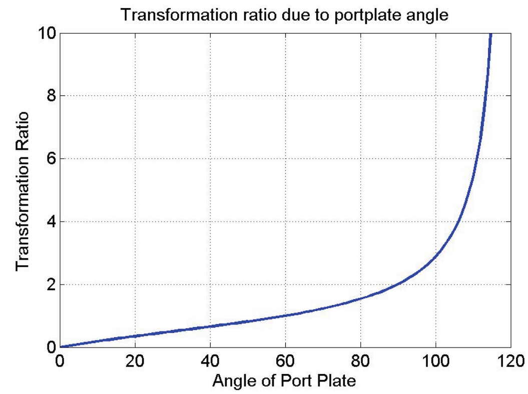


Figure 4: Transformation as a function of port plate angle

Figure 5: IHT port flows by one piston over one cycle at 30deg port plate angle

Sizing comparison: Since the IHT configuration is a single unit and the PM consists of two pump/motors, it is often claimed that IHT will be more compact than PM [1]. How much bigger a PM configuration needs to be has not been computed previously. In our sizing study, the flow capabilities of the configurations at all transformation ratios are to be matched and the total displacements of all the pistons are used for size comparisons. For the PM case, this is just the sum of the maximum displacements of the pump and the motor. The maximum rotational speed is assumed to be the same for both configurations.

Three methods have been used to compare the sizes. In the first method, the size of PM is scaled until its flow capability (at the maximum rotational speed) at *all* transformations matches or exceeds those of the IHT. This is shown in Fig. 6 where the displacements of the pump and motor are 86.6% of the IHT. Therefore, the total displacement of the PM is 2x0.866=1.73 times that of the IHT. In the second method, the size of the IHT is scaled until its flow capability at *all* transformations matches or exceeds that of the PM. This is shown in Fig. 7 and the total PM displacement is 49% larger than that of the IHT. The third method involves finding the PM displacements such that the 2-norm of the difference between the flow capabilities of the PM and of the IHT at all transformation ratios is minimized. This is shown in Fig. 8 and results in the total displacement of PM being 65% larger than that of IHT. Thus, it can be said that PM configurations are 50-70% larger than IHT. Other configurations that involve different port connections may allow the transformer sizes to be reduced for a given application.

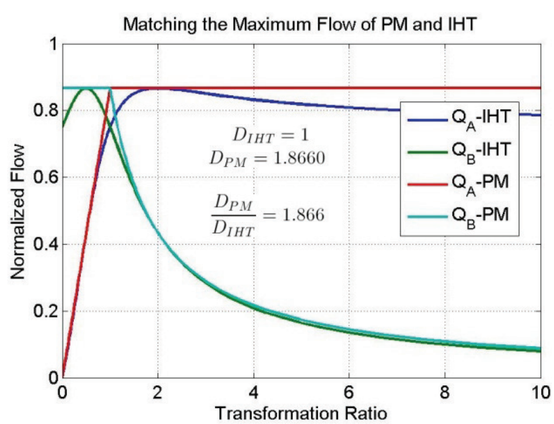


Figure 6: Method 1: matching the Maximum Flow of IHT

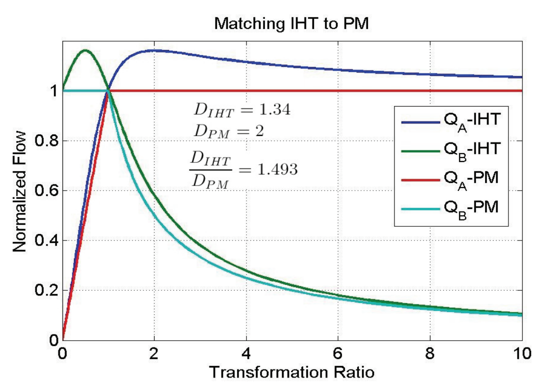


Figure 7: Method 2: matching the Maximum Flow of PM

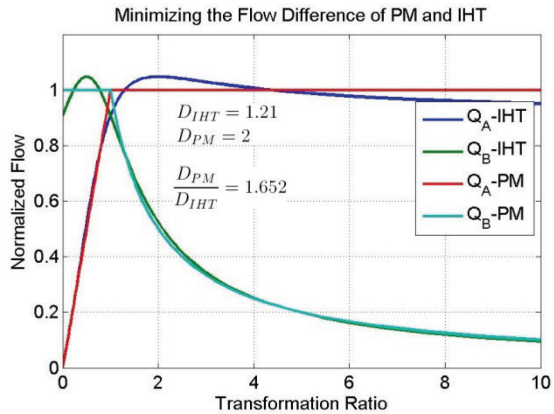


Figure 8: Method 3: minimizing the flow differences

<u>Ideal piston-by-piston model and flow ripples</u>: In addition to the average model that considers only the net flow and torque effects over one cycle, a piston-by-piston model that distinguishes the flow and torque profile during a revolution has been developed for both the IHT and PM configurations. Initially, losses are ignored. The ideal models are used to quantify and compare the flow ripple characteristics of the two transformer configurations.

Flow ripples (and torque ripples) originate from the port flow profile due to one piston shown in Fig. 4 (for IHT) and Fig. 9 (for PM). Whereas for the PM, the piston flow switches from one port to another at the end of the piston strokes when flow is zero (Fig. 9), for the IHT, they occur at various locations dependent on the port plate angle and often with non-zero flows (Fig. 4). The latter leads to sharp changes in port flow profiles. The total port flow profiles are obtained by combining the port flow profile for all pistons with the appropriate phase shifts.

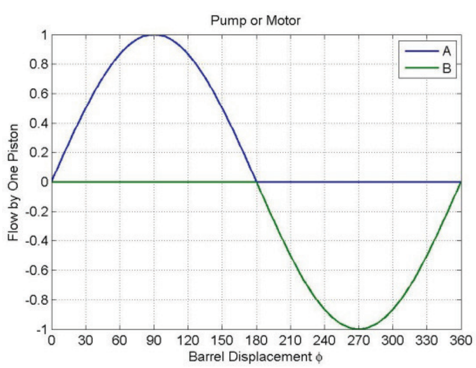


Figure 9: Flow is equally split into 2 ports P/M

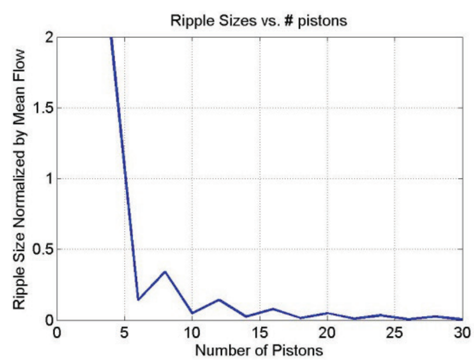


Figure10: Flow ripple size in P/M

The flow ripple size (as a proportion of the mean port flow) versus total number of pistons is shown in Fig. 10 (PM) and in Figs. 11-12 (IHT). For the IHT case, the ripple size depends on the port plate angle (or transformation ratio). Thus Figs. 11 and 12 illustrate two cases - 30deg and 100degs (transformation ratios of 0.5 and 2.87).

For the PM, flow ripple size decreases monotonically in increments of 4 total pistons (2 for each pump and motor) [9, 14], with 2(2n+1) total pistons (odd number of pistons for each pump and motor) being more favorable than 2(2n) total pistons. The flow ripple is 10% at 10 pistons and 0.5% at 30 pistons.

For the IHT, flow ripple size also decreases generally in increment of 3 pistons. However, the ripple sizes are higher than in the PM case and decreases more gradually with more pistons. Since the magnitude of ripple does not decrease with net port flow, the port with a lower flow will have a larger relative ripple size.

For example, at 30 degree port plate angle (0.5 ratio), the ripple size at output port is 19% with 10 pistons and 7.8% at 30 pistons. In 100 degree case (ratio is 2.87), the ripple size at the same port is 115% at 10 pistons and 58% at 30 pistons. As transformation ratio increases (output flow decreases), so does the ripple size at output port.

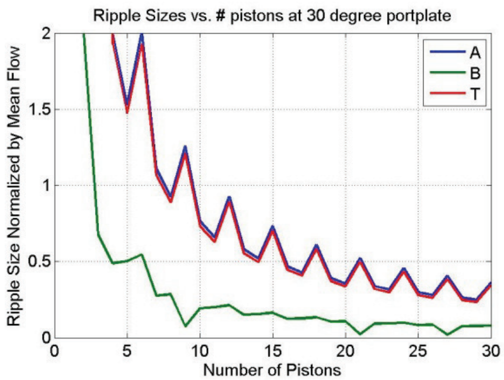


Figure 11: Ripple Size at Transformation Ratio 0.5

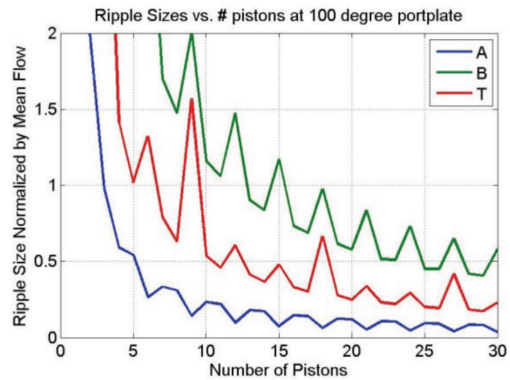


Figure 12: Ripple Size at Transformation Ratio 2.87

The flow (and torque) ripple effects are quite significant as illustrated in the dynamic simulation of the average and piston-by-piston models of the two transformer configurations with a constant supply pressure and an orifice load (Fig. 13). Whereas the average model captures the dynamics of the PM case quite well, the ripple effect overwhelms the response of the response in the IHT case. The large ripple also contributes to the noise reported in [16].

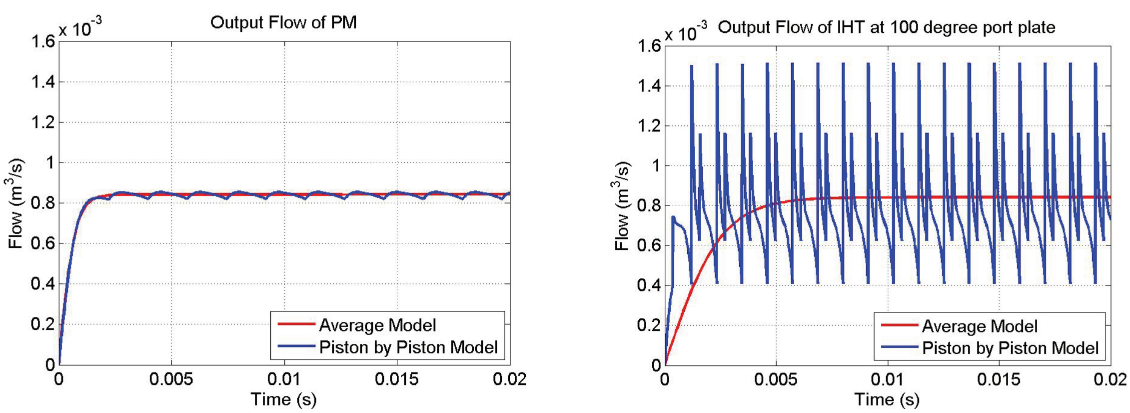


Fig. 13: Average and piston-by-piston models for a transformer with an orifice load (left: PM, right:IHT). The PM has 5+5 pistons and the IHT has 10 pistons.

<u>Lossy piston-by-piston model:</u> In order to compare the efficiencies of the two transformer configurations, a piston-by-piston model that includes various losses is being constructed and is near completion. This model includes friction losses on the swash plate, port plate, inside the piston chamber, as well as flow losses through piston, port plate and swashplate. Loss models are obtained from literature on variable displacement pumps. [17]

<u>Future Plans</u>

The next immediate step is to understand how to design and operate a transformer based system in a typical application. To this end, duty cycle information is being collected and generated and will be used in case studies. In particular, a humanoid robot model has been assembled and combined with human gait data to generate a set of duty cycles corresponding to the robot walking. Other duty cycles from the construction industry or from the new testbed 4 are also being collected/requested.

With the comparison between the basic IHT and PM configurations nearly complete, other configurations involving port-switching, gear ratios, and inertia will be studied next. These combinations may offer sizing, efficiency or regeneration benefits.

An experiemental set up is being designed and built to study various configurations of transformers experimentally. Initially, PM configurations will be constructed using fixed displacement mico-piston pumps of various displacements. The experiments will be used to confirm modeling predictions.

Precise motion and force control using transformer will also be studied. We will begin with simple configuration of a single actuator, followed by an application based control study, such as human power amplification in the new TB4.

A prototype variable transformer will be constructed in the next year. This will likely involve modifying the fix-displacement micro-piston pumps into variable displacement units or by installing a rotatable port-plate.

C. Member company benefits

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

D. References *Include published literature, patents, etc.*

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Project 1E.6: High Performance Actuation System Enabled by Energy Coupling Mechanism

Research Team

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	Perry Li, University of Minnesota, Mechanical Engineering
Graduate Students:	Daniel Skelton, Shaoping Xiong
Undergraduate Student:	Jordan Garrity
Industrial Partners:	Eaton, Moog, Parker Hannifin

1. Statement of Project Goals

The goal of the project is to develop high performance actuation mechanisms to enable new high bandwidth valves and improve the performance and efficiency of existing systems. The concept is based on coupling energy storage mechanisms with translational movement to increase the speed and controllability of linear actuators. The high speed linear actuation method is being applied to hydraulic proportional valves. The stored actuation energy (such as a rotating mass) is intermittently coupled and decoupled to produce linear or rotary motion in the primary actuator.

2. Project Role in Support of Strategic Plan

The project will allow for higher bandwidth control valves leading to an increase in the efficiency and speed of fluid power systems. This project addresses the technical barriers of efficient components and is an enabler for efficient systems. Hydraulic valves are found on nearly every fluid power system in production. Compact, modular, high performance, scalable valves would be enablers or enhancers on every test bed in the center. The orthosis and robot test beds would become more compact and efficient. The hydraulic hybrid and displacement control excavator test beds would benefit either from new high efficiency pump/motors enabled by these valves, or from increased bandwidth displacement control when using current state-of-art variable displacement units (swashplate, bent-axis, etc.).

3. Project Description

A. Description and explanation of research approach

The project goal is to develop a new class of high performance valves that can be easily scaled for different applications. The valves can utilize poppets or spools for control of fluid paths. To give greater impact and to broaden the potential applications, the valve can operate as either an on/off or as a proportional valve. The valve needs to demonstrate consistent performance regardless of flow and pressure in the system, be able to operate without pilot pressure, and to operate safely with contaminated fluids. To continue the success of the CCEFP the valves will leverage the previous work of CCEFP and international researchers and leverage recent advancements in automotive, industrial, and electronic applications.

This research has the potential to significantly change the actuation strategies for hydraulic control valves while requiring less power consumption, with higher performance, and providing higher flow ratings with less metering losses.

B. Achievements

Project 1E.6 started with a brainstorming process that yielded many different designs to consider for the prototype. The concepts and constrains listed above guided the design process, leading to the current prototype. After the initial idea was accepted the process of designing the valve on the computer was started. Figure 1 shows one of the conceptual designs resulting from this exercise. This design was then simulated to predict the performance.

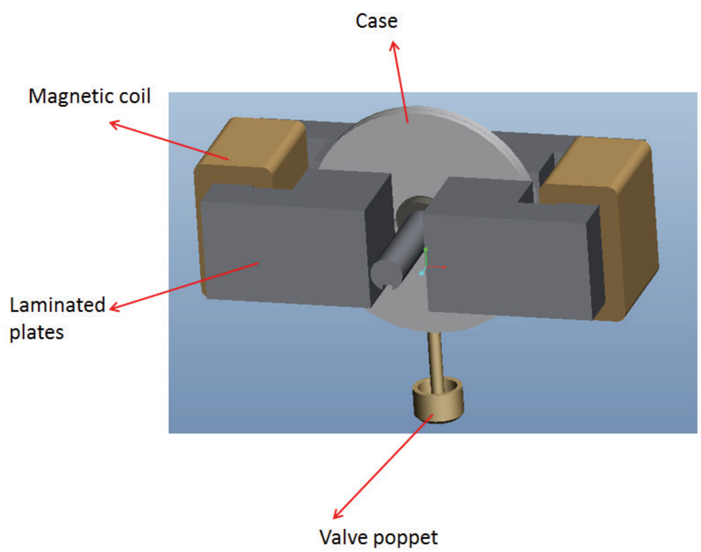


Figure 1: Valve design concept

The linear actuator (in this case a poppet valve) can be opened or closed by energizing the coils on either side of the rotary plate. The actuation force is created by increasing the yield stress of the MR fluid within the magnetic field. The model of the actuation system primarily focuses on the rheological stress of MR fluid when influenced by an electromagnetic field, which is time-dependent during valve stroke. Since the electromagnetic core shaft can be laminated, eddy currents are insignificant and can be neglected in the model. The model in general is a transient coupled-physics system solved by coupling a finite element static electromagnetism model and a lumped parameter electric circuit model. A look up table for magnetic flux density versus coil current was obtained from a static electromagnetic finite element analysis (FEA) using an electrical current profile based on the solution of the electric circuit equations. The transient yield stress of the MR fluid creates the actuation force used to accelerate the linear actuator (poppet valve).

Using the design illustrated in figure 1, the electromagnetic system was approximated by analyzing a 2-D axisymmetric model using finite element software, as shown in figure 2. The electromagnet shape in figure 1 was replaced by a circular one based on an equivalent area approach.

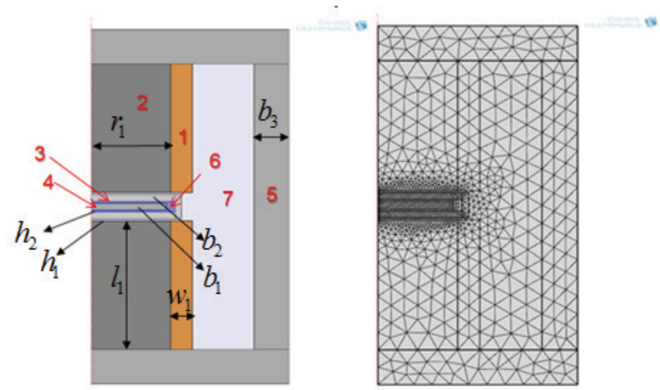
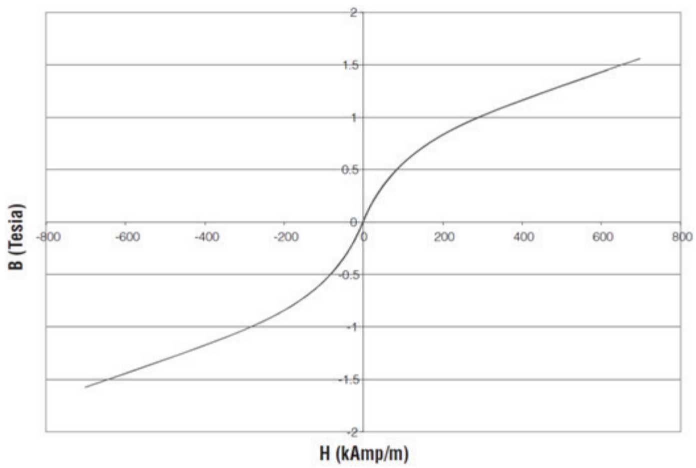


Figure 2: COSMOL 2-D axisymmetric model for electromagnetic domain

The MR fluid used is Lord Corporation MRF-DG, and its relative permeability is estimated using the B-H curve provided by Lord Corporation (Figure 3).



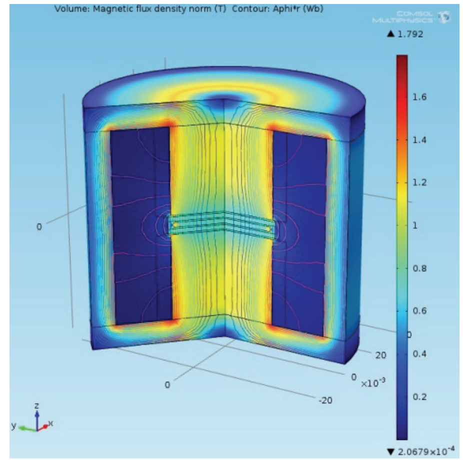


Figure 3: Figure 11.B-H curve of MRF-132DG [5]

Figure 4: Flux density solution with contour plot for magnetic vector potential (2D revolution)

Figure 4 shows the FEA solution for magnetic flux density at 5V.The radial distribution of magnetic flux density B(r) can be approximated as uniform, therefore the average magnetic flux density $B_{average}$ over the disc area (used to calculate the yield stress of the MR fluid) is calculated using equation (1).

$$B_{average} = \frac{\Phi_B}{A} = \frac{\int_0^{r_1} B(r) 2\pi r dr}{\pi r_1^2} \tag{1}$$

where Φ_B is the magnetic flux through disc area and A is the area of disc.

The electromagnet driving circuit used in this model can be represented as a resistor-inductor circuit. A peak-and-hold voltage profile is used to activate each electromagnet. A peak & hold voltage profile is utilized to decrease the amount of time required to develop the magnetic field in the MR fluid. The equation for this circuit is shown in equation (2).

$$L\frac{di}{dt} + iR = v(t) \tag{2}$$

The coil current versus time can be calculated using equation (5):

$$i = \begin{cases} \frac{V_{peak}}{R}\left(1 - e^{-\frac{R}{L}t}\right), & t \le t_p \\ \frac{V_{hold}}{R} + \left(i_p - \frac{V_{hold}}{R}\right)e^{-\frac{R}{L}(t-t_p)}, & t > t_p \end{cases} \tag{3}$$

where V_{peak} is the peak voltage value, V_{hold} is the holding voltage value to maintain the operational current; t_p is peak voltage duration time and

$$i_p = \frac{V_{peak}}{R}\left(1 - e^{-\frac{R}{L}t_p}\right) \tag{4}$$

is the electrical current during the peak and hold transition.

To model the actuation force resulting from the MR fluid coupling, a constitutive equation for the MR fluid stress needs to be developed. This consists of two parts, stress due to viscosity, and yield stress due to the magnetic field. For the disc shape being studied here, the MR fluid coupling constitutive equation is shown in equation (5):

$$\tau = \eta \frac{\omega r}{h} + \tau_{yd}\left(B\right) \qquad (5)$$

where η is dynamic viscosity of the MR fluid, h is the MR fluid gap, ω is the angular velocity of the rotary disc, r is the radial position, and $\tau_{yd}\left(B\right)$ is the yield stress due to magnetic flux density[5].

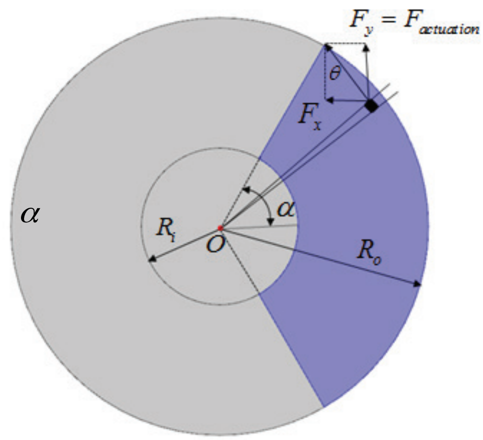


Figure 5: Schematic diagram of shear force analysis on rotary disc

A polynomial interpolation can be used to obtain a constitutive equation of rheological stress against magnetic flux density, shown in equation (6).

$$\tau_{yd}\left(B\right) = a_4 B^4 + a_3 B^3 + a_2 B^2 + a_1 B + a_0 \qquad (6)$$

where a_0=0.1442 kPa, a_1=13.708 kPa/T, a_2=158.79 kPa/T^2, a_3=-176.51 kPa/T^3 and a_4=52.96 kPa/T^4 [8]. Note that the yield stress saturates at 50kPa with the magnetic flux density increasing to 1.2 T.

Actuation force can be calculated by combining results from the static FEA electromagnetic model and the electric circuit model. Figure 6 plots the force and resulting motion versus time when V_{peak}=42V, V_{hold}=5V and t_p=6ms. The actuation system, using an MR fluid coupling, is able to provide over 70N in actuation force in less than 6ms.

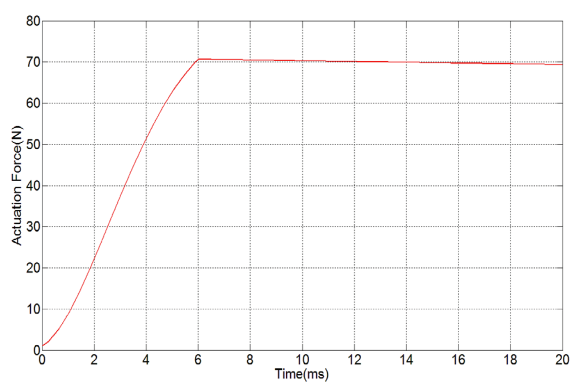


Figure 6: Actuation force profile for valve enabled by MR fluid coupling

Assuming a poppet valve stroke length of s=2mm for this example, and a translational moving mass of m=0.042kg (based on a mass analysis of the solid model), a valve poppet motion profile, as shown in Figure 7 demonstrates a valve transition time of less than 4ms.

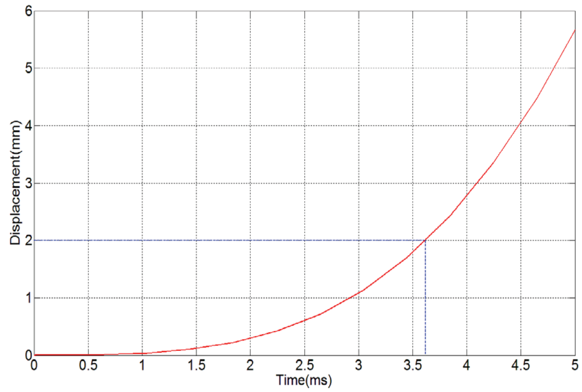


Figure 7: Motion profile for valve enabled by MR fluid coupling

Figure 8 shows a cross section of the valve along with the actual components. The idea of this prototype is to have a case that encloses a spinning disk and MR fluid. The case will sit in a C shaped laminated core that will pass a magnetic flux through the MR fluid. The fluid then becomes solid and causes a shear between the disk and the case.

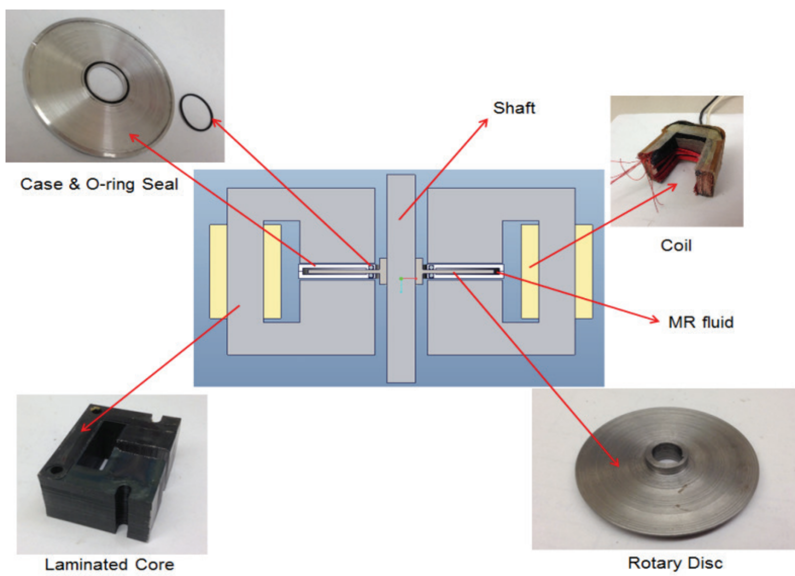


Figure 8: Prototype cross-section with components

The benefit of the current prototype is there are only a few components that have to be manufactured, the rotary disk and the case, allowing for many of the components to be purchased off the shelf and allow for little time in waiting for manufacturing. With all of the components now in house the process of assembling everything is underway. The next step in the testing of the prototype is to finish the assembly and to start testing the actuation of the valve. The results from the tests will be compared to the results from the simulation to try and validate the model and to allow for testing and changing parameters of the design before building the final valve.

C. Member company benefits

This project will continue to benefit CCEFP member companies by providing new high performance actuation system, and indirectly will benefit companies through its role as an enabling technology for other CCEFP test beds.

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Project 1F.1: Variable Displacement Gear Machine

Research Team

Project Leader:	Andrea Vacca, Department of Agricultural & Biological Engineering and School of Mechanical Engineering, Purdue University
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Undergraduate Students:	1 REU/year
Industrial Partner(s):	Parker Hannifin Corporation – Gear Pump Division

1. Statement of Project Goals

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

Objective 1 (O1): formulate a new design principle for VD-EGM
Objective 2 (O2): propose a novel and general design methodology for EGMs.

2. Project's Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

Key factors of success for EGMs in fluid power applications are the low cost, reliability and ease of manufacturability. Despite these advantages, EGMs are fixed displacement and they cannot be used as primary energy conversion units in hydraulic systems requiring variable displacement (VD) units. A typical design of a pressure compensated design of EGM is depicted in Fig. 1 (p_{max} ≈300 bar). The adoption of VD units permits more energy efficient layouts for controlling hydraulic actuators, such as load-sensing system architectures to the more recent displacement controlled configurations [1,2]. With the exception of cases where the unit operates at fixed pressure and flow rate, the energy consumption of fluid power circuits based on fixed displacement units can be as much as 70% higher than standard VD system layouts. For this reason, both industry and academia have been dedicating effort in formulating VD design solutions for EGMs, with the aim of preserving the advantages of limited cost (about 10 times lower than existing VD units with the same capacity) and reliability. However, because of the inherent complexity of the phenomena involved in the operation of EGMs and the lack of proper tools suitable for detailed design considerations, past research has not led to any practical solutions. EGMs currently available in the market are mostly based on empirical design processes rather than the consequence of predictive simulations. Therefore, many fluid power systems are still based on inefficient fixed displacement layout configurations, to take advantage of the low cost and reliability of EGMs; while in other cases EGMs are being replaced with more expensive units, for the sake of improved energy consumption.

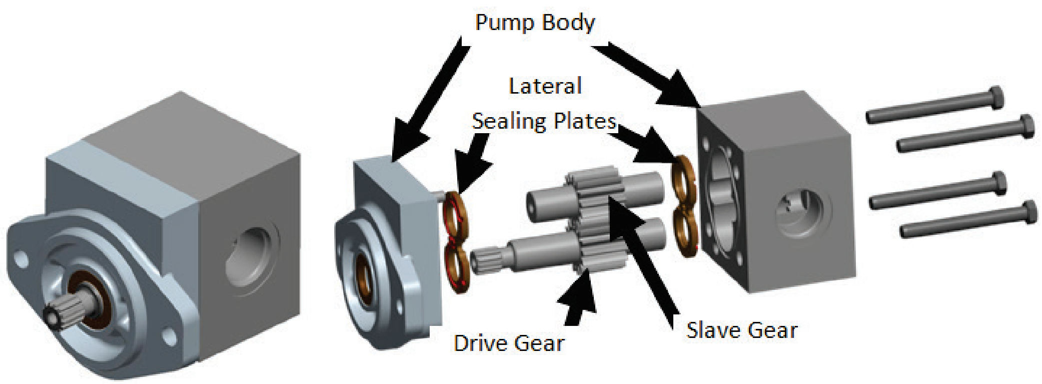

Figure 1: pressure compensated external gear machine, exploded view

Previous works
With the aim of creating low cost pumps and motors for VD systems, research has been performed following two different paths: the “system” approach, that combines standard fixed displacement units with fast on/off valves to permit the flow regulation (these solutions are also called “virtually variable displacement solutions” [3]) and the “component” approach, wherein VD-EGM ideas are investigated at a component level.

Despite the theoretical validity of virtually variable displacement solutions, their application in real systems is hampered by the limited time response of current on/off valves as well as compatibility issues of current fixed displacement pumps with the introduction of additional severe pressure pulsations. At the component level, several concepts for VD-EGM have been proposed using different principles for obtaining a relative motion between the gears (Figure 2) [4,5]. However, these concepts vary significantly from the standard EGM design (Figure 1), and none of the proposed ideas have ever reached the level of commercialization due to the inherent complexity of the design involved in the VD actuation and manufacturability.

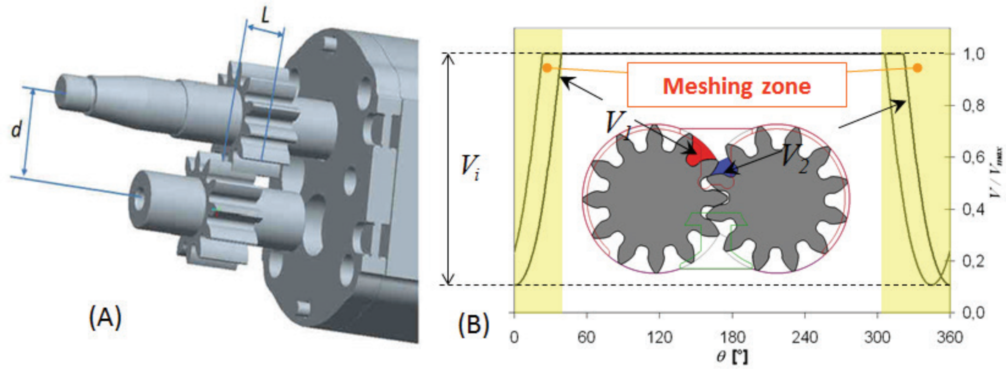

Figure 2: (A) Varying the EGM displacement: acting on the active depth (L) and acting on the distance between gears (d). L and d directly affect the variation of the displacing volumes in the meshing zone (B)

Related to both objectives of the research (O1 and O2), there is also the analysis of new design principles for gear profiles. Only recent research is investigating the advantages of adopting novel profiles, such as cycloid-based unit recently commercialized, which allows for a lower noise emission level by mean of a smoother flow delivery pulsation [6]. Unconventional profiles applied to EGMs however, were never investigated in a systematic way. One example is given by the multi-involute profile principle considered for applications like mechanical power transmission systems.

Adaptation of methodologies such as the one described in [7,8], which formulate the direct gear design based on the several different parameters which control the shape of the involute profile, for EGMs would lead to a definition of profiles that permit for a better control of the tooth space volume (TSV) variations with gear rotation. Investigating these solutions would permit to define new designs for fixed displacement

EGM with better efficiency and lower noise emissions, but will also permit to maximize the effectiveness of the concept of VD-EGM presented in this research, described in the next section.

The proposed solution for VD-EGM

Variable displacement in EGMs can be obtained by proposing an innovative concept of variable timing of connections between the displacement chambers (tooth space volumes, TSVs) and the inlet and the outlet ports. A schematic representation of this idea is shown in figure 3.

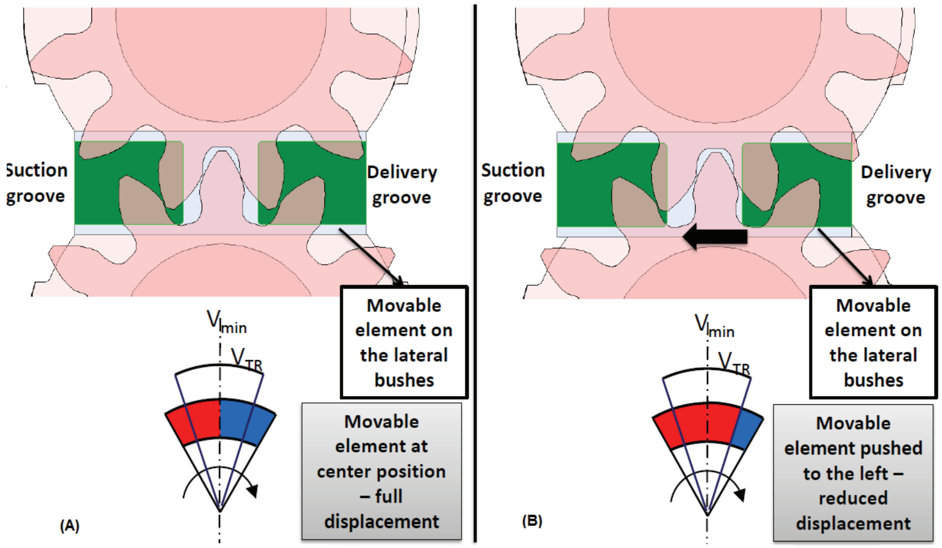

Figure 3: VD – EGM principle. The lateral bush include a sliding element to change the timing of connections as shown. A simplified profile for the relief grooves is utilized to better represent the concept of VD

In this new design, the delivery and the suction grooves are machined on an additional movable sliding element which is a part of the lateral bush as shown in Figure 3. Displacement variation is achieved by moving this element. When the movable element is moved to the left the volume of the fluid which is trapped between the contact points of the teeth of the gears is connected to the delivery for a larger interval of time as shown by the timing diagram. The balancing of the lateral bush with the additional movable element proves to be challenging. Also, this design can be actuated by different methods: pure hydraulic to electro-hydraulic solutions.

B. Achievements

Achievements prior to the reporting period:

The PI's research team has been involved in the research challenge of developing a omni-comprehensive simulation tool for the simulation of EGMs for years. The tool, named HYGESim (HYdraulic GEar machines Simulator) is capable simulating the operation of gear pumps and motors, including also elasto-hydrodynamic deformation effects in the lubricating gaps [9,10]. HYGESim permits the understanding of the influence of the design parameters on the EGM performance in terms of efficiencies, power losses, local pressure peaks and cavitation, flow pulsations etc. HYGESim is a multi-domain simulation tool built in LMS.AMESIM® platform to facilitate complete hydraulic systems and it consists of several parts (Figure 4): a) Geometrical Model capable of generating the various details necessary for the lumped parameter model from CAD drawings, b) a lumped parameter fluid dynamic model for the study of the main flow through the unit, c) a mechanical model to study the radial balance of the gears considering the micro motions of their axis d) a fluid structure interaction model to study the lubricating gap between gear and lateral bushes and the axial balance of the machine. Although HYGESim was capable of performing a complete simulation of conventional EGMs, the geometrical model was not flexible enough to handle no involute profiles of the gears, such as cycloidal and multi-involute profiles (Fig. 4).

Achievements during the reporting period:

Started in summer 2012, the research has talked the two research objectives (O1 and O2) to extend the simulation capabilities of HYGESim to: a) simulate the VD-EGM solution; b) extend the geometric option for the tooth profile; c) enhance the modeling of the lateral gap model to study inherent power losses due to leakage and shear stress associated with the lubricating gap between gears and lateral bushes. The tool is now capable of handling profiles like the ones represented in Figs. 4B and 4C.

In parallel, a parametric generator of gears geometry geometric is close to completion, to permit the combined use of HYGESim for numerical optimization algorithms like the one described in [11]. Already adapted to handle the input parameters for non-involute profiles, this tool will be able to design gears both conventional and multi-involute gears based on the user inputs which govern the gear profile. A conceptual diagram of the optimization tool is given in Fig. 5. The main challenges which arise due to the functional dependences of the design variables and the tooth profile have been studied.

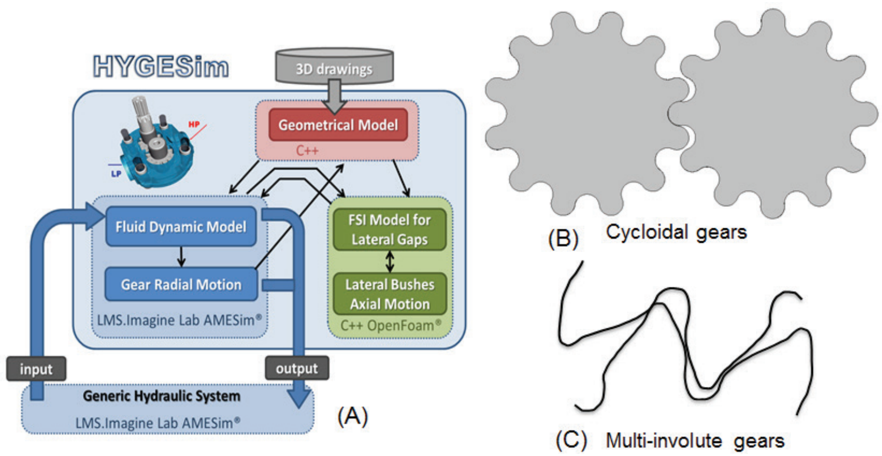

Figure 4: (A) Structure of HYGESim (B) Cycloidal gears (D) Multi-involute gears

The simultaneous design optimization method for the gears and lateral bushes has been identified and a workflow has been formulated. A simple schematic of the workflow is shown in Fig. 5. HYGESim will be used to evaluate the objectives functions which are: 1) Minimize delivery pressure pulsations, 2) Minimize internal pressure peaks, 3) Minimize local cavitation, 4) Maximize volumetric efficiency. For the VD-EGM and additional function: 5) maximize displacement variation, will be introduced (see next section).

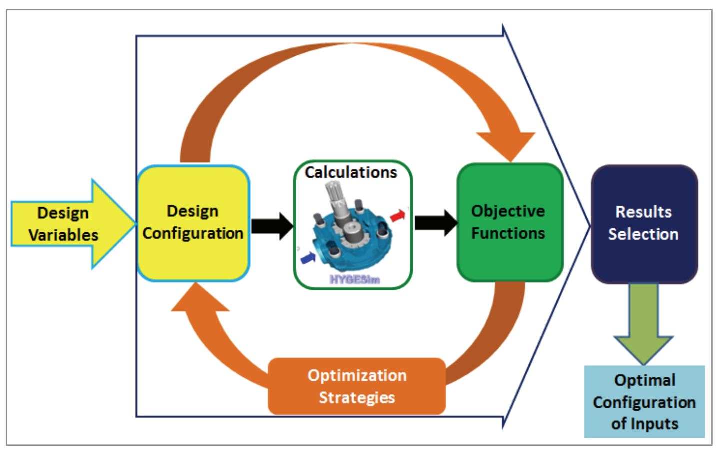

Figure 5: Optimization workflow

<u>Planned achievements following the report period</u>

Numerical optimization of unconventional profiles (multi involute gears) with HYGESim, fixed displacement EGM (O2)

- Deliverables:
  - Drawings and simulation model for the optimal solution with unconventional profiles (summer 2013)
  - Simulation results purporting the benefits of unconventional designs over standard designs (fall 2013)
  - Realization of a prototype (in collaboration with the industrial sponsor) (spring 2013)
  - Testing of the prototype at Maha: validation of modeling results in terms of efficiency level, noise emissions (summer 2014).
  - Extension of the research to parametric cycloidal profiles (long term)

Formulation of design principle for the VD-EGM

- Deliverables:
  - Actuation system for changing the displacement in the proposed VD-EGM design (summer 2013)
  - Realization of a first prototype of VD-EGM with standard gear profile (summer 2013)
  - Model of the VD-EGM in HYGESim (summer 2013)
  - Testing of VD-EGM and model validation (fall 2013)
  - Optimal design of VD-EGM (non involute profile): HYGESim model (spring 2014)
  - Optimal design of VD-EGM (non involute profile): optimization results (drawings and simulated performance parameters) (summer 2014)
  - Optimal design of VD-EGM (non involute profile): prototype manufacturing with industrial sponsor (fall 2014)
  - Optimal design of VD-EGM (non involute profile): prototype testing at Maha and model validation (fall 2014)
  - VD-EGM (non involute profile): development of system architectures for VD-EGM for fluid power machines: high efficient fan drive system and integration on TB.1 (fall 2014-long term)
  - VD-EGM (non involute profile): extension to VD system architecture, definition of general criteria and range of application (long term)
  - VD-EGM (non involute profile): design of VD solutions for ultra-high pressure levels (long term)

C. Member company benefits

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

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Project 1G.1: Energy Efficient Fluids

Research Team

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Industrial Partner(s):	Afton, Eaton, Evonik, ExxonMobil, Parker Hannifin, Poclain, Sauer-Danfoss

1. Statement of Project Goals

The goal of this project is to model and investigate the effects of boundary friction, traction, compressibility, and high pressure shear-thinning on the efficiency of hydraulic components and systems. Studying the interactions of hydraulic fluid properties through high pressure rheometer, bench-top tribometer, and hydraulic dynamometer testing will help to bridge the gap between the performance of fluid power components of complex geometry and the fundamental understanding of tribology. This knowledge will be used to develop models to predict hydraulic fluid efficiency and propose new fluid formulation strategies to improve system efficiency.

2. Project Role in Support of Strategic Plan

This project addresses the efficiency barrier by providing a deeper understanding of hydraulic fluid behavior through an analysis of the impact of boundary friction, traction, fluid compressibility, and high pressure shear-thinning characteristics on system efficiency. Fluid formulations will be developed using design of experiments for mixtures and evaluated in high pressure rheometer, bench-top tribometer, and hydraulic dynamometer testing. Models that predict hydraulic fluid efficiency will be developed. Improving fluid efficiency is of strategic importance within the CCEFP because hydraulic fluids interact with nearly every component in a hydraulic circuit. Increased fluid efficiency makes possible the use of smaller pumps, motors, and prime movers. This investigation will be conducted in coordination with the elastohydrodynamic research of Professor Bair (3D.2). Test Bed integration will be coordinated with Professor Chase (TB3).

3. Project Description

A. Description and explanation of research approach

There is a gap to be bridged between the fundamental understanding of tribology and the performance of fluid power components of complex geometry. This project bridges the gap between the fundamental understanding of tribology and the performance of fluid power components of complex geometry by investigating the effects of fluid boundary friction, traction, compressibility, and high pressure shear-thinning characteristics on system efficiency. In previous research reductions in boundary friction yielded double-digit increases in the low-speed efficiency of hydraulic motors [1]. Tysoe and Kaltchev proposed that friction reduction from boundary lubrication additives corresponds to the formation of Langmuir-Blodgett monolayer films [2]. Jahanmir pointed to a reduction in the free energy of the surface as an explanation for film formation in terms of physical chemistry [3]. Spikes characterized common zinc-dialkyldithiophosphate (ZDDP) reaction films as thick, rough, iron and zinc phosphate-based coatings [4]. Devlin posited that friction modifiers reduce friction by creating thin tribofilms of uniform surface roughness [5]. These tribological perspectives are founded upon experimental results produced in benchtop tribological instruments. Project 1G.1 seeks to bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power components by studying fluids in the dynamometer shown in Figure 1.

Figure 1: Low-speed high-torque dynamometer

B. Achievements

Dynamometer testing of micro-textured hydraulic motor components produced by Professor King of UIUC has been completed (1D). The results have been reported separately. Recent investigations have focused upon testing Spikes' "thick film" ZDDP and Devlin's "thin film" Friction Modifier theories. The prototype hydraulic fluids shown in Table 1 were evaluated in five hydraulic motors and three benchtop tribometers. Two of the fluids were formulated with Group I base oils and two were formulated with Group III base oils. Fluid "A" contained a Group I base oil plus a sulfur-phosphorus ashless antiwear additive. Fluids "B" and "C" contained Group III base oils but differed in antiwear additive chemistry. Fluid "B" was formulated with the sulfur-phosphorus ashless antiwear additive while fluid "C" utilized a ZDDP antiwear additive. "D" was similar to "A", with the addition of 0.5% alkylphosphonate friction modifier.

Table 1: Test Fluids

Fluid	Base Oil	Vis @ 40°C mm2/s	Viscosity Index	API Gravity	Antiwear Additive Chemistry
Fluid A	Group I Paraffinic	46.5	104	29.8	Sulfur-Phosphorus Ashless
Fluid B	Group III Paraffinic	43.9	127	35.7	Sulfur-Phosphorus Ashless
Fluid C	Group III Paraffinic	43.9	127	35.7	Zinc Dialkyldithiophosphate (ZDDP)
Fluid D	Group I Paraffinic	46.5	104	29.8	Sulfur-Phosphorus Ashless plus 0.5% alkylphosphonate

Friction and traction coefficients were measured for each fluid in three benchtop tribometers; a Mini Traction Machine (MTM), an Anton Paar Tribocell, and a High Frequency Reciprocating Rig (HFRR). As shown in Figure 2, Fluid "D" exhibited the lowest MTM traction (70°C, 150 mm/s, 35N, 100 S/R) and Anton Paar friction coefficients. Fluid "A" exhibited the lowest friction coefficient in the HFRR. In previous work, HFRR friction and MTM traction coefficients were found to correlate with low speed motor efficiency [6]. Recent investigations indicate that the HFRR is unable to differentiate certain hydraulic fluid chemistries and produces rough wear scars that are not well suited for surface analysis.

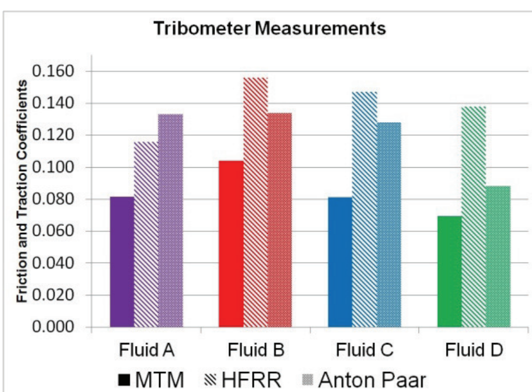

Figure 2: Time dependence of friction in Anton Paar Tribocell

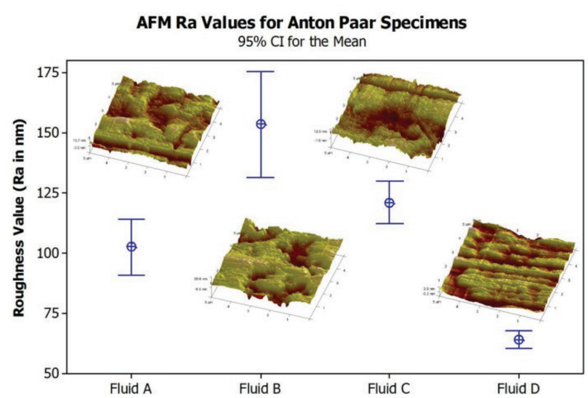

Figure 3: AFM Contact Mode Images of Anton Paar Tribocell Specimens

Wear scars produced in the Anton Paar test are well suited for surface analysis. Images of these surfaces were collected using a Bruker MultiMode atomic force microscope (AFM). Silicon probes with a 2nm tip radii were used to scan a 5 micron area of the specimens in contact mode at a rate of 0.75 Hz. While operating in contact mode, the AFM measures the cantilever position and adjusts the scanning head to maintain a deflection setpoint, thus ensuring continuous contact with the test specimen. Sixteen Ra values were sampled for each AFM scan. As shown in Figure 3, the surface produced by fluid "D" exhibited uniform surface roughness, consistent with the theory of Devlin.

The test fluids were evaluated in the five hydraulic motors listed in Table 2. The geroler and radial piston motors are designed for low-speed high-torque duty. The axial piston and bent axis motors are capable of higher speeds. The mechanical efficiency of each motor was evaluated per ISO 4392-1. In the ISO 4392-1 standard test method, the torque output of a hydraulic motor is measured as it rotates at 1 RPM for 1 minute with a constant supply pressure. Hydraulic mechanical efficiency is determined by dividing effective torque by the theoretical torque [7].

Table 2: Test Motors

Motor Type	Displacement [cc]	Maximum Speed [rpm]	Maximum Pressure [psi]
Radial Piston	330	200	6525
Geroler	235	390	2900
Geroler	325	440	4500
Axial Piston	100	3300	6000
Bent Axis	110	5350	6525

Typical 1 RPM test results are shown in Figures 4 and 5**.** Fluid "D" exhibited higher mechanical efficiency in the axial piston, radial piston, and geroler motors. The effect of the friction modifier in fluid "D" was negligible when evaluated at speeds greater than 10 RPM.

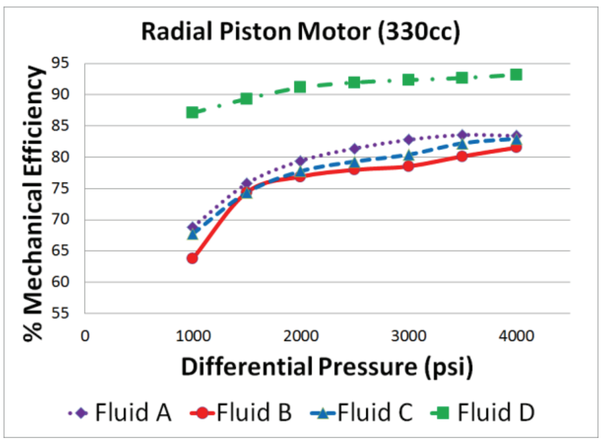

Figure 4: Radial Piston Motor 1RPM Efficiency

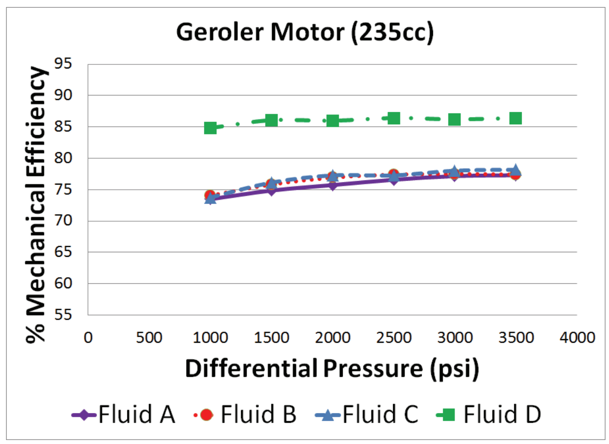

Figure 5: Geroler Motor 1 RPM Efficiency

The efficiencies of Group III ashless ("B") and ZDDP based fluids ("C") were evaluated in bent axis motors. Fluid "C" was 2 to 3 % more efficient than fluid "B" at 1 RPM. After testing, the bent axis motors were disassembled and tribological surfaces were analyzed via EDX. Elemental analysis of valve segment and piston ring surfaces revealed that the ZDDP tribofilm exhibited a higher ratio of additive elements to iron as shown in Table 3. The ZDDP tribofilm also exhibited a higher ratio of additive elements in the Anton Paar specimens. Note that the additive-to-iron ratio was lowest for the friction modified fluid "D". These findings are consistent with the thin and thick film theories of Spikes and Devlin.

Table 3: EDX Analysis of Tribometer and Bent Axis Motor Surfaces, Atomic %

Element	Anton Paar Plates				Valve Segment		Piston Ring	
Atomic %	Fluid A	Fluid B	Fluid C	Fluid D	Fluid B	Fluid C	Fluid B	Fluid C
Iron	48.3	48.5	37.6	66.3	46.6	49.6	65.6	68
Phosphorus	5.5	5.7	7.4	1.2	0.9	2.1	1.5	0.8
Sulfur	0.5	0.5	7.6	4.2	0.7	1.1	0.3	1.4
Zinc	1.1	2.5	11.3	0.0	0.0	1.9	0.0	0.9
Additive/Iron, %	15%	18%	70%	8%	3%	10%	3%	5%

Near-term Goals

High speed motor efficiency tests have been conducted on several fluids. As shown in Figures 6 and 7, hydraulic motor volumetric and mechanical efficiencies are a function of dimensionless viscosity [8]. In the next six months, efficiency models for hydraulic motors that incorporate fluid rheological and boundary lubrication properties will be developed. These models will estimate the operating pressures and flow rates required for motors to produce torque throughout a wide range of speeds.

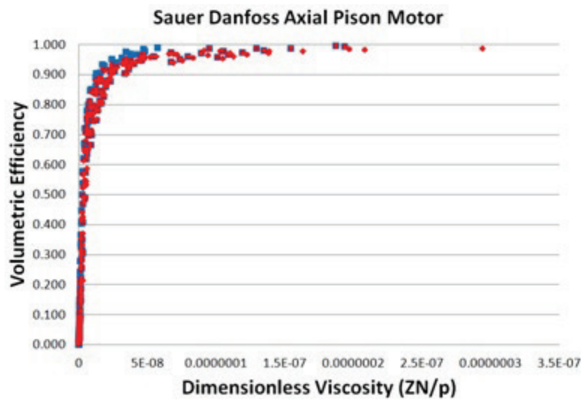

Figure 6: Volumetric Efficiency Stribeck Curve

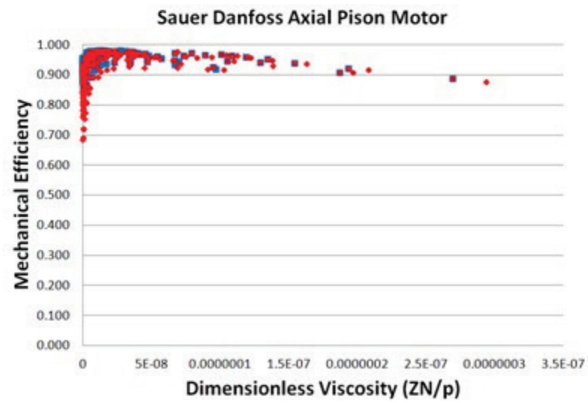

Figure 7: Mechanical Efficiency Stribeck Curve

Long-term Goals

Over the next five years, this project bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power components by studying the relationship between molecular structure and the compressibility, traction, and shear-thinning characteristics of hydraulic fluids. Recently high bulk modulus fluids have been developed for fluid power applications [9]. The incompressibility of these fluids results from intermolecular forces that reduce free volume, and molecular structures that inhibit bond rotation. These molecular characteristics increase the dynamic response of a hydraulic system, but they also increase viscous friction (traction). The significance of viscous friction is very clear in hydraulic systems since it affects pressure drop in lines and valves, plus losses in pumps and motors. Mounting data suggests that increasing the viscosity of a hydraulic fluid through the use of shear-stable VI improvers increases hydraulic system efficiency [10]. Resistance to permanent viscosity loss due to shear has been identified as the key VI improver requirement. Yet VI improvers increase the shear thinning characteristics of a lubricant. In collaboration with Professor Bair, we will examine the effects of base oil and VI polymer structure on bulk modulus, traction and shear thinning. Project milestones are shown in Figure 8. In the long term, this project will make possible the development of models for selecting energy efficient fluids that are based upon hydraulic system architecture, duty cycles, and the underlying tribological conditions.

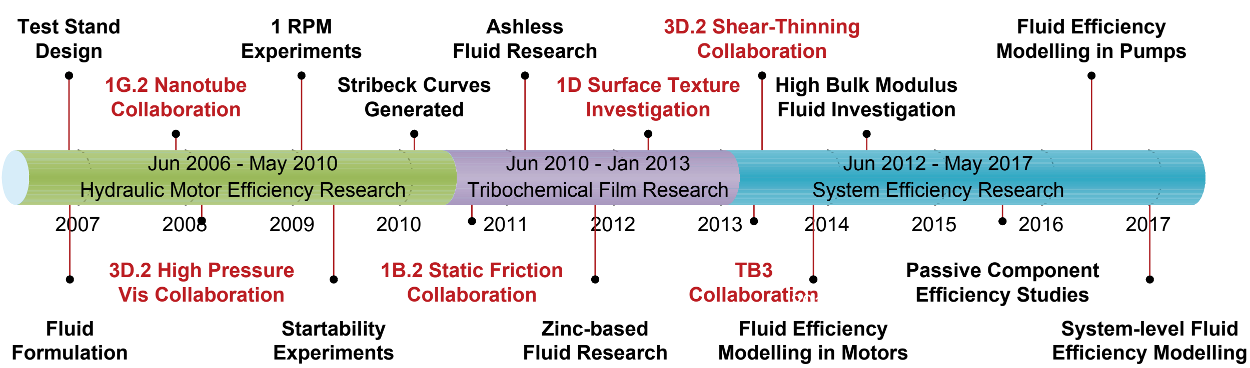

Figure 8: Project Timeline with Major Research Milestones. Collaborative efforts are highlighted in red.

Task List
1) Validate fluid selection for TB-3 [3 months]
2) Evaluate high pressure shear-thinning characteristics of fluids at Georgia Tech [6 months]
3) Develop fluid efficiency models for motors [6 months]
4) Conduct dynamometer experiments on prototype hydraulic fluids to probe the effects of fluid compressibility, shear stability, and thin film friction on hydraulic system efficiency [3 to 12 months]
5) Evaluate high bulk modulus fluids [15 months]

Milestones
1) TB-3 fluid formulation and characterization [Q1 2013]
2) Completion of fluid efficiency model for motors [Q3 2013]
3) Procurement of high bulk modulus fluids [Q2 2014]

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 fluids that affect hydraulic system efficiency and translate that technology into practical application. The discovery of correlations between bench-top tests and system wide efficiency will make possible the systematic development of new fluids that increase the productivity and efficiency of hydraulic machinery. Since conversion to an energy efficient hydraulic fluid often does not require a modification of the hydraulic system, this technology can immediately benefit the existing equipment of member companies and their customers.

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Project 1J.1: Hydraulic transmissions for wind energy

Research Team

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	Haonan Sun, University of Minnesota
Industrial Partners:	Eaton Corporation, Clipper Windpower

1. Statement of Project Goals

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

A hydrostatic transmission (HST) functions as a continuously variable transmission and eliminates the need for the gearbox. Gearbox reliability is a major issue and gearbox replacement is quite expensive. In a recent study by Reliawind, it was reported that the major components contributing to low reliability and increased downtime of wind turbines are the gearbox, power electronics and pitch systems [1]. An HST has the potential to increase system efficiency, improve system reliability and decrease the lifetime cost of energy. The application of HST is mainly on the mid-sized wind turbine since most commercially available hydraulic components (pumps and motors) match that power level well. This reduces the technology risk of developing new hydraulic components for the turbine.

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

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

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

- Short-term energy storage for mid-sized hydrostatic wind turbine
  Mid-sized wind turbine, typically defined as 100 kW to 1 MW, fits into the sweet spot of HST applications since the components needed for this application are commercially available in this power range. Preliminary study demonstrated the need and advantages of using hydrostatic transmissions in mid-sized wind turbines. It is shown that a variable ratio hydrostatic wind turbine can produce more power than a fixed ratio and fixed speed gearbox turbine even given the lower efficiencies of the HST. But most modern wind turbines are variable speed, pitch controlled turbines. In this case, commercially available off-the-shelf hydrostatic drives may not be able to compete with gearbox drives in energy production even though the lifetime cost of energy may be lower owing to the higher reliability and lower initial cost of hydrostatic drives. To make hydrostatic drives more attractive, this study investigates the use of short-term energy storage using hydraulic accumulators to increase the Annual Energy Production (AEP). The use of short-term energy storage during turbulent wind oscillations is focused on the region around the rated wind speed (between region 2 and region 3).

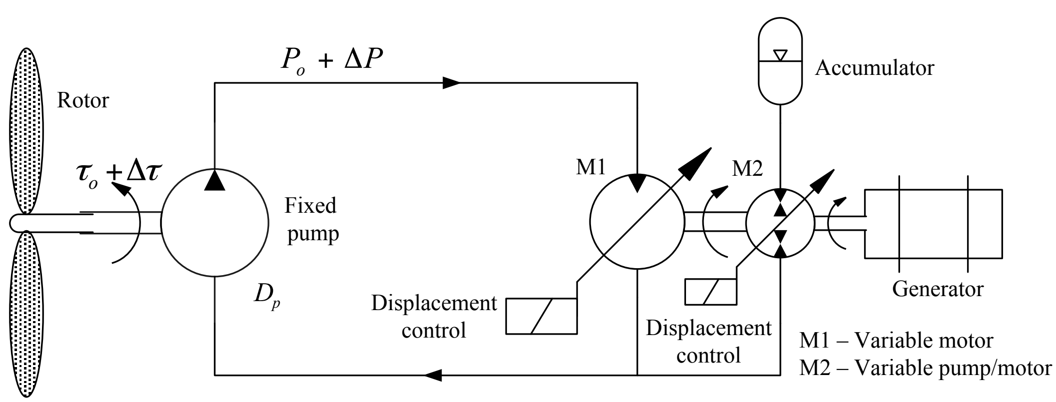

Figure 1: Simplified schematic of a hydrostatic wind turbine with energy storage

Accomplishments:
1. Propose a system configuration for the energy storage of the hydrostatic wind turbine;
2. Develop a rule-based control strategy for the proposed energy storage system;
3. Obtain a turbulent wind profile based on FAST code;
4. Build a dynamic simulation model to verify the energy storage concept;
5. Conduct a sensitivity study of the accumulator size on the annual energy production;

6. Compare the annual energy production between the systems with and without the energy storage system.

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

- Hydro-mechanical transmission for mid-sized wind turbine

  Mid-sized turbines are usually designed as fixed speed machines which reduce costs by eliminating the power converter. However, fixed speed operation does not allow the rotor to capture the maximum energy as wind speed varies. To capture wind energy more efficiently, a variable transmission such as a hydrostatic transmission (HST) is needed. Yet, the low efficiency of an HST compared to gearbox drives often makes it undesirable. Therefore, a hydro-mechanical transmission (HMT), combining the high efficiency of a gearbox and the variable ratio function of an HST, offers a more competitive solution for mid-sized turbines.

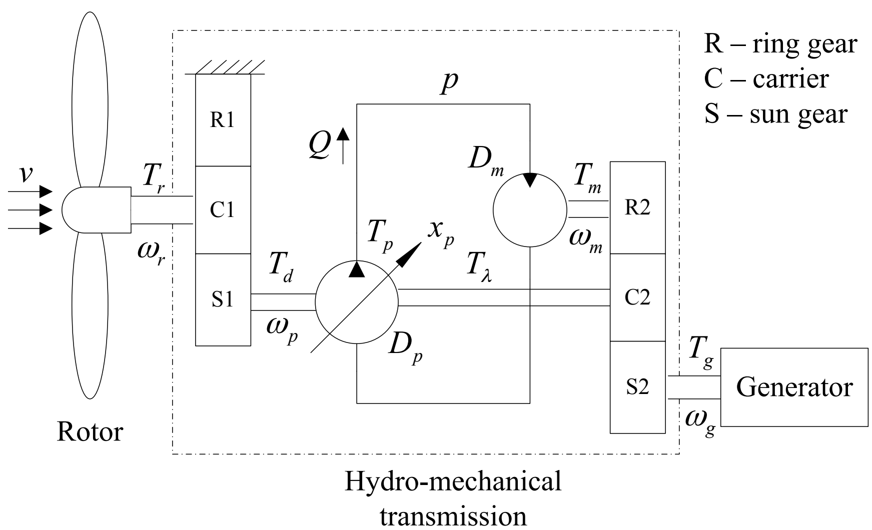

Figure 2: Schematic diagram of the HMT wind turbine

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

Due to the variable ratio characteristics of the HMT, the rotor speed can be adjusted with the varying input wind speed so that the optimum tip-speed ratio and maximum rotor power coefficient can always be obtained. The high efficiency of the planetary gear improves the overall drivetrain efficiency and increases the generator power output. Simulation results are compared with the theoretical results based on steady-state characteristics. As predicted, the ratio of the rotor power transferred through the mechanical path increases with the increasing wind speed. This is desired since higher wind speeds have more power than lower wind speeds.

The drivetrain efficiency and the generator power of the HMT and HST wind turbines are compared. Simulation results show that an HMT turbine has higher drivetrain efficiency and generator output power than an HST turbine. If the additional cost is low enough, a hydro-mechanical transmission could be a more cost effective solution than a hydrostatic transmission for mid-sized wind turbines.

- 55 kW test stand for hydrostatic wind turbine research
The objective for constructing a test stand is to allow testing and validation of the modeling and simulation on hydraulic transmissions for wind turbines, the University of Minnesota is installing a new test stand. The test stand will have a rating of 55 kW and will be capable of testing both hydrostatic and hydromechanical transmissions. It will have a hydraulic regeneration system to reduce power consumption. Initially, the test stand will be used to validate numerical analysis completed to date by the research team.

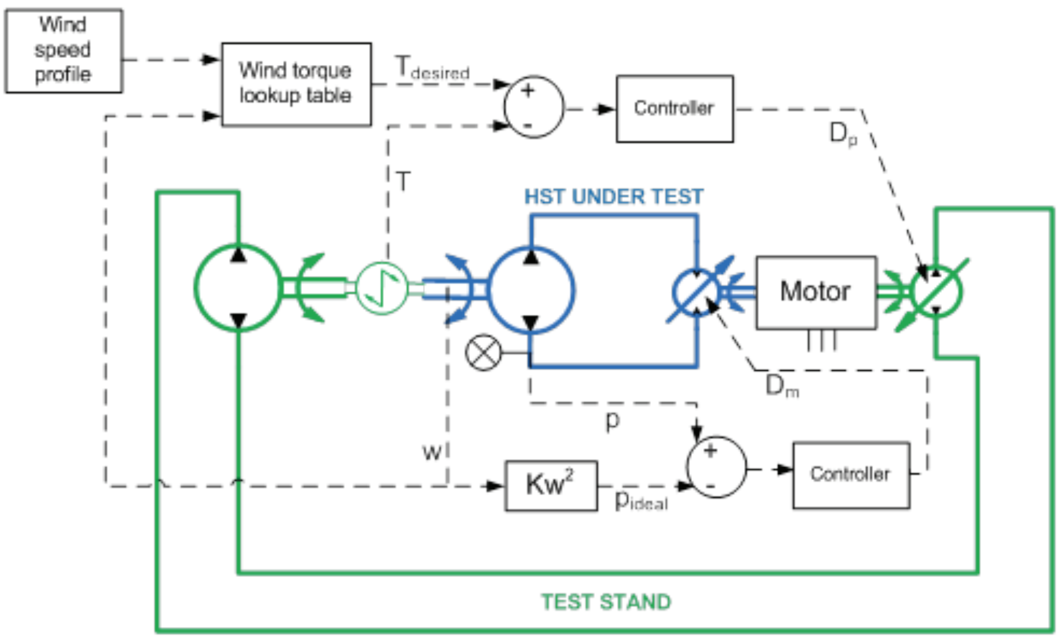

Figure 3: Schematic diagram of the 50 kW hydrostatic wind turbine test stand

Accomplishments:
1. Propose a hydraulic schematic diagram of the test platform;
2. Conduct a system parameter design and determine the system operation points;
3. Develop controllers to simulate the wind input and to track the desired rotor speed.
4. Conduct a CAD design of the test platform.

Most components in the test platform come from donation. Currently almost all the components are ready. The next step is to design a DAQ system for the measurement and control of the test platform, measure the generator power and the drivetrain efficiency and implement different ideas on the test bench.

B. Achievements

Achievements in previous years:
- Developed a high fidelity dynamic simulation model for the hydrostatic wind turbine
- Developed a control strategy for the hydrostatic wind turbine
- Investigated the performance of short-term energy storage for mid-sized hydrostatic wind turbine
- Investigated application of a hydro-mechanical transmission in a mid-sized wind turbine

Planned future work:

- Complete the hydrostatic wind turbine test stand
- Implement the short-term energy storage concept on the test stand
- Implement the hydro-mechanical drivetrain concept on the test stand
- Explore other energy storage systems and implement it on the test stand
- Develop a model predictive control to maximize the wind energy capture and implement it on the test stand

C. Member company benefits

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

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Project 2B.1: Free-Piston Engine Compressor

Research Team

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Undergraduate Students: Nithin Kumar

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

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

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

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

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

B. Achievements

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

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

In Willhite and Barth [18], a dynamic model of a free liquid piston that exploits piston geometry to produce a high inertance was developed for use in a free piston engine compressor. It was shown that for the size scale targeted, advantageous piston dynamics can be achieved with a reduced piston mass compared to a rigid piston design. A patent on this device was filled in 2010 and was granted in 2012 (US Patent # 8,297,237). Modeling work on the former separated combustion chamber prototype revealed certain energetic losses associated with the fast dynamics of the piston motion. Following from this motivation, the concept of inertance was exploited to slow the dynamics of the piston motion while concomitantly reducing the mass of the piston. It was shown that a high inertance liquid piston with a mass of 0.414 kg has the equivalent dynamic response of a 12.5 kg liquid piston of uniform cross sectional area. It was also shown that the required "inertance tube" section of the high inertance liquid piston exhibits manageable viscous losses for the geometries considered. Finally, the dynamic response of the high inertance liquid piston resolved significant issues when incorporated into a free-piston engine compressor device. These issues are: 1) valve sizing, 2) complications associated with a separated combustion chamber, and 3) a balanced engine.

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

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

To achieve higher pressures, increase efficiency, lower weight, and decrease vibration, a redesign was started in September of 2011. A computer render of the compressor alongside a photograph of the fabricated hardware is shown below in Figure 1. Many components are constructed using stereolithography which dramatically lowers the total weight and allows for intricate, strong, and compact components. The unique figure-8 arrangement of the liquid piston contributes toward self-balancing the device to reduce vibrations and eliminates the need of opposing cylinders. The compressor is controlled with a micro-computer and compact, efficient electronics.

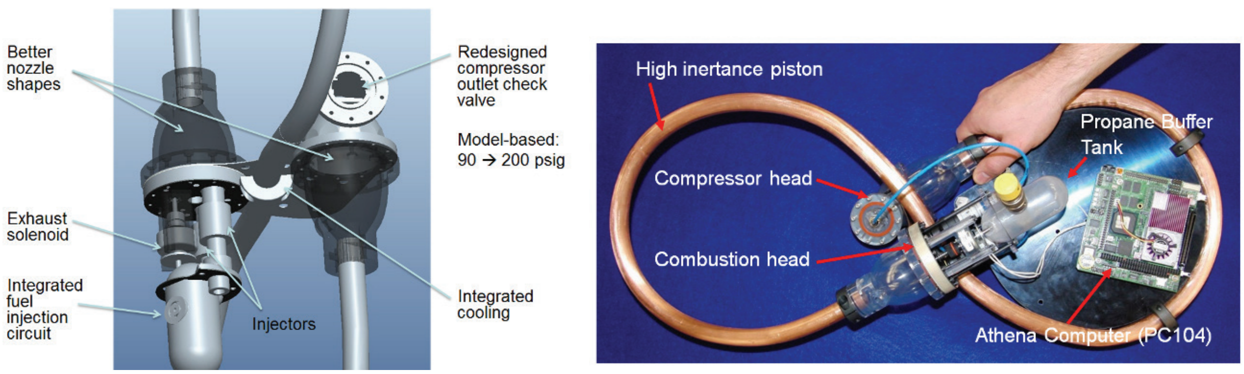

Figure 1: (a) CAD drawing of design, (b) High inertance free piston compressor hardware with self balancing figure-8 design

This engine has been instrumented and tested at a component level. The closed loop controller has been implemented and produces consistent operation. The engine was placed on the crawler (Figure 2) and was easily carried. A full demonstration of the engine-compressor powering the crawler was not achieved due to a failure in the electronic board controlling the exhaust valve. While at Georgia Tech, the engine did run briefly on the lab bench before this failure. This was somewhat disappointing and we did not get a second chance due to travel costs and scheduling.

Regardless of the lack of a full demo on the testbed, experimental results combining data from the figure-8 prototype and the previous prototype, which contained more extensive instrumentation in order to validate the dynamic system model and fully energetically characterize the device, do tell a compelling story. Mass and size are best characterized by the most recent figure-8 prototype. As a self-contained device, the figure-8 prototype included an on-board microcontroller and all supporting electronics, but contained minimal instrumentation. With regard to the previous prototype, the measured efficiency (lower heating value of propane fuel to pneumatic potential energy) ranged from 3.45% to 6.63% with an output power range of 9.6 W to 17.9 W [22]. A virtual-cam control approach applied to this prototype yielded an improved efficiency range of 4.4% to 8.1% with a pressure output range from 380 kPa to 720 kPa (40 to 90 psig) and slightly higher output power [25, 26]. The figure-8 prototype had a mass of 5.9 kg and was able to deliver compressed air up to 1.2 MPa (157 psig), an improvement over the previous prototype due largely to model-guided design changes in the compressor head check valve and inertance nozzles [27].

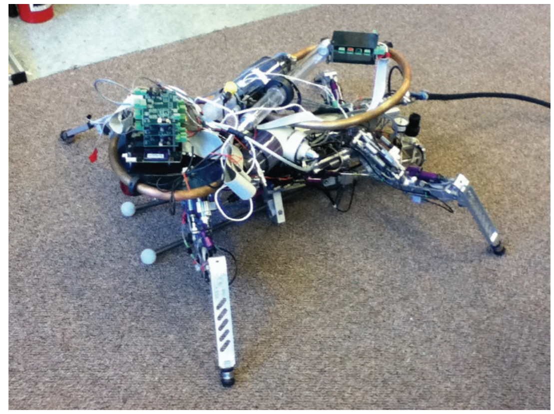

Figure 2: Photograph of the figure-8 free-piston engine compressor on the rescue robot testbed.

Although these efficiencies seem low, it must be remembered that this is the combined efficiency of an internal combustion engine and a compressor, all in a relatively small package. The data suggests that pneumatic systems using the FPEC as a power source would exhibit system energy densities comparable to, if not better than, the best electromechanical systems. The experimentally demonstrated energy density of the FPEC ranges from 2040 kJ/kg to 3750 kJ/kg (resulting stored pneumatic potential energy per kilogram of fuel) compared to about 700 kJ/kg for Li-ion batteries. Accounting for roughly 50% efficiency of the actuation (pneumatic actuators or motors with gearheads), this translates to a specific work of 1020 kJ/kg to 1875 kJ/kg for the FPEC powered system with pneumatic actuators, compared to about 350 kJ/kg for a Li-ion battery powered system with DC servomotors. Combined with the inherent power-density and therefore weight advantages and direct-drive capability of pneumatic actuators over DC servomotors, devices like the FPEC position pneumatically actuated systems as an attractive option for human-scale, untethered robotic systems. Further design and control optimization of the FPEC is also possible.

Expected Milestones and Deliverables (Project ended in May 2012)

- Milestone 1: High Inertance Prototype (HIFLPC) Completed *DONE*
  - Task: Unloaded tuning *DONE*
  - Task: Constant load energetic characterization *DONE*
- Milestone 2: HIFLPC Energetically Characterized at Ideal Conditions *DONE*
  - Task: Full model experimental validation *DONE*
  - Task: Injection controller for varying loads (reservoir pressures) *DONE*
  - Task: Energetic Characterization over operating envelope *DONE*
- Milestone 3: Controlled Prototype Energetically Characterized *DONE*
- Milestone 4: Design Compact Rescue Crawler ready prototype (FIGURE-8) *DONE*
- Milestone 5: Stand-alone Power Supply System Completed *DONE*
  - Task: Ship to Georgia Tech, work with Georgia Tech to resolve any issues
- Milestone 6: Power Supply Fully Characterized on Test Bed 4 (5/31/12 – the crawler could easily carry the fully fueled device. However, we could not make both pieces of hardware work simultaneously.)

C. Member company benefits

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

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

Research Team

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

1. Statement of Project Goals

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

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

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

3. Project/Test Bed Description

A. Description and explanation of research approach

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

B. Achievements

Brief Overview of Previous Achievements

The project started September, 2008. In the last reporting period (Feb. 2011 – Jan. 2012), a generation 2 prototype was fabricated, which is about 12 cm long with 12.5 mm engine bore size, and weights 260 grams. Various unique design features ensured alignment of components, and minimal friction while maintaining relatively good sealing.

The prototype operated in free-piston mode and pressurized a 530mL air tank to 6.7 bar from 2.4 bar in 38 seconds. Experimental data was analyzed and the output compressed air equivalent power was estimated to be 5 W. The low efficiency of converting the 48 W indicated output of the engine to 5 W of compressed air output was due to leakage in the compressor, compressing heating effect and friction in the engine and compressor.

Experimental data were compared with the simulation model and verified that the model was able to predict key engine compressor characteristics. Combustion analysis showed the heat release process associated with glow-plug ignition in the free-piston engine compressor prototype was not optimal and HCCI combustion has good potential to improve efficiency since it has a much faster combustion heat release process.

Achievements in the current year (Feb. 2012-Jan. 2013)

Further testing and data analysis

The free-piston engine compressor was designed to be self-regulated without using active control. As a result, cyclic variation was a barrier to running the engine. In weak cycles, if the piston did not travel far enough to uncover the exhaust and transfer port for sufficient time, the scavenging process would be interrupted, making the engine stall on the next cycle. In strong cycles, the piston might travel too far and encounter destructive metal to metal collision against the end stop.

To accommodate for this variation, the device was designed to have 2 mm over-stroke, so that the pistons could travel 2 mm further than nominal BDC position of a crankshaft engine. In strong cycles, the pistons travel further than nominal BDC while the rebound spring and compressor absorb more energy. After the pistons travel to the end of the 2 mm over-stroke, rubber bumpers absorb extra energy if present. These measures enabled the free-piston engine compressor to handle some variation in the amount of energy released from combustion product expansion. The energy balance is shown in Figure 1. Variation of expansion process energy release could be in a relatively wide range, while the piston travel was still long enough to enable scavenging but not so long to result in metal to metal collision.

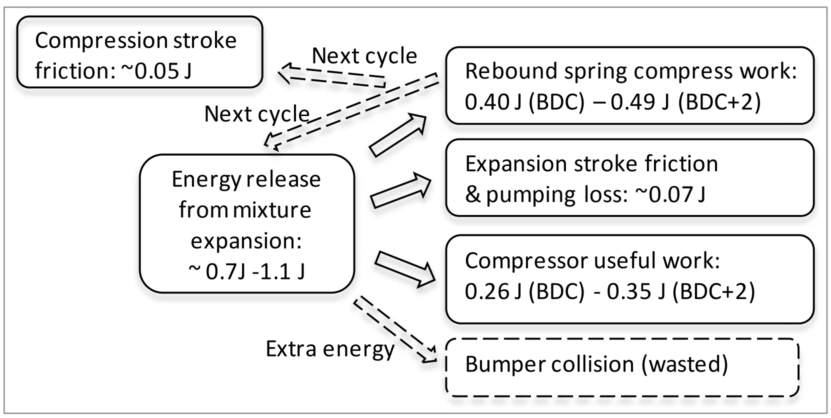

Figure 1: Energy balance in free-piston engine compressor at 4.5 bar compressor output

At lower compressor output pressure, the compressor absorbed less energy and more energy was wasted in the bumper collision. When the piston position was at 14mm it collided into the rubber bumper, and it was assumed that the kinetic energy at that moment was wasted in bumper collision. The average bumped energy was calculated by averaging about 20 consecutive cycles. The results are shown in Figure 2. Compressor absorbed work was calculated by assuming a polytropic compression process inside the compressor with a compression index of 1.3. Bumping avoidance efficiency was calculated by dividing compressor work by the sum of compressor work and bumping energy.

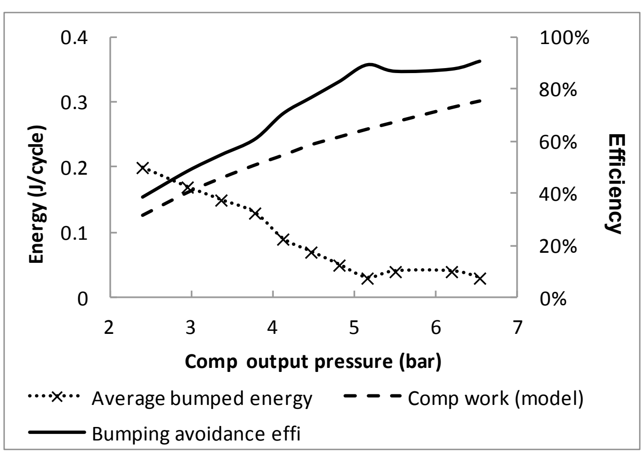

Figure 2: Analysis of bumping in the free-piston engine compressor prototype

At different compressor output pressure, the sum of average bumped energy and compressor work was about 0.32 J per cycle. As the load absorbing capacity of the compressor increased with output pressure, less energy was wasted in bumping, resulting in a higher bumping avoidance efficiency. However, higher compressor output pressure increased the chance of engine stalling if a weaker cycle occurs.

Hardware issues and solutions

The gen II prototype uses the piston and liner from 'AP Hornet .09' model aircraft engines. Piston material is hyper-eutectic aluminum alloy with high silicon content in the alloy for lubricity. The cylinder liner is brass, plated with a thin layer of chrome. Measurement showed that the cylinder liner had negative clearance around top dead center (TDC) position and tapers off towards bottom dead center (BDC), when the engine is at room temperature. As a result, model aircraft engines are tight to turn over TDC position when they are cold. This isn't an issue for model aircraft engine as force is used to turn over crankshaft during start up and the momentum of crankshaft and flywheel overcomes the tightness during warming up. As the engine warms up, top of liner gets hotter than bottom, thus the heat expansion counters the liner taper, resulting in straight bore and good seal against the piston.

The negative tolerance around TDC was a problem for a free-piston engine during starting, as there was no force to overcome the tightness at TDC to achieve needed compression ratio; the only force available during starting up was from the rebound spring, which was not enough to overcome the tightness of negative clearance and achieve high enough compression ratio.

To address the negative clearance problem with the chrome plated brass liner, sanding and reamer machining were used to bring the clearance to an appropriate positive value, so that the piston cylinder fit was good for cold starting. But after the engine warmed up, heat expansion of the top of the liner resulted in too loose clearance fit, causing inconsistent sealing.

According to Murray (1975), a smooth surface finish with less than 0.5 μm R_a (the arithmetic average of the absolute values of roughness) is needed to avoid piston scuffing. Sanding the chrome surface with sand paper proved to be too rough and caused the scuffing. Reaming was attempted, and the 0.4925 inches (12.510 mm) reamer were found to work well with engine side cylinder liner, and the 0.4930 inches (12.522 mm) reamer were found to work well with compressor side cylinder liner. However scuffing and piston-cylinder seal deterioration were still present and prevented longer run time. Piston life was found to be 5 to 6 minutes running time at best in the prototype.

The same material piston and cylinder liner might work better. If cylinder liner is chrome or nickel plated aluminum, the expansion factor of liner and piston can match up better, might result in more consistent seal with cold and hot engine. Furthermore, PTFE (Polytetrafluoroethylene, or Teflon) material could be a good candidate for eliminating compressor side piston scuffing. According to Wilson (1975), filled-PTFE material has been used in reciprocating compressor piston rings with success in both lubricated and non-lubricated conditions. If the compressor side piston of the prototype is custom made with filled-PTFE and run in non-lubricated condition, considerably better seal could be expected compared to current metal to metal seal. However, suggested useful continuous temperature limit of these filled-PTFE material are 150-160 degrees Celsius (Wilson 1975), and as a result it is not suitable for engine side because of plastic deformation of the material when exposed to higher temperature.

Another hardware issue was compressor check valve failure. The prototype compressor check valves were fabricated from thin stainless steel foils. They suffered fatigue problems and cracked after minutes of run time. The fatigue and cracks were due to the absence of a valve stop, stress concentration in valves, and that some lubrication oil and fuel leaked into the compressor during running, resulting in fluid flow out through the output check valve, exaggerating valve deformation. Solution to this problem includes (1) A valve stop needs to be designed for this reed check valve; (2) valve needs to be re-designed to avoid stress concentration; (3) The compressor piston should be custom fabricated from filled-PTFE material and run dry, so that no lubrication oil or fuel would go through the output check valve.

Engine compressor standalone package
An engine compressor standalone packages was fabricated as shown in Figure 3, which integrated the engine compressor prototype, an air tank, a fuel tank, valves and plumbing on a waist pack. The waist pack serves as a standalone fluid power supply, and connects to a pneumatic ankle foot orthosis with a quick connect air hose. Several issues were found with the setup including lubrication oil choking the air hose, quick air tank pressure change due to small tank size, and engine compressor vibration.

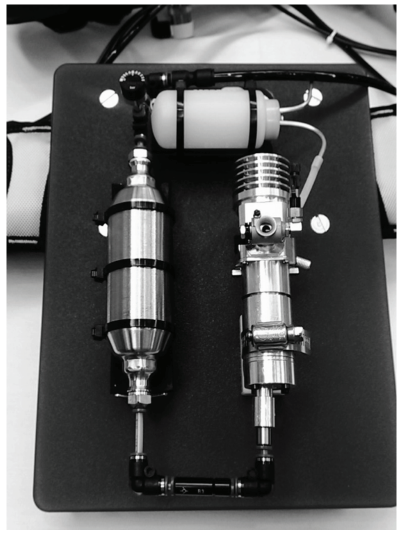

Figure 3: Engine compressor standalone package

Expected milestones and deliverables

Task 1: Addressing engine compressor hardware issues

- Practical problems encountered with the prototype should be addressed, which include piston scuffing problem, carburetor fuel delivery at starting up, piston-cylinder sealing, scavenging loss, compressor valves sealing and compressor valves fatigue.
- Among the practical problems, the piston-cylinder sealing and scuffing problem, and scavenging loss problem could possibly be addressed by custom made piston, cylinder liner and scavenging passages with appropriate materials.
- It should be noted that if components are updated and optimized, modeling of the engine compressor should be carried out again to re-establish optimized operating speed and design parameters.

Task 2: Investigate in starting and longevity of the engine compressor

- Consistency in starting and running needs to be improved. Currently the prototype starts in a 'hit or miss' manner and could only sustain continuous run times up to about 6 minutes before stalling. The fuel delivery, scavenging and combustion during starting need to be investigated and improved for consistent starting in a free-piston engine. Wear and fatigue of engine compressor components need to be understood and addressed.

Task 3: Implementation of HCCI

- Pure HCCI should replace the glow ignition system to yield faster combustion and higher cycle efficiency. Pure HCCI requires higher compression ratio thus piston-cylinder leakage should be minimized to deliver high enough compression.

Task 4: Running with alternative fuel

- Alternative fuels should be considered. Currently the prototype utilizes methanol based fuel to work with the simple carburetor and the platinum catalyst of glow ignition system. Dimethyl ether might be promising, because it is non-toxic, has high Cetane number thus easier to ignite in HCCI mode and it is a gaseous fuel which can be stored in a compressed fuel canister. A pressurized fuel canister based system might provide more consistent fuel flow metering than the current carburetor setup.

C. Member company benefits

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

D. References

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Project 2B.3: Free Piston Engine Hydraulic Pump

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

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

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

3. Project Description
A. Description and explanation of research approach

Background and Motivation

Fluid power is very effective at energy transmission due to its superior power density and flexibility. The current practice for energy storage is using hydraulic accumulators to store high-pressure fluid. However, the energy density of the fluid system is lower than the electrical system and poses a serious challenge for its wide use in mobile applications. An alternative approach is to store the energy in the form of hydrocarbon fuel and convert it to fluid power in real time. This configuration offers the ultimate power density and energy density (order of magnitude higher than electrical systems) and therefore become extremely attractive for mobile applications. However, to realize this concept, it is necessary to convert the chemical energy into fluid power in real-time to match the dynamic power demand. The hydraulic free-piston engine (FPE) is a promising candidate due to its fast dynamics (output can be changed on a cycle-to-cycle basis in milliseconds), resulting from its unique architecture, low inertia and modular design. The objective of this project is to develop a hydraulic free-piston engine as a compact and efficient fluid power source for on-road and off-road vehicles. A picture of the research prototype and the schematic diagram of the hydraulic free-piston engine we are investigating are shown in Figure 1. Combustion in the right cylinder will push the inner piston to the left and outer piston to the right, which will compress the gas in the left cylinder and generate high pressure fluid in the inner hydraulic chamber. Similarly combustion in left cylinder will return the inner piston to the right and outer piston to the left.

Attracted by its great potential, many researchers are actively working on the development of the FPE technology. Achten [1] reported a single-piston hydraulic FPE with 17 kW output power. The control strategy of this work is similar to that used by Hibi [2] on a 5kW opposed-piston hydraulic FPE. The main idea is to utilize hydraulic circuits with calibration-based control to achieve identical piston motion of each engine cycle. A waiting period, which can be adjusted by a flow control valve, is imposed between the consecutive cycles. Therefore, the output flow rate of the engine can be changed in real time. The advantage of this strategy is that it produces nearly constant efficiencies across the engine power output range. However, this approach is only applicable to the abovementioned FPE architectures, and its robustness is relatively low. Johansen [3] developed a control system for a diesel FPE connected to a power turbine. The control system regulates the engine power and piston motion by adjusting the valve timing and it contains a calibration based valve timing control and a PID bottom dead center (BDC) and top dead center (TDC) control. Stable engine operation was achieved with the proposed control. However, the engine operation flexibility was limited by the robustness and the discrete nature of the controller. Tikkanen reported the first cycles testing results of a 11.3 kW opposed-chamber hydraulic FPE without any feedback control [4].

Previous works on FPE have shown limited success mainly due to the major technical barrier of this technology: large cycle-to-cycle variation, especially during transient operation, which induces engine misfire. For a conventional internal combustion engine (ICE), the crankshaft is the mechanism, which brings the engine back to normal if misfire occurs. However, for a FPE, the piston motion depends on the combustion and loading dynamics and precise and robust piston motion is not automatically guaranteed.

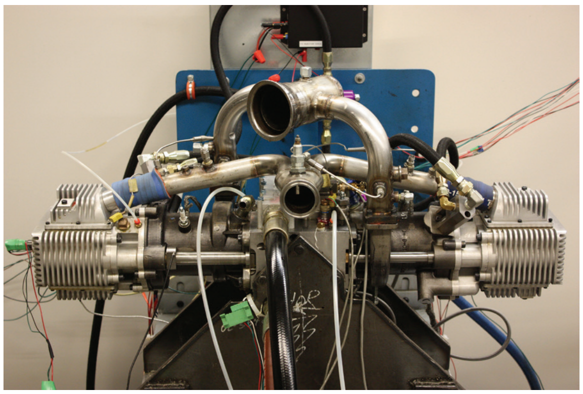

Figure 1(a): Free Piston Engine-Driven Hydraulic Pump

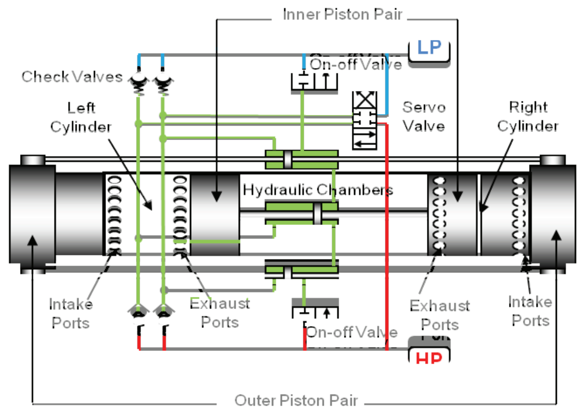

Figure 1(b): Schematic of the Free Piston Engine Driven Hydraulic Pump

Research Approach

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

Active Piston Motion Control

The design of a model based active control offers a robust and effective solution to overcome the FPE control challenge. The controller works as a “virtual crankshaft” that guides the piston to follow a pre-defined trajectory instead of the mechanical linkage. It controls the piston motion via hydraulic servo valve and high pressure fluid in the hydraulic accumulator. The advantage of the virtual crankshaft over mechanical crankshaft lies in its ultimate flexibility of compression ratio control. Specifically, the control algorithm and the reference trajectory of the virtual crankshaft can be altered digitally to achieve a wide range of piston motion profile within a short time period, which is not achievable through mechanical crankshaft. Not only can the virtual crankshaft guarantee a stable operation, it will also regulate the engine to run at maximum efficiency. With a mechanical crankshaft, the piston trajectory is fixed and is independent from engine speed and load. Thus, there are limited means for optimizing the engine efficiency. However, with the virtual crankshaft, the piston trajectory can be varied in real time by altering the reference signal. Optimal trajectories will be determined for the engine under various frequencies and load conditions, so that the engine would always run at its maximum efficiency.

Design Optimization of the Free Piston Engine Driven Hydraulic Pump

To increase system controllability as well as efficiency, we will investigate alternative designs for the free piston engine driven hydraulic pump. First, digital flow control approach will be studied and simulated to assess its effectiveness in improving the performance of the HFPE. Currently, check valves as shown in Figure 1(b) are used to enable suction of fluid from the low-pressure reservoir and pumping it to the high-pressure reservoir. Despite its simple and reliable design, this approach introduces some limitations on the operation of the HFPE under different scenarios. This limitation arises from the fact that these valves are passively controlled by the pressure difference between up and down stream and could not be actively adjusted. To overcome this limitation and provide further flexibility in the operation of the HFPE, we propose to replace the check valves and the servo valve with high speed digital on-off valves. System simulation will be conducted to investigate the feasibility of this approach. Second, we propose to control the intake and exhaust process with an electro-hydraulic camless valve actuation system [5-8] 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 therefor improve the combustion phasing control.

B. Achievements

From June 2010 to June 2011, comprehensive physics-based models were constructed [9]. The simulation results provided us with new insights into the engine performance under different loading conditions. A novel methodology for stability analysis of the HFPE was also developed, which predicts the stability of the engine operation at specified operation points in a systematic manner [10]. Furthermore we compared an FPE with a linear alternator with an FPE coupled with linear hydraulic pump to study the various architectures of FPE [11]. To conduct experiments and collect data, several engine sub-systems were installed: the driver for Moog and Lee valves were identified and installed. The lubrication system was built for both inner and outer piston pairs. A displacement transducer, pressure transducer and thermocouples connected to the combustion chamber and hydraulic chamber, were properly conditioned and calibrated. A dSPACE system that realizes real-time control was set up and connected to the sensors and actuators. One of the main milestones during 2011 was the successful development and implementation of the piston motion control system (virtual crankshaft) for the HFPE [12].

In the past year, our research team has demonstrated precise tracking control of the piston motion with the active controller in engine motoring and combustion tests. Figure 2 shows the experimental results. The virtual crankshaft is able to produce a stable and repeatable motoring, and the piston tracking performance is excellent considering the fact that the moving mass and stroke length of the system is much larger compared to typical fluid power applications, whereas the actuation force (hydraulic force) is almost the same level as the resisting force. The effectiveness of the virtual crankshaft allowed us to conduct engine firing tests. A multi-spark CDI ignition control box is used to guarantee a quick and complete combustion. And a gasoline direct injection (GDI) system enables us to control the injection timing precisely. With the previous motoring data, we calibrate the injection and spark timing with respect to the piston position. Figure 3a) and 3b) show the in-cylinder fuel injection and in-cylinder spark respectively. Figure 4a) shows the PV diagram of the single-occurrence combustion and the combustion chamber pressure trace. The two graphs are compared with a pure motoring case. Following the single-occurrence combustion, multi-occurrence combustion tests are conducted in the test cell. There is a transient period after each combustion event, in this case, we add a waiting time to each fuel injection. The PV diagrams of these combustion events are plotted in Figure 4b). Cycle-to-cycle combustion variation can be observed from the graph. However, we are still able to achieve a stable engine operation, which further demonstrates the effectiveness of the proposed active motion controller.

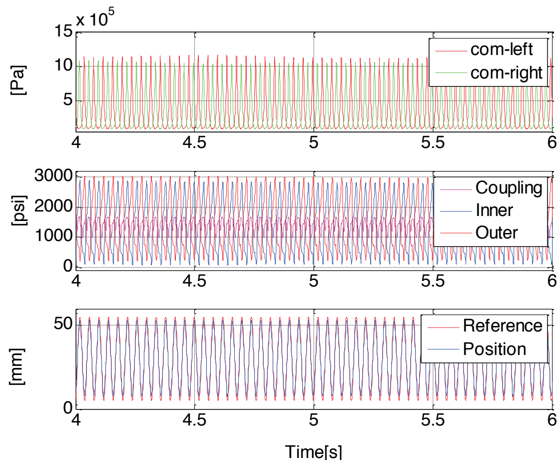

Figure 2(a): Motoring data (from top to bottom): combustion chamber pressure, hydraulic chamber pressure, tracking performance

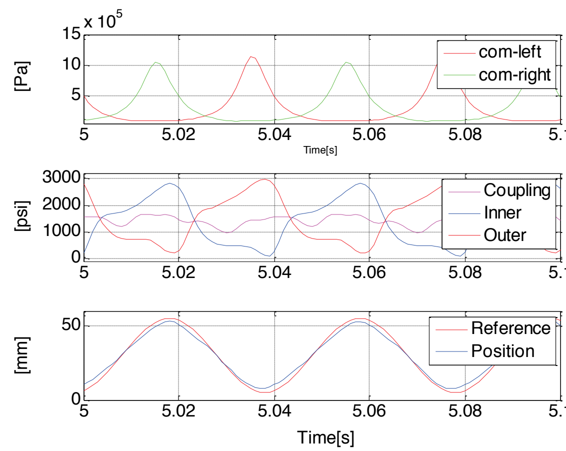

Figure 2(b): Zoomed in motoring data

Figure 3(a): In-cylinder fuel injection

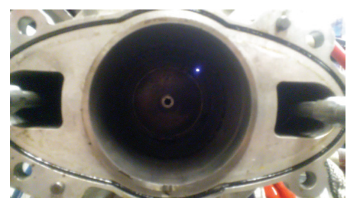

Figure 3(b): In-cylinder spark

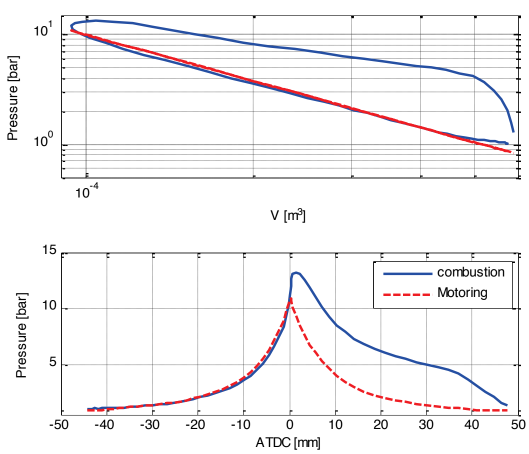

Figure 4(a): PV diagram and pressure trace of Single-occurrence combustion test

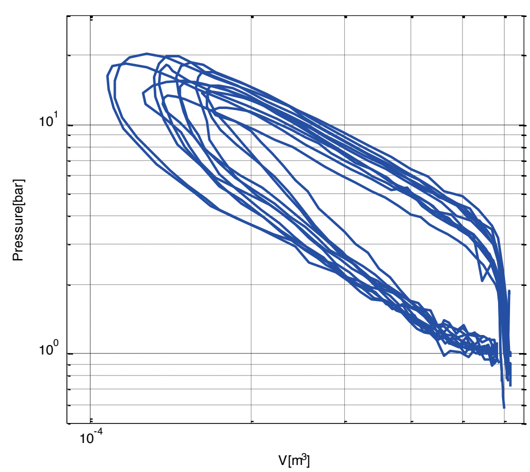

Figure 4(b): PV diagrams of multi-occurrence combustion test

Plan for the Next 5 Years

1) Hydraulic free-piston engine tests under various loading conditions

During the course of the proposed research work, the recently-developed piston motion control methodology will be applied to control the output hydraulic power of the HFPE by coordinating the combustion process and the fluid power generation. Specifically, we will first design a control system for regulating the piston motion as well as the engine output power (see Figure 5). During the engine operation, the virtual crankshaft will utilize the high pressure stored in the accumulator to force the pistons to follow a predefined trajectory. However, to extract maximum usable energy from the combustion, the power and motion controller will help to put minimum control effort of the virtual crankshaft to maintain the desired piston trajectory. The controller will adjust the amount of fuel injected and spark timing every cycle based on the desired and actual power output. Second, we will optimize the desired piston motion trajectory to improve engine efficiency. Third, the developed system will be fully tested at various loading conditions and benchmarked against crankshaft-based internal combustion engine driven pump system.

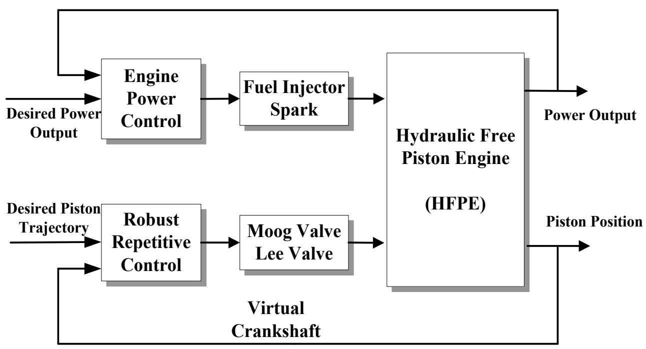

Figure 5. HFPE active control architecture

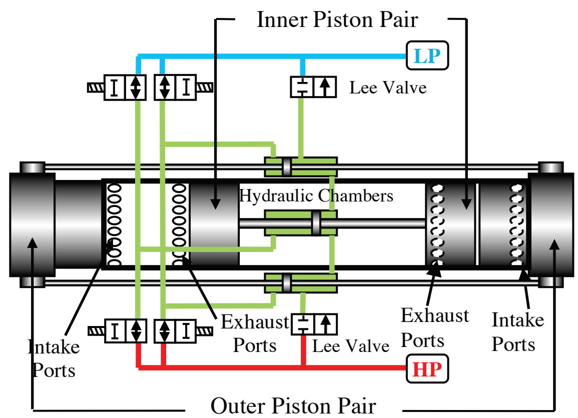

Figure 6. Engine configuration with digital hydraulic valves

2) Digital flow control approach

Digital flow control approach will be studied and simulated to assess its effectiveness in improving the performance of the HFPE. To overcome limitations and provide further flexibility in the operation of the HFPE, we are proposing a digital flow control approach (Figure 6). In this approach, the check valves are replaced by digital on-off valves which could be actively controlled to achieve certain operational objectives. Furthermore, by employing well known pulse width modulation (PWM) techniques, the flow rate could also be adjusted. This digital hydraulic design could also replace the Moog valve for the engine startup to further reduce system cost.

3) HFPE-in-the-loop test and optimization

Based on the above proposed work and to further explore the applications of the HFPE, we are proposing a flexible testing platform to emulate on-road or off-road vehicles powered by the HFPE. Comprehensive physics-based models of various components of the vehicle as well as environmental conditions are developed and used to create a virtual vehicle interacting with the HFPE. As in the case of a hydraulic hybrid vehicle, the vehicle dynamics as well as the drivetrain dynamics will be modeled [13-14]. This virtual system is run in real time parallel to the actual HFPE to emulate the loading conditions of the HFPE. The schematic diagram of the engine-in-the-loop test setup with load emulating system is shown in Figure 7. This simulator outputs a hydraulic pressure and flow command to the loading system which adjusts its flow control valve to achieve the desired level of hydraulic fluid supply. The amount of injected fuel per cycle is also controlled along with the Moog valve to achieve required hydraulic pressure at the HFPE outlet. The load-emulating system provides the specified loads to the engine and absorbs the energy by converting it to heat, and dissipate the heat through a heat exchanger.

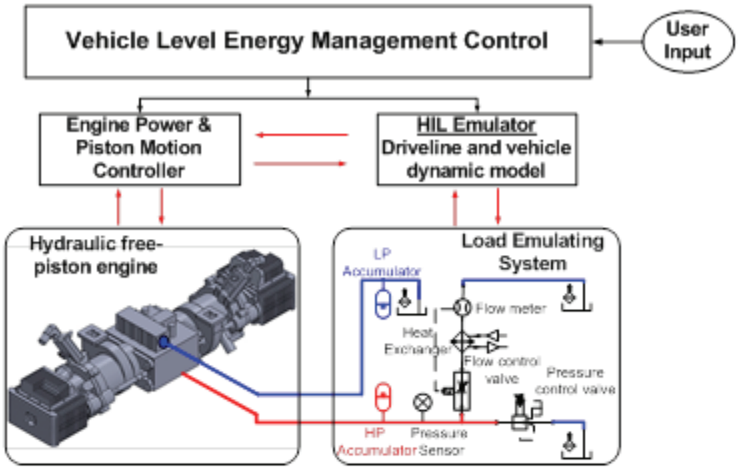

Figure 7. Schematic diagram of the HFPE-in-the-loop test setup with load-emulating system.

<u>Timeline of major milestones</u>

- Task 1: HFPE test under various loading conditions [18 months]
    - Deliverables:
        - Continuous combustion tests with advanced control methodology [5/31/2013]
        - HFPE tests and benchmarking against crankshaft based engine driven pump under various loading conditions [11/30/2013]
- Task 2: Digital flow control [6 months]
    - Deliverables:
        - Simulation results and performance evaluation of the HFPE with digital flow control system [5/31/2013]
        - New HFPE design with digital flow control system [11/30/2013]
- Task 3: HFPE-in-the-loop emulation platform [6 months]
    - Deliverables:
        - HFPE-in-the-loop test platform for on-road or off-road vehicles [3/31/2014]
        - Optimized operational conditions for HFPE for different applications such as on-road or off-road vehicles [5/31/2014]
- Task 4: Series hydraulic hybrid vehicle implementation [30 months]
    - Deliverables:
        - Vehicle design (11/31/2014)
        - Series hydraulic hybrid vehicle prototype (5/31/2016)
        - Test drive and benchmarking against other hybrid vehicles (11/31/2016)

C. Member company benefits

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

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Project 2B.4: Controlled Stirling Themocompressors

Research Team

Project Leader: Eric Barth, Vanderbilt University, Mechanical Engineering
Graduate Student: Mark Hofacker
Undergraduate Student: Nithin Kumar

1. Statement of Project Goals

The research goals of this project are: 1) employ a physical feedback control design approach to purposefully design an unstable Stirling-based thermocompressor that generates power, and assess its merits, 2) study the scalability of the Stirling thermocompressor from miniature pneumatic power supplies up to industrial pneumatic compressors. By the end of the second year, this research will be demonstrated as a silent, low vibration, 20W, 80 psig, high energy-density pneumatic power supply for the Orthosis Test Bed (TB6). Based on the success of this goal, and based on the findings regarding scaling, research beyond the second year will focus on applying the fundamental research results to an efficient industrial-scale compressor. Fundamental research will result in a dynamic, as opposed to thermodynamic, understanding of Stirling thermocompressors. Dynamic models will be developed. Furthermore, Stirling thermocompressors will be recast and reinterpreted from a dynamic systems and controls perspective. This view will afford a feedback control design that assigns groups of physical parameters to feedback gains. In this manner, the complex dynamic interactions can be made to cooperate to produce a self-running compressor upon the addition of external heat (no combustion pulses).

2. Project Role in Support of Strategic Plan

This project contributes to two thrusts within the Center: compactness and efficiency. Enhanced compactness is particularly needed at the scale of TB6 (10-100W). Compactness will be achieved due to 1) the simplicity of the proposed device, 2) the high gravimetric energy density of the driving fuel, 3) the characteristically high efficiency of the Stirling cycle. This project will contribute to the Center's goal of breaking the barrier of low energy density power sources for untethered devices. This project also has the appeal of alternative energy since the source of heat utilized can encompass geothermal to solar (concentrator). Finally, as a larger goal, this project contributes toward future sustainability of the Center by continuing the line of research begun by the free-piston engine compressor as a foundational element of a Pneumatic Center of Excellence based at Vanderbilt.

3. Project Description

A. Description and explanation of research approach

The need for this research is evident on multiple disparate scales. According to the U.S. Department of Energy [1], 10% of electricity used in U.S. manufacturing industries is used for compressed air systems. 70% of the U.S.'s manufacturing facilities have compressed air systems. As pointed out in [2], a Stirling thermocompressor has optimal thermodynamic performance and can have advantages over Otto-driven mechanical compressors. Therefore, an improvement in the efficiency of large-scale industrial compressors would make a large impact. On the medium scale, portable compressors driven by small combustion engines could be replaced with Stirling thermocompressors that are more efficient and with low noise levels relative to current portable compressors. On the small scale, those in the Center are well aware of the lack of portable power supplies for devices such as the compact rescue crawler or the ankle/foot orthosis.

A Stirling thermocompressor, a cousin of the Stirling engine, is a device that uses heat to compress cold air into cold, high pressure air. A high temperature output is avoided through the use of a regenerator. The basic operational principle of a Stirling thermocompressor comes down to the role of the displacer piston. As shown in Figure 1, the displacer chamber is subjected to a heat source on one end (heater), and a heat sink on the opposite end (cooler). The movement of the displacer shuttles compressible fluid between the hot space and the cold space. For example, as the displacer moves down, it moves gas from the cold side to the hot side where the gas absorbs heat resulting in an increase in temperature and pressure. As the displacer is moved in the opposite direction, the gas temperature is decreased thus decreasing the pressure. When the pressure drops, the thermocompressor draws in outside air through a check valve. As the pressure increases, it pumps the air to a reservoir or subsequent thermocompressor chamber to further increase the pressure. It is important to note that because the displacer piston is a regenerator that allows gas to flow through it, there is no effective pressure difference across the displacer and therefore no pressure induced forces on the displacer. Without appreciable sliding friction or flow restrictions, it takes only the work required to move the displacer's inertia and the viscous friction of the gas flowing through and around the displacer to change the pressure. If the displacer is additionally connected to a conservative forcing source, such as a spring, it theoretically takes only the work required to overcome the viscous friction of the gas flow to vary the pressure.

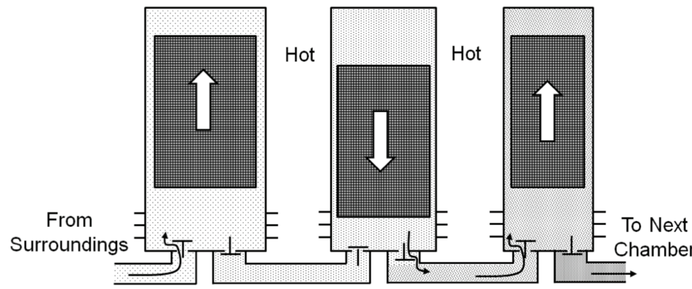

Figure 1: Schematic of multi-stage Stirling thermocompressor. The alternating motion of the displacer pistons varies the pressure in each chamber such that the gas is pumped into increasingly higher pressure stages.

Stirling machines have long held the promise of being an efficient, clean, reliable, and nearly maintenance-free source of power. However, after more than a century of research, the reality of Stirling engines has unfortunately fallen far short of these promises. Why is this the case? The primary reason appears to be low power density – a heavy engine producing small amounts of useable power – particularly at the sub 10kW scale. Free-piston Stirling machines are recognized as possibly holding the key to increasing power density without sacrificing the Stirling cycle's characteristic high efficiency. Historically, the design of the parent device – the Stirling engine – 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. By replacing bulky, complicated kinematic linkages with small, lightweight dynamic elements, free-piston arrangements can be significantly lighter, more compact and operate with fewer losses, and thereby possess higher power densities than their kinematic cousins. Losses are further reduced in the Stirling thermocompressor over the Stirling engine since it has 1) fewer moving parts (no power pistons), 2) does not require intricate high temperature seals (the displacer is a lose-fit) or components. Perhaps one of the strongest reasons for miniaturization of the Stirling thermocompressor and the reason to its proposed application to TB6, is that heat transfer rates are enhanced as the device becomes smaller, thereby increasing power density.

One of the challenges with designing dynamic Stirling machines is the lack of design tools needed to address the significant effects that the dynamics have on the performance. Prior work by the PI funded by NSF has developed such design tools that take a dynamic systems and controls perspective [3, 4]. This is in sharp contrast to the decades' long thermodynamic perspective taken thus far. This project will therefore leverage the use of well-understood models of compressible gas machines previously developed by the PI, with well-understood control design tools as a constructive design approach for free-piston Stirling machines.

The problem with the current state-of-the-art in design of Stirling engines, and Stirling machines more generally, arose when purely dynamic, or free-piston, Stirling engines begin to be considered. In the early 1960's William Beale determined that kinematic linkages were not a necessity for a Stirling engine to operate [5]. The invention of Beale's free-piston Stirling engine was the first dynamic Stirling engine. Primary advantages of a free-piston arrangement include the ability to completely seal the engine, the elimination of side forces on the pistons, and the ability to pressurize the engine to obtain higher power densities [6, 7]. However, since the time of Beale, inadequate design and analysis tools have prevented the design of free-piston Stirling engines from escaping a large degree of trial and error selection of the system parameters. Here, the analysis technique has largely continued down the path of an assumed solution in time, but due to the lack of kinematic linkages altogether, the task of selecting such an assumed solution becomes all encompassing. This is where the "design" of free-piston Stirling engines becomes less constructive. Instead of a constructive design method that reveals intuition and insight regarding the effect of each engine parameter on the metric of interest (such as power, efficiency or indeed even whether the engine will run or not), the designer is left to test each candidate set of design parameters in a trial-and-error manner. Extensive numerical codes exist for this purpose [8, 9, 10, 11]. Although accurate, these codes are unfortunately no better for gaining insight into a particular design than simply building the machine and seeing if it runs, seeing how much power it produces, or seeing how efficient it turns out to be [12]. Despite this, certain dynamic Stirling configurations have been constructed and shown to work, such as many of Beale's arrangements [13, 14], the Harwell Thermomechanical Generator [15, 14, 16], or even the ingenious liquid piston Fluidyne Stirling engine by West [17, 18], among many others. When such free-piston engines have been constructed that run, the selection of their parameters, and their ability to run with respect to the *sensitivity* of their parameters, is not generally well understood [14]. The combination of this fact, along with the numerical simulation based trial-and-error nature of the current design strategy, results in engine designs that are not robust and not generally well understood.

Prior Work

Given that the proposed design methodology is model-based, physics-based lumped parameter models of all non-negligible energy storage elements and power transfer mechanisms will be formulated. Following such modeling, each element will be experimentally validated on experimental prototypes using position, pressure, temperature and mass flow sensors. The proposed modeling will draw heavily on the detailed modeling efforts present in the literature. A. J. Organ has extensively modeled many elements of Stirling engines, including the regenerator [19] in particular. Other Stirling engine modeling by authors such as G. Walker, G. T. Reader, O.R. Fauvel, I. Urieli, N. Isshiki, D. Gedeon, M. B. Ibrahim, M. Carlini, L. Bauwens, and others, will be drawn upon. The author himself has experience with the design, nonlinear modeling and nonlinear control of compressible fluid power systems, including monopropellant-based chemofluidic systems [20, 21, 22, 23], free-piston engine-compressor modeling and design [24, 25, 26, 27], internal ballistics modeled as a compressible fluid power system with internal energy release [28, 29], energy-based control of pneumatic systems [30, 31], passivity-based modeling and control of pneumatic systems [32], and general modeling and control of pneumatic actuation.

B. Achievements

The work of [33] regarding the achievable pressure ratios in a thermocompressor was used to determine a preliminary design for a miniature Stirling thermocompressor intended to TB6. The ratio of the temperature of the heat source compared to that of the heat sink dictates the amount of compression that can be achieved in a single stage. For a temperature ratio of 2, the pressure can be increased by 1.38 in each stage. Based on this, the compressor was designed to have six stages, where each stage would feed compressed air into a smaller chamber which in turn would compress the air even further. By going through all six stages, the device would compress atmospheric air (~15 psi) to 103 psi (88.9 psig). A 3d model of the compressor is shown in Figure 2. The compressor stage cylinders range from 0.75 to 0.33 inch in diameter. The height of the device is 6 inches and is designed to wrap around the orthosis. Also shown in the figure is a fuel (right) and high pressure reservoir (left).Funded by the CCEFP, Riofrio, et al [15, 16] designed a free piston engine compressor specifically for a lightweight untethered air supply for actuation of traditional pneumatic cylinders and valves, using hydrocarbon fuels as an energy source. The piston, acting

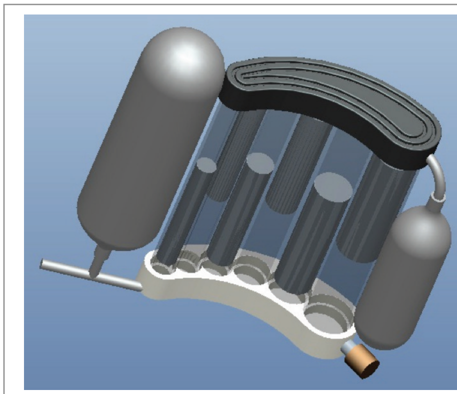

Figure 2: 3D model of Stirling thermocompressor.

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.

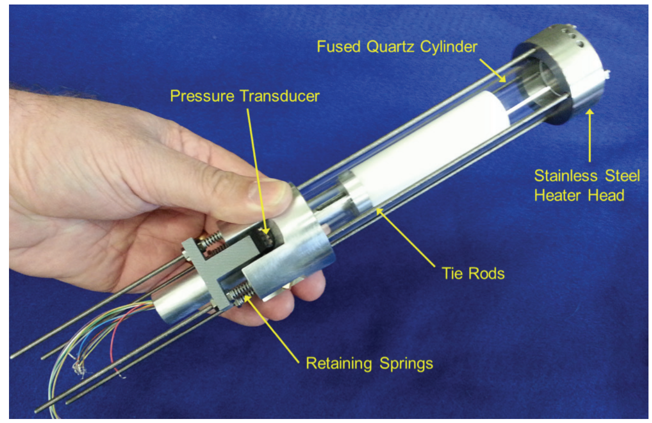

Figure 3: First prototype of the Stirling thermocompressor

Following from this initial design, an experimental prototype was designed and constructed (Figure 3). The prototype will compress atmospheric air to 550 kPa (80 psig) to power a pneumatic rotary actuator mounted to the ankle foot orthosis. To reach the target pressure in a single stage, the temperature of the heat source would have to be maintained at over 1600°C. The thermocompressor is designed to accommodate the highest temperature permitted by the use of non-exotic materials and accordingly the prototype has been designed for a source temperature of 1000°C. Assuming the heat source is maintained at this temperature and the temperature of the heat sink is 100°C, this yields a pressure ratio of 3.4, which corresponds to a maximum outlet pressure of 50 psig. To reach the target pressure of 80 psig, at least two stages need to be integrated in series, with the first stage reaching 35 psig. The prototype can emulate the second stage by subjecting it to a higher inlet pressure. In this manner, it will be used for model validation. The first validation will be done without the device pumping. Excluding the mass flow dynamics will allow a model validation of the heat transfer and pressure dynamics. The second validation will be done with mass flow to validate the remainder of the model.

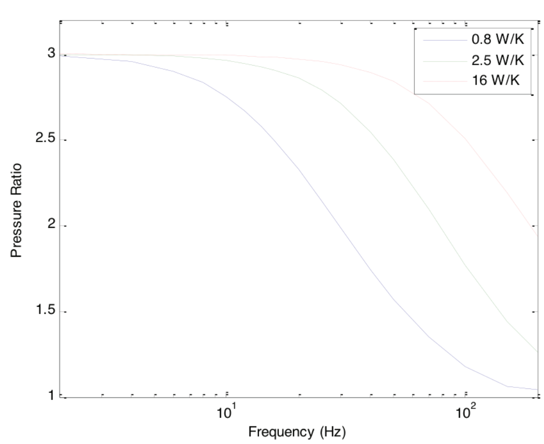

Figure 4: Pressure ratio vs. Frequency.

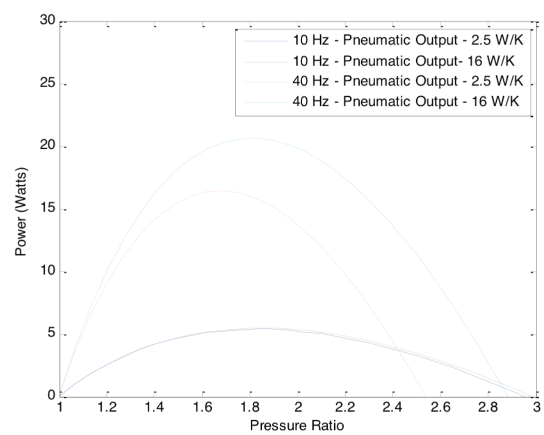

Figure 5: Output power vs. Pressure Boost

Initial dynamic modeling has indicated the required coefficient of heat transfer in the hot and cold spaces. A novel heat transfer mechanism has been conceived that we believe will be able to achieve the required heat transfer rates (but unfortunately cannot yet be disclosed since it has not been protected). Figure 4 shows the predicted pressure ratio in the sealed prototype for different heat transfer rates as a function of the piston reciprocation frequency. Figure 5 shows the predicted pneumatic power output of a single stage at two different frequencies and heat transfer rates. This output power is a function of the ratio of outlet to inlet pressure. This plot essentially shows that a 40 Hz reciprocation will result in a three stage device outputting 60 W of 72 psig air. The anticipated motor power consumption is about 15 W, resulting in a net power delivery of 45 W. Future versions of the device will be conceptually designed and studied to possibly incorporate a pneumatic reciprocation mechanism that will make the device free of the electric motor to drive the piston.

Expected Milestones and Deliverables

- Milestone 1: Stage 1 initially designed and constructed. [Completed]
- Milestone 2: Stage 1 Pressure ratio experimentally characterized [3/31/13]
- Milestone 3: Other thermocompressor components completed [9/31/13]
    - Task: Low profile check valves (reed valves)
    - Task: Hot end insulation
    - Task: Fuel-based heating system
- Milestone 4: System Modeled and Validated [12/31/13]
- Milestone 5: First Prototype Stand-alone Power Supply System Completed and Characterized for TB6 [6/31/14]
- Milestone 6: Second Prototype [Year 3]
- Milestone 7: Second Prototype Testing and initial work on scaling the concept to industrial-scale compressors [Year 4]
- Milestone 6: Experimental work on industrial-scale designs [Year 5]

C. Member company benefits

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

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Project 2C.2: Advanced Strain Energy Accumulator

Research Team

Project Leader:	Eric Barth, Vanderbilt University, Mechanical Engineering
Graduate Students:	John Tucker (Graduated with M.S. in 2012), Dan Cramer (joined in 2013)
Undergraduate Students:	Jake Noble
Industrial Partners:	Bosch-Rexroth, Gates Rubber

1. Statement of Project Goals

The objective of this work is to extend the state of knowledge in the use of strain energy storing materials for the engineering design of compact energy storage devices. Specifically, this project seeks a low cost, low/no maintenance, high energy density accumulator primarily targeted toward a fluid powered automotive regenerative braking system (hydraulic hybrid). This project will focus on extending the energy storing capabilities of accumulators for the specific purpose of storing large amounts of hydraulic energy with an energy density appropriate for applications such as regenerative braking in passenger 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 could 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 transformational goal 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". Compact energy-dense storage solutions are critical to the success of this migration. This project addresses the knowledge level of this goal (explore new energy density concepts) by seeking a design to provide the enabler (improve energy density of storage mechanisms) and ultimately the needed system capability (reduce size and weight of FP systems to work in passenger vehicles) for this important goal [4]. This project will be demonstrated on the sUV testbed (TB3).

A new aspect of this project is the use of this concept in pneumatic systems. There is a great potential for energy savings, and hence increased efficiency, in industrial pneumatics and pneumatic systems more generally. A prototype was designed for the Ankle-Foot Orthosis (TB6), constructed and tested at Vanderbilt, then constructed and implemented at UIUC. It was experimentally demonstrated on the test bed to have an energy savings of 17.5% relative to operating with no accumulator.

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 used in accumulators. A control strategy and control laws for regulating power flow will be formulated and implemented. Concerns regarding the efficiency of the hydraulic pump/motor will be out-of-scope and left to researchers in the efficiency thrust.

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

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

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

If the energy stored in the compressed gas of such an accumulator is not retrieved soon, the heat flow from the gas to its 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]. Methods to mitigate these heat losses have been proposed. For PAGP, one promising method involves placing an elastomeric foam into the gas enclosure. This foam serves as a regenerator absorbing the heat generated during gas compression, and returning it to the gas during expansion. According to Pourmovahed, “the insertion of an appropriate amount of elastomeric foam into the gas enclosure [can] virtually eliminate thermal loss” [2]. Elastomeric foam has been shown to greatly improve accumulator efficiency and is a simple modification.

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

Material Selection

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

Scientific and Engineering Research Goals

Scientific discovery: expand 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

<u>Achievements before February 2012</u>

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

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

Using material data obtained from CCEFP member company, Gates Rubber (NBR 6212), the stress-strain curve of the material showed a theoretical material energy density of 33 kJ/l. Accounting for the hydraulic fluid, this would result in a system energy density of 17 kJ/l. FEA modeling revealed a material energy density of only 4 kJ/l and a resulting system energy density of 3.6 kJ/l. Further investigation into the model revealed an effective transmission ratio between wall thickness of the bladder and the held hydraulic pressure of the fluid inside the inflated bladder. The thinner the wall, the better the strain was distributed in the material, but the lower the hydraulic pressure in the bladder. This fact necessitated a change in the bladder geometry 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.

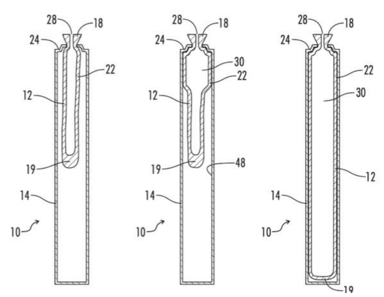

Figure 1: Original PCT patent application.

Several embodiments have been conceived, including the original “balloon in a shroud,” (Fig. 1) the “integrated reservoir” concept (Fig. 2), the “series configuration” (Fig. 3), and the distributed piston elastomeric accumulator (Fig. 4), designs.

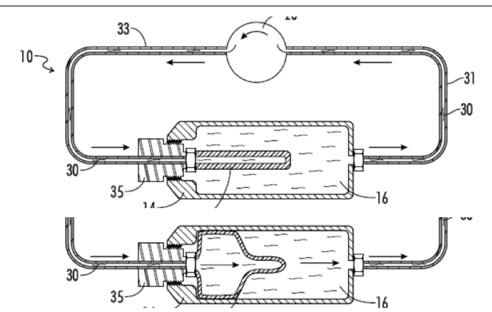

Figure 2: Integrated Reservoir PCT application

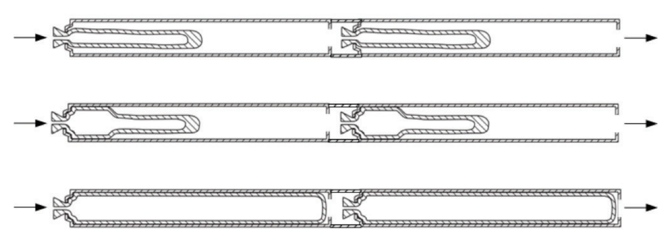

Figure 3: Series configuration to multiply pressure. PCT application filed jointly with Georgia Tech.

Much of the work since 2011 was focused on a concept we call the “distributed piston accumulator” because of its energy storage dependent cross sectional area. The Distributed Piston Accumulator (DPEA) configuration exhibits “inverse ballooning.” Figure 4 shows this configuration. As will be explained below, this configuration: 1) more fully utilizes the material (thereby achieving a higher energy density) by eliminating radial strain gradients experienced in the balloon configuration, 2) exhibits a P-V curve that is similar in shape to the balloon configuration (due to an axially propagated “inverse ballooning” similar in function in keeping a relatively constant pressure), and 3) enables the fluid pressure to be a multiple of the maximum stress in the material through a designable

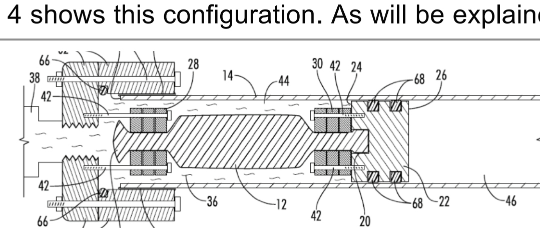

Figure 4: Distributed Piston Accumulator PCT patent application.

ratio of the exposed piston area to the unstretched cross sectional area of the elastic member. This concept encompasses the features of the first three “balloon” concepts into a single device (series configuration not necessary) with a more easily manufacturable elastomeric shape.

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

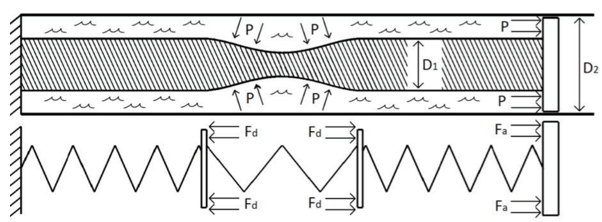

Figure 6: The mechanism of “inverse ballooning”.

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

Achievements in this reporting period

Work on the DPEA approach has developed geometry-based design equations [Tucker and Barth 2013] that yield design tradeoffs for different configurations. These design equations detail the pressure-volume curve shaping, maximizing material utilization for energy storage, the beneficial effects of minimizing dead volume, among other concerns. A prototype DPEA accumulator was constructed and experimentally evaluated with two different polyurethane materials. Experimental testing of polyurethane bladders and uniaxial tension specimens was conducted, with the highest performers showing 15 kJ/l with 17% loss hysteresis. These results were then used to project a full scale device with regard to its overall system energy density. These projections were compared to an idealized gas-charged accumulator.

Five separate cases were considered for comparison: two conventional gas charged accumulators, and three DPEA accumulators. The design equations and the material testing data were then utilized to calculate the system energy density and maximum strain for a range of material energy densities and pressures. These results are illustrated in Figs. 7 and 8 below. As expected, a higher material strain energy density gives rise to a higher system energy density. Given that the densities of the fluid and elastomeric materials are near 1 kg/L, the gravimetric energy density of these systems in kJ/kg are similar numerical values to their volumetric energy density (excludes the mass of the containment vessel). With regard to the containment vessel, recent progress on fully composite piston accumulators [Otte, et al., 2012] indicates a weight savings of 70% to 80% over typical steel piston accumulators. Such a technology made to house a DPEA accumulator with an appropriately high energy density elastomeric material offers the potential of a compact and lightweight energy density system.

Figure 7 shows that a DPEA accumulator has a system energy density (energy stored divided by the sum of the volume of the material, the fluid volume, and the dead volume) that becomes many times larger than conventional gas charged accumulators as the material strain energy density of the material increases. Figure 8 shows that as the operating pressure of the designed DPEA is increased, the required maximum elongation of the elastomer *decreases*. This illustrates the potential of this strain energy accumulator concept to overcome not only the gas diffusion difficulties of gas-charged accumulators, but to also not exceed material strain limits as the pressure increases; the DPEA concept is not limited by maximum elongation considerations.

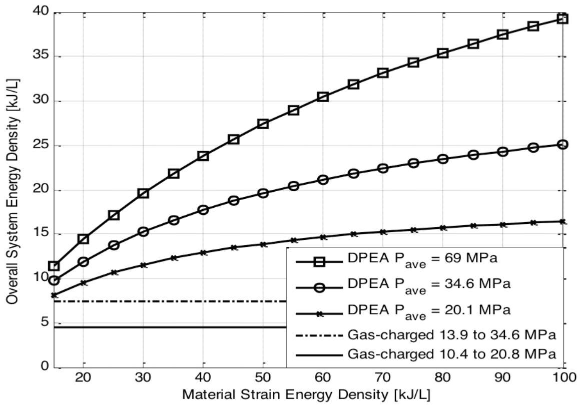

Figure 7: System energy density of DPEA as a function of material strain energy density

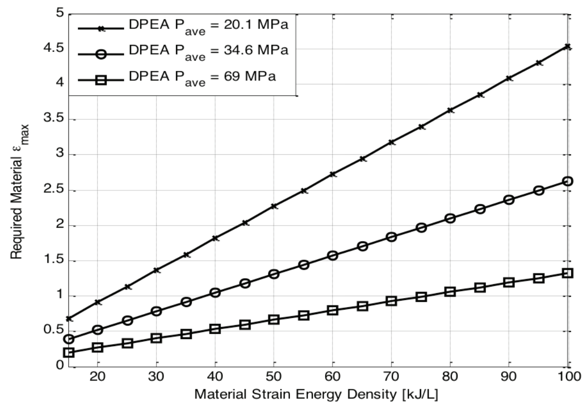

Figure 8: Required material elongation (maximum strain) of DPEA as a function of material strain energy density

The DPEA, like all strain energy accumulators, provides a solution to the gas diffusion problem which plagues conventional gas bladder accumulators. In addition, it maximizes material utilization while minimizing dead volume. The DPEA provides a predictable and favorable relationship between the stress-strain behavior of an elastomer and the fluid specific energy density of the accumulator which houses it. Consequently, the DPEA accumulator shows potential increases in volumetric system energy density over gas-charged accumulator systems.

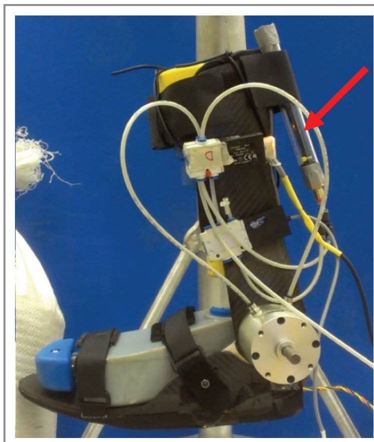

Figure 9: Pneumatic strain energy accumulator implemented on TB6

In addition to the hydraulic version, this reporting year saw the strain energy accumulator applied to a pneumatic device – the Ankle-Foot Orthosis Test Bed (TB6). A balloon-in-shroud version of the strain energy accumulator was designed and constructed to recycle the exhaust air of the pneumatic rotary actuator of the testbed. It was experimentally demonstrated to have an energy savings of 17.5% relative to operating with no accumulator. This is shown in Figure 9.

Expected Milestones and Deliverables

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

C. Member company benefits

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

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

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

1. Statement of Project Goals

The goal of this project is to develop a high energy density hydraulic storage system, the flywheel-accumulator, through a coupled modeling, design, and experimental approach. The influence of baffles on fluid swirl will be studied using CFD and experiments with an existing low energy density system. A multi-energy domain dynamic model will be developed in levels of increasing complexity, focusing on the primary sources of energy loss. This model will be used to optimize parameters for a prototype design. A high-energy density demonstration prototype will be designed and fabricated and the used to experimental validate the dynamic model and further explore physical phenomena.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

Hydraulic energy storage is important in numerous applications including emerging areas of hydraulic hybrid vehicles and wind turbines with hydraulic drive trains. There are two primary limitations of conventional hydraulic accumulators. First, the energy storage density of hydraulic accumulators is significantly lower than other energy storage mediums. For example, the specific energy of nickel-metal hydride and lithium-ion batteries is 216 kJ/kg and 432 kJ/kg respectively [1], compared to the 6 kJ/kg for a composite hydraulic accumulator [2]. The consequence of this for applications such as hydraulic hybrid vehicles is a concession in the energy storage capacity based on packaging and weight constraints. The second limitation of conventional accumulators is that the system pressure varies by a multiple of 2:1 or 2.5:1 as a function of the energy stored in the hydraulic accumulator. The pressure ratio variation requires oversized components capable of meeting the desired performance at the lowest system pressure, resulting in bulky and heavy components and introduces control challenges.

Much research on improving the energy density of hydraulic accumulators has primarily focused on isothermalizing the compression and expansion of the gas in the accumulator. Successful results have been obtained by adding foam [3-5] or fine metallic strands to the gas volume [6]. These approaches have provided incremental increases in the energy density of hydraulic accumulators, yet the energy density is still orders of magnitude lower than competing technologies.

The CCEFP has been instrumental in supporting novel energy storage research. The project leader was a co-inventor of the open accumulator, which allows both air and hydraulic fluid to be independently added to a pressure vessel, theoretical improving the energy density by an order of magnitude [7, 8]. By modulating the method of energy storage, the hydraulic system pressure can be controlled independent of the quantity of energy stored. A major challenge in efficient implementation of the open accumulator is the large size of the air compressor/expander required to provide isothermal operation. For this reason, the current line of study is focusing on the stationary application of grid energy storage for wind power. Another concept currently under development in the CCEFP is the elastomeric accumulator, which stores energy in the strain of a cylindrical elastomer. The concept theoretically improves energy density to approximately 12-20 kJ/kg and provides a relatively flat pressure-volume curve [9].

Similar to how energy is stored in two modes in the open accumulator, the project leader invented the flywheel-accumulator, which combines hydro-pneumatic energy storage with rotating kinetic energy storage. Advanced flywheels combine high energy density of 325 kJ/kg [10], extremely high power density, and negligible environmental concerns. Previous works have investigated using a fixed inertia flywheel energy store coupled with a hydraulic transmission [11, 12]. The novel approach in the proposed work is integrating a hydraulic accumulator and a flywheel into a single energy storage device. A key benefit of this approach is the natural crossing of energy domains by using the hydraulic fluid as a means of changing the inertia of the flywheel. Varying the inertia of the flywheel allows the hydraulic pressure to be controlled independently of the quantity of energy stored, similar to the open accumulator. In addition, the ability to maintain constant or near constant pressure in the accumulator reduces the secondary control challenges faced by conventional accumulators.

Previous works have explored variable inertia flywheels using a variety of means. Harrowell discussed the use of a vulcanized rubber elastomeric flywheel where the angular velocity is constant with changing energy due to the centripetal acceleration causing radial strain [13]. Numerous works have used moving solid masses to change the inertia of a flywheel including flyball governors, masses on tracks [14], and the band-style variable inertia flywheel [15, 16]. Multiple patents have addressed using fluid to change the inertia of a flywheel [17-19]. To our knowledge, no previous work has integrated a flywheel and a hydraulic accumulator to minimize fluctuation in hydraulic system pressure and increase energy density.

Flywheel-Accumulator

The integral flywheel-accumulator conceptually is a cylindrical piston-style accumulator rotated about its central axis and coupled to a pump/motor, Figure 1. Hydraulic fluid enters and exits the flywheel-accumulator at the center of one end of the cylinder. On the opposing side of the piston is nitrogen gas at a precharged pressure.

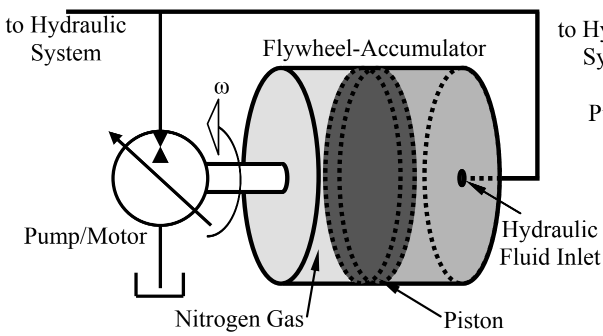

Figure 1. Flywheel-accumulator system. The pump/motor is coupled to the flywheel-accumulator directly or through a geared connection. The hydraulic inlet is at the center of the opposite end.

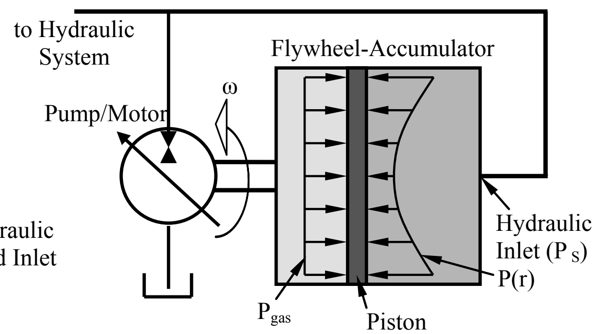

Figure 2. Pressure distributions of the gas and hydraulic fluid in the device. Due to the centripetal acceleration and density of the hydraulic fluid, a parabolic pressure distribution is formed.

As in a conventional accumulator, when hydraulic fluid enters the flywheel-accumulator, the piston moves axially and the gas is compressed. Because the density of nitrogen is low, the centrifugal force has little influence on the gas pressure distribution. However, the centrifugal force does create a significant radial pressure gradient in the hydraulic fluid, due to the higher density. From a force-balance on a fluid element subject to centripetal acceleration, the pressure of the fluid as a function of the radius is [20]:

$$P(r) = \frac{\rho \omega^2 r^2}{2} + P_S \qquad (1)$$

where ρ is the mass density, ω is the angular velocity of the flywheel, r is the radius of interest, and P_S is the pressure at r = 0, which is equal to the pressure of the hydraulic system. This parabolic pressure gradient can be visualized in Figure .

To establish equilibrium, the axial forces acting on the piston due to the gas and hydraulic pressure must be equal. By integrating the two fluid pressures across the area of the piston, the hydraulic system pressure is described by [20]:

$$P_S = P_{gas} - \frac{\rho \omega^2 r_o^{\,2}}{4} = P_{charge} \frac{V_{empty}}{V_{empty} - V_{oil}} - \frac{\rho \omega^2 r_o^{\,2}}{4}. \qquad (2)$$

where P_{gas} is the pressure of the nitrogen gas, assumed to be constant with radius, P_{charge} is the initial precharge pressure of the nitrogen gas, and V_{empty} and V_{oil} are the volume of the empty accumulator and oil in the accumulator respectively.

When hydraulic fluid is added to the flywheel-accumulator, the mass moment of inertia increases. Assuming the density of the hydraulic fluid is constant with radius, which is reasonable for a high bulk modulus fluid, the mass moment of inertia of the flywheel-accumulator is described by:

$$I = I_{flywheel} + I_{oil} = I_{flywheel} + \frac{\rho V_{oil} r_o^2}{2} \qquad (3)$$

where $I_{flywheel}$ is the inertia of the empty flywheel and I_{oil} is the inertia of the hydraulic fluid.

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

To illustrate the behavior of the flywheel-accumulator, a simple example is provided using a first-order analysis that neglects dynamic behavior. Consider the case where energy is being stored in the flywheel-accumulator at constant power. The flywheel-accumulator will start with a low state of charge, defined by low angular velocity and no hydraulic fluid in the device. The energy will be stored in both rotating kinetic and pneumatic forms as controlled by a variable displacement pump/motor, with the goal of maintaining a desired pressure.

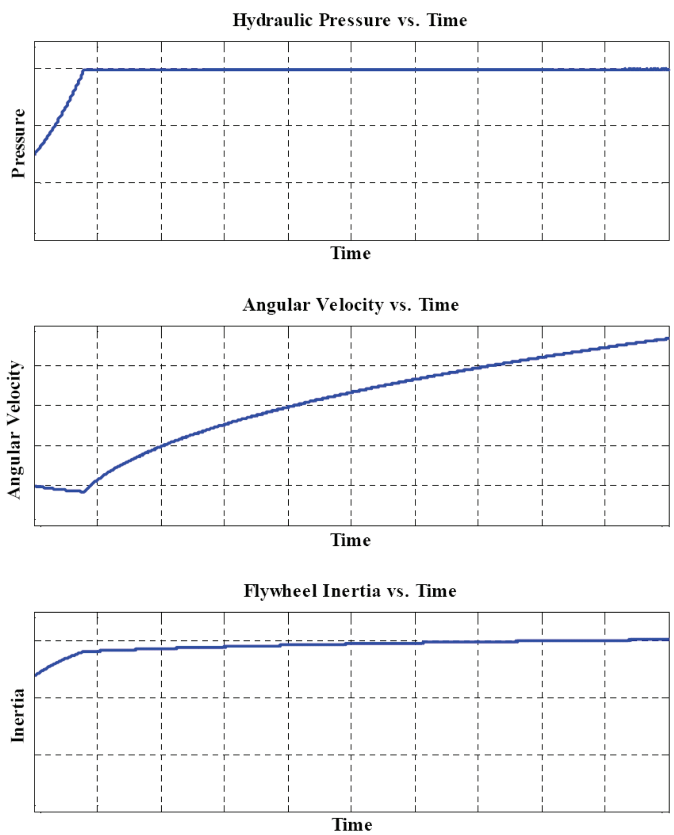

Figure 3. Flywheel-accumulator parameters during the energy storage simulation

Numeric examples and details on the simulation method can be found in a previous work [20], while the general trends will be discussed here. As seen in the top plot of Figure 3, the pressure starts near the precharge pressure of the accumulator. Because this pressure is below the desired pressure, the hydraulic motor is set to zero displacement and all of the energy is stored by adding hydraulic fluid to the flywheel-accumulator. Adding hydraulic fluid results in an increase in the gas and hydraulic pressure and an increase in the mass moment of inertia. Because to no torque is applied during this period, the angular velocity decreases inversely to the moment of inertia. Once the hydraulic pressure reaches the desired pressure, energy is stored both by adding hydraulic fluid to the flywheel-accumulator and by using the hydraulic motor to apply a torque to the device. By modulating the displacement of the motor, the hydraulic system pressure remains constant with increasing energy storage.

The example illustrates a few important characteristics of the flywheel-accumulator:

1) *Energy Storage Capacity:* With reference to the top plot of Figure 3, the maximum capacity of a conventional accumulator is reached once the maximum pressure is reached. By also storing energy in rotating kinetic form, the flywheel-accumulator can store significantly more energy. By a conservative estimate, the flywheel-accumulator increases energy storage capacity by more than an order of magnitude [20]. This is an enabling element to numerous technologies. The limit of energy storage density is primarily a function of the allowable stress and deflection of the flywheel-accumulator shell. These limits will be explored computationally in the proposed work.
2) *Constant Pressure:* With a conventional accumulator, the pressure significantly varies with the quantity of energy stored. This creates both control challenges and requires the hydraulic components to be oversized to meet the power demands at low system pressure. The flywheel-accumulator allows the hydraulic system pressure to be directly controlled independent of the quantity of energy stored.
3) *High Power Levels:* In the example, the power level was within the capability of the hydraulic motor. However, the hydraulic pump/motor coupled to the flywheel-accumulator does not need to be sized to meet high power transient events. During short-term high-power events, hydraulic fluid can be directly added or removed from the flywheel-accumulator, creating a change in the system pressure. Over a longer period, the pump/motor can reestablish the desired pressure. This allows the use of a smaller displacement pump/motor, which improves compactness while decreasing mass and cost.

Two models and a low-energy density bench top prototype have been developed. The models, a steady-state pressure model and a simple closed-form two-dimensional fluid dynamics model based on the Navier-Stokes equation, were used to predict the hydraulic fluid pressure gradient and fluid swirl during acceleration. A low-energy bench top prototype with a transparent cylinder, Figure 4, was constructed and instrumented to demonstrate the concept and explore physical phenomena. The measured pressure gradient results confirmed the steady-state pressure distribution model [21]. During acceleration to a constant speed, the transient fluid dynamics model predicted the pressure distribution trends seen in the experimental data, yet a temporal delay existed in the experimental data not predicted in the simplified model [22]. In the proposed work, the transient model will be used to validate the computational fluid dynamics results. In addition, the low-energy prototype will be used to explore the influence of baffles on viscous energy loss due to swirl of the hydraulic fluid during acceleration.

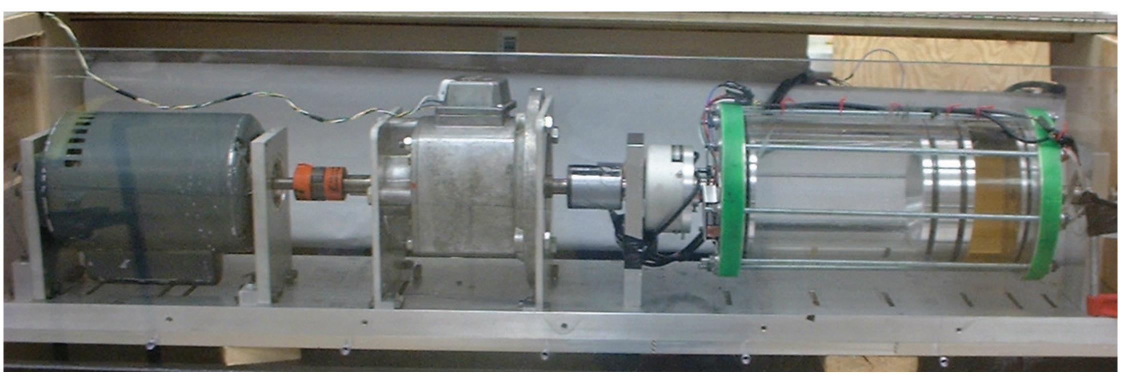

Figure 4. Low energy bench top prototype system.

This promising concept poses multiple research and development challenges, many of which are being addressed in the funded work. However, several issues are outside the scope of the current work. A few of these issues that will need to be addressed in the future research include:

1) Gyroscopic Torque: For operation in mobile applications, changing the pitch, yaw, or roll of the vehicle creates a gyroscopic torque. The gyroscopic torque can be minimized by rotating the flywheel about the vertical axis so changes in yaw do not result in an applied torque [11]. Alternatively, the gyroscopic torque can be eliminated by using two counter rotating flywheels or by mounting a single flywheel in a gimbal.

2) Rotor Failure Modes: As with any form of energy storage, in the event of a failure, the flywheel-accumulator rotor can release energy in a dangerous manner. In the proposed experimental work, the vacuum chamber will be designed as a containment chamber to absorb the energy in the case of failure. An area for future work is leveraging research in high-speed composite flywheel rotor design for energy dissipation during failure to minimize the energy absorption requirement of the chamber.
3) Seal and Bearing Design: Bearing and seal friction can be major sources of energy loss in high-speed flywheel systems [23]. The proposed work will compare various commercially available high-speed seals and low friction bearings to determine appropriate components for the experimental devices. However, the design of new seals and bearings for this application is outside the scope of this work.

B. Achievements

Prior work with the flywheel-accumulator demonstrated the feasibility of the concept, yet involved oversimplifying assumptions. Furthermore, the system complexity increases at higher energy levels, both in individual phenomena and the coupled behavior, but for the most part the physics of each process are well understood. Thus, the primary contributions and challenge of the research are the capture and integration of the collective behavior and systems engineering. A coupled computational modeling, system design and optimization, and experimental approach will be used. Specific tasks include:

- Task 1: Develop a computational fluid dynamics model of viscous fluid shear during flywheel acceleration to quantify the energy loss as a function of baffle count and baffle geometry.
- Task 2: Perform designed experiments with the existing low-energy flywheel-accumulator to study influence of baffles and acceleration profile on fluid swirl. The fluid swirl will be quantified by: 1) comparing the measured pressure distribution with the steady-state pressure profile for a given speed, 2) measuring the shaft torque required to create a given acceleration and compare the effective inertia with the inertia under the assumption of a rigid body, and 3) utilizing high-speed video to track tracer particles in the fluid to determine flow regime and behavior for comparison with the CFD results.
- Task 3: Develop a multi-energy domain dynamic computational model for quantifying sources of energy loss and studying design parameter trade-offs. This model will integrate: 1) dynamics of the piston motion due to a balance of the fluid forces and stick-slip conditions at the seal. 2) a pump/motor model including transient response of the swash plate to a position command and non-linear volumetric and mechanical efficiencies based on the work by McCandlish [24]. 3) flywheel energy losses such as bearing friction, aerodynamic drag, and vacuum chamber pumping losses. These flywheel related losses will be evaluated using previously developed methods such as those described by Genta [23]. 4) rotor dynamics of the flywheel-accumulator as a function of geometry and various operating conditions for the purpose of identifying critical speeds and possible whirl motions. This portion of the model will leverage existing work investigating the rotor dynamics of high-speed flywheels using magnetic bearings, where the dynamic behavior of the bearings changes the effective stiffness of the system [23, 25].
- Task 4: Design high-energy-density bench top system with a target energy density of 20 kJ/kg. The design will include custom solutions for a telescoping baffle, ensure proper piston sealing by designing the piston and cylinder to strain at equal rates, and a high-speed rotary union. Off-the-shelf solutions will be sought for low-friction bearings, vacuum/containment chamber, and hydraulic components. The design will utilize an early generation of the multi-energy domain model to optimize geometric and operating parameters.
- Task 5: Fabricate high-energy-density experimental system, instrumentation, and data acquisition. Perform basic system debugging.
- Task 6: Perform designed experiments with the high-energy-density experimental system. The primary experiments will include: 1) Measuring the hydraulic fluid and gas pressure distributions as a function of angular velocity and piston position during static and transient events and comparing the results with the computational work, 2) Identifying the critical operating frequencies and compare the result with the computational predicted frequencies, 3) Quantify the energy density and efficiency of the system during a charge and discharge cycle by measuring the hydraulic power in and out during under varied conditions. Operating parameters that will be varied include power levels, hydraulic system pressure, hold time between charging and discharging, and pump/motor control schemes.

Milestones:

- Results of CFD model evaluating the influence of baffle geometry on viscous shear energy losses [month 5]
- Experimental results regarding influence of baffles on energy loss, effective inertia, and flow behavior [month 5]
- Simplified multi-energy domain model completed [month 9]
- Design of high-energy-density experimental system complete [month 14]
- High-energy-density experimental system fully operational [month 20]
- Full multi-energy domain model completed [month 24]
- Results from high-energy-density experiment [month 24]

C. Member company benefits

Compact energy storage is one of the transformational barriers facing fluid power. The availability of higher energy density accumulator provides a significant opportunity for use in hydraulic hybrid vehicles and holds the potential to expand existing and open new market opportunities for CCEFP member companies.

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

Research Team

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Industrial Partners:	Orbitec (associated project), Parker

1. Statement of Project or Test Bed Goals

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

In collaboration with Test Bed 6 and Project 2B.2, minimal-mass, heat-dissipating/-shielding PAAFO components were to be designed, analyzed and fabricated for the integration of the portable power source. Resulting from an excessive budget cut of ~20% from that proposed, Project 2D was directed at Year 5's end to research only the thermal-management aspects of the lattice structures; so, the proposed investigation into using engineered structures for noise abatement was then eliminated from this project.

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

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

Project 2D addresses the transformational barrier of compact 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. Additionally, the fluid-power technical barriers of efficient systems, safety, quietness and containment (leak-free) will be addressed by extension.

3. Project Description

A. Description and explanation of research approach

Fluid power technology's competitiveness and market penetration, despite high theoretical volumetric and gravimetric energy and power densities, is significantly hindered by the lack of efficient commercial components, and the levels of noise generated. Fluid power struggles to compete with electronics due to dead weight, poor energy management, highly-modular design and noise. The most profound result of this is average fluid-power-system efficiencies of only 22% [Love et al., 2012]! The industry must develop the equivalent of three-dimensional integrated circuits if it is to successfully compete. This is the innovation required.

The innovation of Project 2D is then the coupling of the structure's stiffness requirements for bearing loads, leveraging the structure-characterization work completed in Years 1-4, with the lattice-spacing requirements for filtering noise and effectively dissipating heat through natural convection and radiation, within a fully-integrated lattice structure. Figure 1 shows a conceptual sketch of such a lattice that integrates the mini-HCCI engine into the Test Bed 6 orthosis structure, while also dissipating the waste heat of combustion and providing noise suppression for the engine. This approach is a significant design advancement because three functions are integrated into the design of a single structure. It must be noted, however, that in this coupled system, not all functions can be fully optimized: trade-offs are necessary.

Figure 1: (Left) concept sketch of the mini-HCCI engine with an integrated noise-filtering and heat-dissipating structure to improve acceptance and safety when in proximity to people. The structure can also bear mechanical loads; so, it can be further integrated into the structure of the Test Bed 6 orthosis itself. (Center) a conceptual model of this integration into the PAAFO. (Right) a conceptual model of a belt-worn structure that maintains the engine's temperature, while also protecting the wearer and reducing noise.

The primary barrier to the development of this technology is the lack of available software that can effectively couple the FEA data with design software, and export the final fabricatable design. That proposal was rejected by the Center in the 2010 selection. Presently, four separate software packages are used to manually design, analyze, populate and process the geometries. This will all be combined and automated in future work, allowing for significantly more time to consider alternative designs. The realization of such automated software remains a major goal for MSOE.

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

B. Achievements

<u>Prior to current reporting year</u>

- Unit-lattice structural characterizations [Knier, 2009; Cook et al., 2010]
- Software algorithms for automated structure generation [Vikberg, 2010; Cook et al., 2010]
- Preliminary optimizations of fluid-power components [Knier, 2009; Cook et al., 2010; Remmers et al., 2010]
- Preliminary characterizations of lattice unit cells for acoustic attenuation – REU 2010 – "sonic crystals" vs. viscous damping vs. Helmholtz resonance [Bongiorno]
- Experimental comparative study of engineered TMS with off-the-shelf aluminum foam and equivalent-mass finned heat sink [Cook and Gervasi, 2011; Cook et al., 2011; Newbauer et al., 2011]
- Unit-lattice thermal-conductivity characterizations [Cook et al., 2011]
- Structure-generation scripting
- Preliminary investigation of thermoelectric energy conversion – REU 2011 – micro turbines vs. thermoelectric generators
- 25W mini-HCCI TMS designs and analyses [Cook et al., 2012]
- Integrated-seal and reduced-mass design for custom TB6 actuator [Hsiao-Wecksler et al., 2012; Remmers et al., 2010]

<u>Recent work (February 1, 2012 – August 31, 2012)</u>

<u>*50W mini-HCCI thermal-management structure*</u>

The mini-HCCI is now projected to generate 50W of waste heat, in close proximity to the orthosis wearer. A section of the structures shown in Figure 1 has been re-designed to; safely dissipate this heat, maintain a reasonable engine temperature, and hold the surface-contact temperature below the FDA mandate (Figure 2).

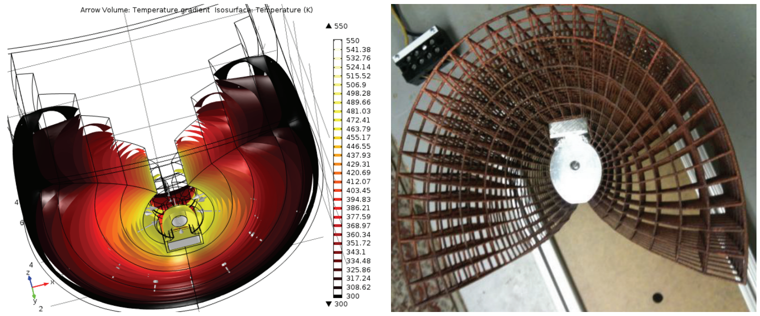

Figure 2: (Left) "Bulk" finite-element analysis of mini-HCCI thermal-management structure, using variable thermal conductivities for temperature-differential optimization at 50W of waste-heat dissipation through natural convection. (Right) Equivalent lattice structure, matching the optimized thermal conductivities, showing the surrogate aluminum block and cartridge heater installed in the TMS to test the functionality.

This composite structure was then tested with a surrogate aluminum block and electric cartridge heater (Figure 2), simulating engine waste heat, over a range of values. Both natural and forced-convection modes were tested (Figures 3 & 4); and, both the targeted block and surface-contact temperatures were achieved under natural convection. The 40W fan used was oversized for the orthosis application; but, it is expected that the added mass, even for smaller fans, will not balance the afforded structure-size reduction. The performance of this TMS was demonstrated at UMN during the NSF Site Visit.

To minimize mass, this structure was additively-manufactured in nylon, using selective laser sintering (SLS), and plated with 50.8μm of copper. Though the resultant composite structure weighs just 160g, it is quite large, relative to the orthosis. Phase-change materials and forced-convection cooling are being considered as complementary means of maintaining lower temperatures; but, their added mass is likely prohibitive. Efficiency improvements in the power generation are critical.

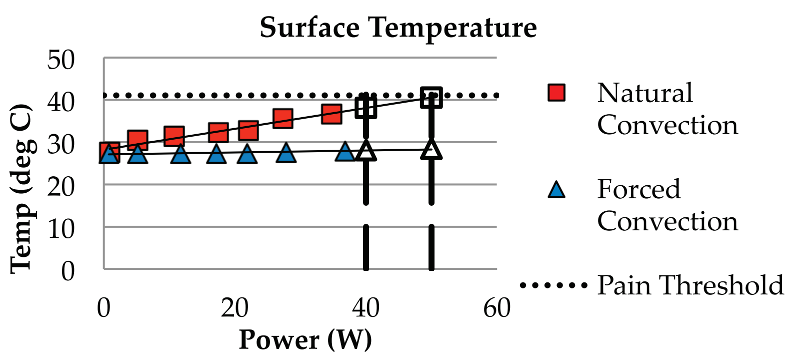

Figure 3: Experimental results for the copper-nylon-composite TMS, in natural and forced-convection modes of heat dissipation, showing the resultant contact-surface temperatures at varying magnitudes of waste heat. The unfilled data points are extrapolated.

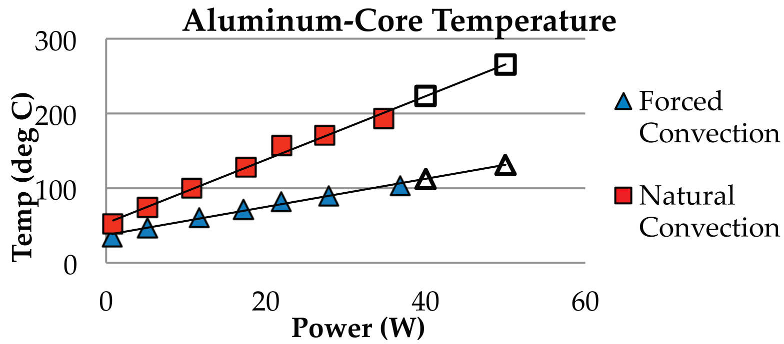

Figure 4: Experimental results for the copper-nylon-composite TMS, in natural and forced-convection modes of heat dissipation, showing the resultant solid-metal-core temperatures at varying magnitudes of waste heat. This core represents the IC engine. The unfilled data points are extrapolated.

<u>Expected milestones and deliverables</u>

- Geometry-dependent effective-conductivity relations defined [October 31, 2011]
- Geometry-dependent structural-acoustic relations defined [October 31, 2011]
  - Project 2D was directed not to continue this effort at the end of Year 5, due to an excessive budget cut. Bongiorno has reported his preliminary REU efforts in this regard.
- Fabrication of nine pistons for fluid-borne testing [February 15, 2012]
  - Project 2D was directed not to continue this effort at the end of Year 5, due to an excessive budget cut.
- Integrative TB6 structure for the mini-HCCI engine installed [February 28, 2012]
  - A TMS was fabricated in nylon, and clad with copper. There were delays in getting specific target heat rates and operating temperatures for the mini-HCCI engine to properly size the structure.
  - The mini-HCCI engine could not run continuously for any significant period of time
- Integrative TB6 structure performance testing complete [May 31, 2012]
  - Though the minimal-mass TMS was fabricated and tested with a surrogate heat source to demonstrate its performance capability, the size of the structure was prohibitive. The mini-HCCI produces too much waste heat. A more efficient power source is likely required.

<u>Plans for the next 5 years (February 1, 2013 – January 31, 2018)</u>

- The PI formally proposed in 2011 to develop an integrative, high-efficiency, pneumatic system for TB6, replacing the mini-HCCI engine and rotary actuator, that will greatly demonstrate the potential for this approach to fluid-power-system design. Employing energy harvesting, as well as thermal energy storage, recovery and conversion, the system has a targeted efficiency of 60%. It is also expected to run for one hour on just 5g of butane. This proposal was rejected by the Center, but has since been submitted to the National Robotics Institute to develop it for legged co-robotics applications.
- The direct-structure-generation software will be developed to expedite the design and evaluation of components and systems.
- Comparisons between composite and solid-metal lattice structures for multifunctional applications will continue.
- As originally proposed, the structural-acoustic relations will be derived for the three unit lattices; and, noise-reducing structures will be integrated into the pistons of fluid-power pumps and motors.
- Energy-balance analyses will be conducted to determine the efficacy of forced-convection cooling of a structure, relative to natural convection, including consideration for mass and volume.

- This structure-design methodology will be modified to allow for the optimization of thermoelectric energy recovery. Valves and sensors, for example, can be powered with this recovered energy.
- Multifunctional structures will be developed for other, larger components & sub-systems, within the Center (TMS for CO2 bottles, sterling thermocompressor, accumulators, etc.), and outside.
- Inclusion of, and optimization for, phase-change materials for superior thermal management, as well as the coupling with thermoelectric generators for controlled energy recovery.

C. ***Member company benefits***

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

Since heat generation can be mitigated through surface treatments, oil additives, etc., safety may be a more important aspect of thermal management than efficiency gains. The FDA mandates a maximal contact temperature of 41°C for medical devices that humans are in contact with [Ritt and Bonner, 2012]. It has been demonstrated experimentally that a safe contact temperature for up to 50W of waste heat can be maintained. Any member companies interested in production of personal-assistive devices, rescue machines, etc. will benefit from this design methodology that has been developed.

Of course, the ultimate goal is multi-functionality – reducing weight, while also passively managing heat and mitigating noise, through structure design. Achieving these meso-scale meta-materials will be of greatest value to the CCEFP member companies, particularly in their competition with electric-based alternatives.

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

Research Team

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Graduate Students: Aleksandr Kerzhner, Roxanne Moore
Industrial Partners: Deere & Company, Phoenix Integration, NoMagic

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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, 16-18] at Linköping University, Tilley, et al. [4, 5, 8, 10, 24, 25, 29] at the University of Bath, and da Silva, et al. [6, 7] at the Federal University of Santa Catarina (Brazil), with more recent work by Pedersen [23] at Aalborg University and Schlemmer, et al. [27, 28] at the Technical University of Aachen. In this related work, the focus has been on traditional optimization approaches with a model of the objective at a single level of abstraction, sampled by the optimizer as a black box model, implemented in an imperative (rather than declarative) programming language. In addition, the work has focused almost exclusively on the modeling of the fluid power aspects of the system with only a few efforts allowing for seamless integration with other disciplines (e.g., structural mechanical, thermal, electrical, controls). Finally, the past work either focused on optimization of the sizing parameters of a specific architecture, or used expert systems to guide the selection of a feasible architecture. ,The efficient exploration and optimization of system architectures has not been addressed.

A new approach

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

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

B. Achievements

The research focused on the top two layers of the framework in Figure 1 - that is a combined focus on system architecture exploration with initial (approximate) component sizing. By combining these two levels, the most promising system architectures can be identified which will then be further analyzed and optimized in two subsequent steps: detailed component sizing through the use of Mixed Integer Non-Linear programming, and robust optimization including dynamic and uncertainty considerations. In addition, a variable fidelity optimization algorithm has been developed which allows the combining of models at different levels of fidelity and different levels of accuracy to solve global optimization problems efficiently. The algorithm is called Value-based Global Optimization (VGO).

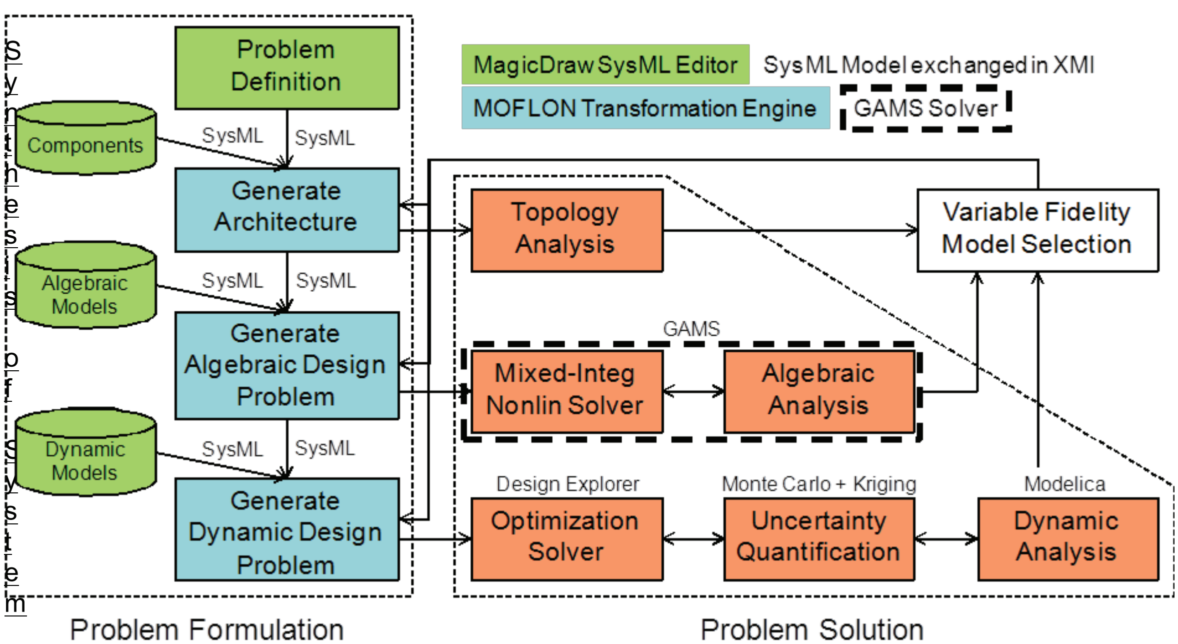

Figure 1: An overview of the proposed three layer systems engineering framework

Architectures

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

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

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

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

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

Detailed sizing optimization under uncertainty

The result of solving layers 1 and 2 in Figure 1 is a promising architecture with reasonable component sizes. To refine the solution further, a more detailed (and hence more costly) analysis is required. Similar to the model transformation approach used to generate algebraic models, a model transformation approach is used to generate system level dynamic models. This is possible thanks to the port-based, object-oriented nature of the Modelica language [9]. A Modelica library for fluid-power systems has been developed [22] and a mapping from SysML to

Modelica to enable the automated generation of system-level models [11, 12]. The computational cost of such dynamic simulations can be significant, especially when combined with uncertainty quantification. Therefore, the Value-based Global Optimization (VGO) algorithm was developed that uses a value-of-information metric to decide which analyses to perform at each step in the optimization/design process.

The approach is based on approximating Gaussian process (kriging) models combined with incremental search-space sampling based on a value of information metric. To incorporate models at multiple levels of fidelity, and hence improve the speed/cost of optimization [19, 20], we have extended the kriging modeling approach [21]. Traditional kriging models are interpolation methods. To support multi-fidelity modeling, the kriging method has been adapted to allow for fitting (rather than interpolating) an approximate model based on samples with only limited accuracy and for which the accuracy may vary from one sample site to the next. In the algorithm, the surrogate model for the objective function has the following structure:

$$y = F^T\beta + \varepsilon + \varepsilon_m \tag{1}$$

where $F^T\beta$ is a regression model, ε is the difference between the true objective and the regression model and ε_m is the error between the true objective and a prediction from one of the (multiple accuracy) simulation models.

As compared to traditional kriging modeling, it is the addition of the ε_m term that allows for multi-fidelity fitting. Both ε and ε_m are represented by Gaussian processes. They are assumed to have a static correlation structure that reflects that the errors, ε_m, if originating from different simulation models, are uncorrelated with each other and are also uncorrelated with the regression error, ε. The VGO approach is different from the seminal work by Kennedy and O'Hagan [14] in that this correlation structure simplifies the maximum least-squares estimation and does not impose the constraint that high-fidelity models can only be sampled at points where low-fidelity models have already been sampled. An implementation of this algorithm has been developed in Matlab (see Figure 2) and its performance was compared to the previous state-of-the-art, namely, the EGO algorithm (Efficient Global Optimization) [13]. The computational experiments show that for a suite of randomly generated global optimization problems, the VGO algorithm finds a solution of the same quality as EGO with a reduction in computation cost of 78%. This is due to the fact that VGO can perform a broad exploration of the optimization space using an inexpensive low-fidelity model, and only use a costly high-fidelity model in the most promising areas near local optima and ultimately near the global optimum.

Next Steps

The principal investigator for this project did not submit a proposal for CCEFP funding in FY 7-8, so the project is no longer active.

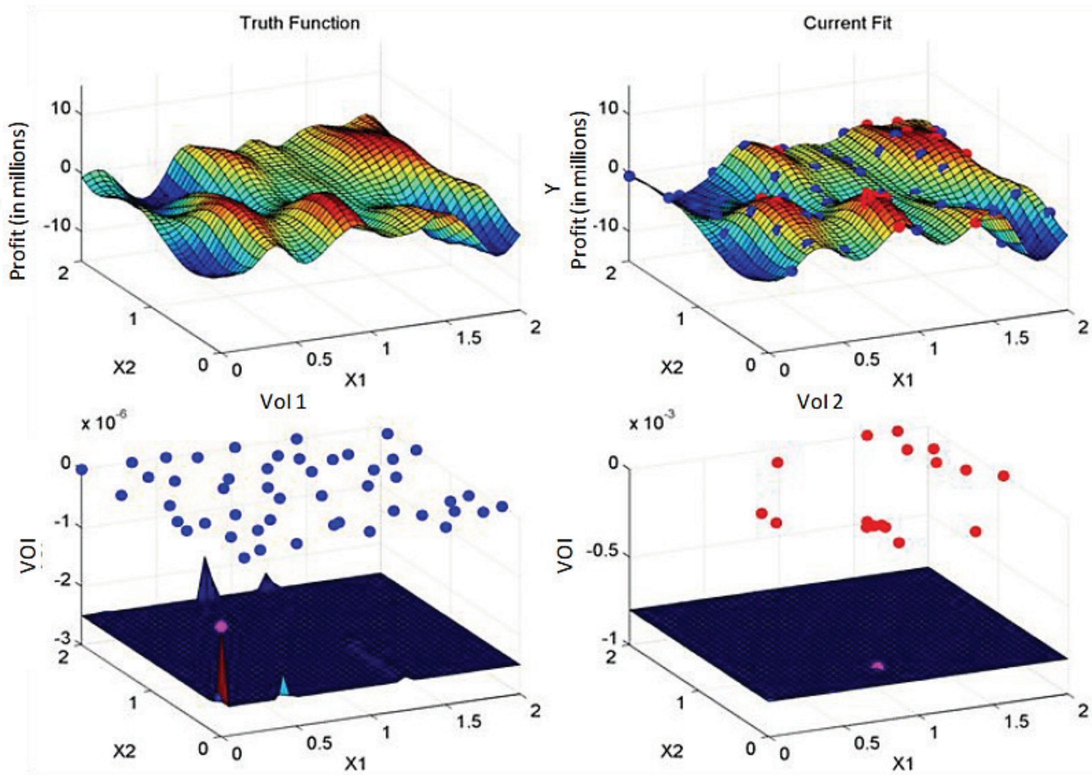

Figure 2: A step in the Value-Based Global Optimization (VGO) algorithm. The true objective function (left top) is in each optimization step approximated using a kriging model (top right). Based on the uncertainty in the kriging predictions, the most valuable sample is determined for either a low-fidelity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

C. *Member company benefits*

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

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Project 2F: MEMS Proportional Pneumatic Valve

Research Team

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

1. Statement of Project Goals

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

Currently available microvalves can only deliver flow rate on the scale of milliliters per minute. We have developed a unique parallel architecture to achieve macro scale flow in our MEMS based devices. Hardware development is augmented by the development of design models that can correctly predict the actuator behavior and fluid flow phenomena.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

Our MEMS valve architecture is illustrated in Fig. 1. It is a one way normally closed proportional valve. The foundation of the valve is a port plate that is placed in a fluid flow path. The plate contains hundreds or thousands of micro-orifices on a single MEMS device. The fully open pressure drop is equal to the resistance through all of the orifices in parallel.

Each orifice is paired with a micro-scale cantilever beam type pallet valve. The micro-orifices enable force to be reduced on each actuator to the range of micro-Newtons. This makes it possible to reduce the actuator size to the MEMS scale. The actuators are opened in parallel to produce macro flow rates. Since each actuator has extremely low mass, the valves are expected to have exceptional bandwidth. MEMS batch fabrication methods are expected to enable manufacturing the valves at low cost when taken to the commercial production scale.

We considered all possible actuation strategies for our MEMS valves during concept generation, including electromagnetic, thermomechanical, electrostatic, piezoelectric, and a variety of exotic schemes [2]. Most strategies are plagued by slow response, high power consumption, or insurmountable scaling challenges.

Piezoelectric actuators are efficient and fast. A particular piezoelectric material, lead zirconate titanate (PZT), outperforms most alternative piezoelectric materials by a factor of 20 or more. PZT makes it possible to scale the actuators to our devices. However, fabricating PZT on the MEMS scale is a specialized process. We have found only one domestic facility having this capability: Pennsylvania State University's Nanofabrication Lab. We have partnered with that lab to fabricate our prototype actuators.

Our valves will utilize a “bimorph” piezoelectric architecture. Two layers of the piezoelectric material are sandwiched between electrodes. The two layers have the same polarity, but they are subjected to reverse voltages. As a result, the bottom layer expands and the top layer contracts, causing the actuator to deform as a cantilever beam subjected to pure bending.

All actuators are shown connected in parallel in Fig.1. Common electrical contact points are used to supply electric current to all actuators simultaneously. As the supply current is increased, deflection of the actuator pallets increases, thereby increasing the flow rate. An alternative wiring scheme would vary the flow rate by fully opening sub-groups of actuators in binary combinations (one, two, four, eight, etc.).

The state-of-the-art in miniature pneumatic valves is summarized in Tables 1 and 2. Table 1 reviews non-MEMS-based miniature valves. The specifications for our new valve are included at the bottom of Table 1 for comparison. 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 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 pneumatic valves. Almost all MEMS based valves have been designed for some specific micro-scale application such as lab-on-a-chip systems [3-5], drug delivery [6], refrigeration [7], fuel cell [8,9] or micropropulsion [10,11].

B. Achievements

Accomplishments since February 2012 include: demonstration of the valve concept on a meso-scale prototype valve, integration of a capacitive displacement sensor on the meso-scale valve, fabrication and testing of a MEMS port plate, fabrication of a learning prototype MEMS unimorph PZT actuator and development of a new compressible flow model. The MEMS tasks have required the development of unique microfabrication process designs. These accomplishments are described in order below. Justification of a schedule adjustment is provided at the end of this section.

Our first prototype valve utilizes a commercially available PZT bender with an envelope of 35 mm x 13 mm x 2.5 mm. We constructed a “meso-scale valve” from this bender in year 6 to test the potential of PZT actuation without the need to fabricate PZT on the MEMS scale. The dramatic potential for power savings offered by PZT technology was made apparent by this prototype valve. The meso-scale piezobender requires only about 1 milliwatt to fully open it. This well exceeds the power requirement of the valves summarized in both Table 1 and Table 2. This discovery motivated us to drop our maximum power input specification three orders of magnitude: from 1 watt to 5 milliwatts.

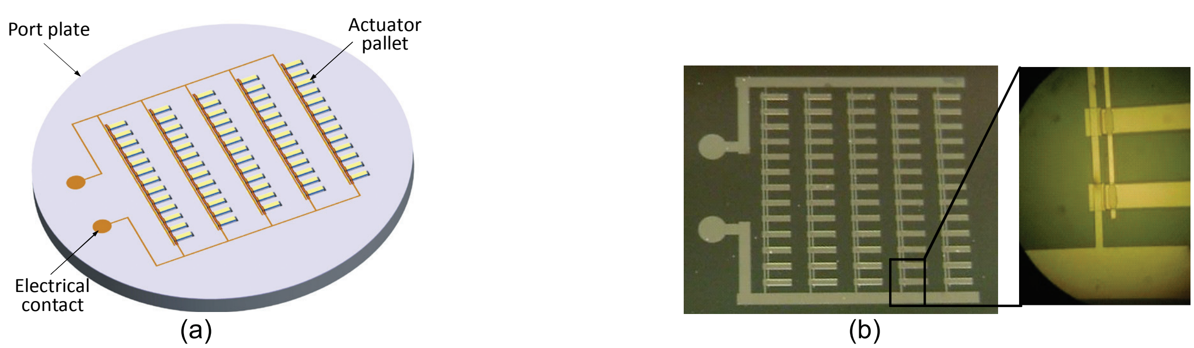


Figure 1. MEMS proportional pneumatic valve
(a) Concept (b) Hardware prototype of "unimorph" actuator array

Table 1. Flow rate capacities of commercially available miniature pneumatic valves. Note: some specifications are extrapolated from vendor data and may not completely be accurate

Manufacturer	Model	Volume Envelope (cm^3)	Maximum Inlet Pressure (bar)	Flow Rate (slpm) for 6 bar venting to 5 bar	Power Consumption (W)
Enfield Technologies	LS-V05s	71	10	125	3.6
Clippard	EVP Series (0.04" dia)	26.4	3.5	20.4	2.3
Parker-Hannifin	HF Pro	28.4	3.5	35	2
IQ Valves	Standard PFCV	395	9.3	280	6
CCEFP Valve	Alpha Prototype	4	7	40	0.005

Table 2. Flow rate capacities of MEMS based valves

Reference	Volume Envelope (cm^3)	Maximum Inlet Pressure (bar)	Flow Rate (lpm)	Power Consumption (W)
Chakraborty et al. [12]	1	1.79	0.9	-
Fazal and Elwenspoek [13]	1.4	4	0.25	< 1
Pourahmadi et al. [14]	1	1.03	0.5	1.1
Lisec et al. [15]	1	1	0.7	1
Kim et al. [16]	< 1	0.01	0.12×10^{-3}	< 1

Valve performance has been further quantified in year 7 using a test stand constructed for the project in accordance with ISO standard 6358 [1]. A plot of flow rate versus actuation voltage is shown in Fig. 2. A second order relationship between voltage and flow rate is observed. A maximum driving voltage of 50V provides a 22.5 slpm of air for 6 bar venting to atmosphere.

The meso-scale valve exhibited substantial leakage at 0 volts. However, back-driving the actuator with -23 V reduces leakage to negligible levels. Since the power consumed is so small, sealing by backdriving may be feasible in some applications.

We added a commercially available capacitive displacement sensor to the test stand in year 7. The purpose is to measure the displacement of the meso-scale piezobender under actual operating conditions, thereby enabling us to fully characterize the relationship between actuation voltage, displacement, pressure drop, and flow. The capacitive sensor has been imbedded in back of the piezobender in the flow channel of the test stand (see Fig. 3(a)). At the time of this writing, we have integrated the probe to the test stand, designed and implemented supporting electrical circuitry, and calibrated the sensor using a micrometer head (see Fig. 3 (b)). Our calibration data points match well with manufacturer's data points (see Fig. 3 (c)). We are currently adjusting the piezobender so that it both seals to the port plate properly and remains within the range of the capacitive sensor.

Port plates for the MEMS valve are made out of silicon wafers used for integrated circuits. Silicon is brittle by nature and fractures easily. Our first attempts at port plates fractured when pressurized.

We fabricated port plates with three different orifice diameters: 29 µm, 80 µm and 86 µm. 6900 orifices having 29 µm diameter were included on a 17 mm diameter port plate, while 130 orifices having 80 µm or

86 µm diameter were included on a port plate of the same size (see Fig. 4(a)). The etching process causes the diameter of the 86 µm holes to grow to 130 µm on the opposite face of the wafer. The thicknesses of all port plates are in the range of 500-525 µm.

The orifices have unusually large aspect ratios of diameter to length. We developed novel fabrication procedures to achieve this. The plates with 29 µm and 80 µm holes were patterned and etched from both sides of the wafer so that they meet in the middle. Precise back side alignment procedures were developed to enable the holes to meet. In contrast, the 86 µm holes were etched from one side of the wafer. Etching these holes required developing new masking procedures so that the etchant did not entirely consume the mask before the necessary hole depth was achieved.

The port plate with 29 µm diameter orifices fractured at pressure of 2.6 bar while the port plate with 80 µm orifices fractured at 5.5 bar. The port plate with 86 µm diameter orifices withstood the maximum design pressure of 7 bar without fracture (see Fig. 4(b)). We attribute the failures to stress concentrations, which were lowered with the larger diameter holes with wider spacing. While the port plate with 86 µm orifices succeeded, the larger orifice size also requires more actuator force, so the MEMS actuators will require re-design.

The graph in Fig. 4(b) also shows the flow rate versus pressure drop through each port plate. The key in the upper left of the figure indicates the number of orifices on the port plate, the diameter of the orifice on the top of the port plate, and the diameter of the orifice on the bottom. For example, the green curve corresponds to a port plate with 130 orifices oriented so that the 86 µm diameters are at the top of the plate and the 130 µm diameters are at the bottom. Flow through the port plates used with the meso-scale piezobender (9-210 µm orifices or 1-630 µm orifice) are also shown on this graph.

Fig. 4(b) reiterates the Year 6 demonstration that multiple orifices do not compromise the flow capacity of the valve. The MEMS scale port plates have higher flow capacity than the meso-scale port plates because their effective orifice opening is larger (4.6 mm^2 for the 29 µm orifices vs. 0.76 mm^2 for the 86 µm orifices vs. .31 mm^2 for the meso-scale orifices).

Our valve concept depends on thin film PZT. We set out with the fabrication of a single layer, or unimorph, actuator, to validate successful fabrication of the PZT. The unimorph actuator replaces the second active PZT layer of the final bimorph actuator with a passive silicon dioxide layer. The displacement of the unimorph actuator will be smaller than the bimorph. As a result, the unimorph enables validating the PZT deposition with a simpler, lower cost device.

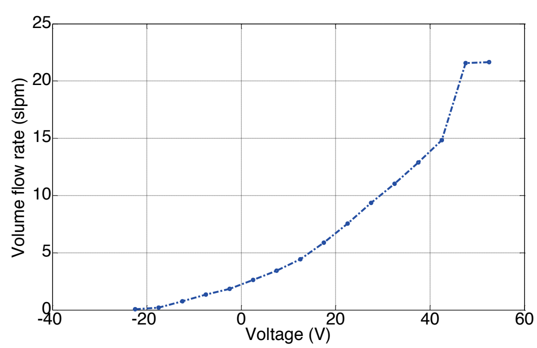
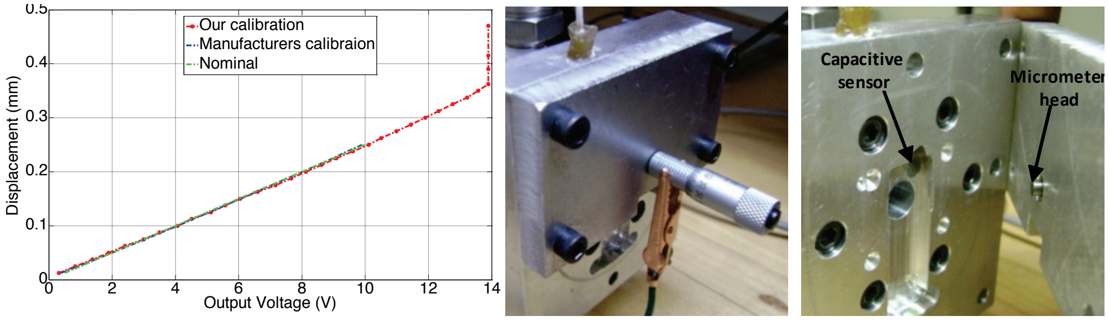
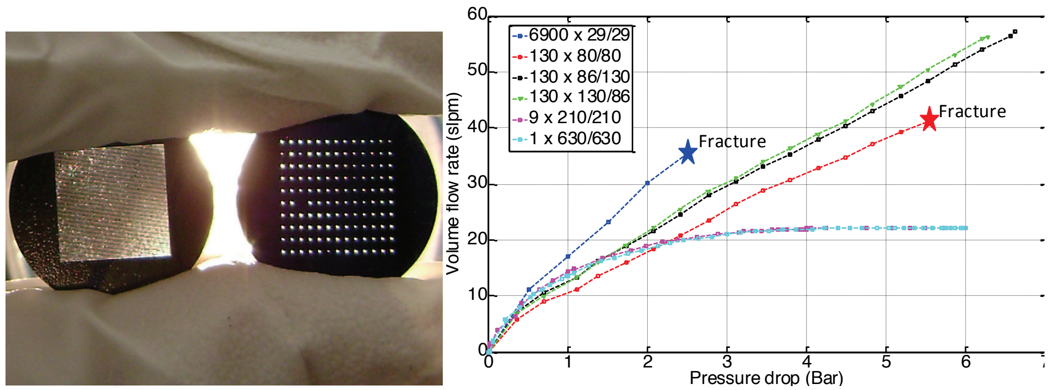


Figure 2. Flow rate versus voltage of meso-scale prototype



(a) (b) (c)

Figure 3. (a) Calibration data points (b) Micrometer head, assembled view (c) Sensor and micrometer probe, open view



(a) (b)

Figure 4. Port plates. (a) 6900 orifices each of 29 μm diameter on the left and 130 orifices each of 86 μm diameter on the right. The diameter of both port plates is 17mm. (b) Testing results.

The fabrication of the unimorph actuator involves 9 main processes. Three are unusual or novel. The first is the specialized PZT deposition step. The second is a novel lift-off process used to electrically connect actuators. The third is a back side deep reactive ion etching process used to suspend the cantilever beam type actuators. The first eight steps were completed in Year 7 and the last step is in process at the time of this writing. A photograph of the prototype unimorph actuator, as of the day of writing this report, is shown in Fig. 1(b).

The MEMS hardware design is being complemented by developing an enhanced flow model to better understand flow through the orifices and actuators. The new model is based on a similar model derived by Fleming et al. [17]. It combines models for two flow scenarios: a model where friction has a significant effect, corresponding to small actuator displacements, and a model where orifice area dominates, corresponding to large actuator displacements. The model was drafted in Year 7 and is currently undergoing refinement.

Our schedule has been set back by several problems in accessing the specialized machinery required to fabricate the MEMS valves. Establishing a contract with Penn State University to perform PZT deposition required a month longer than anticipated. Soon after fabrication at Penn State was initiated, our processing engineer left the group, causing another two month setback. Moreover, we have learned that the machines used for MEMS prototype fabrication are temperamental, and they commonly go out of service for extended periods. A month was lost when a machine at Minnesota used for back side alignment required recalibrating. Another month was lost when a new machine at Minnesota was found to be malfunctioning. Similar machine problems created additional delays at Penn State. As a result, we have had to delay our milestones by four months.

Major Milestones:

- Demonstrate MEMS pneumatic valve actuator assembly (4/30/13)
- Deliver first MEMS bimorph actuator (7/31/13)
- Demonstrate alpha prototype MEMS pneumatic valve with compliant seals (10/31/13)
- Deliver performance specifications (including power consumption, response time and flow characteristics) of alpha prototype MEMS pneumatic valve (1/31/14)
- Demonstrate MEMS pneumatic valve on Ankle-Foot Orthosis (Test Bed 6) (3/31/14)
- Demonstrate learning prototype MEMS hydraulic valve (5/31/14)

C. Member company benefits

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

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

Research Team

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Industrial Partner:	Martin Companies, Charlie Martin, CEO

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

We aim to break the major technical barriers relating to 1) Compact integrated systems (by designing systems where valves, cylinders, and sensors are not separate entities), and 2) making fluid-power systems safe and easy to use (new force sensors will ensure human safety when interacting with machines in an MRI). Furthermore, we will break a transformational barrier by applying fluid power in medicine. This precisely aligns with the CCEFP vision "of transforming and fully exploiting fluid power into a compact, efficient and effective source of energy transmission."

3. Project Description

A. Description and explanation of research approach

Fluidic energy transmission is the only effective way of transmitting energy during imaging in an MRI. Toward achieving necessary compactness, the project determines fundamental engineering principles whereby compact fluid power systems can be manufactured as integrated devices rather than a collection of assembled components, which can lead to compactness and performance advantages compared to traditional assemblies.

Intraoperative image guidance, and particularly use of MRI images which have far better soft tissue imaging capability than other modalities, has the potential to fundamentally change modern surgery which 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, this research aims to provide real-time image feedback during surgery, combined with precise machines able to accomplish the surgeon's objectives accurately. Such feedback can enable the surgeon to visualize the position of instruments in relation to sensitive subsurface blood vessels, nerves, tumors, etc., before incisions are made, and enable the robot to directly position a tool at a desired target specified in a medical image. Both have the potential to make surgery safer and to improve clinical outcomes by enhancing the accuracy of treatment delivery. MRI is a key enabler of this due to its ability to clearly show soft-tissue boundaries and structures which are not visible in other imaging modalities. Fluid power is the only viable technology that can transfer energy to actuate machines without the adverse interference effects associated with by the intense magnetic fields required by MRI or interfering with the imaging itself.

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

B. Achievements

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

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

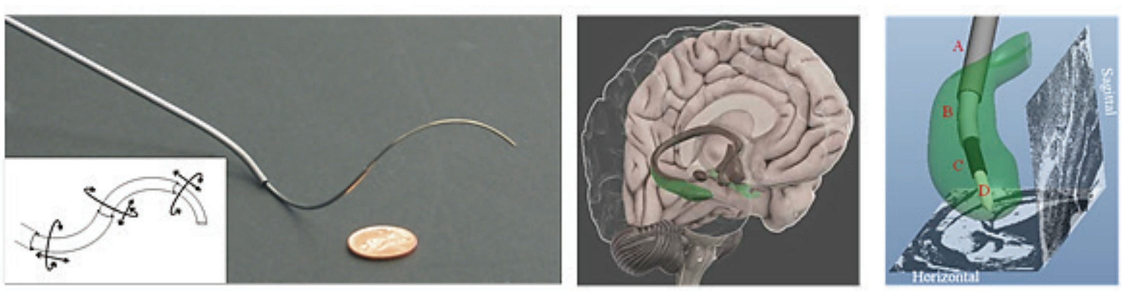

Figure 1: (Left) Concentric tube steerable needle controlled by translation and rotation of component tubes as shown in the inset line drawing. (Center) Image showing hippocampus location in the brain (green structure near center). (Right) Illustration of ablator tip positioned in hippocampus with two projection MRI image views.

<u>Fabrication of MRI Compatible Robot Prototypes</u>: Two prototypes of MRI compatible robots were constructed and tested this year. The robot shown in Figure 2 is capable of controlling 5 degrees of freedom (3 axial translations and 2 rotations of three tubes in a concentric tube robot), and is pneumatically controlled feedback from both optical encoders and pressure sensors. This design won a best poster award (3 in 5 competition) at the 2012 Design of Medical Devices Conference [7]. A modular concept has been pursued so that additional tubes can be added if desired. Rod locks were included for safety. General design objectives were small size with minimum friction to improve control precision. Each steerable cannula tube is translated via an acrylic plate supported

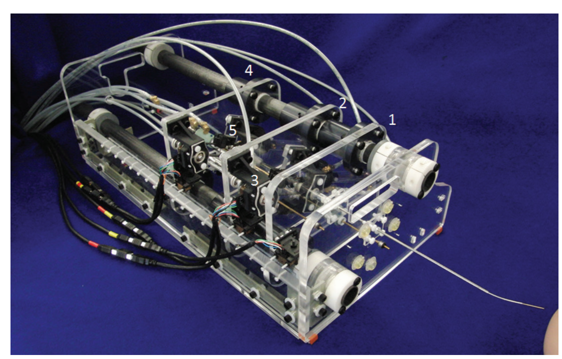

Figure 2: Modular pneumatic robot prototype able to control three tubes to deliver the steerable needle into the human brain in the MRI scanner. 5 DOF with 1, 2, and 4 translational and 3 and 5 rotational.

by two plain linear bearings. Two carbon fiber guide rods support all three sliding plates. Each of one curved elastic tube and one simulated ablator tube rotates via one pneumatic actuator and transmission mounted to its respective acrylic plate. The reciprocating motion of the piston-cylinder is converted to rotation using a timing belt and pulleys. MRI compatibility was tested by placing the robot in a MRI scanner during imaging. No signal-to-noise ratio degradation was apparent, and no robot components were heated excessively. Work at MSOE on pneumatic component integration via rapid prototyping also won 2nd place for best design at the 2012 Additive manufacturing and Users Group Conference.

Nonlinear Control Results: A high precision nonlinear controller for the pneumatic actuators has been developed [5]. The controller for each actuator requires one 4-way spool valve, two pressure sensors, and one optical encoder. The pressure sensors and valves connect to the robot via plastic air lines 3 meters long; sensitive electronics are thus sufficiently removed from the scanner to preclude any measurable image effects. In recent experiments [8], we demonstrated precision position tracking for each of the five base joints on the robot, achieving a mean steady-state error of 0.006mm (encoder resolution) for translational stages and 0.3 degrees for rotational stages.

Initial Image Guidance Results: To begin to solve the problem of aligning the robot's coordinate system with the imager's coordinate system (the "registration problem"), initial in-scanner targeting experiments using a 6 DOF piezoelectric robot in collaboration with Worcester Polytechnic Institute were pursued. The MRI compatibility of the robot was evaluated in a 3 Tesla MRI using standard prostate imaging sequences with an average signal to noise ratio loss of less than 2% during actuator motion. The accuracy of the active cannula tip position was evaluated first in benchtop trials using an external optical tracking system with RMS error of 1.00mm. Three phantom insertions in an MRI scanner showed that cannula trajectories that agreed with kinematic models with RMS tip error of 0.61-2.24 mm. These accuracies are promising, but additional experiments are needed to establish statistical significance. These image guidance results were published in [6] and were nominated for best medical robotics paper at the IEEE International Conference on Robotics and Automation, 2012.

fMRI-compatible Sensors and Haptic Device

Non-magnetic haptic interface with optical force sensing: Fluid-powered actuation in fMRI enables a variety of scientific and medical evaluations in brain-motor coordination through haptic interaction. There is also a strong need from the community for accurate sensing technologies in fMRI. In Y5-Y6 of the project, we developed a fiber-optic force sensor and encoder made from plastic for a pneumatic haptic interface [1, 2, 3]. Ueda and Turkseven invented a new design method based the distribution of strain energy. A newly designed force amplification mechanism improves the resolution of force sensing and obtained a force resolution of 0.06N by effectively reducing the hysteresis due to plastic deformation. A force feedback controller was implemented on an integrated haptic device (Figure 3).

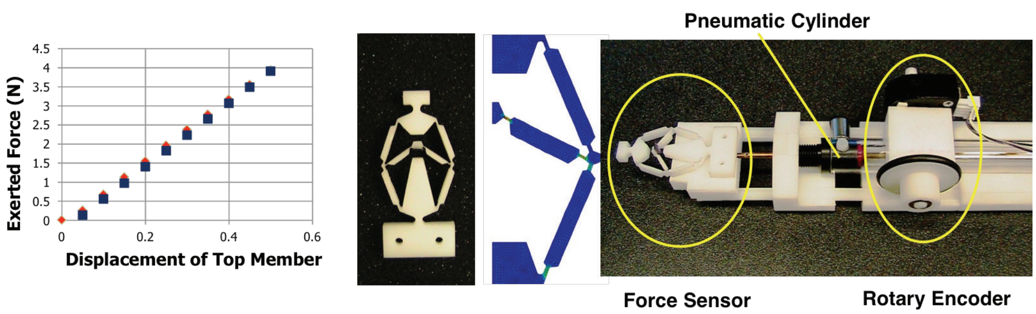

Figure 3: fMRI compatible haptic interface. fMRI technology enables high resolution, real-time, 3-D monitoring of brain during therapy. A high-resolution low hysteresis optical force sensor was developed by using strain-energy-based optimization.

Figure 3 also shows an overview of a 1-DOF haptic interface. A pneumatic cylinder produces bidirectional movement of an end-effector that interfaces with a subject in MRI. The pneumatic actuator is remotely controlled by pressure valves located in a control room. The developed force sensor is attached to one end of the actuator that measures the force produced by the device. A rotary encoder, attached to the device through a pulley, measures the linear displacement of the pneumatic cylinder. The MRI compatibility of the assembled haptic interface was assessed by an MRI device. The displacement sensor used in this project is an assembly of a rotary encoder and a plastic wheel that follows the relative displacement of the surface in contact. Since the displacement sensor does not have to be close to the area of imaging, commercial rotary encoders could be used.

Fiber optic extrinsic sensor technologies are suitable for this project. Among different fiber optic sensing methods, reflective sensing by light intensity measurement is implemented. The sensing principle shown in Figure 4 was adopted. To use the same fiber as the source and the receiver, and to eliminate the instability in the light source, a 2x2 coupler is used in the circuitry. This design reduces the number of fibers attached to the device and facilitates the cable management in the MRI room. A numerical approach for fiber to mirror light transmittance has been initiated. The structure was made of Acetal resin (DuPont Delrin) for its high MRI-compatibility and relatively low hysteresis characteristics. A displacement amplification mechanism (DACM) shown in the figure is advantageous for sensing tasks in a limited volume. The displacement of the top portion was amplified by the mini-link in the middle where the mirror was attached facing to the fiber.

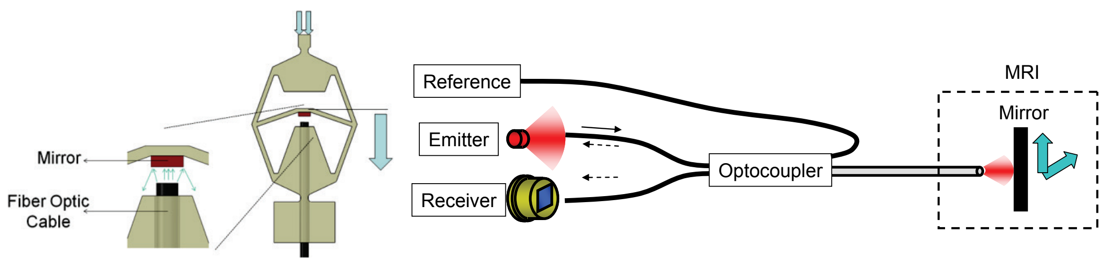

Figure 4: Sensing Principle in MRI: (left) Light, transmitted by a fiber, passes through a fiber-mirror interface. The returning light is measured by a photodiode; (right) Deformable structure of the sensor

We have addressed a fundamental design question of whether deformable strain amplifiers improve the overall resolution or enervate the performance due to increased hysteresis. We have confirmed that sensitivity of a compliant mechanism could be traded for a lower hysteresis error i.e. higher precision. DACMs could be targeted to achieve a low hysteresis error rather than improving the sensitivity in a sensor. Compared to a non-amplifying, basis structure our proposed design achieved a 3-4 times higher signal-to-noise ratio, mostly due to its higher precision [9]. DACM topologies with a lower sensitivity may still improve the performance of sensors since the amplification of displacement can reduce the problem of hysteresis, enhancing the signal-to-noise ratio of a sensor. Lower hysteresis error, hence better precision, is the key factor that makes a displacement amplifying topology advantageous against a simple, flexible, low-stiffness body.

<u>Modeling of pneumatic line transmission delay and attenuation:</u> The compressibility of air causes a delay of air pressure control that could potentially destabilize the closed-loop control. It is also reported that a long transmission line attenuates flow rate due to friction. The resistance of a transmission line rises with the length of the line. The time delay as well as the attenuation in the flow rate increase the response time of the pneumatic system significantly. The rise time of the pneumatic system to the same reference force increases with the length of the connection lines. As a result, the pressure in the pneumatic cylinder in the MRI room is not the same as the pressure of the valve in the control room.

A possible technique to mitigate the control delay challenge is to use the optical force sensor that is mounted on the actuator. The force of the cylinder is characterized by the pressure difference between two chambers. Standard pressure sensors cannot be used in the MRI room, but the optical sensor can be used as an alternative. In addition, the force measurement will be transmitted to the control room instantly, i.e., in the speed of light. Therefore, only the transmission delay in the forward direction, i.e., actuation, should be considered. The optical force sensor can be used to calibrate the pneumatic line dynamics. Design of a sliding-mode controller for impedance control of the haptic interface with transmission delay is in progress.

Design of a pneumatic rehabilitation device (REU 2012): In summer 2012, Joshua Hooks (CCEFP REU) was involved in the development of a fluid-powered finger rehabilitation device. Such a device is expected to provide direct evidence about the efficacy of therapeutic training for stroke rehabilitation. We performed a feasibility study. Joshua performed intensive literature survey on existing finger rehabilitation methods. He also studied the kinematics of fingers to identify necessary specifications for the robotic device. He developed a prototype device using a pneumatic cylinder actuator and several tendons that help the index finger extend. A force feedback controller on a LabView-based system was implemented.

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

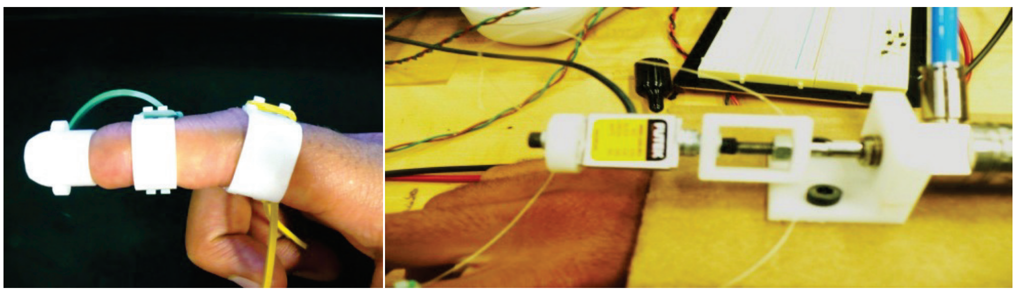

Figure 7: Prototype Pneumatic Finger Exoskeleton

Plan for next 5 years

The miniature integrated fluid-power systems developed in this project can be applicable broadly within the Center to projects where size and weight of components must be minimized, including the quantitative evaluation of Test Beds 4 and 6 using fMRI. PIs Webster and Barth are collaborating with Dr. Joseph Neimat, a neurological surgeon, for clinical insight and guidance of the surgical robot project. They have also begun collaborating with Acoustic Medsystems Inc., a company that makes an acoustic ablator that is ideal for thermal therapy in the brain. They have also submitted a NIH SBIR proposal. PI Ueda has started collaboration with Dr. Shinohara in Applied Physiology at GA Tech so that project results can seamlessly be transitioned to clinical settings. Results may also be applicable to PI Ueda's stroke rehabilitation robot project in collaboration with Dr. Kawahira, M.D. at Kagoshima University, who invented a new therapeutic procedure for hemiplegic limbs. The PIs will continue to seek external funds major funding agencies Dr. Ueda and Dr. King at Danish Technological Institute (DTI) USA DTI have submitted a proposal to NSF Partnerships for Innovation: Accelerating Innovation Research (PFI: AIR) on an application of optical force sensing.

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

C. Member company benefits

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

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Project 3A.1: Teleoperation Efficiency Improvements by Operator Interface

Research Team

Project Leader:	Wayne Book, Mechanical Engineering, Georgia Tech
Other Faculty:	Steven Jiang, North Carolina A&T
	Eui Park, North Carolina A&T
	Perry Li, University of Minnesota
Graduate Students:	Mark Elton, Ryder Winck
	(Heather Humphreys on an associated project is cooperating)
Undergraduate Student:	Michael Baker
Industrial Partners:	Caterpillar, John Deere, HUSCO, Bobcat, Sauer Danfoss, Sun Hydraulics

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 appropriate to on-vehicle and remote operation relevant to deployment in mines and other hazardous locations. 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 with improved operator interfaces 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 patient transfer in home and institutional settings. In most of those systems, human operators directly interact with machines. The necessary communication between humans and machines directly impacts system performance and fuel efficiency [1]. Coordinated control and other more intuitive interfaces have been shown to reduce operator errors and speed up completion time. A negative aspect of the experimental devices used in prior studies was increased physical operator fatigue. Some potential interface improvements would be expensive to implement for an operator on the vehicle, but could be part of a teleoperated system with minimal additional cost if teleoperation were preferred for reasons such as the remoteness of the work site or the risk to an operator. Industry has seriously considered this option. Caterpillar robotic trucks already operate in surface mines in remote areas of Australia.

In designing better human interfaces intuitive correspondence between the operator inputs (e.g. hand motions) and the device actions (e.g. excavator bucket movement) were previously shown to increase operator effectiveness by 81% and resulting fuel efficiency by 18% [2, 3]. This involved coordinated control of the various axes of motion so that the operator did not need to be concerned about the kinematic transformations between his hand controller and the ultimate motion of the tool. Conventional joysticks do require the operator to make this transformation mentally. Even experienced operators make mistakes in this transformation, mistakes that may be costly or dangerous. Assuming coordinated control is implemented, the choice of position, velocity or acceleration control is still in question. Prior studies [4,5] are somewhat conflicting.

With these issues in mind, our research sought to discern (1) an explanation for the preference for velocity control in hydraulic systems, (2) to determine if position control might improve performance and for which systems, (3) to see if augmented human-machine interfaces might facilitate this improved performance, and (4) to improve the design of the hand input mechanism itself to avoid operator fatigue observed in earlier experiments. Discussion with industry partners explored the usefulness and feasibility of various alternatives for improving the interface.

To conduct experiments representative of the complex operating environment the Georgia Tech excavator simulator was employed with new enhancements that provide a more realistic experience for the subject and that allows testing in a more controlled environment. The Bobcat Company donated an excavator providing realistic surroundings for subjects while controlling the simulation. The cab was initially stationary, but more recently it was powered to rotate in correspondence with the dynamic model giving a more realistic experience to the subjects. Dynamics of the vehicle, the soil and their interaction are represented in a graphic display as well as sound variation. With data from TB1, a fuel map was created that allows the simulator to calculate the fuel consumption of the excavator. Testing on TB1 at Purdue was conducted early on in a teleoperated mode, giving us confidence that the simulator was a realistic substitute. Further enhancement of the simulator involving 3D displays are envisioned but not yet realized.

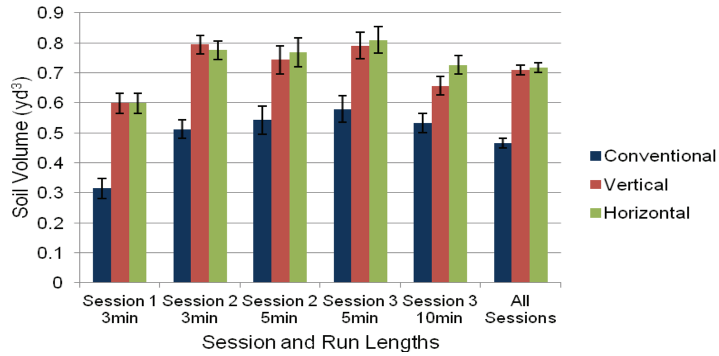
B. Achievements

Achievements for this period will be presented in two groups: (1) results of new hand controllers and (2) results for enhancement of the visual and control interfaces. This summary work does not cover work completed under 3A1 at NCAT on human modeling. Those results will be covered in Projects 3A3.

<u>New hand controllers</u> have been developed to realize the benefits of the position control as discussed above while addressing some of the challenges of employing a position control device on a real machine. Ryder Winck led this work. He completed his PhD and is currently holding a post graduate fellowship at Stanford working in haptics research. Some examples of the challenges are operator fatigue, need for sensors to measure joint positions and the inability of the operator to let go of the joystick without causing machine motion. Six different hand controller prototypes were constructed. Four of these controllers were tested in a brief pilot study. All of the controllers tested in the pilot study use position control of the boom, arm, and bucket and rate control for the swing. The two controllers selected for further study are shown in Figure 1. The primary difference in the two controllers is that the arm control is through motions in a vertical or horizontal plane as the figure shows. Results of extensive testing in the excavator simulator are summarized in Figure 2. The experimental controllers used removed about 53% more soil per unit time across all the tests than the conventional controller and 43% more soil per unit of fuel. The figures show that the tendency to fatigue in longer runs was largely offset by the horizontal configuration which allows partial arm support.

Figure 1: Vertical and horizontal kinematically similar hand controllers used in detailed studies

An example of a potential modification that will likely be explored is the addition of friction to the joints of the position control hand controllers to enable the user to let go of the hand controller without causing unwanted machine motion. These hand controllers must be tested on TB1 to demonstrate their effectiveness in operating a real machine. In addition, we will explore the possibility of commercializing the hand controllers through our partner companies. Long term future work will involve incorporating automation and haptic feedback. As an example of automation, an operator could specify a maximum depth for a trench and the machine would prevent the operator from digging below that preset depth. Haptic cues will be explored as a way to transmit important information to the operator. This will not be limited to coordinated forces but will focus more on the transfer of information, potentially through the use of vibratory cues. Vibratory cues have been demonstrated to provide intuitive information without the need for extensive hardware modifications [6].



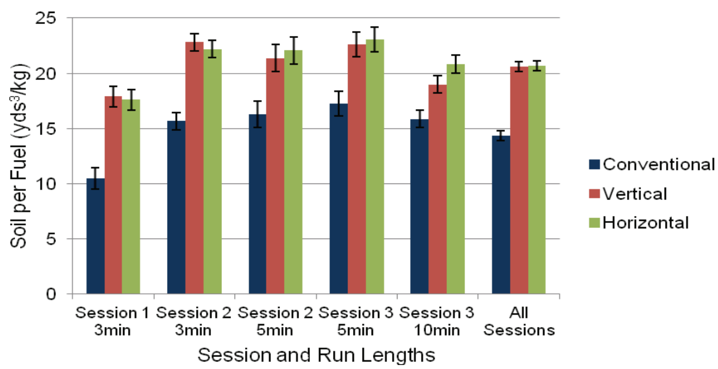


Figure 2: Mean soil volume removed per minute (top) and per kg of fuel (bottom) for each session and trial length. Error bars show 95% confidence intervals for ANOVA test for significance with Tukey adjustment.

Improvements through enhanced visual displays were extensively tested with positive, interesting results for excavators and for other equipment manually controlled. This work was led by Mark Elton who completed his PhD and is currently employed by HUSCO International. Several improvements had been made to the TB1 simulator. Physical cab rotation was mentioned above. A “ghost arm” was added to the simulator that displays either a wire-frame or transparent arm overlay of the commanded arm position. The ghost arm also has the option of leaving a trail of ghost arms (similar to the “tail” option of a computer mouse) that show the path that the real arm will follow to reach the ghost arm, or commanded position. The effectiveness of displaying a ghost arm concept was first tested using simple 1- and 2-D video “games”. Based on these preliminary tests, rapidly conducted, tests on the excavator simulator were planned and executed with results summarized below.

Five simple video games were designed to test how position control, position control with a ghost, and rate control compare for five task (1- and 2-D tracking, 1- and 2D point-to-point motion, and path following). Thirty subjects participated in this study which allowed Mark Elton to test hypotheses about the relative effectiveness of position control and rate control for systems of different dynamic response times. Dr. Elton proposed enhancements that could permit position control to perform better than rate control for some of these systems. One enhancement is the ghost display and a second enhancement is the modification of the control signal to predict the intent of the operator. These enhancements will now be discussed, first for the simple video games and then for the excavator simulator.

Various ad hoc explanations have been given for the superiority of position or rate control in manually operated systems. Dr. Elton sought in his PhD Thesis to explain this as a need to match operator intent with feedback given. This explanation would also give designers a paradigm to design better interfaces across a wide range of applications. Experimental results have been consistent with this explanation [7]. The simple video games included 1D and 2D tracking, point to point jumps, and maze following. These were studied with and without a "ghost" figure and for dynamically fast and slow systems. The fast systems were essentially instantaneous, i.e. only the kinematics of the "plant" was used to couple the joystick input to the output. The slow systems had velocity limitations representative of hydraulic systems such as the excavator in TB1. Both velocity and position control were studied. Figure 3 shows two of the simple displays used and the ghosts, which are the small blue squares with only the corners outlined. Also shown is the ghost display for the excavator simulator. The ghost goes immediately to where the excavator (represented in the simple displays by light colored square with an excavator picture inside) will ultimately go as commanded by the position controller. The operator is to place the excavator in the red square as quickly as possible. In addition to the time, errors of various types were recorded, such as overshoot or initially moving in the wrong direction. With the excavator simulator, a trench was to be dug with spoil placed in a bin on the side.

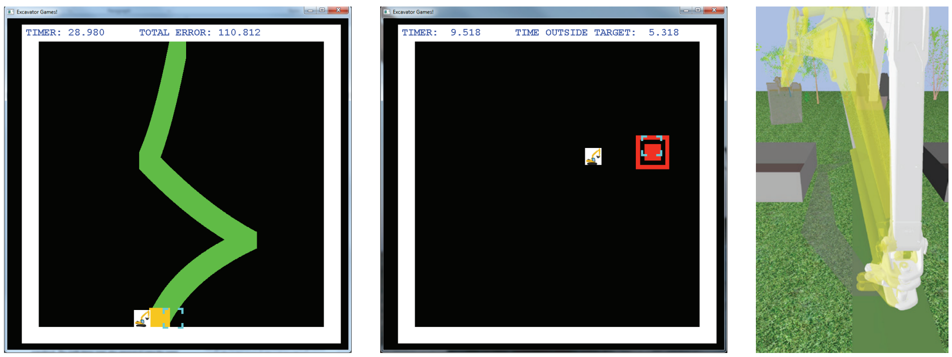


Figure 3. Ghost for the (a) 1D tracking (left) and (b) 2D point-to-point (center) and excavator (right) tasks.

Experiments conducted confirmed that rate control is more productive for slow systems and that position control is more productive for fast systems. The study results are extensive and only one set of results is shown in Figure 4 to convey these findings. Comparisons between the actual and the theoretically optimal speed is also shown, with corrections to optimal made for the subjects reaction time. Later studies confirmed this by choosing a response between the two extremes first used, with performance falling between these extremes. Experiments also showed that ghosting the display enabled the position control to improve, approaching rate control even for the slowest system. Further study would be valuable to quantify the break even response with and without the ghost.

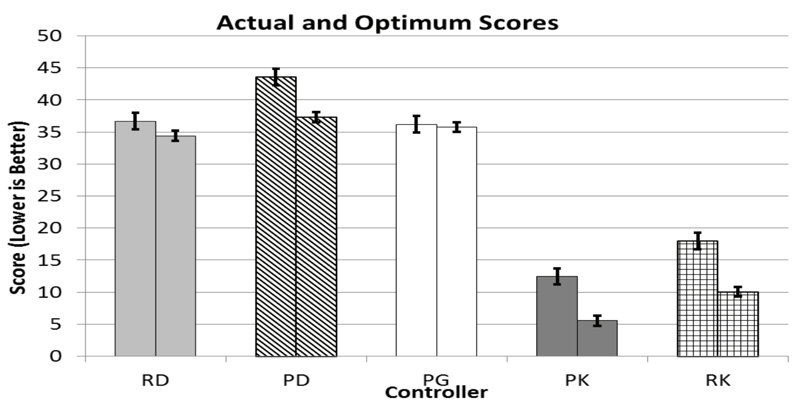


Figure 4: Actual (left) and optimal (right) scores for the 1D point-to-point motion task. RD=rate control/dynamically slow; PD=position control/dynamically slow; PG=position control/dynamically slow with ghost display aid; PK=position control, kinematic response (fast); RK=rate control/kinematic response.

The analysis of "errors" revealed the nature of the delays resulting from position control of dynamically slow systems. While the ghost display is viable for improving performance on teleoperated systems, the technology for implementation on the vehicle is more of a disadvantage due to the incremental cost of augmented reality. Dr. Elton considered modification of the command signal as an alternative and found that pauses, one of the causes of suboptimal performance, could be smoothed out with his “best fit” algorithm which yielded between a 16% and 48% improvement. Elton’s thesis [7] contains much more detail and statistical analysis of these results.

Elton’s experiments with the ghost on the excavator simulator also showed that it improved the performance under position control by about 24%. True to expectations, the complexity of the task made the results much more complicated than for the simple planar studies and clear superiority of position over rate control was not shown. Analysis after the fact showed that with position control the operators were not filling the bucket as well with rate control.

In future work the TB1 simulator graphics will be modified to display on a 3DTV, which will be mounted on the simulator, replacing the current 2DTV. The feasibility of using a ghost arm for tele-operation will be investigated by displaying the arm with 3DTV technology. With both Mark Elton and Ryder Winck graduating, progress has been slowed on interfaces to excavator class of equipment. An appropriate student for this task has been difficult to find and the search is widening to the College of Computing. New concepts in rate control which is also coordinated with the position of the excavator tool are of interest. A virtual configuration change of the hand controller coordinates will allow the operator to push the tool in the arbitrary direction of desired motion as if he or she were pushing on the tool itself. A second approach is to have a kinematically similar hand controller, which moves with the arm structure, but commands the velocity directly and only displays the position of the arm by virtue of feedback from the sensed arm position. This would have the advantage of a physical representation of the arm in the hands of the operator but still allow the operator to command velocities. These concepts will be tested on an off the shelf device (Phantom by Sensable) before consideration of a special device design.

The interface to TB4, which has recently been modified from rescue robot to patient transfer device, has given new fertile ground to plow for research on operator interfaces. Rate control is currently the standard. However a force input to produce the velocity and direct application of that force on the end device holding the patient is under consideration.

C. Member company benefits

The most interested and affected companies are the equipment builders in CCEFP. This includes John Deere, Caterpillar, and Bobcat. Caterpillar has attended our webcasts regularly and has a very active industry champion. Deere, Bobcat, Sun, MTS Systems and Sauer Danfoss have donated equipment that has enabled the studies to be as realistic as possible. HUSCO has been invaluable in critiquing the progress and relating experience with excavator operations.

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

Research Team

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	Eui H. Park, Industrial and Systems Engineering, NCAT
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Undergraduate Students:	E. Frota and P. Franca
Industrial Partners:	Caterpillar

1. Statement of Project Goals

The goal of the project is to investigate human performance in complex fluid power (FP) systems where human operators interact with the machines, and to use user-centered design approach to develop human machine interface for selected fluid power systems (test beds) that are user-centered, safe, easy and comfortable to use.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

Traditionally, human machine interface in many FP systems (such as human-excavator interface) rely exclusively on visual modality (e.g. levers, pedals) and to a lesser extent auditory modality (e.g. alarms) as the pathway for communicating between the human and machine. However, as operator workload/task becomes heavy, the visual modality becomes overloaded due to the limited number of channels through which the machine and the operator can communicate. The overworking of the visual and speech modalities lead to operator fatigue that ultimately results in under-performance and errors. Meanwhile, haptic modality has yet to be fully utilized in the FP systems. A successfully developed multimodal human machine interface has the potential to minimize user's cognitive workload when performing complex tasks as attentional resources will be drawn from different resource pools. Although the haptic interface promises reduced mental workload and improved operator performance over the traditional lever/pedal interface, its use as a control interface for the excavator has not been fully explored because the technology is still being developed. For instance, in order to realize the potential benefits of haptics in the excavator interface, it is important to understand the basic biomechanical, sensorimotor, and cognitive abilities of the human haptic system, to properly determine the design specifications of the hardware and software of haptic interfaces (Osafo-Yeboah, et al., 2010; Franklin, et al., 2011; Osafo-Yeboah and Jiang, 2012). This could be achieved by modeling quantitatively the interaction between the operators and excavators. In a typical excavation task, visual, auditory and tactile feedback information may be presented to the operator to enable him/her to accomplish the desired tasks. The feedback information may be presented through the use of a display, touch or auditory technology. Through this, the operator extracts cues that are then sent to the central nervous system for interpretation and necessary action.

In modeling human-machine interaction, control theoretic models have been used because they provide an analytical approach that can describe the actions of humans in a human-machine system. Control theory deals with the mathematical analysis of dynamic systems and the mechanisms for achieving a desired state under changing internal and external conditions. Control theory modeling could be classified as either “open-loop” or “closed-loop” depending on whether feedback loop is present or not. A system that has no feedback loop is referred to as open-loop while a system with a feedback loop between the input source and the output node is said to be a closed-loop system. In a closed-loop system, output information is fed back to the human operator to help compensate dynamically for errors in the system. In using control theoretic approach to model human performance, the goal is to predict the human performance during task execution.

The human-excavator interaction system is a complex system with high degree of freedom, however, for ease of modeling, and to reduce the level of complexity into a manageable level, the subsystems of the human operator are assumed to be linear. The human subsystems that will be used to develop the quantitative model are signal/cue input, central nervous system the neuromuscular dynamic system, force generator and task dynamics system. The first step in developing the quantitative model for the human-excavator interaction is to develop a transfer function for each dynamic component of the human subsystem as a measurable input-output relation. Thus, to develop a quantitative model for the interaction between operator and the excavator, the human-excavator system is assumed to be a closed-loop control system. The goal of this research is to model how the operator combines and integrates visual, auditory and haptic cues/signals from the task environment to improve his/her performance on the task. In order to develop the mathematical model for both traditional and haptic-controlled excavators, concepts of control theory were used to derive a series of equations describing the interaction between human and machine. To determine a model for the human-excavator interaction, a transfer function for each dynamic component of the human subsystem is obtained as measurable input-output relation. In this model, the human operator receives signals/cues, *R(s)* (made up of visual, auditory and haptic cues) with probabilities ρ_v, ρ_a and ρ_h respectively from the environment. The operator processes this information in the central processing system, sends signals to neuromuscular system that then acts on the haptic manipulator device. The haptic manipulator device sends output to the excavator system dynamics. The excavator performs the excavation task and the output is fed back to the operator. A structural representation of the human operator in multi-sensory excavation task is shown below. As described in the model, signals can come from visual cues, auditory cues or tactile cues. The visual, auditory and haptic cues with known transfer functions Y_v, Y_a and Y_h respectively are integrated based on how a particular cue contributes to overall perception. When the cues arrive at the central nervous system (CNS), they are first processed by the memory filter with a known transfer function.

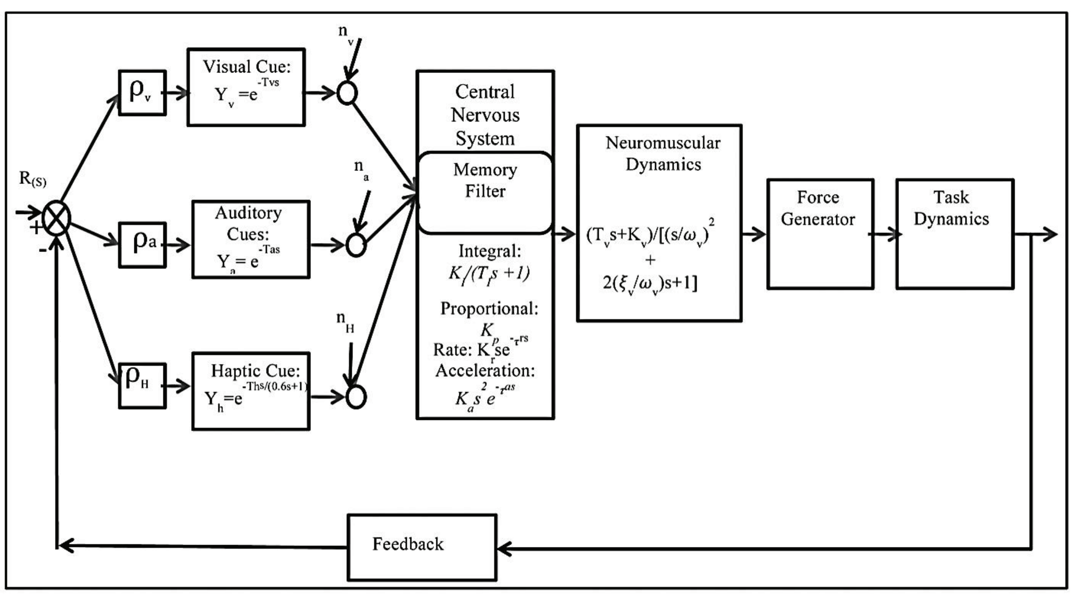

Figure 2: Structural model of human operator in multi-sensory excavation task

Five transfer function blocks are identified for the model. These are the signal input transfer function, the central nervous system transfer function, the neuromuscular dynamics transfer function, the force generator transfer function, and the task dynamics transfer function. Such model was then simulated in Matlab and tools such as Bode plot and Nyquist plot in Matlab were used for assessing system stability. The preliminary results indicated that haptic-controlled excavator was stable as shown in Figure 2. However, experiments need to be run to collect field data to validate this conclusion in the future. In addition, the complexity of the model needs to be improved as well.

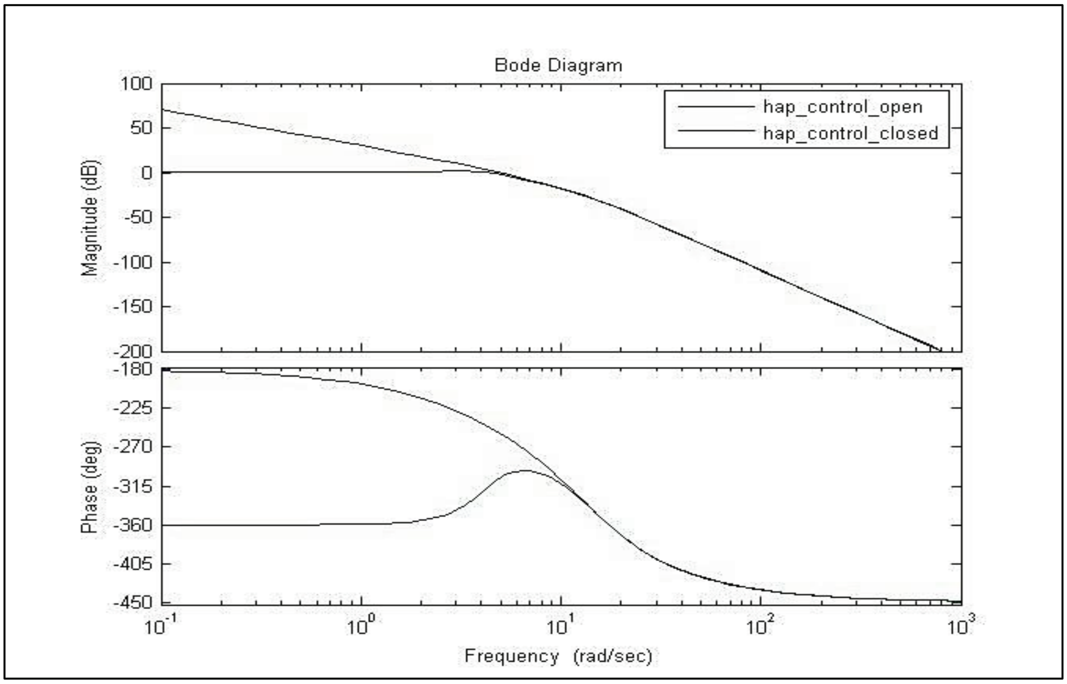

Figure 2: Bode plot of haptic-controlled human-excavator model

Human performance plays a significant role in overall system performance. We have developed an integrated framework that combine cognitive performance and physical performance models for FP application (Hughes, et al., 2010) and applied to investigate human performance issues for selected test beds (Chung, et al., 2010; Hughes and Jiang, 2010; Lee, et al., 2010; Liu, et al., 2010; Hughes, et al., 2011; Chung, et al., 2012). In the next a few years, we will also investigate the effect of fatigue on excavator operators and provide design recommendations based on the findings. While haptic modality needs to be investigated for FP systems such as excavators, there is also a need to continue to study auditory modality. Although auditory modality is commonly used in FP systems (i.e., alert), other types of auditory feedback might have the potential to help ease the visual modality overload. This is especially important to experienced operators who can make decisions with the auditory cues. In this project, we will investigate the impact of the auditory feedback/auditory icon/earcon of components of the FP system and provide design recommendations following the user centered design approach. We have developed a user centered design approach that combines persona and information scent in the past a few years and applied to interface design (Delpish, et al., 2010). User centered design approach is also being followed in developing a clinician-centered rehabilitation robot interface for a portable powered ankle-foot orthosis (PPFAO). In the next few years, UCD approach will be continuously followed to apply the PPFAO to assisted living.

B. Achievements

Achievements prior to February 2012:

- Developed an integrated framework for modeling operator performance in complex FP systems (2008-2010).
- Conducted empirical studies using various developed Jack models (physical model) for the rescue robot operators (2010)
- Conducted an empirical study using eye tracking to assess the effectiveness of the trust instrument for human robotic interaction (2010)
- Conducted a usability study to evaluate the haptic-controlled excavator simulator in Georgia Tech (2010).
- Developed a conceptual model for a user interface suite that interfaces the pneumatic-power ankle-foot orthosis (PPAFO) with clinicians and patients (2010).
- Conducted an empirical study on excavators using the integrated human performance modeling framework (Spring 2011)
- Conducted an empirical study to assess the conflict between multiple modalities of excavator operators (Spring 2011)
- Conducted an empirical study to investigate the effect of haptic force feedback on excavator operator performance and analyzed results (Summer and Fall 2011)

Achievements in this reporting period:

- Revised haptic-controlled excavator interface using user centered design approach – Spring 2012.
- Conducted literature review on quantification of human machine interaction – Spring 2012
- Developed a feedback control system representation of human-excavator model – Spring 2012
- Identified the human subsystems in the human-excavator model – Spring 2012
    - Central processing system
    - Neuromuscular system
- Developed a transfer function for each component of the human subsystem – Summer 2012
    - Signal input transfer function
    - Central nervous system transfer function
    - Neuromuscular dynamics transfer function
    - Force generator transfer function and
    - Task dynamics transfer function
- Developed quantitative models for multimodal human excavator interface – Fall 2012
- Developed a forward and closed loop transfer functions for human-excavator model – Fall 2012
    - Traditional excavator
    - Haptic-controlled excavator
- Implemented models in MATLAB – Fall 2012
    - Traditional excavator
    - Haptic-controlled excavator
- Revised rescue crawler interface – Summer 2012
- Conducted usability testing on the revised interface – Fall 2012
- Conducted literature review on operator fatigue – Fall 2012
- Conducted literature review on auditory feedback – Fall 2012
- Designed games for PPAFO – Spring 2012
- Developed prototype GUI for PPAFO – Fall 2012

Plans for the Next Five Years

- Conduct experiments with operators using the haptic-controlled excavators
- Conduct an empirical study to assess the auditory feedback on operator performance
- Conduct studies of fatigue on operator performance in fluid power systems
- Develop (revise) a multimodal human excavator interface

- Conduct usability evaluation on revised human excavator interface
- Develop a prototype for the clinician-PPAFO interface
- Develop protocols for usability evaluations of the PPFAO prototype
- Conduct experiments using game-integrated GUI with PPAFO hardware
- Develop social multiplayer game where patients engage against each other via the Internet

Expected Milestones and Deliverables

- Case study using the excavator test bed to investigate the effect of auditory feedback on operator performance
- Case study using the excavator test bed to investigate fatigue on operators
- Collection of human data via experiments with operators of haptic-controlled excavators
- A working game-integrated GUI for the PPAFO

C. Member company benefits

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

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Project 3B.3: Active Vibration Damping of Mobile Hydraulic Machines

Research Team

Project Leader:	Andrea Vacca, ABE/ME, Purdue University
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Graduate Students:	Davide Cristofori, Guido, Francesco Ritelli
Undergraduate Students:	One REU/year (for summer 2012: Roy Fisher)
Industrial Partner(s):	Parker Hannifin, CHN

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

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

3. Project Description

A. Description and explanation of research approach

FP systems are routinely affected by *oscillatory dynamics* of moving parts which can lead to stability issues. Undesired vibrations not only worsen *controllability*, but also reduce *productivity* and impact *comfort* and *safety* of operation. Despite the research efforts in finding solutions to control such oscillations, a general solution has not been found yet. *Current damping methods* are designed for specific applications and they can damp oscillations only in a limited range of operating conditions. Additionally, they usually *introduce systems slowdown* (capacitive methods) or *energy dissipation* (resistive methods). A first distinction among methods for vibration dampening is whether the hydraulic system is integrated with electronic control logic. According to this classification, there are pure hydraulic (PH) solutions and electro-hydraulic (EH) solutions.

Pure hydraulic technology: these methods are based on *capacitive* elements (e.g. accumulators) and/or *resistive* elements (e.g. orifices). Being based on fixed parameters these methods are suitable to damp the system only within a small range of operating conditions, and the tuning is typically based on extensive "trial and error" empirical processes made for each single application. The literature reports numerous methods that belong to the pure hydraulic technology category, including the use of accumulators or restrictors. Of particular interest for this research are the dissipative methods based on the applications of counterbalance valves [1, 2].

Electro-Hydraulic (EH) technology: EH technology is based on an optimal management of the power source with respect to a feedback signal representative of the oscillation extent. EH technology has often been combined with PH technology, to extend the range of stability of the hydraulic system and/or to limit

the contribution of pure-hydraulic techniques drawbacks on the entire system. Examples are: active suspensions; earthquake simulators, vehicles braking systems; hydraulic robots; active damping seats.
This research particularly investigates the pressure feedback control methodology, in which the pressure signal is used to indirectly quantify the oscillation. In this case a control based on real-time identification of the relationship between pressure and oscillations is required. Some interesting results obtained in the past have not reached practical application because of the complexity of the proposed controllers and of its model-based nature, which makes it difficult to extend to other applications.
The solution of the drawbacks of the past proposed pressure-feedback techniques represent the main challenge of this project. In particular, the proposed control methodology will address the problem of oscillation damping of FP machines considering:

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

The proposed control solution and its innovative contents
This research applies for the first time to FP applications the adaptation/optimization scheme using the Extremum Seeking (ES) theory. ES is an algorithm able to identify the set of parameters that can produce the maximum or minimum of a given function. Fig. 1 and Fig. 2 describe the idea under the proposed control approach. A controller is used to control the input signals of the control elements (flow control valves, for the case considered in this research), Fig. 1. The input parameters of the controller are signals given by pressure sensors installed near the actuator for which the oscillations have to be minimized. The tuning of the control parameters is achieved through online or offline optimization methods. Fig. 2 represents the idea for the optimization according to the offline scheme. A cost function associated to the oscillation is evaluated using real experiments or computer simulations. The ES algorithm is used to achieve minimum oscillation through a fast convergence loop.

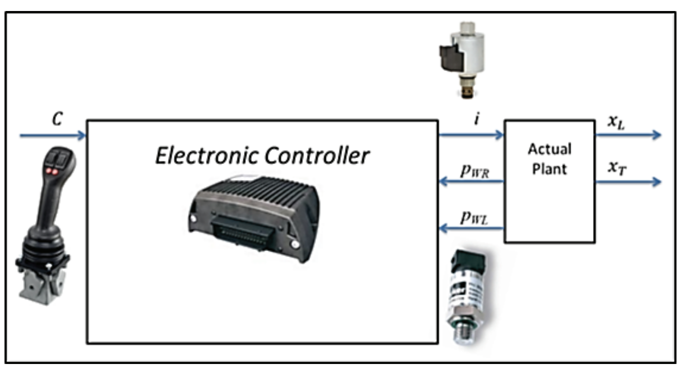

Figure 1: Basic schematic of the controller

The project will focus on the investigation of both the real-time and on-line application of the controller to mobile machine. A successfully online implementation will permit to apply the control technique to a wide range of possible real-world machines.

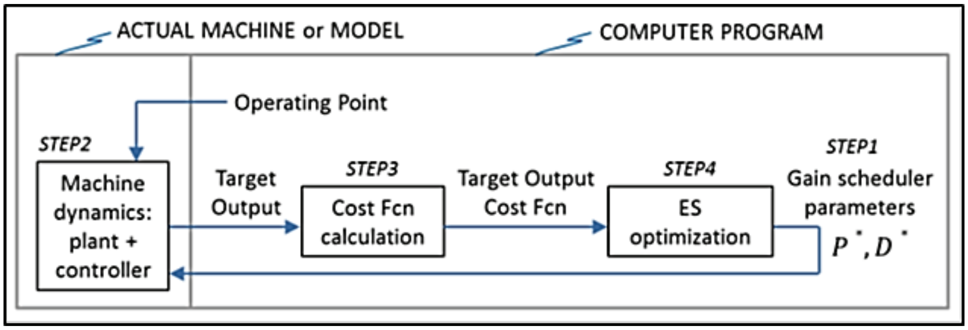

Figure 2: Controller tuning, the optimization process

Two important aspects of the project are to investigate the stability and observability of the control strategy related also to the safe performances of the entire system.

The study of hardware requirements (EH valve bandwidth, speed of electronic controller that implements the scheme of Fig. 1), as well as specifics of ES high-pass filter, demodulator, and low pass filter, designed on the basis of the system dynamics, is a particular topic of this research. The aim of the ES optimization scheme is to permit the creation of fast controllers, based on parameters predetermined with ES-based methods. However, this application of ES only partially meets the main goal of the project of obtaining a controller suitable for every application without the necessity of a pre-tuning phase. This especially is the case of the on-line control mode, in which the ES algorithm alone is not able to guarantee the effectiveness of the controller. For this specific topic on-line identification techniques are investigated in order to improve the convergence speed of the algorithm.

The project verifies the performance of the proposed strategy on particular reference cases in which all sources of oscillations can be excited (e.g. support, hanging load, hydraulic circuit): a hydraulic crane (Fig.3).

Figure 3: Instrumented hydraulic crane installed at Maha Lab

Margin of energy consumption reduction and system simplification

An alternative method to classic hydraulic solutions for controlling oscillations can offer significant advantages in terms of energy consumption and system simplification. The hydraulic crane considered in this research is suitable to prove the energetic advantages of the proposed technology. As described in [1, 3] an acceptable dynamic behavior for this kind of machine operating with suspended load is obtained with a setting of the counterbalance valves (in terms of cracking pressure and pilot ratio) that introduces an additional term of energy consumption in addition to the energy dissipation necessary to handle the load (Fig. 4). No significant research has been done to quantify this source of energy consumption. After evaluating this contribution, the research will show the benefit in utilizing the new control methodology to simplify the design of counterbalance valves and increase their energetic performance.

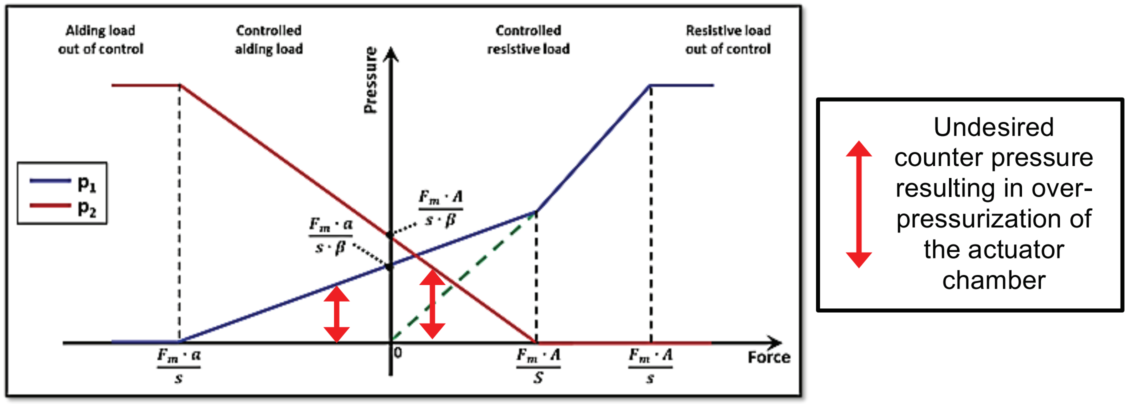

Figure 4: Characteristic plot of a counterbalance valve. Losses introduced by its setting.

A. Reasons of success for the proposed project

Through the formulation a novel adaptive, non-model based method for optimal, energy efficient control through cancellation of low frequency oscillations, this research will advance the area of control of FP systems. Essential element of success is in the combination of features that determine the feasibility and the industrial applicability to most of hydraulic machines currently on the market (like construction, load handling and agricultural machines). In particular:

- the use of pressure sensors makes the solution reliable and inexpensive;
- the adaptive control method proposed is suitable to control any hydraulic actuator and damp vibrations over the entire range of machine operating conditions;
- applicability to every valve-controlled hydraulic machine without significant tuning process;
- cost reduction and energy saving associated with system simplification.

B. Achievements

Started in summer 2012, during the reporting period following activities have been performed:

Control strategy achievements

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

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

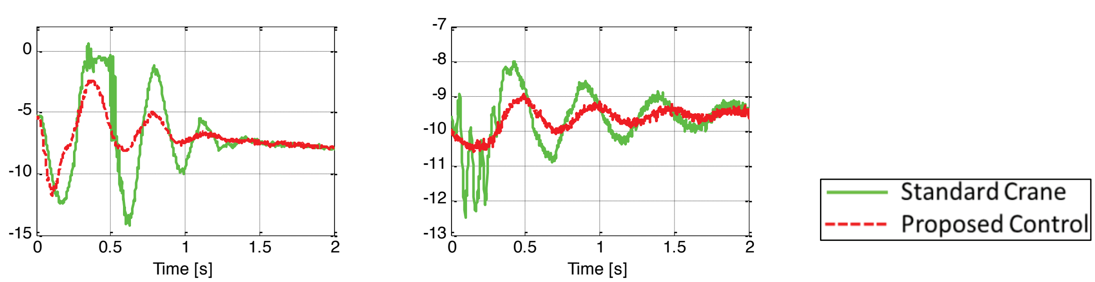

Figure 5: Tangential acceleration (m/s^2): Raise without load (Left); Raise with load (Right)

Energy consumption estimation
In order to perform an estimation of the energy consumption and its possible improvement, a study was conducted on the reference machine, Fig.3, by changing the settings of the overcenter valves. Two typical operating cycles were considered for the study, in order to investigate the overall operation of the machine (lifting/lowering, with/without load).

A detailed AMESim model created on purpose to model the behavior of the valve supported this activity.
Fig. 6 shows a typical result for one of the two cycles, the effect of the valve setting on the energy consumption and on dynamic behavior of the machine is remarkable. As expected, in the case of loaded machine, the difference is minor but still, if properly tuned, a controller is able to make the entire machine more energy efficient. The criticality of a good controller is shown in Fig 7, where the pressure oscillations for gray squared area of Fig. 6 are highlighted. As expected, a softer valve setting is energy efficient but makes the machine less stable.

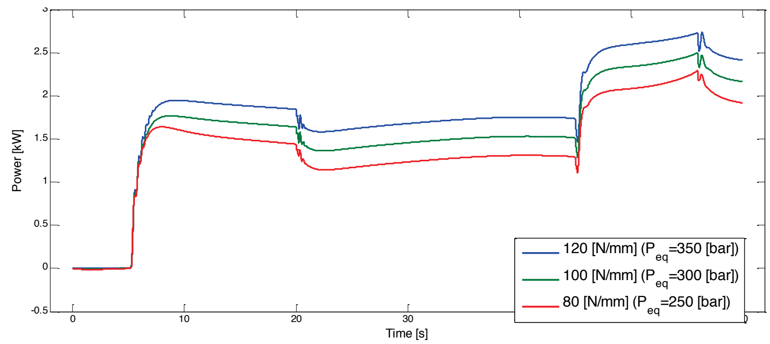

Figure 6: Energy consumption for different configurations of the counterbalance valves
E_{350bar}=109.5 kJ, E_{300bar}=97.4 kJ, E_{250bar}=85.8 kJ

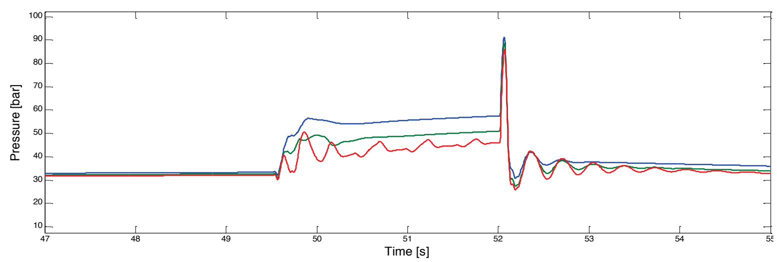

Figure 7: Different dynamic behavior of the crane by varying the counterbalance valve setting

Planned achievements following the report period

- Formulation of ES adaptive control for valve-controlled hydraulic system:
  - Observable proof of the controller formulation (spring 2013)
  - Analytical formulation of the controller completion and its implementation (summer 2013)
  - Analysis of the effects of the controller parameters (fall 2013)
- System control with offline use of ES (spring 2013)
  - Multi-domain (mechanical-hydraulic) model for the hydraulic crane in AMESim®-Simulink® completion (summer 2013)
  - Definition of cost function for offline tuning of the controller (summer 2013)
  - Identification of a test matrix for the evaluation of system performance in term of oscillation damping, energy consumption and productivity (summer 2013)
- Real-time system control with ES (long term)
  - Definition of cost function for online tuning of the controller (fall 2013)
  - Quantification of controller speed and effect of hardware properties (valve bandwidth, processors speed) thereon (long term)
  - Simulation and comparison of performance between real time and offline ES control (Long term)
- Extension to a different and more general hydraulic system:

- ○ Identification of driving cycles for the evaluation of system performance in term of oscillation damping, energy consumption and productivity (spring 2013)
- ○ Test activity and verification of performance on new system (long term)
- ○ Formulation of criteria for application of the novel control strategy for controlling generic hydraulic machines (long term)
- ○ Application to TB6 (spring 2014)

C. Member company benefits

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

D. References (extension of the proposal's references)

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

Research Team

Project Leader: Richard F. Salant
Graduate Student: Yuli Huang
Industrial Partners: Trelleborg Sealing Solutions, Freudenberg, Bosch-Rexroth, John Deere, Caterpillar, Haldex, R. T. Dygert

1. Statement of Project Goals

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

3. Project Description

A. Description and explanation of research approach

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

Past research on rod seals is described in a recent review paper [1]. Serious studies date back to at least 1964, but these have not had a significant impact on the practical aspects of seal design since they ignore both the roughness of the seal surface and mixed lubrication in the seal-rod interface. The present author and his students had made a start in developing a more realistic model of rod seal operation [2]-[4], under a project funded by the National Fluid Power Association. The present project, in the CCEFP, builds on that work. At the same time, several other researchers have been making advances [5]-[9].

The models developed in this project include analyses of the fluid mechanics, contact mechanics, thermal processes (in some cases) and deformation mechanics, and an iterative computational procedure. Inputs to the models include the operating conditions, material properties, macro-geometry, and micro-geometry of the sealing surfaces. Model development involves analyzing the fundamental physics of the various processes, setting up numerical analyses and computational strategies, constructing appropriate algorithms and writing code. Model validation makes use of experimental results obtained from industrial collaborators and from the open literature.

B. Achievements

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

The results of the above simulations have revealed much about the basic physics of rod seal operation. They show that these seals do indeed operate with mixed lubrication, and for a given set of operating conditions and seal design, there is a critical seal surface roughness below which there will be zero net leakage per cycle, and above which the seal will leak. They also show that for a given stroke length, net leakage decreases with rod speed and above a critical rod speed there will be zero net leakage. Comparison of simulations of non-leaking and leaking seals show that the following characteristics are conducive to zero or reduced net leakage: a thinner lubricating film, a larger film thickness during instroke than during outstroke, cavitation in the sealing zone during outstroke, reduced or no cavitation during instroke. The viscoelastic model has produced results similar to those from the elastic model for moderate to long cycle time applications. However, for short cycle time applications, the viscoelastic effects become important and produce cycle to cycle variations. In the course of the viscoelastic study measurements on a seal surface were made using an atomic force microscope (AFM). The results are extremely interesting: very large variations in the viscoelastic moduli occur on the micron and submicron scale. Maximum values of the relaxation modulus are found to be several times the value of the bulk value.

The seal models described above treat the seal surface as rough and the rod surface as perfectly smooth. To examine the effects of the rod surface finish, a seal model that includes the rod surface geometry has been developed. As surface features on the rod move past the seal, they generate film thickness fluctuations, leading to changes in the pressure field due to squeeze film effects. Thus, even though the rod speed and sealed pressure are held constant, the squeeze film term is included in the Reynolds equation. The surface features on the shaft are treated deterministically while the asperities on the seal surface are treated statistically using the flow factor approach of Patir and Cheng. The rod surface features indent the softer seal surface and affect the finite element analysis of the seal deformation. As the rod surface features move past the seal, the seal deformations change with time.

Progress During the Reporting Period

During the present reporting period, February 1, 2012 to January 31, 2013, the seal model including rod surface finish was applied to a rod with a plated plunge-ground finish, the most common form of rod surface finish. The rod surface was modeled with an axial sinusoid, based on measurements on actual rods. Two types of seals were analyzed, a polyurethane U-cup seal and a step seal with a PTFE sealing element. Figure 1 shows the computed fluid transport during the outstroke and instroke, and the friction force, for the U-cup seal.

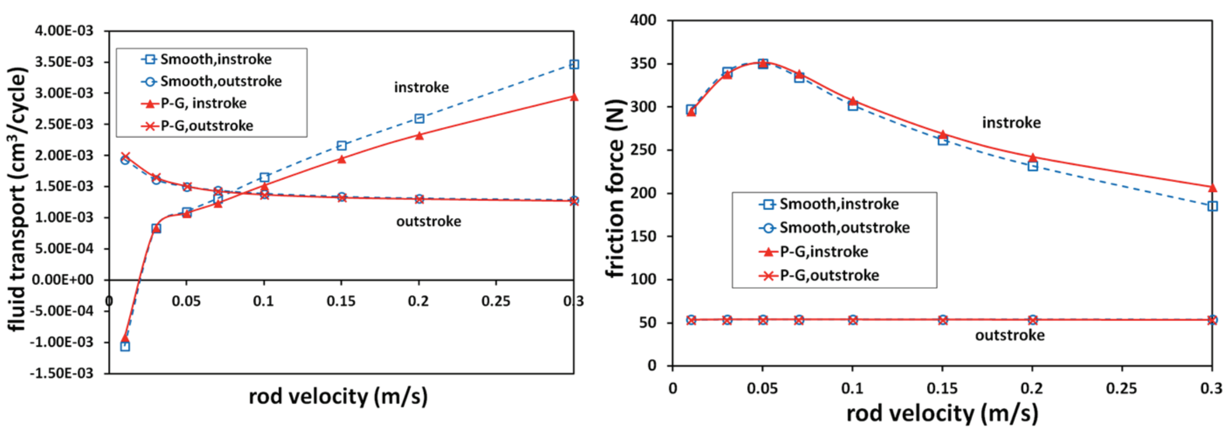

Figure 1: Computed fluid transport (left) and friction force (right) for U-cup seal during instroke and outstroke

Over most of the velocity range, the fluid transport into the cylinder (during the instroke) with the plunge-ground rod is lower than that with a smooth rod, indicating that such a surface finish reduces the ability of the seal to prevent leakage, including that due to imperfections in the lip, non-axisymmetry, and other effects not accounted for in the model. Furthermore, during the instroke the friction force on the rod is higher for the plunge-ground rod than for the smooth rod.

For the step seal, it was found that the plunge ground rod yielded the same performance as the smooth rod, in regard to both fluid transport and friction force. The reason for this difference in behavior compared to the U-cup seal has been determined to be due to the difference in seal roughness: the polyurethane U-cup seal has an rms roughness of 0.8 microns while the PTFE step seal has an rms roughness of 4.0 microns. Simulation of a hypothetical step seal with a 0.8 micron roughness showed the same type of behavior as the U-cup seal, with the surface finish significantly affecting the outstroke fluid transport and the friction force. Simulation of a hypothetical U-cup seal with a 4.0 micron roughness showed the same type of behavior as the step seal, with the surface finish having no significant effect on the fluid transport and the friction force.

It was also found that the plunge-ground rod finish increases the friction force on the rod over most of the velocity range with the U-cup seal (Figure 1), but not with the step seal. However, with both types of seal the plunge-ground finish produces large oscillations in the contact pressure, which are expected to increase the rate of fatigue induced wear.

During the present reporting period work has also begun on the next phase of this project, reduction of the seal friction force, described in the next section on Planned Progress.

The research generated by this project has been published in 9 archival journal papers [11]-[19] (1 additional submitted [20]), presented in 2 plenary and 1 keynote lecture [21]-[23], 2 invited papers [24], [25], 24 additional conference presentations [10], [26]-[48] and 5 seminars [49]-[53].

Planned Progress

During the next two years the major effort will be directed toward determining, through simulation, optimum engineered micro- patterned rod surfaces to reduce seal friction while maintaining zero net leakage. The simulation work done on this project has shown that extremely large friction forces are exerted by the rod seal on the rod, in agreement with experimental measurements by a seal manufacturer (Trelleborg). For a 50 mm (1.97 inch) diameter rod, these forces are in the range of 1000-1500 N (225-337 lbf). For energy conservation and control purposes, there is therefore an obvious need to reduce this friction while still maintaining the sealing effectiveness.

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

In the present project such engineered micro- patterns on the rod surface will be studied for the purpose of reducing rod seal friction, while maintaining seal effectiveness. However, the situation with hydraulic seals is quite different from the machine elements mentioned above, since the seal is compliant and will tend to deform to follow the shape of the mating surface. To account for the two-dimensionality of the micropatterns, a two-dimensional Reynolds equation solver will be constructed. This will involve, as in the past, using the finite volume discretization technique. The two-dimensional discretized equations will be solved with the ADI (alternating direction, implicit) technique on a solution space spanning the seal width, but extending only over a circumferential segment. Periodic boundary conditions can then be applied, allowing the use of the TDMA (tri-diagonal matrix algorithm) and cyclic TDMA algorithms.

Due to the two-dimensionality of the surface features, a three-dimensional finite element computation is required to determine the deformation of the surface. This would normally introduce prohibitively large computation times into the iterative computations. However, a unique approach has been developed (during the present reporting period) to reduce those computation times.

The simulations will predict leakage and friction, as well as the detailed behavior in the sealing zone, as in the past. The particular geometries to be investigated will be chosen during the course of the study. Initial work is proceeding with micro-triangles. Consultation and collaboration with Project 1D: Micro - Texturing for Low Friction Fluid Power Systems will occur during this and later stages of the project.

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Project 3D2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems

Research Team
Project Leader: Scott Bair, School of Mechanical Engineering, Georgia Tech
Industrial Partners: John Deere, Shell, Lubrizol

1. Statement of Project Goals

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

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

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

2. Project Role in Support of Strategic Plan

Compactness

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

Greatly improved understanding of the role of degradation [1,2] and shear-dependent viscosity [3-7] in the forming of EHL films and predictions of film thickness [5-7] have resulted from this program. We have begun an understanding of transient film behavior [8,9].

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

Efficiency

Surprisingly, there has been little progress within EHL over the last forty years in explaining the mechanism of mechanical dissipation in full EHL films. In very recent related work [10-12] using the temperature/pressure correlation devised by this project, the first experimentally validated EHL friction calculation was performed which included thermal-softening and shear-thinning. Fragility has been shown to be the principal property controlling friction. In particular, the results of this project may be used to rank the mechanical energy loss of contacts lubricated by fragile hydraulic oils. A visiting Fulbright Scholar, Wassim Habchi, worked on this project last summer to find the relationships between friction and the dimensionless groups such as the Nahme number and Weissenburg number [11].

The advances listed above were possible due to new correlations of the dynamic properties of oils developed under this project [13-16].

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 [4-6]. Both film thickness and friction may now be predicted [12], for high speeds and loads, from primary properties rather than from fictitious properties adjusted to fit analysis to measurements of film thickness or friction. 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 [17].

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

The present time is propitious for the EHL field to embrace a quantitative description of the temperature and pressure dependence of viscosity since there has been, over the last decade, an interest by the physics community in the pressure evolution of the dynamic properties of the supercooled liquids such as lubricants. Fragility, a property strongly affecting EHL friction [12] and transient EHL film response [8] is now being intensely studied in other laboratories. 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.

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

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

B. Achievements

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

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

1. Kumar, P., Khonsari, M.M. and Bair, S., “Full EHL Simulations Using the Actual Ree-Eyring Model for Shear Thinning Lubricants”, J. Tribol., 2009, Vol. 131, Issue 1, 011802, 6 pages.
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Progress during the last twelve months can be classified into three areas: liquid property correlations, film thickness and friction.

An old correlation of viscosity with temperature and pressure has been improved by introducing a more realistic relation for the pressure dependence of free volume expansivity [18]. A comprehensive correlation [16] based on the Ashurst-Hoover scaling has bridged the gap between the two types of free-volume realtions, Batchinsky and Doolittle, with a single equation in terms of the scaling parameter. In the figure below, the viscosities of five very different liquids are represented with only three material specific parameters over a wide range of temperature and pressure to 1.2 GPa.

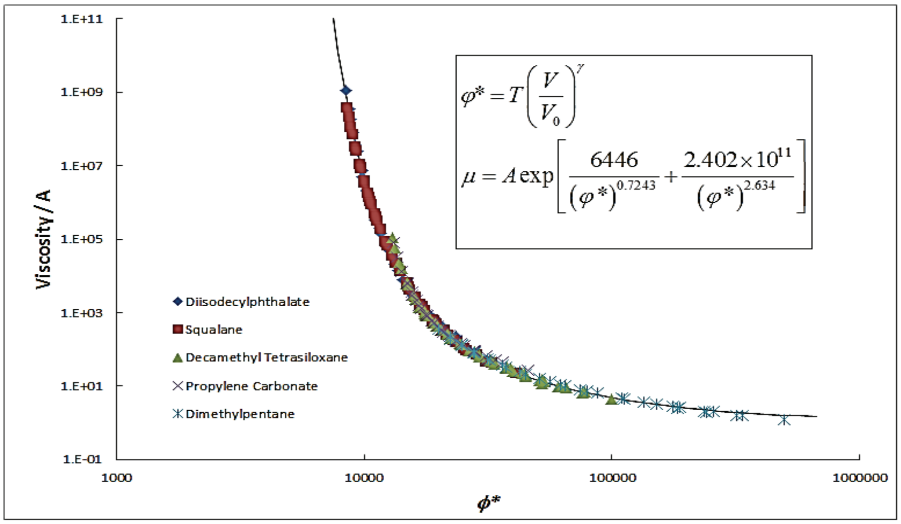

Figure 1: Viscosity correlation

The understanding of the effects of non-Newtonian response on film thickness has been advanced by adding a predictive capability for the film thickness of polymer solutions [7] which are a class of hydraulic oil. Mechanical degradation reduces the viscosity of hydraulic oils and new work explains the surprising effect on film thickness [2] using the new predictive capability. The figure below shows the standard Newtonian prediction for film thickness along with measurements. Although the new and used oils have very different viscosities, the film thickness as predicted, was not altered by degradation.

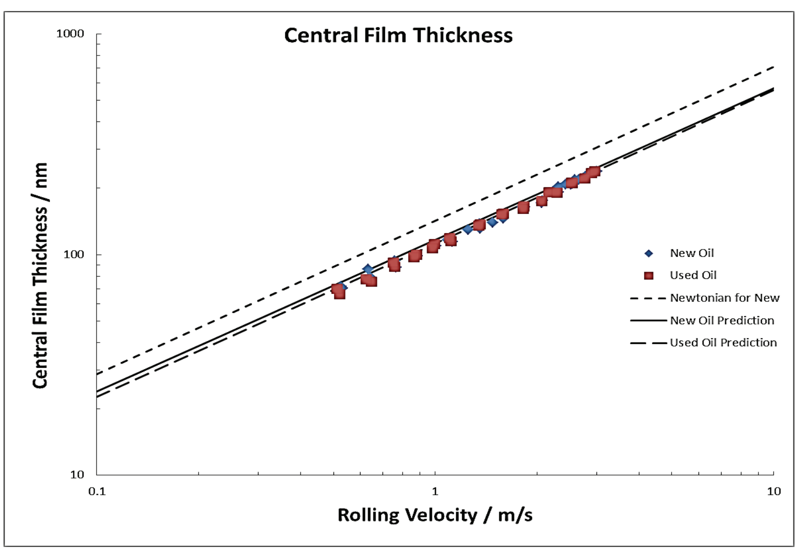

Figure 2: Central film thickness as a function of rolling velocity

For the first time, full-film friction has been accurately predicted from the properties of the liquid before the friction has been measured [12]. The most challenging problem for EHL has been prediction of friction in full-film lubrication. If the mechanism had been understood, friction could have been related to the properties of the liquid decades ago. A major step has been taken by characterizing the individual friction regimes in terms of dimensionless numbers, the Weissenberg number, Wi, the Nahme-Griffith number, Na, the limiting stress number, Li, and a new number which is a combination of the first three [11]. In the figure below the decreasing friction with increased sliding begins when $Ti = Na \times Wi/Li > 100$.

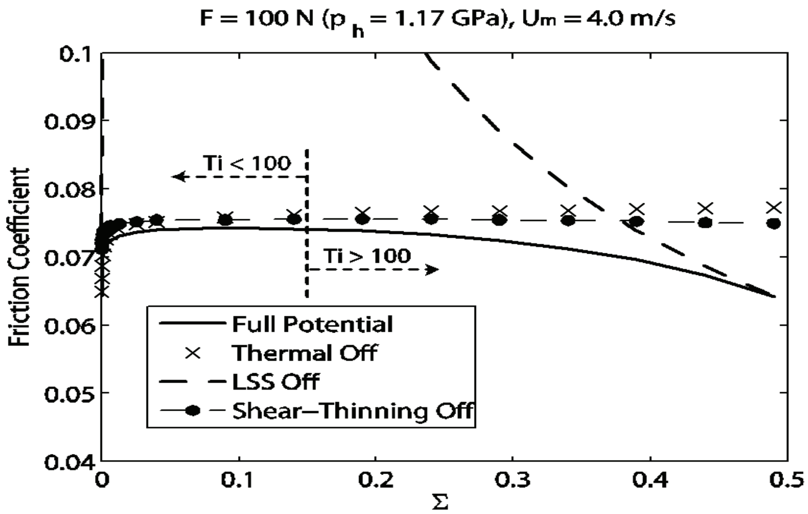

Figure 3: Friction coefficient prediction

The high productivity of this program has been partly due to collaborations but also due to the unstructured plan. Each new discovery has opened the possibility of new opportunities. The same approach will be employed in future work. For examples, work this year has emphasized the need for an improved equation of state for liquids at EHL pressure levels and for thermal properties, especially conductivity. Next year, the experimental capability for compressibility measurement will be extended from 400 MPa to at least 600 MPa. A new thermal conductivity cell will be designed for 700 MPa.

C. Member company benefits

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

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Project 3E.1: Pressure Ripple Energy Harvester

Research Team

Project Leader: Kenneth A. Cunefare, Woodruff School of Mechanical Engineering
Graduate Student: Ellen Skow
Undergraduate Students: Nalin Verma, Aaron Kranc, Zachary Koontz, Brian Hults, Karthika Poonammalla Venkatasubramanian
Industrial Partner: Eaton Corporation

1. Statement of Project Goals

The goal of this project is to model, develop and prototype energy harvester devices capable of producing useful power from pressure ripple in high-pressure hydraulic systems. The application of the devices is for powering sensor nodes within a fluid hydraulic system, as may be used for health monitoring or data acquisition applications. Initial prototype devices will be integrable into Test Bed 1 by Summer 2013; prototypes sized for sensor-node power requirements will be available by Spring 2014. An initial power response model will be available by Summer 2013; a refined model will be a major final deliverable in Summer 2014.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

In a hydraulic system, an energy harvesting technology might be integrated with health-monitoring sensors and eliminate the need for batteries or wires providing power to individual sensors; this would reduce maintenance contact and eliminate potential points of failure. Distributed sensors are common in hydraulic systems, and health-monitoring systems are being deployed within the hydraulics industry, such that there are immediate applications for the technology. Whereas the commonly explored “energy harvester” technologies developed to date have been applied to energy sources of relatively low energy density [1-4], the pressure ripple in an hydraulic system represents a relatively high energy density source by comparison. Indeed, the energy density is so high that material and system nonlinearities, not encountered in energy harvester applications considered heretofore, will come into play.

A fundamental challenge of harvesting energy from typical acoustic noise is the very low energy density that is typically available; note that pressure ripple is just an industry-specific term to describe fluid-borne acoustic noise. For example, in air, a 60 dB plane wave has an intensity of approximately 1 $\mu W/m^2$, the intensity for a 100 dB plane wave is 10 mW/m^2, and the intensity of a 140 dB plane wave is approximately 100 W/m^2. These sound fields correspond to a conversational level, an uncomfortable loud level which would cause hearing damage from continuous exposure (and a temporary shift in hearing threshold for shorter exposures) and a level beyond the threshold of pain. If one seeks to harvest energy from a typical low level acoustic signal in the environment, either one must have a large device, or a means of achieving an efficient focusing of the available energy, or have a need for only very low power levels (microwatt or less). In pumped fluids, however, the situation is significantly different, as the use of positive displacement pumps can lead to high intensities within fluid systems [5], with intensities on the order of kW/m^2 being possible.

While there are numerous publications on energy harvesting from low density sources such as thermal, vibration, wind turbulence, flow turbulence, we have found no citations to work that directly exploits the pressure ripple directly as we consider here. There has been some work on energy harvesting from air borne noise by various means, but the low energy density of such fields has led to the use of techniques and devices that would not be appropriate in a pressurized hydraulic system.

Taylor et al. [6] developed an electromechanical acoustic energy harvester based on a Helmholtz Resonator as a means for increasing the pressure amplitude from an acoustic field. This development, as well as those of Liu et al. [7] and Phipps et al. [8] considered the electromechanical Helmholtz Resonator energy harvester for use as an element within a self-powered active control method for noise within the nacelle of a jet aircraft engine. One wall of the Helmholtz Resonator was a circular piezoceramic plate, such that the pressure response of the resonator would drive the piezoceramic and thereby permit electrical energy extraction. Phipps asserted that the sound field within engine nacelles could approach 160 dB, an intense airborne field. In a related development of the concept, Horowitz et al. [9] considered a MEMS; it must be pointed out that the energy harvesting results reported did not include a resonator. A key point to make about this approach, though, is that the power output of a Helmholtz Resonator-based energy harvester is still limited by the incident intensity of the acoustic wave field; a Helmholtz Resonator acts as a concentrator and effectively increases the “size” of the device, but it can’t extract more energy than is actually present.

Addressing the low intensity of typical airborne acoustic wavefields, Wu et al. [10] used a periodic array of rods to create a “sonic crystal” to focus incident sound into a cavity within the sonic crystal. They placed a PVDF membrane inside the cavity and were able to generate a peak output of approximately 35 nano-watts from a 7 Pa pressure difference across the membrane (it is unclear if this is the acoustic pressure, if so, it corresponds to a 111 dB sound field in the cavity; the incident sound field on the sonic crystal was not specified).

Lallert et al. [11] considered a means to increase the energy harvesting efficiency from an acoustic source through a nonlinear harvesting circuit. The device used a circular PZT disk on a baffled flexible metallic membrane exposed to an incident wave field. The device generated up to 55 μW for excitation at resonance with an imposed 100 dB sound pressure level. The surface area of the membrane was 78.54 cm^2, such that the surface power density of the device was 0.7 $\mu W/cm^2$.

A related class of work uses an acoustic response as an intermediate energy conversion process. For example, Kim et al. [12] developed on energy harvester using a Helmholtz resonator excited by a mean flow with electromagnetic transduction. Stevens implanted a thermoacoustic engine driven by the temperature difference between ambient air and ground; electrical conversion was handled using the thermoelectric effect. Hernandez et al. [13] used flow instability to excite a tonal response of a pipe; a piezoelectric element was used for electrical energy production.

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

B. Achievements

Since project inception in June, 2012, significant progress has been made in device modeling as well as device prototyping; the project is ahead of schedule. The devices developed here are termed Hydraulic Pressure Energy Harvesters (HPEH). Figure 1 depicts the key elements of an HPEH mounted on a fluid hydraulic system. The housing of the HPEH retains a multilayer piezoelectric stack, and has a connection to the fluid system. The stack is exposed to pressure forces in the fluid system through an interface that serves to isolate the stack from the fluid, while permitting pressure forces to be coupled into the stack. The stack has a cross-sectional area A_{stack} while the interface has area $A_{interface}$; these areas need not be equal, and indeed, if $A_{interface}>A_{stack}$, greater force would be coupled into the stack than if the stack alone was exposed to the system pressure. The effective area of the HPEH may be represented as $A_{eff}=\gamma A_{stack}$, where γ is typically greater than unity.

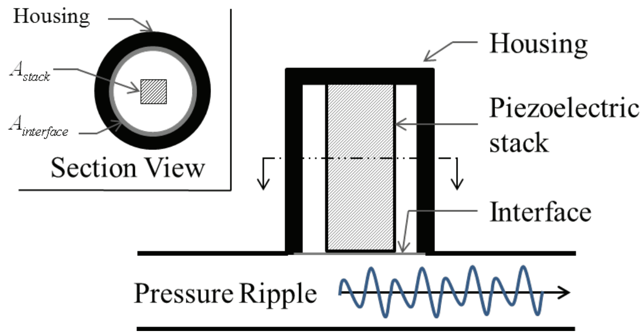

Figure 1: Simplified schematic of hydraulic pressure energy harvester, where the interface implements fluid-mechanical coupling between the piezoelectric stack and pressure ripple in a pressurized fluid with pressure ripple present.

Modeling

A model has been developed that enables performance prediction of HPEH designs. Consider an HPEH using a multi-layer stack as its active element, terminated with a resistive load as depicted in Figure 2a (more sophisticated energy harvesting circuits are available in the literature, but are not within the scope of this project). An electrical equivalent model is depicted in Figure 2b, where the stack is represented as a current source in parallel with a capacitance. Each layer within the stack has a piezoelectric d_{33}^i coefficient assumed to be the same for each layer, and capacitance C_p^i also assumed to be the same for each layer. If the stack has *N* active layers in parallel, all subjected to the same force *F*, then the effective d_{33} and capacitance of the entire stack may be expressed as

$$d_{33}^{eff} = Nd_{33}^i \text{ and } C_p^{eff} = NC_p^i.$$

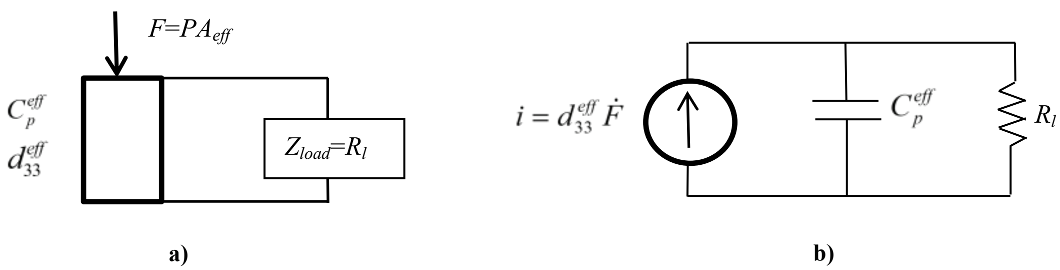

Figure 2: a) Multi-layer stack terminated with a resistive load impedance and subject to an applied pressure force, b) Equivalent electrical circuit with the stack modeled as a current source in parallel with a capacitance.

Assuming bulk values for the capacitance and d_{33} then leads to

$$C_p^i = \frac{\varepsilon_{33}^T A_{stack}}{h} \tag{1}$$

where *A* is the cross-sectional area of each layer, and *h* is the thickness of each layer. Consideration of the voltage response of the system leads to a predictive model for the power output of the device as

$$\Pi = \left|\frac{V_0^2}{R_l}\right| = \frac{R_l}{1+\left(\omega R_l C_p^{eff}\right)^2}\left(\omega d_{33}^{eff} F_0\right)^2. \tag{2}$$

The maximum power output is obtained for the load resistance that maximizes Eq. (2), which is found by

$$R_l^{opt} = \frac{1}{\omega C_p^{eff}}. \tag{3}$$

such that the maximum power output into a resistive load is then

$$\Pi_{\max} = \frac{\omega N h d_{33}^2 F_0^2}{2\varepsilon_{33}^T A_{stack}}. \tag{4}$$

With the applied force amplitude equal to the applied pressure times the effective area then

$$\Pi_{\max} = \frac{\omega N h d_{33}^2 \left(P_0 A_{eff}\right)^2}{2\varepsilon_{33}^T A_{stack}} = \frac{\omega \mathbf{V} d_{33}^2 \gamma^2 P_0^2}{2\varepsilon_{33}^T}, \tag{5}$$

where $\mathbf{V}$ is the volume of the active layers of the stack. Equation (5) enables design modeling of HPEH devices.

Prototypes

Three generations of HPEH prototypes, depicted in *Figure 3* have been developed. The devices were designed to withstand a static pressure of 34.5 MPa (5000 psi). All of the devices were designed and fabricated by REU students.

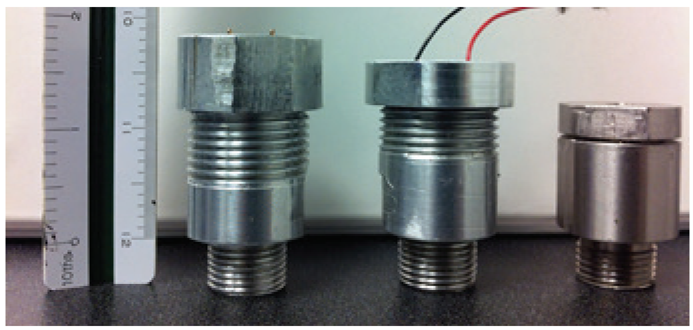

Figure 3. HPEH prototypes with threaded connector for attachment to fluid hydraulic system; successive generations, left to right, designed for smaller piezoelectric element and more compact package.

Results

Testing of the HPEH prototype devices was performed on hydraulic flow rig, schematically depicted in ***Figure 4***a, that employed a nine-piston pump operating at 1500 rpm, yielding a fundamental pressure ripple frequency of 225 Hz. The needle valve in the rig was used for setting the static pressure. The HPEH was installed on a mounting block within the rig; the mounting block permitted exposure of the HPEH to the pressure fluctuations within the hydraulic fluid, and included a dynamic pressure sensor enabling calibrated measurements of the pressure fluctuations. The data acquisition system is schematically represented in ***Figure 4***b, where the decade resistance box was used to set and vary the resistive load impedance applied to the HPEH.

Example time traces of the dynamic pressure in the mounting block and the corresponding voltage produced by the HPEH are presented in Figure 5. The voltage produced is closely matched to the pressure waveform, indicating effective coupling to the pressure input as well as effective energy conversion. The spectral content of the input pressure and the response voltage is depicted in ***Figure 6***. The bulk of the acoustic energy in the pressure ripple for this example application is in the second harmonic of the pump passing frequency, at 450 Hz.

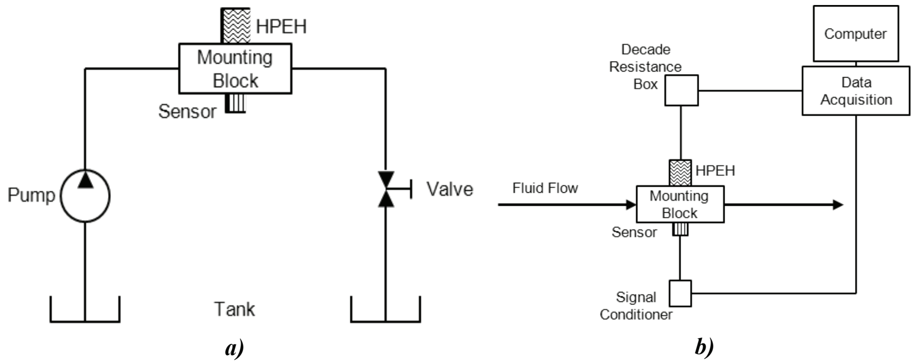

Figure 4. Testing configuration for HPEH devices, including the sensor and the data acquisition system.

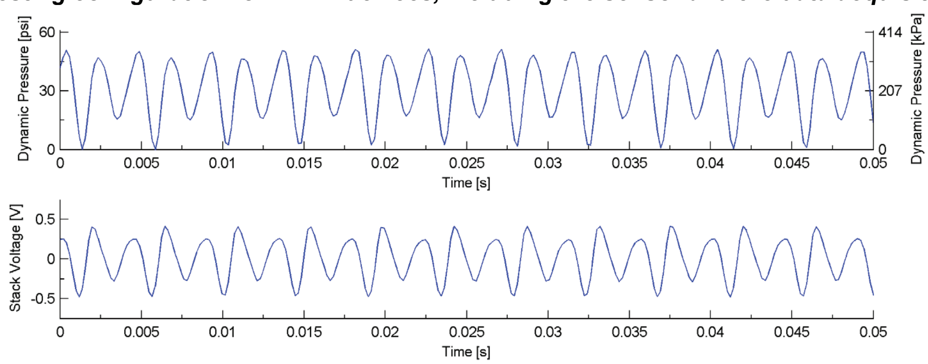

Figure 5. Dynamic pressure and stack voltage at static pressure 3.45 MPA (500 psi), load resistance 120Ω.

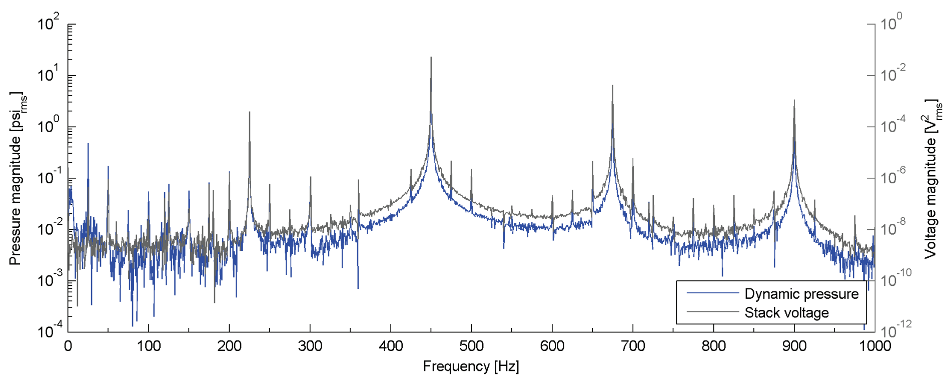

Figure 6. Spectrum of measured pressure and HPEH response voltage at same conditions as Figure 5

The measured and modeled power produced by the HPEH for a range of load resistances at static pressure setpoints of 2.07 and 3.45 MPa (300 and 500 psi) on the test rig is depicted in ***Figure 7***. Note that the static pressure is not significant for the power conversion operation of the HPEH, rather, the pump produces different magnitude of pressure ripple at different static pressure setpoints. The data in Figure 7 reflects consideration of the total actual pressure in the pressure input, as well as just the pressure at 450 Hz where the bulk of the acoustic energy is present. However, the relatively flat response implies a relative insensitivity to error in setting the load resistance for maximum power. Also of significance in ***Figure 7*** is that the power produced by the HPEH at the 3.45 MPa (500 psi) setpoint exceeds 1 mW; this is well above the power requirement reflected in the literature for wireless sensing nodes. And, the 3.45 MPa setpoint is low for hydraulic systems, which commonly operate in the 20 to 35 MPa range and higher, and would have correspondingly greater pressure ripple.

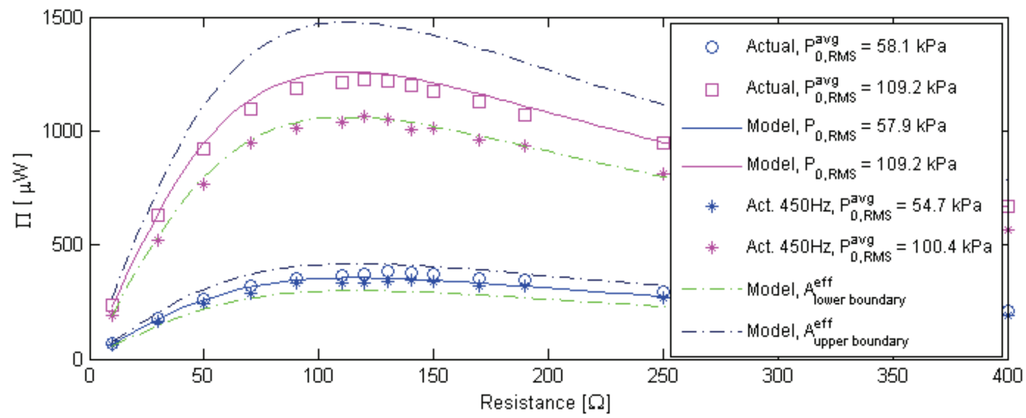

Figure 7. Comparison of the total power generated and the power generated at the peak harmonic of 450 Hz at static pressures of 2.07 MPa and 3.45 MPa; the 2.07 MPa setpoint yielded an average p_{rms} of 58.1 kPa, while the 3.45 MPa setpoint yielded an average p_{rms} of 109.2 kPa.

In light of the above achievements in terms of modeling and prototyping, this project is well ahead of schedule as of this writing.

C. Member company benefits

This project is yielding very positive results that are strongly rooted in practical application and the development of new technology. Beyond the immediate application to health monitoring systems, the technology is enabling of self-powered sensors at almost any type conceivable; it also enable self-powering of low-powered control valves, solenoids, etc. This concept has the potential for broad application far beyond its original inspiration.

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Test Bed 1: Heavy Mobile Equipment (High-Efficiency Compact Excavator)

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1. Statement of Test Bed Goals

The compact excavator test bed has been a demonstrator of throttle-less hydraulic actuation technology since the inception of the Center through spring 2012. This technology, called displacement control (DC) or pump-controlled actuation (PCA), promises fuel savings for multi-actuator machines used widely in the construction, agriculture and forestry industries. Following predictions based on system simulations, significant fuel savings have been demonstrated on the test bed over the standard excavator system.

Beginning February 2012, the test bed has been transitioning to a demonstrator of a novel hydraulic hybrid configuration, called series-parallel hybrid DC system, for which a patent was applied in 2011. The series-hybrid architecture will introduce secondary controlled actuation for the swing drive in combination with the implementation of an energy storage system in parallel to the other DC actuators for the remaining working functions. Such architecture enables energy recovery from all actuators, capture of swing braking energy and 50% engine downsizing. It promises fuel savings beyond those achieved with the prototype non-hybrid DC excavator, as was previously shown through simulation studies in project 1A2 ('Multi-Actuator Hydraulic Hybrid Machine Systems'), which concluded in June, 2012.

The goals for the project are 50% fuel savings over current state-of-the-art excavator systems, meeting current exhaust emission standards and no degradation in machine performance.

2. Test Bed Role in Support of Strategic Plan

The compact excavator test bed primarily addresses the efficiency thrust of the Center. The prime role of the test bed is to be a demonstrator of energy savings that are possible in multi-actuator machines, through efficient system architectures (utilizing throttle-less actuation, enabling energy recovery and storage) and through advanced power management strategies.

These concepts were investigated in project 1A.2 from 2006-2012 and the test bed draws upon theoretical results achieved to meet these goals. The test bed has also been used for demonstration of a novel human-machine interface as part of project 3A.1. It is well positioned for testing of energy-efficient fluids researched from Project 1G.1 and for evaluation of high efficiency, virtually variable displacement pump/motors from projects 1E2 and 1E3. With the transition of the test bed to a series parallel hybrid DC system, it will also open the door for testing new accumulator technologies researched within the Center (e.g. the advanced strain accumulator, Project 2C.2).

The successful demonstration of DC will open new applications in both large scale mobile machinery and robots, and in human-scale applications like surgery robots or other portable devices where efficient and compact actuator technology is necessary.

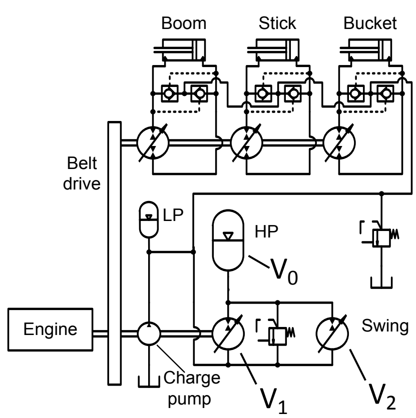
3. Project/Test Bed Description

A. Description and explanation of research approach

The state-of-the-art in hydraulic drive and actuation technology involves the use of different forms of resistance control through the use of valves. Most mobile applications use load-sensing (LS), negative flow control (NFC), positive flow control (PFC) or similar architectures. In those systems one or two hydraulically controlled variable displacement pumps provide flow to all actuators by adjusting the system pressure to the highest required pressure of all actuators. Control valves throttle flow from the operating pressure to the desired actuator pressure and meter flow in accordance with respective operator inputs. This leads to large throttling losses across the control valves supplying all actuators except the actuator operating at maximum pressure (in a typical cycle, only one or two actuators operate at high pressures, with the others at low or medium pressures). Further, energy from braking or lowering of actuators is either recovered very inefficiently or not at all, through these architectures.

Displacement controlled (DC) actuation is a very efficient throttle-less actuation with simultaneous utilization of energy recovery without energy storage. The basic circuit for linear single rod cylinders was introduced in 1998 [1]. One variable displacement pump/motor is used per working actuator in a closed-circuit and throttling valves are entirely eliminated. The only control element is the pump displacement and the unit automatically moves over-center to allow energy recovery. The challenge is to demonstrate that pump control can compete with the performance of valve controlled systems with respect to bandwidth and accuracy. Another challenge is to define the maximum number of pumps required in multi-actuator machines by introducing pump switching architectures and new control concepts. This complete new hydraulic actuation technology has been demonstrated on a wheel loader where measurements showed 20% higher fuel efficiency [2]. As a first result of the CCEFP research, a four pump DC system with multiple switching valves was implemented for the eight actuator mini-excavator test bed. 40% fuel savings have been demonstrated through independent, side-by-side testing at a Caterpillar facility over the standard machine in August 2010. The technology offers several new energy efficient features to be introduced to mobile machines. In an associated project, energy efficient active vibration damping of the boom and machine cabin was demonstrated on a skid-steer loader [3]. Competing throttle-less actuation technologies are open-circuit DC actuation [4] and hydraulic transformers [5]. Open-circuit DC actuation is a feasible alternative. However, it involves the use of several logic valves per actuator and accompanying control laws. The INNAS Hydraulic Transformer (IHT) concept is not yet a proven technology that has been demonstrated on mobile multi-actuator machines.

In the hybrid DC version (Fig. 1) of the test bed (Feb 2012 onward), braking energy of the swing is captured in a hydraulic accumulator, by using a secondary-controlled, over-center, variable displacement motor for the swing drive, as opposed to a fixed displacement motor that was previously in use. The energy stored in the accumulator may be re-used either for reducing the load on the engine or for powering the swing at a later stage. The proposed system architecture does not require any additional units compared to the DC non-hybrid prototype, and energy from the boom, stick and bucket can be recovered through the DC circuits.



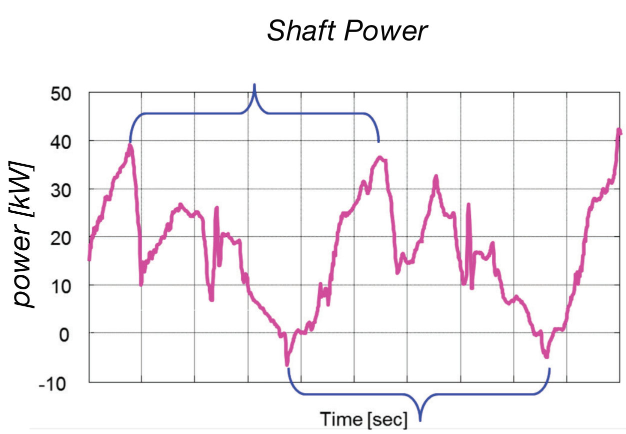


Figure 1: Series-Parallel Hybrid DC Excavator

Figure 2: Excavator Truck-Loading Cycle Power Requirement

The typical cyclical operation of these machines, together with added energy storage capability, leads to the idea that engine downsizing is possible with appropriate power management. Peak power requirements would be met by assistance from the accumulator. On the test bed, the engine will not be downsized, however through the use of appropriate power management, engine load will be limited to 50% of peak power in order to demonstrate the feasibility of the concept in a functioning machine.

Caterpillar will soon be releasing (April 2013) the hydraulic hybrid version of a 37 ton excavator (336E H) and next year will announce the release of a hydraulic hybrid loader. The 336E H uses a parallel hybrid architecture, wherein an extra pump/motor is added to the engine shaft, in parallel to the pumps supplying the working actuators. The additional pump is responsible for charging and discharging the accumulator. Caterpillar has claimed 25% fuel savings over the 336E, and although details are not yet available, it is claimed that swing braking energy is captured. However, the addition of another pump in the Caterpillar system will introduce additional power losses to the system. This is not the case in the in CCEFP proposed new series-parallel hybrid DC architecture. Also, due to the fact that all remaining functions are still valve-controlled, it is not possible or very unlikely that energy can be recovered from other working functions like boom, arm or bucket in the 336E-H Caterpillar machine.

B. Achievements

Achievements Prior to Reporting Period

- Four variable displacement pumps were installed on TB1 (compact excavator) along with associated sensors and electronic control hardware. From 2008-2011, all 8 functions (swing, boom, stick, bucket, track drives, boom offset, and blade) were displacement controlled.
- Control laws for pump displacement, actuator position and actuator velocity control were designed and implemented on TB1.
- The DC hydraulic system 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.
- Simulation and measurement results determined that at least 50% of the cooling power requirement in the system could be reduced
- Productivity and fuel test for TB1 with DC hydraulics was conducted in cooperation with Caterpillar, Inc.; TB1 consumed 40% less fuel, on average, than the standard machine while moving the same amount of dirt and productivity was increased by 16.6%, which lead to a fuel efficiency (tons/kg) improvement of 69%.
- A proposed optimal power management algorithm from Project 1A2 was evaluated and fuel efficiency results indicated a 56.4% improvement for an artificial pipe-laying cycle, without power management.
- In April 2011, the prototype DC excavator was evaluated for fine actuator control to the satisfaction of a team of Bobcat expert operators, test and system engineers in Bismarck, ND.
- Through project 1A2, a feasibility study predicted that the novel series-parallel hybrid system could be limited to half of the maximum engine power, suggesting that the engine size could be reduced without sacrificing the productivity of the machine for the truck loading cycle.
- With a very conservative power management strategy demonstrated that this hybrid configuration together with downsized engine, can achieve 52% fuel savings compared to the standard machine (> 20% over the prototype DC excavator) [6]. Optimal power management promises around 27% fuel savings over the non-hybrid DC excavator [7].
- Optimal sizing studies using dynamic programming were undertaken that evaluated various possible unit (primary and secondary units) and accumulator sizes and pre-charge pressures, independent of system control strategy [8]. Component sizing on the prototype hybrid DC excavator uses the results of the optimal sizing study.

Achievements During Reporting Period

Optimal Sizing of Series-Parallel Hybrid DC Architecture

The initial reported results of the series-parallel hybrid DC excavator system showed 20% fuel savings over the DC system and the potential for 50% engine downsizing in a simulation using a conservative static sizing methodology as well as a conservative power management strategy [6]. Within the reporting period, an optimal sizing study was undertaken [8] that evaluated various possible primary and secondary units and accumulator sizes, as well as pre-charge pressures, independent of system control strategy.

Component sizing on the prototype hybrid DC excavator was made using results from the sizing study – with closest available components being used to the optimal sizes (Table 1).

Table 1: Actual Component Sizes Used on Hybrid DC Prototype Excavator

$V_{d,1}$	$V_{d,2}$	$p_{hp,min}$	V_0
18 cc/rev	40 cc/rev	250 bar	6 L

System Integration

The detailed circuit currently implemented for the swing drive on the test bed, is shown in Fig. 3.

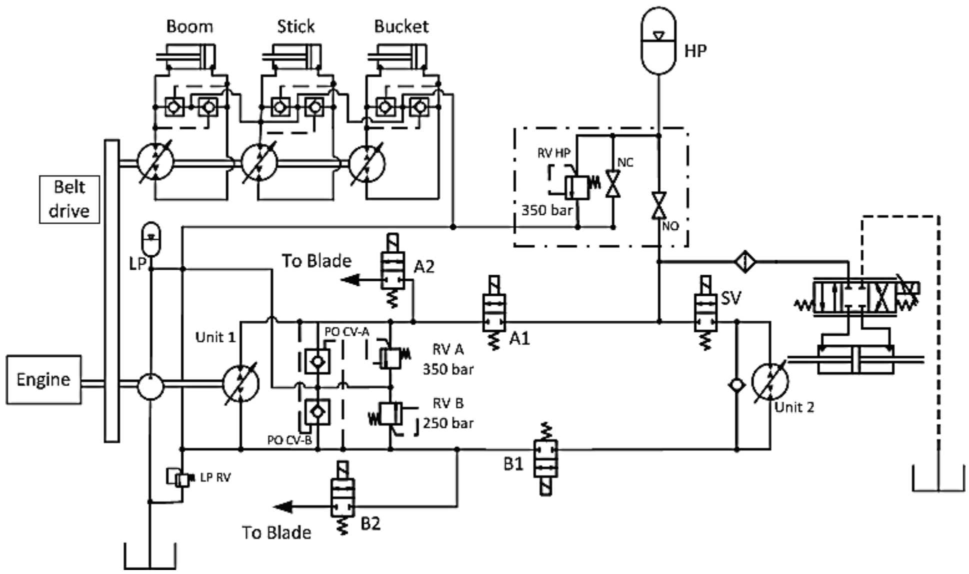


Figure 3: Detailed Schematic for Swing Drive on Prototype Excavator

The fixed displacement swing motor (820 cc) previously used on the DC non-hybrid prototype, has been replaced with a secondary-controlled, variable, over-center swing motor (40 cc, bi-directional, 'unit 2' in Fig. 3). Unit 2 is secondary-controlled and is part of a series-hybrid configuration together with unit 1 (unchanged 18.3 cc variable pump/motor from the non-hybrid version of the test bed, which was used as pump to drive swing on DC, non-hybrid test bed).

A 2-stage planetary gear-box (ratio 19.46) used on the latest M-series of Bobcat excavators (which use 31 cc fixed displacement swing motor) has also been incorporated on the test bed. It provides a higher gear reduction (i_g = 147.2) between unit 2 and cab (previously i_g = 5.35), thus allowing unit 2 to run at higher speeds (up to 1350 rpm), with cab speeds as before (up to 9.5 rpm).

Unit 2 is operated in a speed controlled manner, with the operator joystick command being interpreted as a speed command for the swing motor. The requisite sensors for speed and swash-plate position sensing have been instrumented on the test bed. A position sensor has also been added for closed-loop position control to hold the cab at rest against unexpected loads (gravity, side-loads during digging or from tracks).

Logic valves A1, B1 are opened (while A2 and B2 are simultaneously closed) provide flow from unit 1 to swing circuit. In the opposite configuration, with A2 and B2 open (with A1 and B1 closed) unit 1 provides flow for actuating the blade. A safety-valve 'SV' is used to shut-off unit 2 from the high pressure accumulator during loss of power. Swash-plate adjustment for unit 2 is done using high pressure from the accumulator. A safety block between the accumulator and both units houses a high pressure relief valve ('RV HP', 350 bar), a bleed valve 'NC' to empty the accumulator after operation, and an enabling valve 'NO' that is kept open during operation.

Results from Preliminary Testing
The hybrid hydraulic DC system is now operational on the test bed. The linear working actuators (boom, stick and bucket) are functional as before, while the secondary-controlled swing motor is now showing desired behavior (Fig. 4(a) and 4(b)).
In preliminary testing, the speed command is followed reasonably well by unit 2 (Fig. 4 (a)), while unit 1 is currently controlled so as to maintain a high pressure (200 bar) in the accumulator. It can be seen from Fig. 4(b) that unit 2 moves over-center during braking of the swing motor. There are still certain issues that need to be addressed such as the over-shoot in speed and the lag in response during start-up.

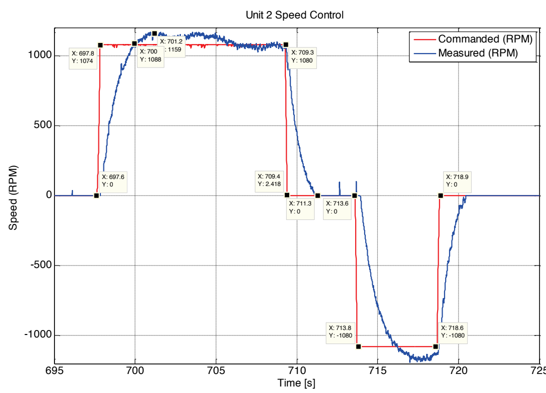


Fig. 4(a): Speed Control of Unit 2

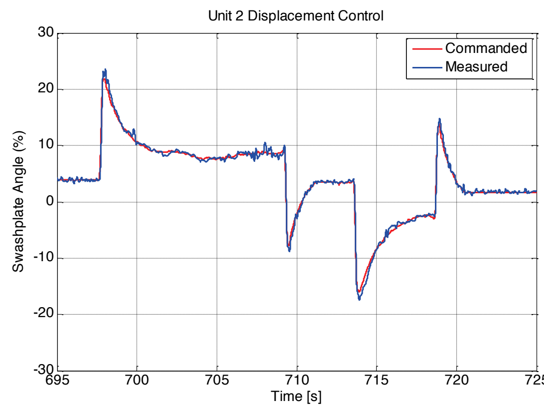


Fig. 4(b): Displacement Control of Unit 2

Significant progress has been achieved on the excavator in the past three months, and testing will resume from March, 2013 to meet the planned achievements on the test bed.

Planned Achievements following the reporting period
Deliverables driven by results from Project 1A2

- Further improvements to the speed control of the swing motor will be made. [03/15/2013]
- Simulations will be performed that will predict the fuel and energy consumption of hybrid DC excavator for a typical digging cycle, with the full-sized engine. [03/15/2013]
- The excavator will be operated in a typical excavator loading cycle, for demonstration purposes. [04/10/2013]
- ‘Single-point’ power management strategy [6] will be implemented on the test bed during the expert truck-loading cycle. [06/01/2013]
- Fuel testing and measurements will be done on the test bed, after sufficient development of energy-saving control, for an expert truck-loading cycle. [06/15/2013]
- Advanced power management strategies [9, 10] that exploit all possible degrees of freedom available on the system, including variation of engine speed. [09/15/2013]
- Incorporation of pump-switching architectures and control strategies that would enable maximum number of combinations of actuators to be used with the minimum number of pumps in DC hybrid machines (from new project 1A2). [10/01/2014]
- Incorporation of system prognostics schemes. [06/01/2015]

Deliverables for results related to associated projects

- Integration of high speed valves from project 1E2 to create a virtual variable displacement pump for low pressure system and measurements or resulting energy savings [03/01/2014]
- Comparison of energy consumption of the test bed using standard hydraulic oil and energy efficient fluids developed in project 1G1 [06/01/2014]
- Integration of next generation of efficient pumps from project 1B1 for control of a single actuator [2016]

C. Member company benefits

The results gained from TB1 are directly transferable to industry and have already offered benefits to member companies. Below are some of these benefits:

- Test bed 1 was actively evaluated and tested by industry members (Caterpillar, Bobcat, Parker Hannifin and CNH) during its time as a DC, non-hybrid prototype excavator. In the future, it can be tested and evaluated in its hybrid configuration. This saves them much time and money compared to building their own prototypes in order to evaluate the potential of DC actuation as well as that of the hybrid DC architecture.
- 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 hybrid DC excavator architecture being developed in this project will help OEMs meet upcoming exhaust emission regulations, together with providing the resulting monetary benefits.

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Test Bed 3: Hydraulic Hybrid Passenger Vehicle

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Industrial Partners:	Bosch-Rexroth, Eaton, Parker Hannifin, Sauer-Danfoss, and others

1. Statement of Test Bed Goals

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

2. Test Bed Role in Support of Strategic Plan

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

3. Test Bed Description

A. Description and explanation of research approach

The high power density of hydraulics makes it an attractive technology for hybrid vehicles since it should be able to provide both high mileage and high performance. A few hydraulic hybrid vehicles have been developed for heavy, frequent stop-and-go applications such as garbage or delivery trucks. However, hydraulic hybrids have not yet reached the much larger passenger vehicle market. In order to succeed in this market, hydraulic hybrid drivetrains 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.

Electric hybrids provide the closest competition to hydraulic hybrids. While hydraulic hybrids cannot match the energy density provided by electric batteries, they have superior power density. This is particularly valuable for regenerating braking energy. Furthermore, hydraulic hybrids eliminate the need for batteries, and thereby eliminate the cost, life and environmental concerns associated with them.

Three possible families of architectures for hybrid drivetrains are series, parallel and power split. A series drive transmits all power from the engine to the wheel with hydraulic pumps and motors. This architecture enables running the engine at its most efficient combination of torque and speed; however, it cannot take advantage of the high efficiency of purely mechanical power transmission through a shaft. A parallel architecture augments the engine with a pump/motor. It transmits power to the wheels through the efficient mechanical shaft, but it has less ability to keep the engine at its best operating point. TB3 focuses on power split architectures, which combine the positive aspects of both approaches.

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

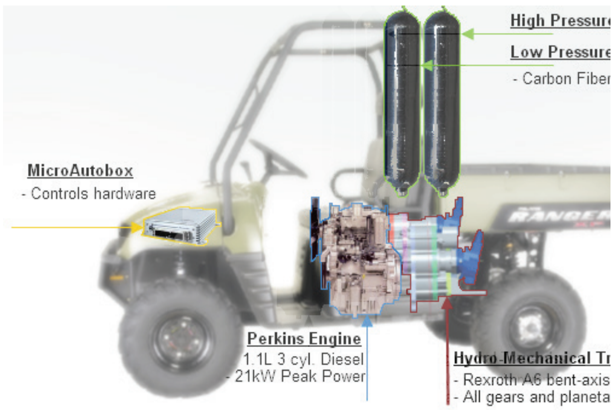

Figure 1: Test Bed 3 Generation I vehicle

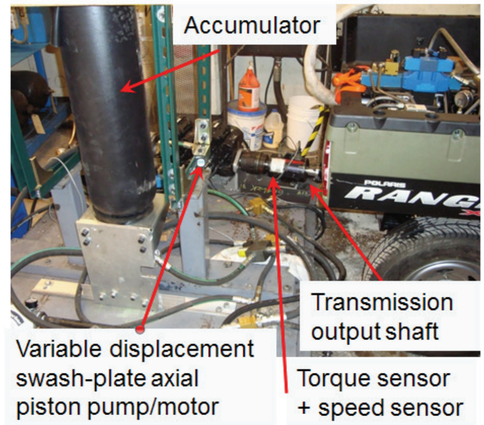

Figure 1: Hydrostatic dynamometer connected to the output shaft of the vehicle transmission

The "Generation II" vehicle is being developed in partnership with Folsom Technologies International (FTI). It is built on the platform of a F-150 pickup truck, which has refined vehicle dynamics capable of highway speeds. Its power-train utilizes a custom-built continuously variable power split hydraulic transmission developed by FTI which will be complemented with hydraulic accumulators to enable hybrid operation. The powertrain is built as a compact, integrated, self-contained package. However, the integrated package prevents changing the hydraulic pump/motors or instrumenting them individually. Also, the transmission is not optimally sized for hybrid operation and presents some control restrictions when operated in hybrid modes. Therefore, the "Generation I" vehicle is being continued despite the pending availability of the roadworthy "Generation II" vehicle.

B. Achievements

Achievements Applicable to Both Vehicles

Controls firmware upgrades (previous years): The Generation I vehicle has previously used "xPC Target" firmware to interface the controller with the powertrain. We have converted to real time firmware that is popular for automotive systems, "Micro-Autobox". The conversion improves both the hardware and software robustness. Since Micro-Autobox is a standard system for automobiles, utilizing it for implementing the TB3 controllers simplifies migration of the controller to the Generation II vehicle.

Energy Management Strategy (previous years): An energy management strategy which can be applied to the control of either vehicle has been developed based on the Lagrange Multiplier method. The original method [5] is limited by two restrictions: (1) the accumulator is assumed to remain at a constant pressure, which is equivalent to assuming that it is infinitely large, and (2) the drive cycle must be known beforehand. The new strategy overcomes the first restriction. Two alternative implementations of the new strategy are possible. The first approach is more computationally intensive in real time, while the second gains in computational efficiency by optimizing it in advance of applying it in real time. Both alternatives are able to maintain the state of charge of the accumulator within its physical limits. The new approaches exhibit only a 3-5% penalty on fuel economy compared to dynamic programming, which is the best, but most computationally expensive, optimization method.

Achievements Applicable to the Generation I Vehicle

Drivetrain Redesign (previous years): The original drivetrain for the Generation I vehicle utilized differentials which did not meet the torque specifications of the drivetrain, and it had poor reliability due to excessive usage of chains and belts. Therefore, the drivetrain was completely redesigned in 2010 to utilize gears exclusively. Assembly of the new transmission was completed in August 2011.

Hydrostatic Dynamometer System Design and Implementation (2011-12): A hydrostatic dynamometer was designed in-house in 2011 and constructed in 2012. The dynamometer is designed to test mid-size vehicles through EPA's Urban Dynamometer Driving Schedule and Highway Schedule. The reason for building an in-house dynamometer is to provide rapid and repeatable experimental evaluation of the hybrid powertrain's performance. The dynamometer eliminates the need to transport the vehicle to a test track or an off-site chassis dynamometer with motoring capability, neither of which is conveniently available. It also enables testing with reasonably repeatable environmental conditions during all seasons. Figure 2 shows the dynamometer connected to the output shaft of the transmission of the Gen I vehicle.

A novel controller was implemented to enable the dynamometer to exert the desired torque on the vehicle output shaft. First, a system identification procedure was performed on the pump/motor utilized within the dynamometer. Since the dynamometer is used to mimic the road load as if the vehicle is driving on the ground, the inertia torque of the vehicle must be estimated and included in the dynamometer torque. However, calculating the inertia torque requires the acceleration, which in turn requires information from the future; i.e., it is a non-causal parameter. In order to solve the causality problem, a "virtual vehicle" concept was devised. The controller tracks the virtual vehicle speed instead of estimating the acceleration directly. This approach guarantees that the dynamometer output torque is correct. This algorithm also allows fuel economy evaluation for vehicles of different weights.

Regenerative braking event experimentally tested (2012): The dynamometer was designed with the ability to motor so that regenerative braking events can be simulated, which constitute an important benefit from hybridizing the powertrain. A maximum motoring torque of 85 Nm was achieved and the equivalent vehicle speed decreased from 50 mph to 9 mph. The pressure in the vehicle's accumulator increased from 82 bar (1200psi) to 102 bar (1500psi), indicating successful energy recuperation. Graphs showing the experimental data corresponding to this event are shown in Fig. 3.

New Engine Installation and Characterization (2012): The vehicle originally had a 1.1L diesel engine. That engine was damaged in Fall 2012. We had learned that the original engine was undersized due to the underestimation of the losses from the valves and pump/motors. Simulations using actual loss data revealed that the engine size should be 1.5L, so a replacement engine of that size was purchased and installed. The new engine required extending the vehicle frame. However, it is now capable of driving the vehicle through federal cycles in the presence of valve and pump/motor losses.

An engine efficiency map is necessary to optimize the drivetrain operation of the vehicle. Engine performance data provided by the manufacturer is inadequate to create this map. Therefore, our hydrostatic dynamometer was utilized to characterize the engine. Figure 4 shows engine efficiency map created from our experimental results.

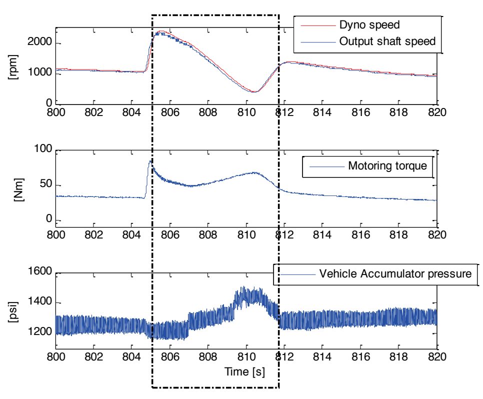

Figure 3: Regenerative braking event experimental data. Top: Drive shaft speed. Center: Motoring torque. Bottom: Vehicle accumulator pressure.

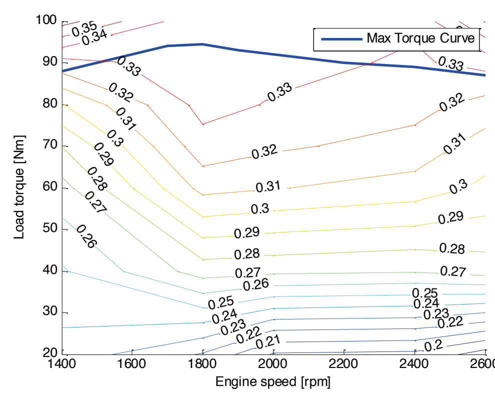

Figure 4: Engine efficiency map generated from experimental results. Note: curves above max torque curve are artifacts of extrapolation.

Hardware and Electrical Upgrades (2012): Three significant mechanical upgrades were made on the Generation I vehicle chassis to improve performance and reliability. First, the engine throttle control was upgraded from a problematic stepper motor and cable based system to fuel solenoid control. Second, the charge pump was removed from the transmission and replaced with an electric motor to drive it. This change eliminated potentially problematic scenarios where charge pressure would not be sustainable.

Third, a hydraulic circuit to facilitate start-up of the vehicle was developed. The original design had a flaw that the valves utilized to set the direction of the vehicle's pump/motors require pressure to operate. However, the pressure was obtained from the high pressure accumulator, which required flow from one of the pump/motors to pressurize it. The problem was temporarily solved by replacing one of the directional valves with a cross-over plate, which eliminated the ability to reverse one of the pump/motors. The new start-up circuit enables developing initial pressure in the high pressure accumulator with the charge pump. Once enough pressure is developed to operate the directional valves, the charge pump is switched out of the high pressure circuit, eliminating the need for the cross-over plate.

The vehicle's wiring was also improved. We discovered that many of the vehicle's electrical circuits were unintentionally routed through a switch. This arrangement was resulting in a 25% voltage drop to many of the vehicle's systems. The vehicle chassis was re-wired, which resulted in significant simplification and improved electrical performance.

<u>Achievements Applicable to the Generation II Vehicle</u>

Efficiency Map Test Plan and Test Results (previous years): In order to fully optimize the operation of the hybrid hydro-mechanical transmission, one must identify the overall efficiency of the transmission in various hybrid operating conditions. A method has been developed at the University of Minnesota for approximating this efficiency even though the pump/motors in this transmission are intrinsically coupled and cannot be tested individually. The efficiency of the FTI transmission is determined using a 400 HP dynamometer available at the FTI facility. Two different types of transmission fluid have been tested: conventional automatic transmission fluid (ATF) with a viscosity of 5 cSt and an Evoniks Rohmax fluid with a viscosity of 15 cSt. A graph in the Year 6 report reveals that the Rohmax fluid has greater or equal efficiency under all conditions tested, peaking at 92%.

Transmission Test Data Analysis (2012): FTI provided what was expected to be a final set of performance data for the Generation II vehicle transmission, obtained using their dynamometer, in mid-2012. However, Minnesota's anaylsis of that data revealed that the transmission was leaking excessively. FTI identified the source of the leakage as broken seals in the transmission's pump/motors. At the time of this writing, the problematic seals have been replaced, and we are waiting to gain access to the FTI dynamometer to obtain corrected performance data.

Controls Hardware Integrated (2012): Minnesota prepared a Micro-Autobox unit for the Generation II vehicle and shipped it to FTI. Development proceeds in three stages. The first is "software in the loop" (SIL), in which all hardware functions are simulated. The second is "hardware in the loop" (HIL), in which actual sensors and actuators are connected, but the engine and transmission performance are simulated. The third is full hardware implementation. We are currently in the SIL phase. Ford is developing signall conditioning and actuation circuits for the HIL phase, which they will donate to the project.

<u>Plans for the Generation I Vehicle</u>

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

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

A project which utilizes the Generation I vehicle as a test bed for Project 1G.1 (Tribofilm Structure and Chemistry in Hydraulic Motors) is planned. A synthetic biodegradable ester will be utilized as the hydraulic fluid, which is expected to exhibit higher efficiency at low speeds [10]. The new oil will be compared with a shear stable high viscosity index hydraulic fluid which serves as the baseline oil for the vehicle. The new vehicle dynamometer will be utilized for these tests.

Hybrid operation will be tested next with the implementation of various energy management strategies. Both the modified Lagrange multiplier strategy and Project 1A.1's rule-based control strategy will be implemented. The more complex Stochastic Dynamic Programming (SPD) and Model Predictive Control (MPC) algorithms developed in Project 1A.1 will be implemented and tested in Summer 2013.

The vehicle will be tested on ground in a parking at the University of Minnesota. After that, the synthetic biodegradable ester will be utilized as the hydraulic fluid and tested on the vehicle again in hybrid mode. The controllers will be fine-tuned using data gained from these tests.

The bent axis pump/motor used as pump/motor "S" will be replaced with a pulse width modulated virtually variable displacement pump/motor (VVDPM) designed in Project 1E.1 during Fall 2013. Simulations have been performed to optimize the gear ratios for the pulse width modulated pump/motor [8]. The actual efficiency using the new pump/motor will be experimentally determined and compared to the baseline efficiency.

Two new accumulator designs will be tested during the 2013-2014 period. Discussions are currently in progress for testing an efficient accumulator developed by an outside corporation that operates at near isothermal conditions. Also, a prototype of the strain energy accumulator being developed by Project 2C.2 is expected to be ready for testing next year. The strain energy accumulator will have the advantage of constant pressure operation, thereby improving its energy density. The modular architecture of the redesigned transmission enables the pump/motors to be changed out.

Plans for the Generation II Vehicle

Dynamometer tests will be performed to generate a performance map for the transmission in the same state as it is expected to be installed in the F-150 truck. Much of the controller development that has been completed for the Generation I vehicle will be adapted to the Generation II transmission with only fine tuning required to account for architectural differences. After the Generation II vehicle is fully functional, a continuously variable transmission control strategy and hybrid control strategy will be tested.

Milestones and Deliverables

Gen I:

- Efficiency evaluated in continuous variable transmission (CVT) mode (3/13)
- Efficiency of alternative hydraulic oils compared in CVT mode (4/13)
- Project 1A.1 control schemes compared using MN dynamometer (6/13)
- Ground driving tested (7/13)
- Efficiency of alternative hydraulic oils compared in hybrid mode (8/13)
- Project 1E.1 pump/motor installed as Pump/Motor "S" in Generation 1 vehicle (10/13)
- Project 2C.2 strain energy hydraulic storage integrated on Gen 1 vehicle (1/14)

Gen II:

- Transmission dynamometer testing completed (6/13)
- Dynamometer testing data analyzed and model correlated (7/13)
- Transmission installed in F150 chassis (8/13)
- CVT control strategy demonstrated (11/13)
- Hybrid control strategy demonstrated (3/14)
- EPA cycle fuel economy evaluated (5/14)

Gen III:

- Initiation of Generation 3 transmission design on mid-size sedan vehicle (5/14)

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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Test Bed 4: Patient Transfer Device (formerly Rescue Robot)

Research Team

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1. Statement of Test Bed Goals

The goal of this test bed is to demonstrate a mobile fluid powered patient transfer device, an example of a portable, un-tethered human scale fluid power application. It is intended to transfer mobility-limited patients, including bariatric patients, for example, from bed to wheelchair, wheelchair to shower chair, or wheelchair to car. Current patient lifts are typically electrically actuated, or have a manual hydraulic pump; with only one actuated degree of freedom, they are antiquated and insufficient for current patient needs. Our goal is to develop a highly maneuverable, powerful, compact patient transfer device that can be easily operated by a single caregiver. It should be able to operate for a reasonable time without charging (all day for typical transfers), produce sufficient force to transfer bariatric patients (up to 500 lbs), and have precise, intuitive control.

2. Test Bed Role in Support of Strategic Plan

The Patient Transfer Device occupies the power range from ~100W~1kW in the CCEFP'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 control. It provides a system for testing component technologies, as well as developing intuitive control and expanding the use of fluid power into the healthcare sector.

3. Test Bed Description

A. Description and explanation of research approach

Overview

Test bed 4 is a human scale CCEFP test bed. Originally, TB4 was targeted as a rescue robot which will be dealt with briefly here and in the advancement section. We are now redirecting this effort to a patent transfer device intended for moving mobility-limited patients, for example, from bed to wheelchair, wheelchair to shower chair, or floor to wheelchair. This application fits well with the CCEFP goals in that a system for this application requires attributes of a fluid power system that the CCEFP is working to achieve, such as compactness, low leakage, low noise, high power, reliability, and intuitive, effective control. Similar research challenges occur in both the rescue crawler and the patient transfer device, such as interaction with human operators and impaired individuals. Furthermore, we can take advantage of advancements in the same areas as the rescue robot without some of the obstacles irrelevant to fluid power research. For example, the large number of degrees of freedom and multiple copies of custom hardware made the rescue robot highly sensitive to failure; the patient transfer device requires fewer degrees of freedom and less custom hardware components. Also, DoD and DARPA have invested large sums of money into development of robots with challenges similar to the rescue crawler, including fluid powered devices such as Big Dog. Meanwhile patient transfer, a less glamorous but widely acknowledged need, has been largely ignored. The ultimate commercial potential of an improved patient transfer has stimulated considerable interest among our industrial stakeholders. Finally, complimentary interests with the Quality of Life Technology (QoLT) ERC have prompted collaboration and cooperation in our separate areas of expertise. QoLT pursued electrically actuated devices with the attendant advantages and limitations. Hydraulic systems provide advantages over the conventional electrical systems for these devices in several aspects. They allow for higher force-to-weight ratios than electrical actuation. Furthermore, fluid power technology allows for the power source to be located away from the joints. This is advantageous for implementing a design with multiple degrees of freedom, which are needed in this application. It also allows for the use of the power source as a counterweight.

The rescue robot idea was conceived at the proposal stage of the CCEFP as a cooperative effort between Vanderbilt University and Georgia Tech. The initial power supply was to be chemofluidic (hydrogen peroxide) of high purity. Restrictions placed on the access to this fuel at high purity levels became onerous, and air and nitrogen were used in development. Operator interface, passivity based control and pneumatic power supply were the primary projects linked to the test bed. The last of these to be tried was the free piston engine/compressor. It was developed and fitted to the robot in the previous year and was able to demonstrate functionality but was not a reliable source of power for sustained operation. The planned change to hydraulic power depended on one project for a light weight, untethered source: the hot gas vane pump. When that project was discontinued the rescue robot was no longer an attractive test bed. An alternative that could reliably demonstrate hydraulic power in this power range was needed. The interaction with the Quality of Life Technology Center at the Annual ERC Conference led to a choice of a patient transfer device as a substitute.

We believe there is a significant market need for an improved patient lift device. Current devices are antiquated, with only one actuated degree of freedom, and insufficient for the needs of many current users. Back injuries are a major risk to clinicians and caretakers ([1],[2]), with more than 10% resulting from patient transfers. The population of older Americans is dramatically increasing, as are the obesity rates [3]. Fluid power is particularly useful in handling bariatric patients. Family caregivers in the home are the largest source of long-term care in the United States, and an estimated 29% of the U.S. adult population is providing care to someone who is ill or disabled; there is a significant need for an improved patient transfer device [4], particularly targeted to home settings.

High Level Needs and Goals

Hydraulics provides the capability for a compact device design that is capable of producing high forces with multiple actuated degrees of freedom. These features are most beneficial in a home environment, where there are more obstacles and often less accessibility than in clinical settings. It is also helpful in serving a broader range of weight limits, including bariatric patients.

The device should be capable of performing most typical home transfers, with maneuverability sufficient to work within the space constraints of a typical home, and adequate lift capacity in any kinematic configuration. In a home setting, often only one caregiver is present; therefore, the device must be operable by a single caregiver, with an intuitive control strategy and minimal user effort. It must also be smooth and stable under all working conditions.

Background and Needs Assessment

The first step in developing a new patient transfer device was to gain an understanding of the currently available devices. The most commonly used type of patient lift is shown in

Figure 1. This design has remained essentially the same for several decades. The patient sits in a sling, which is attached to the hanger bar. The device has only one actuated degree of freedom, the rotational lifting joint. It rolls on casters, and the base can spread to a wider V-shape. The devices are actuated either electrically or by a manual hydraulic pump.

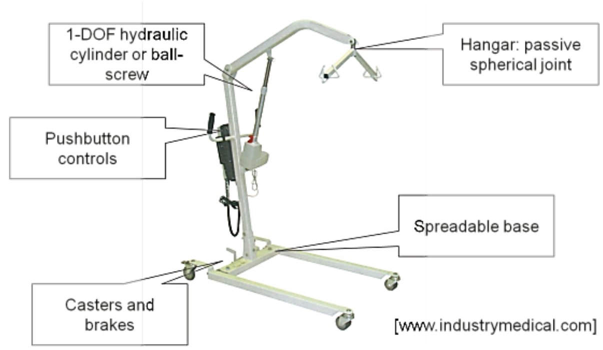

Figure 1: Conventional patient lift

Early in the project we visited QoLT ERC in Pittsburgh, spending the day with Dr. Rory Cooper and Dr. Chris Atkeson. This informed us of the target population of their "StrongArm" device, enabling us to take a complimentary approach. Further consultation with Prof. Stephen Sprigle of Georgia Tech's Center for Assistive Technologies and Environment Access (CATEA) has also guided our direction. We have performed an extensive needs assessment for the patient lift device. Our research has consisted of two forms of input, informal one-on-one interviews and a formal focus group. As for the individual interviews, we met with representatives from the lift device industry, a number of clinicians, and a wife of a bariatric paraplegic patient. The focus group included six clinicians, three spinal cord injury patients, and two home caregivers. These have provided us with a sound understanding of the current state of the art, as well as some ideas for additional needs, some of which are categorized below.

- *Maneuverability*: The current devices, with only one actuated degree of freedom, are difficult to maneuver into places where they're needed. Bariatric patients are particularly difficult to move, because of their larger size and weight. It is the large, rigid rolling base that encounters the most obstacles, such as chair legs, couches, bathtubs, toilets, bed frames, etc. Many current lifts do not reach floor level. Car transfers are particularly difficult because of limited space.
- *Caretaker Interface*: With the current devices, the sling and hanger bar provide substantial freedom to adjust the orientation and position of the patient manually, while the device actuates only the lifting. The caretaker maneuvers the patient by pushing on the body. It is often very difficult to position/orient the patient while simultaneously maneuvering/controlling the lift device.
- *Capability to Handle Bariatric Patients*: Bariatric patients present a few additional considerations. First, the device must be capable of lifting heavier load, up to at least 500 lbs. Second, powered wheels on the base are needed, particularly for moving the device on carpet.
- *Slings*: A time consuming aspect of a transfer operation is getting the patient in a sling. However, this 'soft goods' design is outside the core competencies and interests of the CCEFP, so we will focus on other aspects.
- *Cost*: Cost is a substantial limitation for new devices, since most are purchased through insurance. However, the availability of powered assist devices has improved greatly in recent years.

Figure 2 shows some of the feature ideas that were proposed to the focus group. In addition to mechanical design ideas, we also proposed a new form of user input, using a force/torque sensor mounted near the patient for coordinated force-amplifying control of the device.

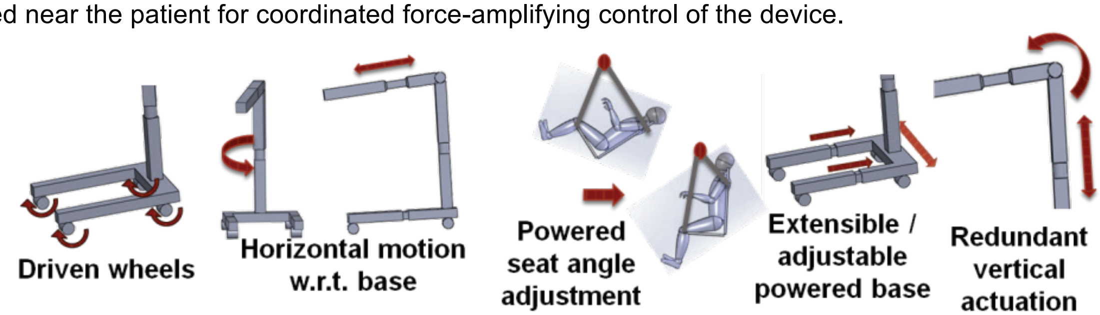

Figure 2: Some ideas presented to focus group

The additional degrees of freedom with adjustable base should help considerably with maneuverability, especially with bariatric patients. In order to implement horizontal motion with respect to the base, the device will need a control strategy which maintains stability and prevents any motion which could risk tipping. The participants generally responded positively to the proposed features.

B. Achievements

Rescue Robot

The primary achievement of the rescue robot test bed during this reporting period was testing of the free piston engine/compressor in May of 2012. The robot was equipped with outriggers to enable the demonstration of both mobility and manipulation using its limbs. The robot was extensively checked for robustness and modifications made where appropriate. The engine was brought to Georgia Tech, tested on the bench and mounted on the robot as shown in Figure 3.

The engine showed promise but was subject to a material failure in a fuel line componenet while testing and before real studies while mounted on the robot could be performed.

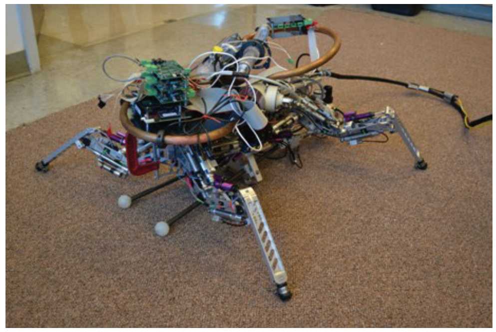

Figure 3: Rescue robot with free piston engine/compressor mounted.

In addition to serving as the engine test bed, the rescue robot served as test bed for passivity based control conducted by Venkat Durbha and Prof. Perry Li. Although this project graduated, the PhD. thesis experimentation of Mr. Durbha was not completed until this reporting period. The hardware will continue to be available for associated projects, including the PhD dissertation work of Hannes Daepp who is applying model reference adaptive control to pneumatic systems. He is funded by a NDSEG fellowship.

Pre-prototype

As a first step, we chose to create a simple pre-prototype device for the purpose of gaining experience performing transfer operations and controlling the hydraulic device. The pre-prototype (Figure 4) is a repurposed device from an earlier project. It is currently fully functional with two degrees of freedom, vertical and horizontal; however, it is not mobile. It is also helpful for determining suitable operating parameters (e.g. speeds, forces from the operator, etc.).

Figure 4: Exploratory pre-prototype patient lift device

The pre-prototype is controlled using a coordinated force-amplifying control strategy. The operator input is measured from a force sensor mounted on the end of the boom. The input force corresponds to the speed and direction in which the patient moves. This setup allows for testing of appropriate speeds for device motion, appropriate locations and types of user inputs, suitable input force ranges from the caretaker, and testing of controllers. It has also exposed some critical aspects such as required range of motion and placement of the control handle and force sensor.

Design and Simulation of Prototype Device

The next step in the design is to create a simulation of the patient lift device. First, a simple CAD model was created with an appropriate kinematic configuration and inertia properties. The lift device model can then be used to answer several key questions. First, what is an appropriate range of motion for the device? This question can be answered primarily using motion studies in CAD software, as illustrated in Figure 5. The device can be moved through typical configurations and limiting conditions to determine the smallest appropriate range of motion for each joint.

The dynamics of the device are being analyzed, for the purpose of determining needed joint forces and torques, in order to find parameters for the hydraulic system and the controller. Simulink provides the capability to import the CAD model, including inertia properties, and create a block diagram simulating the mechanical dynamics. We can use that information to develop requirements for both the hydraulic system and the control system performance. We can then integrate the dynamic models of the mechanical system, the controller, and the hydraulic system, all within Simulink. As a first step, a Simulink simulation of a simplified version of the device is shown in Figure 5.

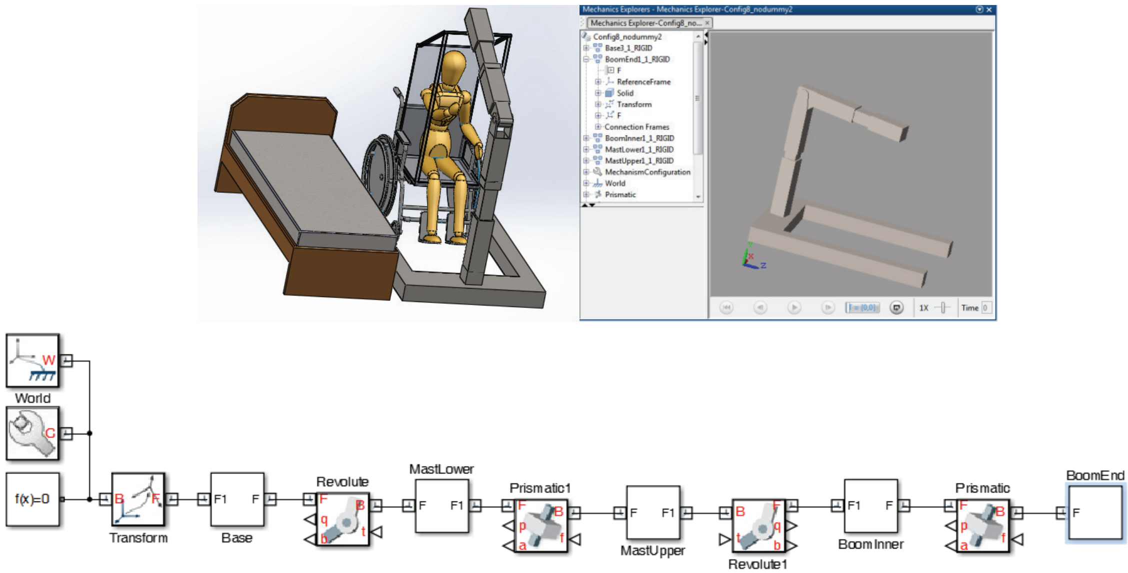

Figure 5: Simplified lift device mechanical system dynamic model in Simulink

The hydraulic system design will include a battery powered pump with mobile, onboard hydraulic power. The system will use a small pump and flow control servo valves, and it will be actuated by hydraulic cylinders and motors.

Control and User Interface Features
We are proposing three main unique control features.

1. The operator input will be from a force sensor mounted near the patient, within reach of the caregiver. This will provide a method for coordinated control, and give the caregiver an intuitive means to control the device with one hand, while maneuvering the patient as needed with the other hand. There are several ways to implement such force-amplifying control, one of which is a passivity based method that is a former CCEFP project.
2. Clinicians have indicated that oscillation tends to occur primarily when the base hits an obstacle (e.g. rolling over a cord). This oscillation can be cancelled using active vibration compensation, which is a current CCEFP project 3B.3. This method will be implemented on the patient transfer device.
3. Avoiding tipping is critical in this application; however, this presents a tradeoff with maneuverability. It is desirable to maximize the maneuverability of the arm with respect to the base, for the purpose of avoiding obstacles. Therefore, an anti-tipping stability control strategy will be implemented, similar to that which was implemented on the compact rescue crawler. It utilized a model predictive /shared control scheme to prevent any motion which would cause the device to tip over.

CCEFP Project Integration and QoLT ERC Collaboration
This test bed provides an opportunity for collaboration with the Quality of Life Technology Engineering Research Center (QoLT). The QoLT has considerable experience with developing assistive devices for mobility limited patients. We have visited the QoLT and toured their facitilties, and we intend to continue this collaboration throughout the project. There are four main CCEFP component projects that will be implemented and tested on Test bed 4. Other CCEFP projects will also provide input to the design (e.g. minimizing noise and leakage).

- Hydraulic transformer (1E.5) –Perry Li, U. Minnesota
- Active vibration damping (3B.3) – Andrea Vacca, Purdue
- Human-centered design (3A.3) – Eui Park & Steven Jiang, NCAT
- Operator interface design (3A.1) – Wayne Book, Georgia Tech

The first generation prototype will be built with conventional hydraulic components, and the CCEFP hardware component technologies will be integrated and tested at a subsequent stage.

Next Steps
The next step for this test bed is to complete the detailed design of the device, as well as the simulations. Then the hardware system can be implemented and tested, along with the control system. The CCEFP component projects will be integrated. Finally, human operator studies will be performed to evaluate the effectiveness and performance of the design.

C. Member company benefits
Fluid power component manufacturers stand to gain additional new sales from the expansion of fluid power into this new healthcare based application. We may also be able to recruit new member companies who manufacture patient lifts.

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

Research Team

Project Leader:	Elizabeth Hsiao-Wecksler, MechSE UIUC
Other Faculty:	Will Durfee, ME Minnesota Geza Kogler, Applied Physiology, Georgia Tech
Graduate Students:	UIUC: David Li; Morgan Boes, Mazharul Islam UMN: Kathy (Braun) Houle, Jicheng Xia
Undergraduate Students:	UIUC: Lee Ann Monaghan (undergrad diversity supplement), Megan Hodgson (REU – Johns Hopkins) UMN: Ellen Weburg (REU), Kali Johnson, Connor Mulcahy
Industrial Partner:	Parker Hannifin

1. Statement of Test Bed

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

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

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

Human assist devices developed in TB6 provide functional assistance while meeting these additional requirements: (1) operate in the 10 to 100 W target power range, (2) add less than 1 kg of weight to a given segment of the body, excluding the power supply, and be designed to minimize physical interference during use, and (3) provide assistance from 1 to 8 hours. The focus of this test bed 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 test bed goals.

2. Test Bed Role in Support of Strategic Plan

This test bed 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 test bed benefits society by creating human-scaled fluid power devices to assist people with daily activities and is creating new market opportunities for fluid power, including opportunities in medical devices.

3. Test Bed Description

A. Description and explanation of research approach

Problem Statement: In the US alone, individuals who suffer from or have been affected by stroke (4.7M), polio (1M), multiple sclerosis (400K), cerebral palsy (100K) or acute trauma could benefit from a portable, powered, daily wear lower limb orthoses [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.

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

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

Research Approach: We are following a roadmap for developing portable fluid powered AFO devices with increasing complexity and performance requirements. In 2008, the design and construction of an energy-harvesting AFO that selectively restricted joint motion using a pneumatically-driven locking mechanism was completed [6, 7]. The lessons learned during this design process were used to accelerate the design of a portable fluid powered AFO. Using a systems engineering approach, the fluid powered AFO system has been divided into four subsystems that align with our core system challenges: power supply, actuator/valving, structural shell, and control system (electronics, sensors, and HMI). The subsystems have target specifications that must be met to realize a fully functional device. The power supply must weigh < 500 g, produce at least 20 W of power, run continuously for ~ 1 hour, and be acceptable for use near the human body. The actuator and valving must weigh < 400g and provide a minimum of 10 Nm of assistive torque at a reasonable efficiency. The structural shell must weigh < 500 g, be wearable within a standard pair of slacks (fit inside a cylinder with 18 cm OD), and operate in direct contact with the body. The control system must control the deceleration of the foot at the start of stance, permit free ankle plantarflexion up to mid stance, generate a propulsive torque at terminal stance, and block plantarflexion during swing to prevent foot drop; all in a robust and user friendly manner. In 2008, University of Minnesota students were added to the test bed team to examine opportunities to increase propulsion torque and power through high pressure hydraulics. Over subsequent years, Illinois and Minnesota teams have been using the portable fluid powered AFO platform to explore lower pressure pneumatics and higher pressure hydraulics, respectively, as promising technology paths for tiny fluid power systems suitable for untethered human assist devices.

B. Achievements

Portable Pneumatic AFO (PPAFO) UIUC

In 2010, we constructed our first generation portable powered ankle-foot orthosis (PPAFO) using off-the-shelf (OTS) components to demonstrate device feasibility [8-10]. The Gen1.0 PPAFO is an improvement over state-of-the-art passive and active systems [4, 5] because it provides subject-specific motion control and torque assistance without tethered power supply or electronics. The device can provide modest dorsiflexor (toes-up) and plantarflexor (toes-down) torque actuation at the ankle. A U.S. patent on the technology embodied by the PPAFO has been filed; co-inventors are CCEFP students and faculty from the U Illinois, U Minnesota, Georgia Tech, and MSOE [11]. While the Gen 1.0 device demonstrates the feasibility of utilizing low pressure pneumatics to provide torque assistance at the ankle, this test bed platform highlights the need for advancements in miniaturized fluid power systems.

Over the years, we have been working on improving the efficiency, compactness, control, usability, and possible applications of the PPAFO. Using an off the shelf pneumatic rotary actuator located lateral to the ankle and a canister of compressed CO_2 at the waist to serve as a placeholder for a more compact power source, the Gen 1.0 PPAFO can generate up to 12 Nm at 100 psig with run times less than 30 minutes.

To address efficiency improvements, we have performed efficiency studies, explored regenerating exhaust gas with an accumulator, and investigated thermal regulation of the CO_2 power source. Preliminary theoretical component and system efficiencies of the Gen1.0 PPAFO system suggest an overall efficiency of 19% based on calculations from the product of component (50%) and system (39%) efficiencies [12]. That analysis also suggested that the exhaust gas from the higher pressure plantarflexor actuation (100 psig) could be captured into an accumulator and then recycled to power the lower pressure dorsiflexor actuation (30 psig). In 2012, bench-top tests, conducted by REUs during the spring and summer, found 11 J of total work loss across all components, and expected fuel savings of up to 30% with a fixed volume accumulator. Recent testing on the effect of two actuation control schemes on net work and fuel consumption during walking tests found that the regenerative scheme improved fuel consumption by 17% [13]. Working with students at Vanderbilt on Project 2C.2 (strain energy accumulator), we constructed a pneumatic elastomeric accumulator for use with the recycling scheme that was tested during the walking tests (Figure 1). In 2013, we are investigating the bench-top and walking test differences in fuel savings, issues with losses and actuation timings, and additional design changes to the accumulator. We will also explore the implementation of a thermal regulation scheme on the CO_2 power source. Our previous REU and E&O sponsored senior design team studies in 2011 suggested that the thermal cooling nature of liquid CO_2 and subsequent pressure decrease over time could be mitigated by maintaining an isothermal condition for the canister or hoses.

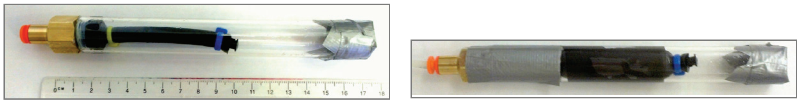

Figure 1: Elastomeric accumulator

To address compactness, we have been pushing the development of pneumatic ankle actuation systems with higher torque output (target: 25Nm @ 120 psig) than commercially available, modular and integrated shell structures and promote the need for miniature pneumatic valves and power sources. We realized that the compact integrated rotary actuator developed by MSOE in 2010 would not be a viable design (max capable 50psig for 6 Nm). Therefore, in effort to continue to drive a technology pull for a compact pneumatic actuator, we pursued three avenues. (1) In 2011, MSOE tried to improve their original design and also proposed a new design based on bellows technology (35Nm @ 115psig). However, no further work on either design was pursued due to funding cuts to MSOE and project 2D. (2) In 2011, we began collaborating with CCEFP industry partner Parker Hannifin to utilize their expertise in pneumatic rotary actuators to design a custom product. This work has substantially slowed in 2012 due to Parker work priorities and manpower issues. The design is nearly complete, but there are issues with finding cost-effective fabrication methods. (3) During the 2011-12 and 2012-13 academic years, CCEFP sponsored a Mechanical Engineering capstone design team each year at Bradley University in Peoria, IL. The first team developed a prototype using additive manufacturing to create a novel rotary actuator with integrated planetary gear train; unfortunately the design had leakage problems and could not be tested. The current team decided to design a completely different actuation system using a linear actuator and modified rack & pinion configuration. We continue to seek solutions for compact and higher torque actuation systems. In 2012, we developed a lighter and less complex structural shell design for the Gen 2.0 PPAFO, which will allow for swapping of modular components. The new shell no longer requires metal vertical struts and has no medial support (Figure 2). We are currently awaiting multiple sized (S, M, L, XL) foot and shank bilateral shells to support testing on a variety of sized test subjects. We continue to work with Project 2F (MEMS proportional valves), Project 2B.2 (HCCI engine) and Project 2B.4 (Stirling engine) to address compact pneumatic valves and power sources. The thermal shroud for the HCCI engine (Project 2D) was halted in 2012 due to funding cut of Project 2D at MSOE.

To address PPAFO control for appropriate gait function across a variety of user populations (able-bodied and impaired) and walking environments (level ground, stairs, ramps), we have examined different actuation-timing control strategies, solenoid vs. proportional control and recognition and control for different gait modes. Our initial controller for level ground walking was a simple direct event threshold-based control using just the heel and toe sensors [9]. To better accommodate impaired gait, we developed a model-based state estimator controller that also added the angle sensor [8]. In 2012 and 2013, we are examining how the pneumatic system (work and fuel use) are affected by these two controllers [13]. A simulation and bench-

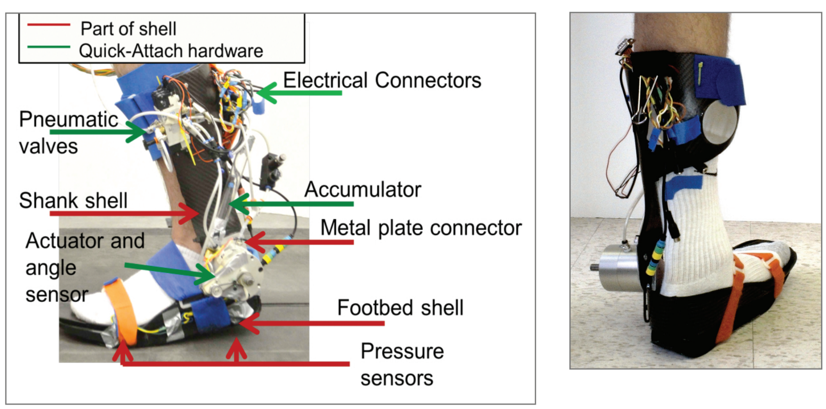

Figure 2: Gen 2.0 PPAFO. Includes elastomeric accumulator, revised valving, and new shell without metal struts or medial side. Modular hardware can be swapped between different sized shells.

top study highlighted that proportional valve control has better tracking and efficiency performance compared to solenoid valves [10]; however, due to low torque generation ability of current actuator systems, inclusion of proportional control on the PPAFO has not yet been implemented. These results again highlight technological barriers to compact fluid-powered orthoses. In 2011, we began work in recognition and control for different gait modes using a 6DOF inertial measurement unit (IMU) [14]. Progress in 2012 resulted in success rates of identifying level ground, stairs, or ramps of 97-99% on average. It was determined that only stair or ramp descent require a different control scheme than level ground or stair/ramp ascent, and differential gait mode control has been implemented [15]. Control issues will continue to be addressed based on applications for the device.

We have targeted the PPAFO to be a portable gait assistance and rehabilitation device. Starting in 2011, CCEFP faculty and students at NCAT began development of two user interfaces: (1) a computerized clinician user interface for tracking patient medical history and therapy progression, and (2) an interactive game interface (using a serious gaming approach) to be used by the patient while using the PPAFO as a joy stick as part of a seated rehab therapy. In 2012, project 1 was halted and progress on project 2 was slowed due to funding cuts to NCAT. In 2012 and beyond, an associated project at UIUC is determining if the PPAFO can be used as a gait initiation cueing device for people with Parkinson's disease [16]. A highlight story on this associated project is included in the Y7 report. We are also working with clinical researchers about possible applications in stroke and partial foot amputee rehabilitation.

Hydraulic AFO (HAFO) activity at Minnesota

In 2009, we identified high pressure hydraulics as a promising technology path for tiny fluid power systems suitable for applications such as the untethered AFO. In 2010, theoretical analysis of tiny hydraulic systems was conducted to understand their limits [17]. Additionally, a compact fluid power electrohydraulic actuation system was assembled with LiPoly battery, Maxxon motor, Oildyne cartridge pump and Bimba hydraulic cylinder to demonstrate the capabilities and limits of using off-the-shelf components.

During 2011 and 2012, continuing theoretical analysis of tiny hydraulic systems resulted in identifying the design guidelines of the HAFO. The analysis showed that a piston pump and a gear head should be used to minimize the weight of the system. Further analysis showed that the power unit of the HAFO must be separated from the actuator unit to capitalize on the weight advantage of hydraulic actuation over the equivalent electromechanical system.

In 2012, we identified the key design parameters for the pumping and actuation components for the HAFO [18]. We finished sizing the electric DC motor and gearhead based on the AFO requirements and the available electromechanical components in the market. We also built a test stand to validate the mathematical efficiency models of the O-ring sealing element that is crucial to tiny hydraulic systems. The seals were tested under different speeds and loading conditions. Key validation results are shown in Figure 3. The experimental validation of the seal efficiency model is significant because it justified the system level comparison between the small-scale hydraulic systems and electromechanical systems we executed in 2009. The validation results also set the foundation for the subsequent HAFO system design and performance prediction.

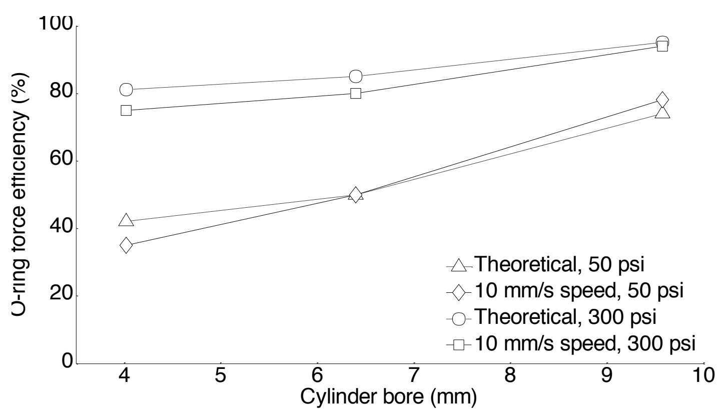

Figure 3 Experimental validation of the O-ring efficiency models

Publications

During 2012, work associated with Test bed 6 has resulted in 4 peer-reviewed publications in scholarly journals, 9 conference proceedings, and 1 trade journal article.

Plans, Milestones and Deliverables for Next Year

PPAFO:

- (Spring 2013) Investigate bench-top and walking test differences in fuel savings, and issues with component losses and actuation timings. Continue to work with Bradley and Parker actuators.
- (Summer 2013) Develop comprehensive model for design elastomeric accumulators. Identify and implement thermal management intervention.
- (Winter 2013) Demonstration of HCCI engine with PPAFO
- (Spring 2014) Demonstration of MEMS proportional valves on PPAFO

HAFO:

- (Summer 2013) Full system efficiency analysis of ver2 HAFO, for dynamic load application; Finish customizing piston pump (modified from Oildyne pump) and cylinders
- (Fall 2013) Fully functional and integrated ver2 HAFO; Design a control strategy for ver2 HAFO

Plans, Milestones and Deliverables for Next Five Years

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

Planned work:

Pneumatics: Push development of compact proportional valves, actuators, power sources; increase run time through thermal regulation of portable CO_2 power source and improved component/system efficiencies. Continue to develop user interfaces and clinical applications for PPAFO.

Hydraulics: Continue theoretical analysis of tiny hydraulic systems, with experimental validation though component and system testing.

New areas:

1. Develop comprehensive and accurate mathematical model of complete pneumatic AFO system. Use model to create pneumatic AFO devices that optimize efficiency with the goal of increasing run-time and decreasing weight. Explore pressure & air flow control for torque & rotational velocity control. Explore additional energy harvesting through human power harvesting.
2. Create new knowledge on a high pressure pneumatic AFO device where "high pressure" means around 500 psi. First assess this technology with comprehensive mathematical models, then validate the models by designing, constructing and evaluating physical devices.
3. Continue to research tiny hydraulic devices operating at about 2,000 psi. Critical needs include (1) validated, comprehensive mathematical models that can be used to predict behavior of hardware, (2) concepts for generating pressurized fluid from either battery or hydrocarbon fuel stored energy sources, (3) comprehensive assessment of safety when high pressure tiny hydraulic devices are used in close proximity to humans.
4. In collaboration with Gillette Children's Hospital, St. Paul MN, develop child-size AFO emulator based on tiny hydraulics for use in a novel automatic AFO prescription system for children with gait impairments resulting from cerebral palsy.

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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(references after [5] are from work directly supported by this test bed)

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CENTER FOR COMPACT AND EFFICIENT FLUID POWER
A National Science Foundation Engineering Research Center

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

Thrusts, Projects and Program Objectives	Promote STEM Learning	Promote Awareness of Fluid Power	Fluid Power Curriculum	Culture of Research and Education Integration
Thrust A: Public Outreach **Bringing the message of fluid power to the general public**				
A.1 Interactive Exhibits Fluid Power	x	x		x
A.3 Multimedia Educational Materials	x	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	x	x	x
B.3 Hands-on Fluid Power Workshops	x	x		
B.4 gidaa STEAM Programs	x	x		
B.5 BRIDGE Program	x	x		
B.7 NFPA Fluid Power Challenge Competition	x	x		
Thrust C: College Education **Bringing fluid power education to undergraduate and graduate students**				
C.1 Research Experiences for Undergraduates (REU)	x	x		x
C.2 Fluid Power OpenCourseWare	x	x	x	x
C.3 Fluid Power Projects in Capstone Design Courses	x	x	x	x
C.4 Fluid Power in Engineering Courses	x	x	x	x
C.5 giiwed’anang North Star Alliance	x	x		x
C.6 Fluid Power Simulator	x	x	x	

C.8 Student Leadership Council (SLC)	x	x		x
C.9 Undergraduate Research Diversity Supplement (URDS)	x	x		x
C.10 Graduate Research Diversity Supplement (GRDS)	x	x		x
C.11 Innovative Engineers (IE)	x	x		x
Thrust D: Industry Making connections between CCEFP and industry				
D.1 Fluid Power Scholars/Interns	x	x		x
D.2 Industry Student Networking	x	x		x
D.5 CCEFP Webcasts Series	x	x		x
D.6 Graduate Internships in Fluid Power (Proposed)		x		x
Thrust E: Evaluation Measuring CCEFP program effectiveness	x	x	x	x

Introduction

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

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

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

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

The objectives of the Education and Outreach Program are to:

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

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

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

Thrust A: Public Outreach

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

Project A.1 Interactive Exhibits on Fluid Power
The staff of the Science Museums of Minnesota (SMM) is creating, field-testing and displaying exhibits that demonstrate basic attributes of fluid power and highlight CCEFP research. These exhibits serve as models for dissemination to other science museums, student centers at technical universities, and/or lobbies at fluid power companies. Fluid Power exhibits currently on display at SMM include an axial piston pump, hydraulic hybrid car, hydraulic transmission, super-mileage car and a hydraulics lab. SMM has also developed a fluid power activity kit that volunteer staff use to introduce visitors to fluid power concepts.This project is now being extended in order to engage undergraduate engineering students, enrolled in Senior Capstone Design courses, in developing prototypes of interactive exhibits relevant to fluid power, working with industry mentors wherever possible. These prototypes will be further developed by SMM staff and eventually housed in industry and university sites around the country. [Project Leader: J Newlin, SMM]

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

A.3a Fluid Power Educational Smart-App for Mobile Devices
Video gaming is one of America's growing past-times. The CCEFP is leveraging this cultural phenomenon, especially with the advent of smartphones and tablets, to create a gaming mechanism attractive to both the expert and the novice "gamer". By utilizing this interactive mode of learning in the educational realm, gaming through smart device applications can reach a broad audience and a wide range of gaming enthusiasts. The project is the development of a Fluid Power Educational Smart-App - a gaming mechanisms using physics, hydraulics and pneumatics for smart phones and tablets targeted towards a broad audience. Users will be able to input system pressure and modify the cylinder areas, stroke lengths, valve sizes, etc., to launch a projectile or to smash objects. Component costs would scale by performance (size, speed, etc.), so that when a maximum cost is imposed, or reflected in the score, users can decide what "design" tradeoffs provide the best performance. Selecting "question mark" icons while choosing components would pop-up a small "tutorial" on how that component functions, some basic equations, etc. Once a certain score is reached, additional components (pump, accumulator, etc.) can be purchased. [Project Leaders: John Lumkes, PU]

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

Project B.1 Research Experiences for Teachers (RET)
As a part of the National Science Foundation's RET program aimed at improving science, technology, engineering and mathematics (STEM) education, the CCEFP's RET program enables teachers in pre-college schools to introduce fluid power to their students, drawing on their summer-long experiences in CCEFP research labs. Every summer the CCEFP hosts at least six RET teachers at CCEFP universities. A special CCEFP RET focus is recruiting

teachers from high schools participating in the Project Lead The Way program. [Project Leader: Alyssa Burger, UMN]

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

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

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

Project B.4 gidaa STEAM Programs
The CCEFP, NSF's National Center for Earth-Surface Dynamics and the Fond du Lac Tribal and Community College together organize a number of activities under the name of gidakiimanaaniwigamig (Our Earth Lodge, in Anishinaabe) for K-12 students, with a particular goal of interesting and retaining Native American students in STEAM (science, technology, engineering, arts, and math) subjects. [Project Leaders: Alyssa Burger, UMN]

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

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, Lego Mindstorms and associated software. In order to extend this program to new audiences, a robotics teacher training program has being added in 2012, involving six additional teachers in the gidaa impact area.

A sister program has been launched in the local area with sponsorship from the CCEFP. [Project Leaders: Cameron Lindner, South Ridge School, Alyssa Burger, CCEFP]

Project B.5 BRIDGE Project

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

Project B.7 NFPA Fluid Power Challenge Competition

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

Thrust C: College Education

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

Project C.1 Research Experiences for Undergraduates (REU)

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

Project C.2 Fluid Power OpenCourseWare

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

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

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

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

C.3c Hydraulic Fluid Power for Fuel-Efficient School Buses

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

Project C.4 Fluid Power in Engineering Courses

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

Project C.5 giiwed'anang North Star Alliance

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

Project C.6 Fluid Power Simulator

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

Project C.8 Student Leadership Council (SLC)

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

Project C.9 Undergraduate Research Diversity Supplement (URDS)

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

Project C.10 Graduate Research Diversity Supplement (GRDS)
The Center's Education and Outreach program is committed to broadening the participation of underrepresented students in engineering programs through channels including the NSF and CCEFP Graduate Research Diversity Supplement (GRDS) to current CCEFP research projects. This effort is complemented by the CCEFP's own Undergraduate Research Diversity Supplement (URDS). (See E&O Project C.9.) Ideally, the CCEFP's URDS would positively influence a student to enter graduate school within the Center where a faculty advisor, in turn, would apply for the NSF GRDS award. [Project Leaders: Alyssa Burger, CCEFP, Kim Stelson, UMN]

Project C.11 Innovative Engineers (IE)
The Innovative Engineers (IE) student group was formed in 2010 by engineering students at the University of Minnesota who were inspired to actively pursue renewable energy solutions for people in remote and developing areas. IE fills a need at the university by providing a space where engineering students can take part in active pedagogy, learning and honing their engineering skills by working on real projects. The CCEFP and the Eolos Wind Research Consortium have partnered with the Innovative Engineers Student Group to promote student engagement and to bring an awareness of fluid power to the student engineering community by sponsoring projects with fluid power components. [Project Leaders: Paul Imbertson, UMN]

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

Project D.1 Fluid Power Scholars/Interns
Internship programs bring opportunities for engineering students to gain practical experience working in the fluid power industry while providing host companies with access to a diverse pool of talented engineering students. Working with industry, the CCEFP created the the Fluid Power Scholars/Intern program and launched it in the summer of 2010. Twenty-five Fluid Power Scholars/Interns have been named to date through the cooperative efforts of faculty, industry, and CCEFP staff. Fluid Power Scholars/Interns receive a scholarship to an intensive three and one half-day instructional program in fluid power, taught at the Milwaukee School of Engineering's Fluid Power Institute, and then join a corporate supporter of the CCEFP for a paid summer internship. The Scholars/Interns Program is open to undergraduates who have successfully completed at least two years in an accredited engineering program in the United States. [Project Leader: Alyssa Burger, CCEFP]

Project D.2 Industry Student Networking
The goal of this project is to provide CCEFP students with opportunities to network within the fluid power industry in a variety of ways. In doing so, there are multiple benefits to students and companies: all students will better understand the fluid power industry and the applications of fluid power technology; companies will be able to meet, interact, learn about Center research, and discuss potential employment opportunities with students, benefiting from the fresh insights and perspectives that students bring to these these exchanges; students' efforts to find internships and later job opportunities in the fluid power industry will be facilitated. Channels utilized in this project include company tours, poster sessions, and resume exchanges as well as additional opportunities that extend the Center's outreach to more students and companies. [Project Leader: Alyssa Burger, CCEFP, Student Leadership Council]

Project D.5 CCEFP Webcast Series
The CCEFP hosts bi-weekly webcasts, each with two to three presenters describing either research projects or discussing Center-wide programs such as education an outreach projects, strategic planning initiatives, special topics, or project evaluation. The webcasts are open to all CCEFP students and faculty and to all CCEFP member companies. The webcasts are an important means for Center-wide communication and knowledge transfer. [Project Leader: Cherie Bandy, CCEFP, Alyssa Burger, CCEFP, Student Leadership Council]

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

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

E&O Programs and Projects, On Hold

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

Project C.7 Hydraulics Basic Training *(on hold)*
Work cooperatively with CCEFP industry members and member universities to develop a basic hydraulics training curriculum that can be easily disseminated to CCEFP engineering graduate students and incoming faculty members. Development of a complementary pneumatics curriculum is also planned.

Project D.3 Advanced Fluid Power Engineering Workshops *(on hold)*
The objective of this project is to facilitate knowledge transfer between CCEFP faculty and the Center's industry supporters (with a special focus on engineers in design and manufacturing positions) as well as other faculty and their students. These workshops enable individual faculty members in the Center to share their expertise in advanced topics relevant to fluid power, relating it to current and potential research activities. The first workshops were held in conjunction with a key industry trade show in March 2011. Future workshops will be held via webcasts and in conjunction with meetings generating strong industry and university attendance.

Sunsetted E&O Programs and Projects

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

Project A.3 Discovering Fluid Power Video
The CCEFP continues to reach out to audiences outside academic communities through the production and dissemination of videos. "Discovering Fluid Power, " a 25-minute television documentary produced by Twin Cities Public Television and the CCEFP, is shown nationwide on public television channels and is available for viewing at www.ccefp.org.

Project B.2 Project Lead The Way (PLTW)
Project Lead The Way (PLTW) is a not-for-profit national program dedicated to developing STEM-relevant courses for middle and high students.The National Fluid Power Association (NFPA) and PLTW are affiliated organizations within the CCEFP and, together with the Center, form a three-way partnership for this project. Initially, NFPA funding enabled the inclusion of new fluid power content in several of PLTW's high school and middle school curriculum modules. Now, faculty from CCEFP and engineers from CCEFP member companies serve as subject matter experts for PLTW, reviewing curriculum relevant to fluid power and identifying opportunities where new content can be inserted. CCEFP faculty and students are working with PLTW to develop the hands-on fluid power lab activities to complement PLTW curricula as well as approaches to assist PLTW teachers in using these materials. In addition, PLTW teachers participate in the CCEFP RET program. The newest cooperative effort in this partnership is the development of a fluid power simulator (see project C6). [Project Leader: Will Durfee, UMN]

Administration of the Education and Outreach Program
The E&O Program is lead and coordinated by Education Program Director Paul Imbertson and Education Outreach Director Alyssa Burger, assisted by Education Outreach Coordinator, Cherie Bandy. The Directors report to CCEFP Director Kim Stelson. Additionally, Principal Investigators of specific projects contribute to program direction and implementation.

The Education and Outreach Network (EON), comprised of one representative from each of the seven universities., facilitates communication among the CCEFP sites and is a core working group for a number of E&O initiatives.

Responsibility for fluid power education and outreach rests with every CCEFP participant. Each research and test bed project in the Center has an E&O component. The E&O activities of individual research projects are reported in the project update reports.

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EO Project A.1: Interactive Exhibits

Project Team Science Museum of Minnesota

Project Leader: Director of Physical Sciences, Engineering, & Math, J. Newlin

Other Personnel: Master Prototyper, Forrest Price
Master Prototyper, Peder Thomson
Head of Exhibit Production, Cliff Athorn
Senior Exhibit Developer, Chris Burda
Director of Learning Technologies, Keith Braafladt
Learning Technologies Specialist, Peter Kirschmann

1. Project Goals and Description

The purpose of this project is to educate the public about fluid power and the CCEFP through creating and displaying exhibits that convey the basic message of fluid power as well as exhibits that highlight CCEFP research. Prototypes and exhibits developed and field-tested at the Science Museum of Minnesota, an organization affiliated with the CCEFP, will serve as models for dissemination to other science museums around the world.

2. Project Role in Support the EO Program Strategy

SMM will support CCEFP by developing products for public exhibition that will reach Minnesota museum audiences and that can be replicated and/or adapted by other educators and program leaders for new audiences. These products will introduce public audiences to the concepts behind fluid power and the possibilities for future industrial and social applications of fluid power.

3. Achievements

SMM has pursued three approaches to date: working with senior undergraduate mechanical engineering classes to develop exhibit prototypes as capstone design projects, working with a team of high school students on a supermileage car, and building display prototypes in SMM's exhibit shop.

Capstone Projects In 2007, 2008, 2011, and 2012, small teams of University of Minnesota seniors developed exhibits as part of their capstone design courses. The first (2007) was an exhibit about a hydraulic scheme for regenerative braking in vehicles. The second (2007) was a an exhibit that introduced two basic principles of fluid mechanics - the use of fluids to transmit force and the development of mechanical advantage through coupling cylinders of different diameters. The third (2008) was a comparison of the use of pulse-width modulation for control of electrical lighting circuits with its use for controlling fluid power applications. The fourth (2008) was a prototype of a water-based fluid power experiment lab for use by museum visitors. The fifth (2011) was an exhibit that demonstrates the power of hydraulics to assist human effort and shows a model of a hydraulic-powered ankle orthosis. The sixth (2012) was an exhibit that demonstrates the use of an open accumulator to capture energy from a wind turbine (Figures 6 – 7). The first of these exhibits has been on display at the museum since 2007 (Figure 1). Another inspired the hydraulics lab exhibit (see description below) on display since 2010 and improved by museum staff in 2012. The sixth exhibit has been on display at the museum since July, 2012. Plans for this coming year include rebuilding the hydraulic assist exhibit so it can be placed on the museum floor.

High School Project In 2008, an SMM prototyper (Price) worked an advisor to a team of students from Eden Prairie High School who developed a hydraulic hybrid Supermileage Car. The team ran the car, powered by a 1 cylinder gasoline engine controlled to pump fluid into an accumulator at its most efficient speed and torque, in a supermileage contest and achieved a mileage of 170 miles per gallon. Since the contest did not include stops and restarts, the hydraulic regenerative braking system did not come into play. Students improved the car after the contest and then worked with SMM staff to prepare it for display. It was on exhibit floor from 2008 until summer, 2012.

Museum Projects SMM prototypers have produced two finished exhibits that are now on display on the museum floor. One of these is a hydraulic variable torque transmission with accumulator-based energy storage. This exhibit was on display from 2008 until summer 2012. The second is a working cut-away variable-displacement axial piston pump arranged to pump tall streams of clear hydraulic fluid (Figure 2). This exhibit has been on display since 2008.

SMM built a Hydraulics Lab (Figures 3 – 5) that allows museum visitors to set up their own fluid power demonstrations and experiments. This bench consists of a large shallow work surface mounted on legs at table height. Visitors use clear water tubes with quick-connect fittings to build fluid power circuits that include pumps and reservoirs; check valves and spool valves; flow indicators; raised tanks and pressurized accumulators; and actuators of various kinds. In 2012, SMM relocated and redesigned the exhibit to improve both visitor interaction and daily maintenance. SMM added two attractive hydraulic devices and challenged visitors to make them work. One is an imaginative carousel operated by a Pelton wheel. The second is a large bell that can be rung by operating a double-acting hydraulic cylinder. To make using the lab easier for visitors, SMM installed a touch-screen video display that shows how to make hydraulic tube and device connections and how to build hydraulic circuits that incorporate pumps, check valves, flow meters, spool valves, and accumulators. The Hydraulics Lab includes three exhibits that define simple hydraulic circuits (Figure 5):

a. At Pumped Water Storage, visitors use a cylinder pump with two transparent check valves to pump water from a lower reservoir into a high reservoir. They then open a valve to release the water to operate a Pelton wheel that drives a small generator, which lights several LEDs.
b. At Variable Force Pump, visitors pump water out of a reservoir, through a check valve, into and out of a piston pump, through a second check valve, and back into the reservoir.
c. At Accumulator, visitors use a piston pump to force water from a reservoir through a spool valve into an accumulator. By changing the spool valve position, they allow the pressurized water to flow through a flow meter back into the reservoir.

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

SMM has refurbished and installed an exhibit that uses a very low friction pneumatic bearing to support a large Double-weight Pendulum. This consists of a granite spherical cap supported by air flowing into a spherically-ground concave base. A rod extends vertically from the center of the cap on which visitors may adjust a weight to change the vibration frequency of this double weight pendulum.

There has been an expanding group of Fluid Power exhibits on display at the Science Museum of Minnesota since 2008. They now include Axial Piston Pump, Hydraulic Hybrid Car, Hydraulics Lab, Pneumatic Ball Run, and Compressed Air Wind Energy Storage.

SMM has also developed a Fluid Power Activity Kit that museum volunteers use to introduce visitors to concepts in fluid power. Visitors experiment with a long-tube water level, syringe systems filled with air and water, a hydraulic jack, an "airzooka" that sends a puff of air ten feet, and a set of air-powered cylinders and valves that toss and catch tennis balls. This activity is presented regularly at the Experiment Gallery Activity Station.

Exhibit Brochure: SMM prepared an illustrated proposal of four exhibits that could be replicated for other museums, for CCEFP partner university student centers, or for the lobbies of major fluid power companies. These exhibits include Axial Piston Pump, Hydraulic Transmission, Hydraulic Hybrid Car, and Hydraulics Lab. Replication of single exhibits is fairly expensive with a range of $35,000 to $60,000 each. Producing multiple copies could significantly reduce the cost of single exhibits.

In late August 2010, SMM joined Eric Lanke of the National Fluid Power Association in a presentation and discussion of potential fluid power exhibits at Milwaukee's Discovery World science center. These exhibits could be supported by NFPA companies and at least partially built by NFPA volunteers.

SMM worked with CCEFP E&O staff to develop a proposal for a capstone design competition that would involve mechanical and electrical engineering students from all CCEFP partner universities.

4. Plans, Milestones and Deliverables

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

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

SMM will work with CCEFP and NFPA staff to develop a practicable plan to distribute core exhibits on fluid power to science centers associated with CCEFP partners, to participating university student centers, and beyond.

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

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

Figure 1: Hydraulic Hybrid Car

Figure 2: Axial Piston Pump

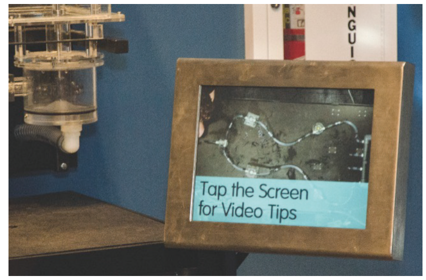
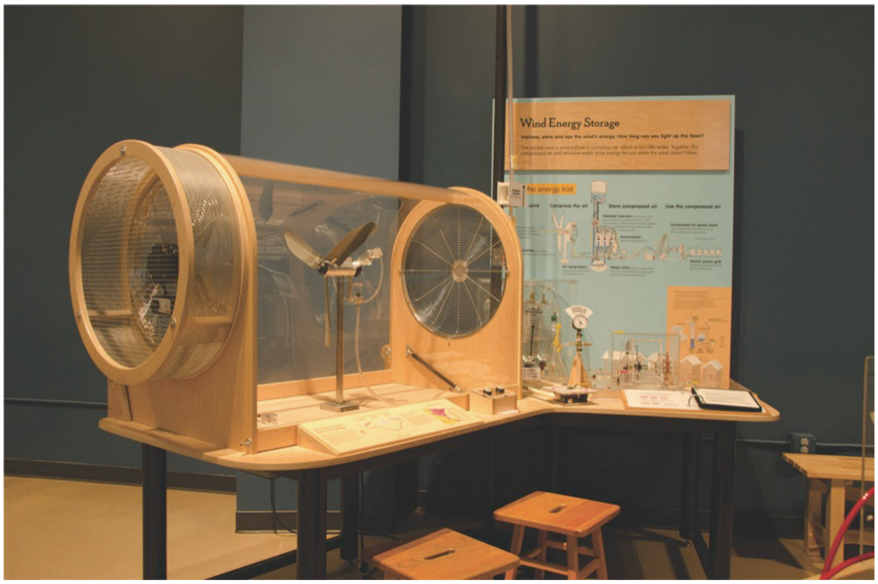


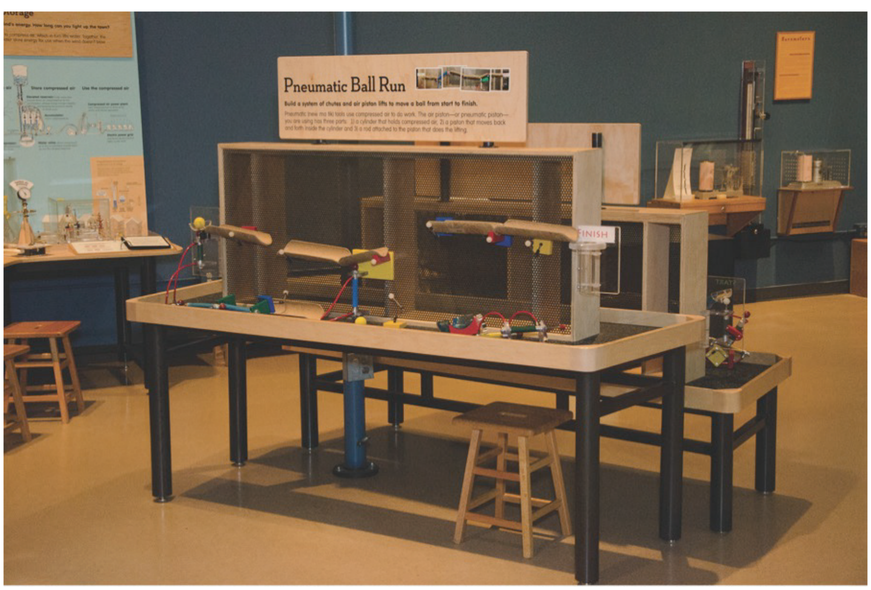
Figure 3: Hydraulics Lab (Left)

Figure 4: Hydraulics Lab Touch Screen Instructions (Above)

Figure 5: Simple Hydraulic Circuits



Figures 6 - 7: Compressed Air Wind Energy Storage



Figures 8: Pneumatic Ball Run

Project A.3: Multimedia Educational Materials

Project Team

Project Leader:	Alyssa Burger, CCEFP Education Outreach Director
Other Personnel:	Kim Stelson, CCEFP Director
Industrial partners:	John Lumkes, Purdue University

1. Project Goals

The CCEFP leverages the use of multimedia to inform, train, educate and interest the general public in fluid power technology. The CCEFP is utilizing audiovisual technology to promote hydraulics and pneumatics to demonstrate how these systems are part of society's everyday operation. In 2008, the CCEFP and NFPA produced two videos: *Discovering Fluid Power* and *Fluid Power: The Force for Change* for both public and private use. Both organizations regularly disseminate the video, it is offered on public television outlets and has been broadcast across the world. The Center's *Discovering Fluid Power* has been successful in this outreach effort. Additionally, a three-part video, *Teaching with Fluid Power*, produced by the CCEFP, is available at the Center website. Lastly, a sponsored CCEFP project includes the Fluid Power Educational Smart-App for Mobile Devices - a gaming mechanism for interactive fluid power learning (See Project A.3a).

2. How Project Supports the EO Program Strategy

The CCEFP's Education and Outreach Program supports the transfer of knowledge among the Center's many constituents. Here, using video as the communication medium, pre-college teachers, students and teachers as well as the general public are the focus for knowledge transfer.

- General public, teachers and students: The new Fluid Power Educational Gaming App is a novel mechanism to providing a fun and engaging teaching and learning tool. The fluid power app will use hydraulic and pneumatic componentry to teach physics principles. The game will allow users to input system pressure, modify cylinder areas, stroke lengths, valve sizes to launch a projectile or smash large objects. Users will be able to utilize points to "purchase" additional components by performance (size, speed, etc.) so users can determine the design of the system for maximum performance. The game will have a tutorial on how the components function with basic equations. There will be a additional levels unlocked with each graduated high score. Educational Impact: The target audience is 6-12 grades, although the App could be downloaded by all ages. Depending on the underlying physics models it could be distributed through pre-engineering programs in high schools, and/or used to supplement PLTW curriculum. At the basic level the game should be fun to play, with the motivation for "learning fluid power" embedded in the ability to score more points. The impact is hard to access in a general sense, since only the number of downloads is known, not how the App is utilized. In a school setting it would be possible, and beneficial, to develop a pre- post-use skills survey to assess the knowledge gained, and the perception of the game. For more information, see Project A.3a.

- Pre-college teachers: *Teaching with Fluid Power* is a three-part video developed to help classroom teachers devise lessons and hands-on activities that will help students better understand fluid power technology. While particularly well-suited for use in Project Lead The Way classrooms, the content of this video can be easily used by all teachers of middle- to high school age students.

- General public, teachers and students: *Discovering Fluid Power,* a 25-minute documentary video, offers a basic introduction to fluid power technology and features footage, with accompanying narratives, which highlight the many applications of hydraulics and pneumatics. The production and distribution of *Discovering Fluid Power* is an excellent example of another CCEFP strategy—

seeking out strong partners to help and support the Center's education and outreach program. Produced in collaboration with the National Fluid Power Association (NFPA is an affiliate organization of the CCEFP) and Twin Cities Public Television (TPT), *Discovering Fluid Power* is a companion to NFPA's video, *Fluid Power: A Force for Change,* which focuses on careers in fluid power. Much of the application footage in both videos was contributed by the Center's industry supporters and by fluid power trade associations around the world. Students and faculty of the CCEFP as well as industry representatives provide the narratives for both videos. *Discovering Fluid Power* and *Fluid Power: A Force for Change* are appropriate for upper elementary, middle and high school students as well as for adult audiences.

3. Achievements

- In Y7, the CCEFP provided a small grant to Professor Lumkes at Purdue University to create the Fluid Power Educational Game App. To date, significant progress has been made by a team of undergraduate and high school students including: choosing a game type, creating the game concept and storyboard, determine which fluid power concepts will be introduced, choosing an open source platform (Android) and educating the team on Java programming. Next steps include game production, program development, graphic enhancement and game level integration. For more information, see Project A.3a.

- The CCEFP applied to the NSF Connecting Researchers with Public Audiences funding solicitation in April 2012. The proposal included a complimentary video to *Discovering Fluid Power* titled *Discovering Wind Power*, in co-production with Twin Cities Public Television. The video proposed to communicate ongoing research in wind energy to public audiences. That proposal received positive reviews but was ultimately rejected.

- 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 2012, the following summary of promotions and successes 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 in Project B.3.

- *Teaching with Fluid Power* is available, at no charge, to the public at the CCEFP website. It is also a resource for Project Lead The Way.

4. Plans, Milestones and Deliverables

- Fluid Power Educational Game App is in the design and production phase. Deliverables include a beta app at the end of the project.

- *Discovering Fluid Power*: The producers at Twin Cities Public Television, along with industry and Center reviewers, took special care to insure a long “shelf life” for this video. With that said, the video will soon be five years old hence active promotions have tapered off. While the video will continue to be available to many audiences through the above channels, active efforts will focus on getting as many copies as possible into classrooms. In doing so, the CCEFP will capitalize on links to industry and educational websites; promote the video as a learning tool to middle school, high school, technical college and university educators; and engage the Center’s universities and other partners in using their networks to promote and distribute the video.

6. Member Company Benefits

The smart app and videos are a promotional as well as an educational tool for the fluid power industry and for the Center. The cooperative efforts between industry, NFPA and the CCEFP in preparing multimedia tools 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 these multimedia devices to as many audiences as possible. The fluid power industry benefits as more teachers and students learn about fluid power. By using the video and game app as a communication tool, the CCEFP is able to reach many audiences in many locations.

A.3a Fluid Power Educational Smart-App for Mobile Devices

Project Team

Project Leader: John Lumkes, Purdue University

Other Personnel: Luke Mishler, Purdue University
Two McCutcheon High School students (seniors)

1. **Project Goals and Description**

Video gaming is one of America's growing past-times. The CCEFP is leveraging this phenomenon that is part of our culture, especially with the advent of smartphones and tablets, to create a gaming mechanism attractive to both the expert and the novice "gamer". By utilizing this interactive mode of learning in the educational realm, gaming through smart device applications can reach a broad audience and a wide range of gaming enthusiasts.

This project relies on mentoring relationships between faculty, undergraduate students, and high school students to help with the development of a mobile "App" for smartphones and tablets. The fluid power based app will use physics based models to complete a game. Users will be able to input system pressure and modify the cylinder areas, stroke lengths, valve sizes, etc., to launch a projectile or to smash objects. Component costs would scale by performance (size, speed, etc.), so that when a maximum cost is imposed, or reflected in the score, users can decide what "design" tradeoffs provide the best performance. Selecting "question mark" icons while choosing components would pop-up a small "tutorial" on how that component functions, some basic equations, etc. Once a certain score is reached, additional components (pump, accumulator, etc.) can be purchased.

2. **How Project Supports the EO Program Strategy**

The target audience is grades 6-12, although the App could be downloaded by all ages. Depending on the underlying physics models it could be distributed through pre-engineering programs in high schools, and/or used to supplement Project Lead The Way Gateway to Technology Fluid Power curriculum. At the basic level the game should be fun to play, with the motivation for "learning fluid power" embedded in the ability to score more points. The impact is hard to access in a general sense, since only the number of downloads is known, not how the App is utilized. In a school setting it would be possible, and beneficial, to develop a pre- post-use skills survey to assess the knowledge gained, and the perception of the game.

3. **Accomplishments**

The first semester of the Fluid Power Educational App project was focused on choosing a game type, establishing when and what fluid power concepts would be introduced, creating the game concept, choosing a platform, and educating the team on Java programming and game design. Many game types were considered and their attributes weighed. For example, demolition games are a perennial favorite because designing destruction is straightforward and immediately gratifying. Specific games that have been particular hits on mobile platforms were also analyzed to see for common characteristics. For example, Angry Birds, Fruit Ninja, and Temple Run (some of the most popular mobile games ever) all feature rapid level progression instead of long play-through levels. It was concluded that a demolition type game would most lend itself to the mechanics of fluid power.

The common components of fluid power systems, including pumps, directional control valves, motors, flow control valves, and cylinders were listed along with the equations and concepts associate with each. The components that are most intuitive, able to teach the most concepts, and are directly related to mechanical motion were selected for use in the game. One such component is the hydraulic cylinder that is simple and mechanical but still demonstrates the relationship between pressure and force, and flow to motion. The final components to be included in the game are cylinders, pumps, motors, tanks, and accumulators.

Combining the decisions from the game and game type analysis, a loose game structure was made. The player will use a machine to drive along a side-scrolling world and demolish buildings. The Machine will have equipment based on real hydraulic demolition equipment (such as a jack hammer, wrecking ball, excavator, shears, etc.). The player will use a separate menu to "Build and Upgrade" this demolition equipment from a component up basis. They will "purchase" components with points earned in the game and will be presented with the proper equations to understand how these components will affect the performance of their equipment.

Android was selected as the platform for the initial game production and release because the programing language (Java) is generally considered easier to learn than the one for iOS (visual-C). Furthermore, there are many more tools and the programing environment availability and flexibility are better for Java.

The balance of the time was invested in educating the team in Java programming. An undergraduate student who has been working with CCEFP outreach programs since he was in high school advised the high school students in this. The students had very little experience with programing, so the basics of programming through the game design and graphic rendering had to be learned. The high school students were also taught the circuitry and fluid power knowledge necessary to understand the fluid power side of the game. Preliminary flow charts for the programing were made.

4. **Plans**

The team feels it is now ready to begin on the game production stage and so program development starting with menus and graphics will begin immediately. Following that, physics and gameplay design will proceed until a working game is developed. The final step in the process will be level design. A significant level library is critical to the success of the app after release and once all of the machine and physics components are in place, level generation should be quite easy.

5. **Milestones and Deliverables**

The milestone and deliverable is to have a working beta version app at the conclusion of the project.

6. Member Company Benefits

This project will directly benefit member companies involved in fluid power by providing a learning and gaming tool to capture the imagination of future engineers, their future workforce.

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

Project Team

Project Leader: Alyssa Burger, Education Outreach Director, CCEFP

Other Personnel:CCEFP faculty advisors

1. Project Goals

The CCEFP's RET program enables teachers in pre-college schools to introduce fluid power to their students, drawing on their experiences in CCEFP research labs. In this six-week summer program, teachers learn first-hand about fluid power basics and are engaged in research through their work in the Center's university network. With these experiences as a foundation, teachers develop research-inspired curriculum modules to bring back to their classroom. Special efforts are made to recruit Project Lead The Way (PLTW) teachers to this program in geographic locations where the Center's RET program is hosted and where PLTW has a presence.

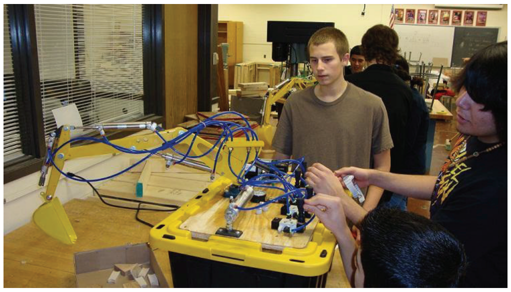
2. How Project Supports the EO Program Strategy

The RET program is an example of the CCEFP's strategy to maximize program impact: one teacher reaches many students; many teachers reach many classrooms. And, in sharing the curriculum modules they develop, RET teachers support another key CCEFP strategy—development of projects that can be replicated and/or adapted by other educators for new audiences. The work of RETs can be used by a host of teachers who have not participated in the RET program.

3. Achievements

- Six teachers participated as RETs in summer 2012, the sixth year of the CCEFP RET program: four at Purdue University and two at North Carolina A&T State University.
- 42 teachers have participated in the CCEFP RET program since it's inception, and several have been repeat participants.
- The CCEFP requires that all RET participants submit their classroom curriculum to the TeachEngineering.com website which is a repository of evaluated and reviewed curriculum modules. The CCEFP is the only ERC to have RET curriculum modules successfully accepted to the site. The three curriculum modules that have been accepted are named below; six more are under review.
    - Hybrid Vehicle Design Challenge - Joel Daniels, Vanderbilt, CCEFP RET 2009
    - Fun with Air-Powered Pneumatics - Jacob Givand, Jeffrey and Melissa Schreifels, University of Minnesota, CCEFP RET 2009
    - Fluid Power Basics - Brian Bettag, Purdue, CCEFP RET 2009

  The CCEFP encourages each RET to beta test the curriculum modules s/he has developed in the school year following the RET experience, modifying as necessary, and then submitting it as a final module at the end of the academic year. TeachEngineering.com then helps to review, edit and craft the curriculum for a well-rounded module. The modules are indicative of state standards as well.
- A 2012 RET team at Purdue University continued to work on the Fluid Power Demonstrator Kit and Curriculum under the guidance of Professor John Lumkes. (See EO Project B.2 of this report for additional details.) Professor John Lumkes, along with two teachers and a number of high school students, visited Bangang in Cameroon, Africa in May 2012. Students will assist local villagers with the task of retrieving fresh water by using fluid power technology and equipment.



    - **Summary:** Students learn about the basic

fundamental concepts of human power pumping, which include defining key terms, history of pumps, and appropriate technology.
- **Engineering Connection:** Engineers have developed many pumps over the years to be used depending on the availability of supplies and location of water supply. Understanding how the basics of water pumping work; will allow continued improvement on the quality of life when engineers and technologists investigate how to use this technology to become more efficient, sustainable and cost effective.
- **Learning Objectives:** After this lesson, students should be able to: Identify different types of hand pumps; Identify and explain basic components and functions of a working pump; Differentiate between different kinds of pumps for certain tasks; Create and test a new pump.
- **Africa Trip:** Professor Lumkes and the RETs chaperoned a group of four senior students from McCutheon High School to the village of Bangang in Cameroon, Africa, May 2012. Students will assist local villagers with the task of retrieving fresh water by using fluid power technology and equipment. The students designed a PVC water pump that worked in local village schools. Students worked on two additional projects: A Hydraulic Clay Brick Press and a PTO shaft water pump. Student successfully raised their own travel funds. A YouTube video captures the result of the activity, from the students' perspective: https://www.youtube.com/watch?feature=player_embedded&v=gYlxvnX969g#!
- Mr. Gary Werner and two McCutheon high school students will visit the NSF Site Team at the 2013 CCEFP Site Visit at Purdue.

- Other relevant work: In addition to their summer research experiences, the CCEFP encourages cross-collaboration with other activities within the Center such as outreach activities, workshops and piloting curricula. RETs are encouraged to remain a part of the Center by bringing their classrooms to campus for a tour, or other such opportunities. Several of these RET projects are connected to other E&O Projects. Also, further work has been invested in an on-line repository of teaching and learning materials at the CCEFP.org website. Materials can be found: *www.ccefp.org -> Get Involved -> Educators -> Teaching and Learning Materials*. Such materials include:
  - TeachEngineering.com fluid power curriculum by CCEFP RETs
  - Teaching Fluid Power video tutorials by Professor William Durfee, UMN
  - Fluid Power Demonstrator Kit and Curriculum by Professor John Lumkes, Purdue
  - Pneumatics Demonstrator Kit (Ball and Cup) and Curriculum by Professor Will Durfee, UMN
  - Fluid Power Hands-on Tools designed by the Science Museum of Minnesota Youth Science Team
  - Supply sources for fluid power teaching and learning materials

- Past CCEFP RET Programs:
  - **2011:** Six teachers participated in summer 2011, the fifth year of the CCEFP RET program: two at the University of Minnesota, two at Vanderbilt and two at Purdue University.
  - **2010**: Six teachers participated in summer 2010, the fourth year of the CCEFP RET program: two at the University of Minnesota, two at Vanderbilt and two at Purdue University.
    - Three of the six were Project Lead The Way (PLTW) teachers. PLTW assists by recruiting PLTW teachers for the CCEFP RET program.
    - The CCEFP held its Annual Meeting in June 2010 at Purdue University in West Lafeyette, IN . All RET teachers attended the meeting which included an program orientation led by Prof. Stacy Klein-Gardner from Vanderbilt University.
  - **2009**: Twelve teachers participated in summer 2009, the third year of the CCEFP RET program: five at the University of Minnesota, two at Vanderbilt, two at North Carolina A&T, and two at Milwaukee School of Engineering.

        - The three teachers from the University of Minnesota from the 2008 program returned for a second summer and leveraged their previous experience in mentoring the new participants as well as getting a head start on their project.
        - Seven of the 2009 RETs attended the Vanderbilt RET Boot Camp in Nashville. This helped cross-collaboration among the teachers, as well as renewed some previous acquaintances as several teachers had participated in PLTW teacher trainings in the past.
    - **2008**: Eight teachers participated in the RET summer 2008 program; three at the University of Minnesota, two at Vanderbilt, one at Georgia Tech, and two at MSOE.
        - At three of the four schools, pairs (one trio) of teachers were hired together in order help all maximize their learning experiences.
        - The 2008 program was the first to bridge with another NSF program by fostering cross-collaboration with the NSF RET VaNTH Site at Vanderbilt University. A total of ten of the 2008 and 2009 teachers have attended the three-day RET orientation there hosted by Dr. Stacy Klein Gardner. In addition to providing a good introduction to the RET program, the event enabled teachers at different CCEFP sites to make connections and begin networking. During the RET "boot camp," participants learned to translate research into a curriculum module and also learned strategies to connect current content with new content. Not only are lesson plans designed around state education standards, but Dr. Klein Gardner also encourages curriculum writing surrounding The Legacy Cycle. Teachers were required to modify their curricula to meet the standards of the NSF-sponsored TeachEngineering.com, an on-line repository of tools for K-12 teachers.

4. Plans, Milestones and Deliverables

- In 2013, the CCEFP commits to hosting four teachers within its university network, two at Purdue, two at NCAT.
- The Center will promote the newly developed fluid power curriculum modules at its website, on TeachEngineering.com, on YouTube and TeacherTube, as well as on other appropriate channels.
- The CCEFP will continue to enable access to this curricula through its OpenCourseWare project (see C.2).
- The Center will continue to leverage the Project Lead The Way (PLTW) teacher network for recruiting.
- The model of multi-year RET participation proved to be successful at UMN in years 2008-2012. The CCEFP will encourage this model wherever possible and will engage the RETs throughout the year in the implementation of their curricula.
- A challenge is to remain connected to the teacher once the summer session is over as well as remaining in contact in the years following the RET experience. The CCEFP aims to encourage faculty advisors to communicate regularly with the teacher participants and inquire as to the status of the curriculum implementation and development.

5. Member Company Benefits

Following their RET experiences, teachers can bring their experiences in university research as well as their expanded understanding of fluid power concepts to their classrooms. New curricula stemming from these experiences should inspire and motivate a next generation of leaders in the engineering, corporate and/or academic arena.

EO Project B.3: Hands-on Fluid Power Outreach

Project Team

Project Leader: Alyssa A. Burger, Education Outreach Director

Other Personnel: Will Durfee, University of Minnesota
John Lumkes, Purdue University
CCEFP Faculty
CCEFP Student Leadership Council
CCEFP Graduate Students

Industry Partners: Donaldson
Bimba Manufacturing Company

1. Project Goals

Through this project portable demonstration kits and curricular materials have been developed for use in hands-on workshops about hydraulics and pneumatics. 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 the EO program strategy in several ways. Workshops based on pneumatics and hydraulics serve to broaden an awareness of fluid power among pre-college students and their teachers, undergraduate students and the general public. The strategy for the CCEFP EO program is to leverage existing networks. Workshop contents could be used in Project Lead The Way curriculum, 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

- In Y7, **1,135** student and community members participated in CCEFP outreach events; more than **614** volunteer hours clocked by ERC staff and ERC students at these events.
- In Y7, teams of Purdue REU and undergraduate students were recruited to help design a new ‘nano’ Portable Fluid Power Demonstrator (PFPD) kit and curriculum. The 2012/2013 efforts have focused on a new multi-actuator smaller educational tool that can be easily transported, doesn’t require any setup or water, can be plugged into any 110/220V outlet, and introduces students to fluid power and the interaction of electronics, microcontrollers, and actuators in fluid power systems.
- In Y7, the original PFPD are still being utilized at Purdue (and other CCEFP institutions) during various K-12 outreach programs, museums, high schools, conferences, and distributed to CCEFP member universities. The previous demonstrators have been successful in classrooms, science museums, on campus programs and other engagement activities. However, their size, weight and large loose components make long-range travel, shipping, and transporting as baggage on airlines unnecessarily difficult.
- In Y7, the Student Leadership Council launched a Project Grant program in which the SLC distributed funds to students at CCEFP institutions to host outreach events, often utilizing the Portable Fluid Power Demonstrator. In the recent year, seven project grant proposals were awarded to students at various institutions by the SLC. Two of those grants were utilized to build

the portable fluid power demonstration excavator kits for their institution. Below is a testimonial from CCEFP students who utilized the project grant program:

> "As part of CCEFP's education and outreach program, we exhibit miniature hydraulic excavators (built in Purdue) at the Engineering Open House (EOH) of UIUC each year. For our exhibit, we displayed two different hydraulic excavators each utilizing a different type of valve actuation. To complement the instructions, we had posters explaining the working principle of these excavators. We also provided the students with learning materials and toys to encourage them to learn more about fluid power and the research projects at CCEFP. The SLC project grant money was used to purchase foam giveaway toys, purchase some components needed to repair the toy excavators, and provide lunch to those helping with the exhibit." - Ashwin Ramesh

- In a single reporting year, over **26** unique fluid power outreach events have occurred across the CCEFP. Outreach events include laboratory and demonstration tours, fluid power activities and engineering workshops, mentoring, special group presentations (Women in Engineering, Juniors Exploring Engineering, Innovative Engineers), challenges and competitions (NFPA Fluid Power Challenge, Hydraulic Bicycle Competition), family fun fairs, math and science fairs, campus engineering week celebrations, etc. Thousands are exposed to fluid power through these outreach events including K-8, high school, community college, undergraduate and graduate students, community and public audiences.

Pneumatics Kit

Portable Fluid Power Demonstrator

4. Plans

- 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.
- 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.
- Plans include kit revision to the pneumatics kit (B.3a); including better availability of hard-to-find components, update the instructions and presentation materials and development a workshop for professionals.
- The near term goals for the Nano PFPD project (Project B.3b) include the development and subsequent assessment of a new, smaller and more portable, fluid power educational platform.

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 2013.
- Updated kit and curriculum for both pneumatics and hydraulics kit.
- The Student Leadership Council is leading an effort to support fluid power outreach events by providing funding to students to organize and initiate additional activities.

6. Member Company Benefits

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

CCEFP Fluid Power Outreach Events – 2012-13

Date	Event type
02.01.2012	Undergrad outreach in Greensboro, NC
02.17.2012	Workshop and Purdue Maha Lab tour
02.17.2012	Outreach to White Earth Indian Reservation - Circle of Life School
02.29.2012	Collaboration with Bradley University
03.09.2012	Engineering Open House; UIUC
03.09.2012	Demonstrate fluid power using mini excavator kits at Engineering Open House; UIUC
03.13.2012	Research Experience for Teachers Program; Vanderbilt U
04.12.2012	Hydraulic bicycle competition; Irvine, CA
04.13.2012	Outreach; White Earth Indian Reservation - Circle of Life School
04.16.2012	Women in Engineering Event; Purdue U
04.16.2012	Women in Engineering Event; Purdue U
05.16.2012	Outreach and Implementation; Jinotega, Nicaragua
06.03.2012	REU Orientation and Welcome; Purdue U
06.03.2012	Engineering Workshop; Purdue
06.04.2012	Annual Summer Enrichment Program on Robotics; Roswel, Georgia
06.26.2012	Outreach; White Earth Indian Reservation - Circle of Life School
07.11.2012	Introduction to Engineering; Purdue ABE Fluid Power Lab
08.22.2012	Outreach to students to promote interest in STEM fields; Vanderbilt U
08.22.2012	Lab Tour; Vanderbilt U STORM Lab
09.26.2012	Lab Tour in conjunction with the National Fluid Power Association Educator's Summit; UIUC
10.17.2012	Outreach; White Earth Indian Reservation - Circle of Life School
11.09.2012	Innovative Engineers / BRIDGE Wind Demonstration; White Earth Indian Reservation - Circle of Life School
11.27.2012	Outreach to White Earth Indian Reservation - Circle of Life School
11.28.2012	Outreach Tutorial; Vanderbilt U
01.07.2013	Education and Outreach to wide public audience; fluid power workforce
01.10.2013	Ongoing mentorship for year-long project

EO Project B.3a: Hands-On Pneumatics Workshops

Project team:

Project Co-Leaders: Prof. Will Durfee, University of Minnesota, CCEFP

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 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

- Outreach workshops using the kits were conducted throughout the year

4. Plans

- Revise the kit, based on feedback from teachers, so that it is more suitable for the typical classroom. The main change is to eliminate from the kit components easily found by teachers but keeping the harder-to-find fluid power components
- Update the teacher instructions and presentation materials
- Develop a version of the workshop for professionals with a target market of employees in engineering, marketing and sales at fluid power companies who are new to fluid power. The workshop would be intended for company in-service training. .

5. Milestones and Deliverables

- Maintain the number of workshops
- Curriculum and instructors guide 2.0
- Revised kit based on teacher feedback

6. Member Company Benefits

Increased awareness of fluid power by a growing number of pre-college students.

Project B3.b: Portable Fluid Power Demonstrator and Curriculum

Project Team

Project Leader: Professor, John Lumkes, Purdue University

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

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

1. Project Goals and Description

The Portable Fluid Power Demonstrator (PFPD) was developed for K-12 classrooms, with an initial focus on middle and high schools. The kits can enhance current and enable new activities for organizations that include PLTW, FIRST Robotics, science museums, children's museums, and for activities within the CCEFP. The PFPD is being used to promote awareness and/or increase interest of fluid power education in high school grades 8-12. Through the addition of microcontrollers the PFPD can be used to teach robotics and mechatronics.

2. Project Role in Support the EO Program Strategy

This project directly supports the CCEFP mission to "develop research inspired, industry practice directed education for pre-college, university and practitioner students; to integrate research findings into education; to educate the general public; and through active recruiting and retention, to increase the diversity of students and practitioners in the fluid power research and industry". Project B.3.b specifically targets the fifth component of the ERC's vision for education, to "increase public and K-12 student awareness of the importance of fluid power, and the excitement and possibilities that new technologies of the Center will bring".

3. Achievements

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

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

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

A careful analysis of learning objectives and other goal related limitations along with the mechanical design of the system resulted in the design of a pneumatic cantilevered gantry crane with position feedback and an electro magnet gripper at the end of a small electric winch. The device will be controlled by a micro-controller.

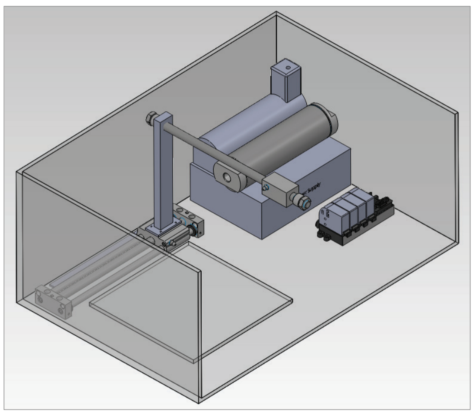
This one small device will demonstrate pneumatics, robotics, and potentially programming in environments where these topics were previously only discussed.

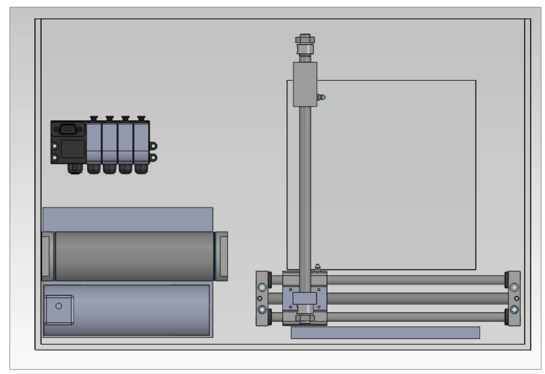
Summary of PFPD outreach activities to date

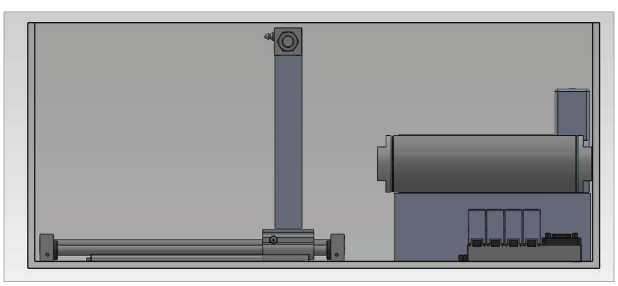
Between February 2012 and January 2013, Purdue offered five pre-college outreach programs. There were 91 participants, of whom 32 were female, 59 were male, and 43 were from under-represented ethnic groups.

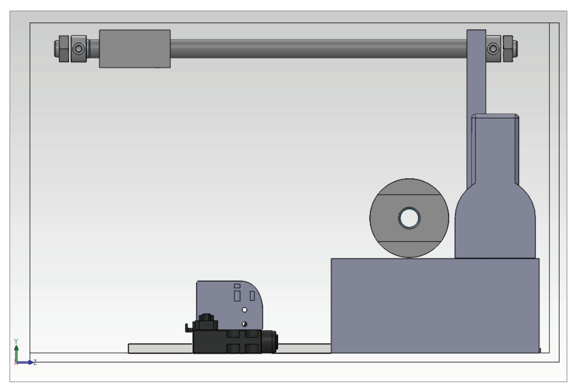
In total, Purdue has offered over 30 programs, reaching over 800 students with over 50% of the participants being female and/or from under-represented groups.

Since the project inception there have been multiple undergraduate students involved in the design, construction, and delivery (outreach programs), along with REU and RET participation in the summer and high school involvement on a variety of levels. The kits have been used at various high schools, state fairs, outreach events, tours, and workshops.









4. **Plans, Milestones and Deliverables?**
The near term goals for the project include the development and subsequent assessment of a new, smaller and more portable, fluid power educational platform.

5. **Member Company Benefits**
This project will directly benefit member companies involved in fluid power by providing a methodology and demonstration kits to capture the imagination of future engineers, their future workforce. All reports and publications will be available to Center members

EO Project B.4: *gidaa* STEM Programs

Project Team

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

Other Personnel: Holly Pellerin, *gidaa* Coordinator
Lowana Greensky, Director of American Indian Education in St. Louis County Schools

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 American students, 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. gidaa is a hands-on STEM outreach program - science, technology, engineering, arts and math, which are taught all together.

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 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.

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.

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)
- Annual local, regional and national science fairs (NCED, CCEFP, *gidaa*)
- *gidaa* manoomin (Wild Rice) Project (NCED, LaCore, Geology - University of Minnesota)

2. How Project Supports the EO Program Strategy

Essential elements of the CCEFP strategic plan include promoting diversity in science, technology, engineering, arts and math fields and preparing Native American youths for these 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 fourth year of the odaangiina anaangoog (Shooting for the Stars) Robotics Program. The *gidaa* feeder schools such as South Ridge School (formerly Albrook School) currently host the robotics activities. This program includes day and after-school robotics courses, CCEFP Project B.4b.
- 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

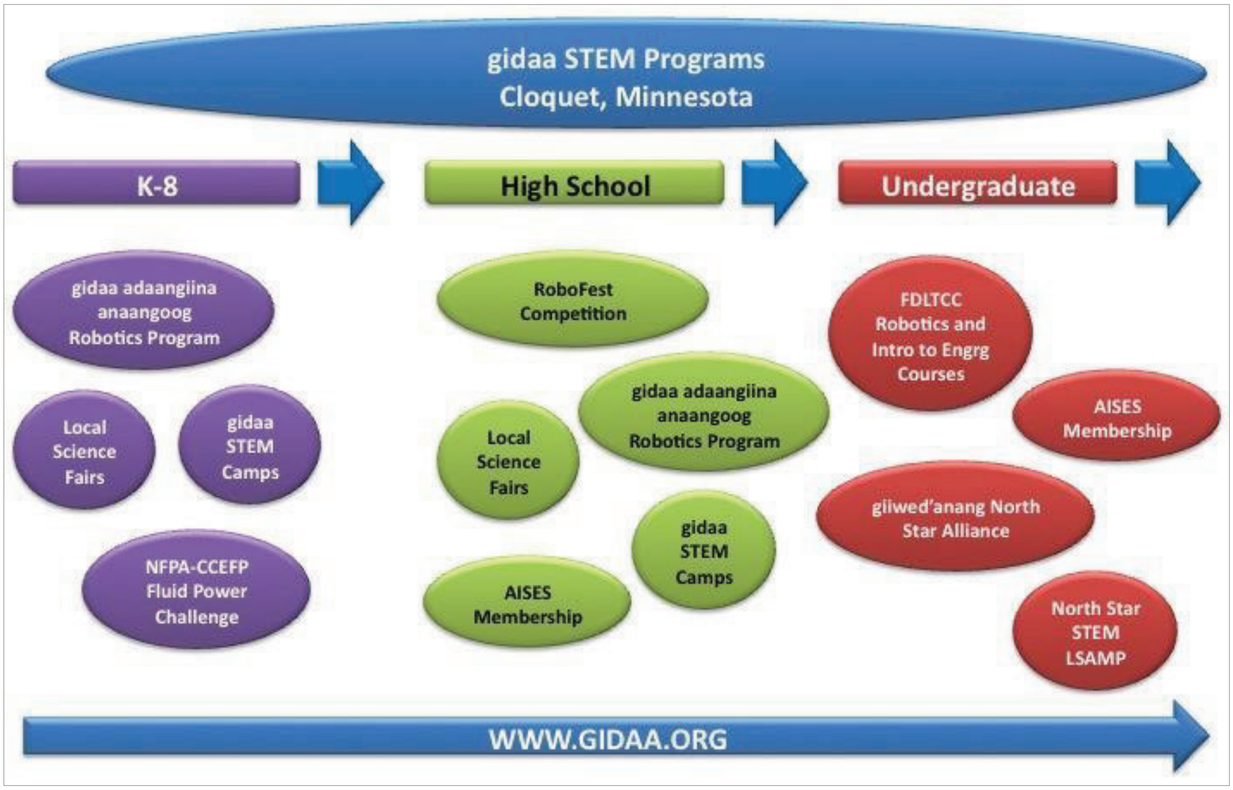
The leadership of the *gidaa* program will continue to apply for funding in order to duplicate *gidaa* in geographic locations where there is a critical mass of Native American communities. The manoomin Project is a good example of the type of funding *gidaa* is seeking. Whenever possible, the two (or more) *gidaa* programs can bridge events and activities to create a stronger network of Native American students learning about STEM. 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.


gidaa STEM Programs
Cloquet, Minnesota
K-8
High School
Undergraduate
gidaa adaangiina anaangoog Robotics Program
Local Science Fairs
gidaa STEM Camps
NFPA-CCEFP Fluid Power Challenge
RoboFest Competition
gidaa adaangiina anaangoog Robotics Program
Local Science Fairs
gidaa STEM Camps
AISES Membership
FDLTCC Robotics and Intro to Engrg Courses
AISES Membership
gliwed'anang North Star Alliance
North Star STEM LSAMP
WWW.GIDAA.ORG

EO Project B.4b: gidaa odaangiina anaangoog (Shooting for the Stars) Robotics Program

Project Team

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

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

1. Project Goals

The goal of the gidaa odaangiina anaangoog Robotics Program is to to interest and prepare Native American youths for STEM careers. This effort is closely aligned with the Center's goal of developing research inspired, industry relevant education for students of all ages. As the successful FIRST Robotics program attests, robotics is an effective channel for introducing children to basic principles of engineering and related disciplines. Under the gidaa STEM Program umbrella, staff and teachers have drawn on lessons learned through FIRST and introduced K-12 robotics day and after-school curricula using Lego Wedo-Webots, NXT Kits, Vex Kits and Textrix kits and software.

2. How Project Supports the EO Program Strategy

An essential part of the CCEFP strategic plan is to promote diversity in science, technology, engineering, and math (STEM) fields. The Shooting for the Stars Robotics Program enables Native American students in and around Cloquet, Minnesota to use concrete learning experiences with robotics to better understand physics concepts; develop mathematical thinking, problem solving, and programming skills; and participate in team-building through hands-on construction engineering. Ideally, graduates of gidaa and the gidaa odaangiina anaangoog Robotics Program will continue their education at a community college or a four-year university. 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 fourth year.

3. Accomplishments

2012:

- South Ridge School has completed its first school year in an entirely new facility, which includes building design to accommodate the robotics education program. All aspects of the robotics program ran smoothly at South Ridge due to CCEFP support.
- The South Ridge robotics day-course has impacted over 27 students thus far. 20 are enrolled the 2012 academic year.
- The after-school robotics program at South Ridge is maintaining a high number of students grades 2^{nd}-12^{th}. The St. Louis County Indian Education Program recognizes the positive effects of the robotics program and supports students by providing transportation home for students involved in the after school program.
- South Ridge students attended the International Robofest Competition at the Lawrence Technical University in Southridge, MI with the support of the CCEFP.

- South Ridge will be hosting its 4th Annual Regional Robofest competition in March with more local schools.
- Robotics Teacher Training was hosted at South Ridge and sponsored by CCEFP in May 2013 with three local teachers attending 10 hours worth of training learning how to implement a robotics program at their schools.

4. Plans

The CCEFP will continue to foster the growth of the academic and educational programs that have been initiated through gidaa. While most of the curriculum development and implementation will happen at the local level, the Center plays a key role in providing the subject matter expertise, resources and encouragement needed to help these students succeed in school and in STEM.

- The CCEFP will continue to identify sources of additional funding and support to expand this program, support more schools and teachers.
- The Robotics Program will continue to identify potential collaborators in the local area to have a network of robotics teachers and to utilize the RoboFest competition to generate additional interest.
- The program will recruit new and interested teachers in teaching robotics activities in the Cloquet and Culver and Fond du Lac Indian Reservation geographic area.
- gidaa will affect change in STEM curriculum across the local school districts. South Ridge School will serve as an engineering feeder school to a pre-engineering program at Fond du Lac Tribal Community College.
- Expanding Lawrence Technological University's Robofest Competition across Minnesota.

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.

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.
- Increase the number of teachers participating in robotics activities
- Demonstrate the effectiveness by identifying students who continue in the robotics program, and who decide to pursue STEM after high school graduation.

6. Member Company Benefits

This program is closely aligned with industry's hope for and support of efforts that prepare for a talented and diverse pool of leaders in academia and in our future workforce.

EO Project B.5: Building Resources and Innovative Designs for Global Energy (BRIDGE) Program

Project Team

Project Leader:	Paul Imbertson, CCEFP Education Director
Other Personnel:	Alyssa Burger, CCEFP Education Outreach Director Francisco Gonzales, Director, INATEC (The National Technical Institute of Nicaragua) Victorino Centeno, Executive Director, AVODEC (Association of Volunteers for the Development of Communities)

1. Project Goals and Description

The BRIDGE (Building Resources and Innovative Designs for Global Energy) Project is a shared endeavor of the National Society of Black Engineers (NSBE), the Innovative Engineers (IE), and the American Indians in Science and Engineering Society (AISES) student groups at the University of Minnesota and continues to thrive through major support from the CCEFP (Center for Compact and Efficient Fluid Power).

Major goals of the BRIDGE Project include:

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

The work is focused in the area of renewable energy, and specifically in renewable energy systems that can be constructed from locally sourced and inexpensive materials using local talents and accessible technologies. University of Minnesota student members of the BRIDGE project coordinate outreach programs with pre-college students in Minnesota and Nicaragua in which they produce and refine renewable energy systems (specifically wind turbine electrical systems at this time) with the goal of implementing these systems in developing nations where modern energy systems are not available. In this way, everyone involved becomes a partner in the endeavor with no identifiable giver of aid or receiver of aid.

The BRIDGE Project has impacted students and communities across the state of Minnesota and in Nicaragua. Participants create designs for renewable energy systems from scrap, waste, or found materials. They use these designs as an easily understandable foundation for outreach for at-risk students in inner-city schools and on Native American Reservations. The project brings engineering concepts and methods to life for at-risk students. The BRIDGE Project uses these designs to implement renewable energy systems in remote communities. This work is done in collaborations with groups in developing nations.

The project has expanded and currently the BRIDGE Project works with the following partners.

- Four partners in Nicaragua: AVODEC (Association of Volunteers for the Development of Communities), Esc. Luis Valencia Albarado (technical school in Jinotega, Nicaragua), UNI (National Engineering University of Nicaragua), and the community of La Hermita, Nicaragua.
- Two high schools in Minnesota: North Community High School in North Minneapolis, and the Circle of Life School on the White Earth Indian Reservation

- Three student groups at the University of Minnesota: National Society of Black Engineers (NSBE), Innovative Engineers (IE) and the American Indian Science and Engineering Society (AISES)

Design work in the BRIDGE Project is an example of service learning. Students engaged in service learning develop solutions to real community problems. Their efforts are not purely academic, but their learning outcomes can be more complete and their understanding can be deeper than they might have obtained through purely academic exercises.

Outreach efforts are based on meaningful learning. Students are brought in as active partners in solving renewable energy problems for remote communities. The high school students are full partners in the BRIDGE mission with the expectation that they will positively impact people and communities far removed from their own experiences, giving them a link to people and communities outside of their neighborhoods.

The CCEFP has partnered with the BRIDGE Project to promote student engagement and to bring an awareness of fluid power to these students.

2. How Project Supports the EO Program Strategy

Beginning in Y6, the CCEFP saw opportunities of partnering with BRIDGE, a program of social and educational relevance for so many audiences. In establishing this partnership, the Center is implementing one of its core strategies--identifying and then working with strong partners. Following CCEFP association with the BRIDGE project, the project now has a fluid power component, which includes the incorporation of fluid power educational activities in the BRIDGE outreach and development of novel fluid power methods in hybrid hydraulic/electric wind systems.

3. Accomplishments

Highlights over the past several years of the BRIDGE project reflect its wide range of influence.

- BRIDGE has sought out ways to engage at-risk high school students by hosting weekly engagement with students at North Community High School (a minority high school in Minneapolis) and by sponsoring visits for these students to university laboratories.

- The project has developed usable designs to use in implementing wind energy systems in remote communities.

- Worked with students at the Circle of Life High School (COL) on the White Earth Indian Reservation in Northern Minnesota in week long summer enrichment programs in 2009 and 2011

- BRIDGE members participate in the University on the Prairie program. This workshop program brings the university to students in farming communities in outstate Minnesota exposing students to opportunities in science and engineering by providing hands-on projects related to energy.

- In total, BRIDGE members have made nine trips to rural Nicaragua to build long-term relationships.

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

- Commissioned a1kW wind turbine in the community of La Hermita, Nicaragua.

- Visited several sites in remote areas of Nicaragua to assess their potential for community buy-in to partnerships that would result in implementation of renewable energy systems.

- Two high school students from the Fond du Lac Indian Reservation participated in a summer research experience designing a wind turbine blade testing jig.

- Involved with a weeklong education program on the White Earth Indian Reservation.

- Four trips to the Circle of Life (COL) school on the White Earth Indian Reservation during which students engaged in turbine designs for developing nations and worked towards constructing a turbine for their school. Monthly trips to White Earth are planned for the foreseeable future.

- Activities and trips have included several exchange students from Norway.

- Over 20 university students have taken lead roles including travel and work in remote areas.

4. Plans

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

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

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

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

- Identify and connect with 3 additional communities in the Jinotega Department of Nicaragua. Work to be done in connection with AVODEC and Esc. Luis Valencia Albarado. The BRIDGE project will encourage and enable the local technical school in Jinotega, Nicaragua to take the lead on these installations and will actively involve inner-city and reservation high school students in in this work.

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

- Expansion to the Little Earth Community in inner-city Minneapolis, MN, the largest urban Indian Reservation in the nation.

- Test hybrid hydraulic/electric wind turbine being developed by students in the Innovative Engineers group in association with the CCEFP.

- Facilitate direct collaboration between students at the Circle of Life School on the White Earth Indian Reservation, North Community High School in North Minneapolis, Little Earth Indian Community, the National Engineering University of Nicaragua, AVODEC, and Esc. Luis Valencia Albarado.

Related Projects

The BRIDGE Project is co-sponsored by the National Society of Black Engineers (NSBE), the Innovative Engineers (IE), and the American Indians in Science and Engineering Society (AISES) student groups at the University of Minnesota. Of these, the Innovative Engineers is also sponsored by the CCEFP and its cross connection has been very useful.

5. Milestones and Deliverables?

- Install wind turbine at the Circle of Life School on the White Earth Indian Reservation.
- Formulate working agreement with 3 additional communities in Nicaragua.
- Enter into long term working relationship with the Little Earth Indian Community.
- Install hybrid hydraulic/electric wind turbine currently being developed by a CCEFP supported project through the Innovative Engineers student group.

6. Member Company Benefits

All of industry, and certainly the CCEFP's member companies, appreciate programs that are socially and educationally relevant. BRIDGE is such a program, building STEM skills among pre-college and university students; contributing to the quality of life within communities in need; and, given its new partnership with the CCEFP, including elements that build an awareness of fluid power, an understanding of its technological base, and new avenues for its application.

EO Project B.7 Fluid Power Challenge Competition

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	Cherie Bandy, Education Program Coordinator Jonathan Meyer, SLC Vice President David Brajkovic, Innovative Engineers Member
Industrial Partner:	Eaton Corporation AirLogic Tolomatic Precision Associates MICO, Inc. National Fluid Power Association (NFPA) University of Minnesota's College of Science and Engineering

1. Project Goals and Description

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

- Actively engage students in learning the basics about fluid power
- Give support and resources to teachers for science and technology curriculum
- Create a fun learning environment for math and science
- Encourage students to acquire a diversity of teamwork, communication, engineering, and problem-solving skills
- Introduce eighth grade students to the fluid power industry
- Help build a strong workforce for tomorrow

2. How Project Supports the EO Program Strategy

This project supports the EO Program Strategy in several ways. Our work with strong partners, such as the National Fluid Power Association and Project Lead the Way, optimize both exposure and promotion of K12 fluid power education. The ease with which this project can be replicated maximizes opportunities for use by many workshop leaders in many settings. An essential part of the CCEFP strategic plan is to promote diversity in science, technology, engineering, and math (STEM) fields. The Fluid Power Challenge Competition enables students in and around Minnesota to use concrete learning experiences with hydraulics and pneumatics to better understand design concepts, physics concepts, develop mathematical thinking, problem solving; and participate in team-building through hands-on construction engineering.

3. Accomplishments

CCEFP Press Release

<u>Minneapolis, Monday, January 7, 2013</u> — The University of Minnesota will host the CCEFP NFPA Fluid Power Challenge, a competition that gets middle school students excited about fluid power. A Workshop Day for the event was held on November 12, 2012, followed by a Challenge Day on January 7, 2013.

During the Fluid Power Challenge, middle school students learn about fluid power technology (hydraulics and pneumatics) and gain hands-on experience while building a fluid power mechanism with real world applicability. The program is designed to introduce the students, and their teachers, to the world of engineering and fluid power careers.

During the Challenge Day at the University of Minnesota, 18 8th-grade teams (four students per team) will design and build fluid power mechanisms that pick an object from one platform, rotate and place it on another. In addition to the number of pick-and-place cycles a school's machine completes, a review of each team's design approach, teamwork and portfolio will be used in the final evaluation.

A student from a past competition said "This opens up more opportunities for engineering and careers kids aren't aware of. It's fun...you get to work with other kids and learn more math and science."

Through the Challenges, the Center for Compact and Efficient Fluid Power (CCEFP) and the National Fluid Power Association (NFPA) hopes to encourage students to select more mathematics and science courses in their high school curricula to keep their options open for technology-based post-secondary studies.

Highlights

- 2012 / 2013 Fluid Power Challenge Competition recruited 18 teams from Minnesota, the majority from the Twin Cities of Minneapolis and St. Paul. Three teams joined the event from outstate western Minnesota.

- Over 80 students and teachers participated in the workshop and competition day.

- Over half of the 8th grade student participants were female. Secondly, by observation, a highly diverse student body.

- Half of the teachers recruited were Project Lead the Way teachers, who have a fluid power module in their PLTW Principles of Engineering curriculum.

- One teacher had participated in 2009, when the first Fluid Power Challenge was held at the University of Minnesota.

- Five fluid power companies sponsored the event, two of whom are not CCEFP industry members. In addition, the University of Minnesota's College of Science and Engineering also sponsored the event.

- Each sponsoring company provided one or two engineers to judge the competition.

- A local news station, NBC's KARE 11 highlighted the Fluid Power Challenge on their 5 pm newscast. It can be viewed at YouTube: http://www.youtube.com/watch?v=_IdvGyWxnTo.

- One of the corporate sponsors, Tolomatic, wrote a blog about the competition: http://info.tolomatic.com/linear-actuator-blog/.

4. Plans
Given the successful efforts by CCEFP to coordinate the Fluid Power Challenge, and the strong interest in industry sponsors and teachers alike, the CCEFP will plan to host a competition each Fall. Goals include gaining more industry sponsorship, to reduce the cost to the Center, including direct funding from NFPA. The sustainability of the project includes identifying external funding sources and continued support from NFPA.

- Host a competition in the Fall of 2013

- Recruit more industry sponsors

- Identify additional funding sources for additional support

- Consider promoting the event to another CCEFP site

Related Projects

This project aligns well with the Center's former relationship with Project Lead The Way (PLTW), where CCEFP and NFPA provided content experts to design a fluid power curriculum module in PLTW's Principles of Engineering course. This competition provides the means and the applicability for PLTW teachers to teach hands-on hydraulics and pneumatics in a design environment.

5. Milestones and Deliverables?

- Host a Fluid Power Competition each Fall at a CCEFP location

- Recruit a minimum of 10 teams to participate in any Fluid Power Challenge Competition

- Recruit a minimum of four industry sponsors

- Keep costs low by finding additional sources of sponsorship and funding support

- Generate interest in fluid power at the K12 level and through teachers

- Market this program and create an investing group of teachers who anticipate participating in this program.

- Get University of Minnesota to buy-in for additional sustainability.

6. Member Company Benefits
The 2012 Fluid Power Challenge corporate sponsors include Eaton Corporation, AirLogic, MICO, Inc., Tolomatic, Precision Associates, National Fluid Power Association (NFPA), University of Minnesota's College of Science and Engineering. Both Tolomatic and Precision Associates are not corporate members of the CCEFP but support the educational initiatives of both NFPA and CCEFP. This program is closely aligned with industry's hope for and support of efforts that prepare for a talented and diverse pool of leaders in academia and in our future workforce.

EO Project C.1: Research Experiences for Undergraduates (REU)

Project Team

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

Other Personnel: CCEFP REU faculty advisors
CCEFP REU graduate student mentors

1. Project Goals

The REU program is aligned with several CCEFP goals: developing research inspired, industry practice directed education; facilitating knowledge transfer; integrating research findings into education; and increasing the diversity of students and practitioners in fluid power research and industry. Through its REU program, undergraduate engineering students from schools nationwide participate in cutting edge research under the mentorship of Center faculty. The program also provides professional development activities for these students.

2. How Project Supports the EO Program Strategy

REU students learn through the expertise of faculty mentors--an example of knowledge transfer. After completing their summer-long programs, REU engineering students are more likely to enroll in a graduate engineering program, often at the REU-hosting school. Further, the Center's efforts to recruit REUs from a diverse student population improve the likelihood of increased diversity among the students, faculty and industry professionals in fluid power.

3. Achievements

- To date, the CCEFP has hosted over 130 undergraduate students in the highly successful REU program.
- Since revising the CCEFP REU program structure in 2008, the CCEFP REU Program has recruited, on average, over 35% women, and over 33% racially or ethnically underrepresented students into the program on a yearly basis. The CCEFP's recruiting strategy includes identifying institutions, programs and people with whom to develop relationships that, in turn, open pathways to CCEFP summer programs and beyond for underrepresented students.
- The CCEFP has applied for the NSF REU Site Award and while recommended for funding after each attempt, the Center has yet to receive the Site Award.
- The CCEFP completed a longitudinal study of our past participants in early 2012. At the time of the report, 55% of all former CCEFP undergraduate researchers enter graduate school, and 33% of those are PhD candidates. Extremely positive statistics.

2012 REU Program:

- Twenty-three REU students participated in summer 2012, the sixth year of the program: three at the University of Minnesota, one at the University of Illinois, nine at Purdue, two at MSOE, three at North Carolina A&T, two at Georgia Tech and three at Vanderbilt University. None of these REU students had previous experience with CCEFP. 10 of the 23 were recruited from outside the CCEFP's core institutions.
- Following a highly successful Fluid Power Bootcamp at the University of Minnesota in 2011, the CCEFP hosted the 2012 REU Fluid Power Bootcamp at Purdue University. Professor Andrea Vacca of Purdue orchestrated the bootcamp curriculum which included three separate fluid power lab sessions led by CCEFP PU graduate students. Those lab sections are: <u>Lab 1</u>: Pump/system Characterization on Water Hydraulic Test Rig; <u>Lab 2</u>: Circuit Construction and Debugging; <u>Lab 3</u>: Displacement Control System. Students had an opportunity to socialize with each other as well as find themselves completely immersed in fluid power technology. The program at PU was so well received, the Center will host the 2013 REU Bootcamp at PU as well.

- Two REUs from North Carolina A&T State University received travel grants from NFPA to attend and present a poster at the Fall 2012 NFPA Workforce Summit and CCEFP Annual Meeting held at the University of Illinois, Urbana-Champaign.

2012 REU Demographics

Number of Students	23
Male	17
Female	6
Percentage of students from underrepresented groups 1) racial or ethnic minority 2) gender minority 3) disability	1) 39% 2) 26% 3) 0%

2012 REU Highlight

Andrew O' Bannon, 2011 CCEFP and Mechanical Engineering Undergraduate Student (Purdue University)

Faculty and Graduate Student Mentor: Andrea Vacca and Davide Cristofori

Project Title: Development of a Water Hydraulic Test Rig as Support to Teaching Activities

"The goal of my project was the development of a test rig for the characterization of water-hydraulic components and compact systems. This experience was extremely exciting because it combined theoretical activities (such as those related to components sizing) to hands-on activities (such as the construction and testing of the system). Additional source of personal satisfaction are represented by two reasons: 1) The test rig I contributed to design is currently exploited in the teaching of fluid mechanic courses at Purdue University; 2) After the presentation of my project during the SURF conference in Purdue, I and my graduate student mentor were awarded (among more than 100 participants) with “Top Research Talk Award” and “Graduate Student Mentor of the Summer” respectively. After this experience I wanted to deepen the study of fluid power and I did an internship with Bosch® in Germany, which was mainly focused on high pressure automotive injectors.”

2011 REU Program:

- Eighteen REU students participated in summer 2011, the fifth year of the program: two at the University of Minnesota, two at the University of Illinois, six at Purdue, two at MSOE, two at North Carolina A&T, two at Georgia Tech and two at Vanderbilt University. None of these REU students had previous CCEFP REU experience. Nine of the 18 were recruited from outside the CCEFP’s core institutions.
- For the first time in program history, the CCEFP hosted an REU Fluid Power Bootcamp. The bootcamp was held at the University of Minnesota and all students participated with the exception of those at Purdue. Led by CCEFP graduate students, the Bootcamp provided teaching and learning experiences for all involved as well as networking opportunities for the 12 REUs in attendance.
- The REU program launched a blog in which all REU students posted weekly updates about their research activities.
- Four 2010 Summer REU Students attended the CCEFP Annual Meeting and NSF Site Visit held at the International Fluid Power Expo in Las Vegas, March 2011. All four participated in the CCEFP Poster Session and one student spoke on behalf of all REUs during the Education & Outreach presentation at the Center’s Annual Meeting..
- The CCEFP has launched a research supplement program for faculty who wish to extend an REU opportunity to an underrepresented student during the academic year. The CCEFP funded two students in 2011, and we expect this program to grow significantly.
- The Center expanded its recruiting database from over 400 schools to 700 schools, with multiple contacts at each school, paying particular attention to minority-serving institutions.

CCEFP 2011 REU Participants at the first Fluid Power Bootcamp at the University of Minnesota.

2010 REU Program:

- Twenty-three REU students participated in summer 2010, the fourth year of the program: five at the University of Minnesota, three at the University of Illinois, seven at Purdue, two at MSOE, one at North Carolina A&T, three at Georgia Tech and two at Vanderbilt University. None of these REU students had previous CCEFP REU experience. Twelve of the 23 were recruited from outside the CCEFP's core institutions. Several REU students from CCEFP schools participated in the research projects of other universities within the Center network.
- The CCEFP held its Annual Meeting in June 2010 at Purdue University in West Lafeyette, Indiana and all REU students attended. Events included an REU orientation that enabled the REUs across the seven Center institutions to meet each other. This was the first time the Center was able to bring all REU students together in person.

- At the end of the summer, 11 REU students attended the CCEFP Student Retreat, held at the University of Minnesota. At the retreat, REUs presented their summer research projects to faculty and graduate students and went on tours of two CCEFP industry members, MTS and Eaton Corporation, both in Eden Prairie, MN.
- Additional poster presentations were made on REUs' respective campuses.

4. Plans, Milestones and Deliverables

- The CCEFP's first and second NSF REU Site Proposal was given high recommendations for funding, but ultimately, was not issued the reward. The CCEFP resubmitted a new REU Site Proposal in August 2012 and awaits word.
- The Center is committed to host between 14 and 20 REU students each summer -- two or three students at each university in the CCEFP network. (Some sites will host additional students due to leveraged funding from other sources.)
- The CCEFP will host its 2013 Fluid Power Bootcamp at Purdue University.
- The University of Minnesota will host two Hispanic REU students from the Rochester Institute of Technology, as an exchange program with Professor Larry Villasmil, who will work on a joint project on wind power with Professor and Director Kim Stelson. The students will be co-supported by RIT's NSF LSAMP Program and CCEFP.
- As in 2011 and 2012 REU program, the students will participate in a research blog, launched and contributed to by the students involved.
- The Center will continue to work with other campus-based REU programs to create a strong network of students at the local level, and also will host activities on-line that foster collaboration and a sense of a greater community outside the walls of the hosting institution. Consequently, students will realize that the program of which they are a part extends into the other six CCEFP universities and that the overall REU program is nationwide in scope.
- Additionally, using its network and database of contacts, the CCEFP will strive to recruit and retain racially underrepresented students as well as women, those with disabilities and recent war veterans.
- The Center will continue to encourage education focused research topics.
- The Center will hold an REU Advisor orientation webcast prior to the start of the 2013 program.

5. Member Company Benefits

Member companies can participate in REU projects through project mentorship. Here, member companies get a first look at a bright, diverse pool of students trained in fluid power who may become future intern or permanent employees. More generally, the REU program contributes to the building of an informed and motivated student group—future leaders for industry and academia.

EO Project C.2: Fluid Power OpenCourseWare

Project Team

Project Co-Leaders:	Prof. Will Durfee, University of Minnesota Prof. Jim Van de Ven, University of Minnesota
Other personnel:	Prof. Paul Michaels, Milwaukee School of Engineering 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.

Open courseware is an education concept that is backed by a consortium (www.ocwconsortium.org), has been popularized by MIT (ocw.mit.edu) and is related to current education experiments such as MOOCs. This project brings the open courseware concept to fluid power education. Education materials that are part of the FPOCW collection are archived under a Creative Commons intellectual property license which essentially allows unlimited use, with attribution for non-commercial purposes. This includes use at companies so long as the FPOCW education materials are not sold for profit.

2. How Project Supports the EO Program Strategy
New departments or four-year majors in fluid power are unlikely. Insertion of fluid power into standard engineering courses is not only achievable but also the most direct route towards increasing the number of engineering students trained in the basics of fluid power.

3. Achievements

- Fluid Power in Fluid Mechanics continues to be developed and used by Prof. Andrea Vacca, Purdue University within ME 309, Fluid Mechanics. In this class fluid power examples are used to illustrate basic concepts of fluid mechanics. Lecture notes, a fluid power lab and a collection of exercises collected in the mini-book “Fluid Power in Fluid Mechanics”(under development) support the project, permitting undergraduate students in ME 309 to become familiar with the fluid power discipline. The material is also being used by Professor Randy Ewoldt at UIUC.
- “Systems Engineering with Fluid Power Applications” mini-book under development by Robert Cloutier, Stevens Institute of Technology. First draft completed.
- Lectures from ME 4232, Fluid Power Control Laboratory, spring semester 2012, taught by Prof. Jim Van de Ven, were captured on video and added to the FPOCW site.

4. Plans
(1) Continue working on mini-books. (2) Develop a MOOC (massive open online course) for college-level fluid power system dynamics. This will be based on current content in FPOCW including mini-book, problem sets, video lectures and lecture slides.

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.

EO Project C.3: Fluid Power Projects in Capstone Design Courses

Project Team

Project Leader: Jim Van de Ven, University of Minnesota

Other personnel: Alyssa Burger, Education Outreach Director, CCEFP
All CCEFP faculty

Industry partners: NFPA and CCEFP member companies sponsoring projects

1. Project Goals
The objective of this project is to work with fluid power companies to sponsor and actively engage with students in capstone design projects with fluid power content. Long-term, this project is to be a collaborative project with the National Fluid Power Association (NFPA).

2. How Project Supports the EO Program Strategy
Engagement in these projects provides undergraduate engineering design students with a hands-on experience in fluid power design and development, reinforcing communications with CCEFP and NFPA member companies. These cooperative efforts are directly in line with the CCEFP's goal of fostering knowledge transfer between industry and universities.

3. Achievements
The CCEFP Education and Outreach program initiated a supplemental funding program for faculty across the CCEFP who wish to advise and mentor a capstone project in fluid power. In this reporting year, four projects have been granted supplemental awards resulting in over 25 undergraduate engineering students gaining direct experience in fluid power. Secondly, the EO Program provided a $6,000 grant (2nd year of funding, EO Project C.3a) to Elizabeth Hsiao-Wecksler at UIUC to host a joint fluid power capstone project with a Bradley University.

CCEFP EO Supplemental Funding Awards:

University	Year	EO Funding	Project Title
Bradley University	Sp. 2013	CCEFP Supp Award	"A Second-Generation Pneumatic Rotary Actuator Driven by Plantery Gear Train" CCEFP Advisor: Elizabeth Hsiao-Wecksler, UIUC
GeorgiaTech	Sp. 2013	CCEFP Supp Award	"Noise Control Device for Plumbing" CCEFP Advisor: Kenneth Cunefare, GT
Purdue University	Fall 2012 / Sp. 2013	CCEFP Supp Award	"Green, Human-Assisted Hydraulic Vehicle Design" *part of the Parker Hannifin Chainless Challenge Capstone Team* CCEFP Advisor: Andrea Vacca, PU
University of Minnesota	Fall 2012 / Sp. 2013	CCEFP Supp Award	UMN Parker Hannifin Chainless Challenge Capstone Team CCEFP Advisor: Brad Bohlmann, UMN
University of Illinois, Urbana-Champaign	Fall 2012 / Sp. 2013	CCEFP Supp Award	UIUC Parker Hannifin Chainless Challenge Capstone Team CCEFP Advisor: Elizabeth Hsiao-Wecksler, UIUC

A compilation of recent fluid power capstone projects at Center schools is shown in Figure 1 below.

University	Year	Sponsor	Project Title
VU	AY12-13	CCEFP	This capstone design course for Mechanical Engineers at Vanderbilt, frequently features some projects involving fluid systems. Indirectly, CCEFP faculty shares lessons learned through ERC research on a case by case basis with student teams doing related projects. (Robert Webster)
UIUC	AY12-13	CCEFP	“A Second-Generation Pneumatic Rotary Actuator Driven by Plantery Gear Train” at Bradley University (Elizabeth Hsiao-Wecksler)
GT	Sp. 2013	CCEFP	“Noise Control Device for Plumbing” (Kenneth Cunefare, GT)
PU	AY12-13	Parker Hannifin and CCEFP	“Green, Human-Assisted Hydraulic Vehicle Design” *part of the Parker Hannifin Chainless Challenge Capstone Team* (Andrea Vacca, PU)
UMN	AY12-13	Parker Hannifin and CCEFP	UMN Parker Hannifin Chainless Challenge Capstone Team (Brad Bohlmann, UMN)
UIUC	AY12-13	Parker Hannifin and CCEFP	UIUC Parker Hannifin Chainless Challenge Capstone Team (Elizabeth Hsiao-Wecksler, UIUC)
UMN	Sp. 2012	CCEFP	Hydraulic Fuel Pump Drive (Brad Bohlmann)
UIUC	Fall 2011	CCEFP	Capstone Senior Design Project with Bradley University, Peoria, IL. Project was to improve torque output of a pneumatic rotary pancake actuator by using a plastic sun gear train. (Elizabeth Hsiao-Wecksler)
UMN	Fall 2011	CCEFP	Parker Hannifin Chainless Challenge Senior Design Project. (Brad Bohlmann)
UMN	Fall 2011	CCEFP	Open Accumulator Display (Perry Li)
MSOE	Sp. 2010	CCEFP	An Investigation of the Tribological Conditions and Lubrication Mechanisms Within a Hydraulic Geroler Motor
MSOE	Sp. 2010	CCEFP	Fluid Power Actuator for use in Active Ankle Foot Orthotics
PU	Sp. 2010	CCEFP	Skid Loader Boom Extension
UMN	Fall 2010	Tennant	Tile Marking Mechanism
UMN	Spring 2011	Eaton	Hydromechanical transmission
UMN	Spring 2011	Science Museum of Minnesota	Fluid Power Ankle Orthosis Exhibit
GT	Spring 2011	CCEFP	An Educational Simulation Tool for Hydraulic Systems

Figure 1: Recent fluid power capstone projects

4. Plans

In the future, CCEFP expects to work with NFPA to promote capstone design projects in fluid power to its member companies. In recent years, NFPA board members committed to sponsoring fluid power capstone projects, likely CCEFP industry members may be interested in the same. A process is to be developed where CCEFP faculty or staff would facilitate matching CCEFP and NFPA companies with an interest in sponsoring a project to the appropriate engineering program, either within or outside the CCEFP network.

Regardless of the anticipated cooperation with NFPA, the CCEFP will continue to launch and support new fluid power capstone design projects every year within the local engineering capstone course. The CCEFP will continue to provide small grants for supplies and travel to faculty who offer to lead or advise capstone design projects.

5. Member Company Benefits

Capstone projects are a way to connect the Center to the engineering program at a local university. Advising a project results in a close relation with the student team and provides an opportunity for industry members to observe students in a job-like situation before selecting the best for job offers. It also provides a way to get bright minds on an engineering problem of interest to the company.

EO Project C.3a Capstone Senior Design Project:
A Second-Generation Pneumatic Rotary Actuator Driven by Planetary Gear Train

Project Team

Project Leader: Prof. Elizabeth Hsiao-Wecksler, MechSE UIUC

Other Personnel: Prof. Martin Morris, MechE, Bradley University
David (Yifan) Li, UIUC Graduate Student
Morgan Boes, UIUC Graduate Student
Matt Petrucci, UIUC Graduate Student

1. Project Goals and Description

This project is a collaboration between researchers and students at the UIUC and Bradley University on a project to develop prototype pneumatic actuators that can be useful in Test bed 6 on the portable pneumatic ankle-foot orthosis (PPAFO). Limitations of the current pneumatic actuator on the PPAFO are torque output and size of commercially available small pneumatic rotary actuators (example: 15 Nm @ 150 psi, dual vane, 2.5" dia, casing height 2.4"; model PRNA30D, Parker Hannifin Corp). (Figure 1)

Figure 1. PPAFO with current commercial rotary actuator.

This E&O project has supported two capstone senior design project teams in the Mechanical Engineering Department at Bradley University in Peoria, IL. Bradley is a small, private university with undergraduate and graduate programs, and is located 90 miles from the UIUC campus. Their capstone design course covers two semesters. Prof. Martin Morris has an expertise in fluids and design, and runs the capstone design course in the ME department. Over the past 12 months, the CCEFP supplemental funds have been used to support two different design teams, one for AY11-12 and another for AY12-13.

The objectives for the first team (AY11-12) were to: (1) increase torque output of pneumatic rotary actuators in a compact housing, (2) explore the possibility of using a planetary gear train constructed from plastic designed to increase the output torque, (3) examine the use of labyrinth sealing in the pneumatic actuator to minimize frictional losses, and (4) perform a thermodynamic analysis to determine if energy consumption of pneumatic fuel (compressed CO_2) could be improved with different design modifications to power source. (Due to the vaporization process of CO_2 from liquid to vapor, cooling of the CO_2 canister is observed. Temperature of a gas is negatively correlated with gas density, which could affect fuel efficiency.)

The original objectives for the second team (AY12-13) were to: (1) retain, as a minimum, the torque output generated by the compact, first-generation pneumatic rotary actuator while increasing the number of activation cycles, (2) explore the possibility of increasing the efficiency of the plastic planetary gear train, (3) improve the effectiveness of the labyrinth seal in the pneumatic actuator to maintaining low frictional losses, and (4) improve the utilization of the driving gas energy (the available energy). However, as the school year has progressed and the students brainstormed alternate actuator designs, these original objectives are not being addressed since the team decided not to continue to focus on just modifying last year's design.

For both teams, a working prototype actuator is the primary deliverable from the 9 month capstone senior design project experience.

2. How Project Supports the EO Program Strategy

The primary educational impact of this project is to expose a team of undergraduate engineering students to concepts of fluid power design, specifically rotary torque generation using a pneumatic power source. All of the students participating in the capstone design course will be exposed to fluid power issues as they participate in the gated review process which includes four oral progress report presentations by the design team. The results from the project will be revealed to the entire campus community on both campuses during two campus-wide expositions. The project has exposed the student teams to first-hand experiences with fluid power through pneumatic design issues such as torque generation, leakage and seals, fluid dynamics, and also thermodynamic analysis of dealing with expansion of compressed gas (CO_2).

3. Accomplishments

The first-generation prototype (Figure 2) was delivered at the end of AY11-12. It had a diameter of about 3.5” with a casing height of about 1.5”, and utilized labyrinth sealing. The torque output for the prototype actuator was designed to deliver 40 N-m of torque with a relative motion of 55° between the components using a supply pressure of 100 psig. The planetary drive train was designed to deliver a torque amplification of about 3. Actual testing of the design by the end of the 9 month period was not possible due to leakage in the system. The thermodynamic analysis found that if the power source (compressed CO_2 canister) was allowed to remain at an isothermal as opposed to isentropic condition, then the system could have a ~10% improvement in actuation duration.

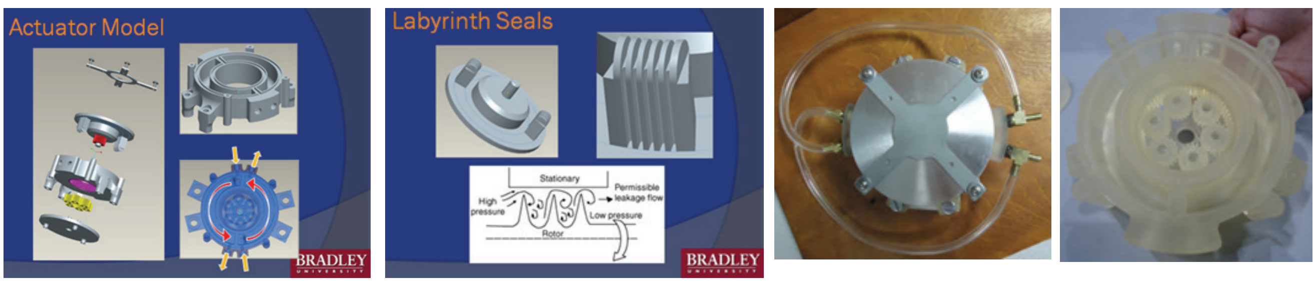


Figure 2. CAD and physical models of first-generation pancake pneumatic rotary actuator driven by planetary gear train that were completed by AY11-12 team

The second team’s school year is still in progress; however, they have decided to follow a completely different design approach with respect to achieving the desired torque output and compact design. This team has decided to use a commercially-available pneumatic actuator in order to avoid the leakage problem that can be encountered by designing one’s own actuator. Further, instead of designing a pancake rotary actuator, they have decided to use a linear actuator combined with a limited range sector gear in order to convert translational motion to the linear actuator into rotation motion at the ankle (Figure 3).

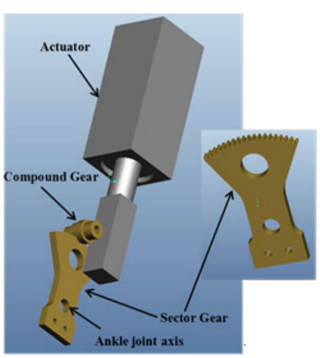


Figure 3. CAD model of proposed design by AY12-13 team which uses an off-the-shelf linear actuator with sector gear to create torque about the ankle axis.

The Bradley design teams for both years have consisted of four Mechanical Engineering students, two of which are women for each year.

Bi-weekly teleconference meetings have been held between UIUC and Bradley team members throughout this project. UIUC faculty and students also virtually attended staged gateway review presentations, which are used to evaluate team progress and deliver concurrent feedback by clients, Bradley faculty, and other design teams.

AY11-12 Bradley students presented their design during the University of Illinois' College of Engineering Open House in March 2012 (Figure 4). Engineering Open House weekend attracts thousands of students (K-college), teachers, and the general public from across Illinois and the Midwest. The Bradley students also presented their results as part of the annual Bradley University Student Exposition during Parents Weekend in May 2012.
AY12-13 Bradley students also presented a poster on the first generation design and thermodynamic analysis at the CCEFP Annual Conference in September 2012 (Figure 4).

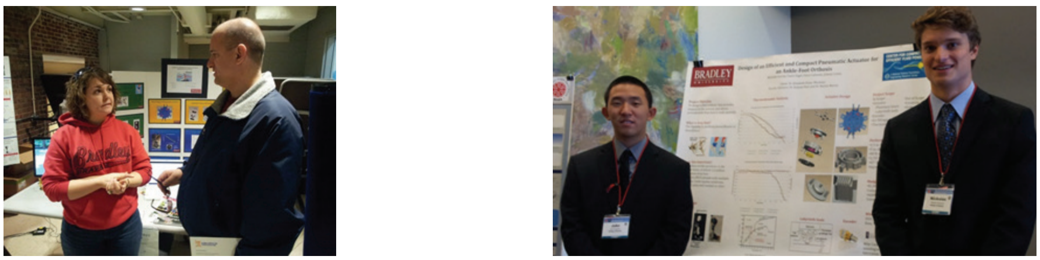


Figure 4. (left) Bradley student presenting team's work during the University of Illinois' Engineering Open House weekend. (right) Bradley students at CCEFP Annual Meeting student poster show.

4. Plans

If funding for this project were to continue over the next three years, future student teams would work on refined versions of the previous actuator prototypes with focused efforts to continue to improve system efficiency in terms of fuel consumption while continuing to address the need for higher output torques generated from smaller packages. Another project might be to enhance recent efforts to use an elastomeric accumulator in Test bed 6 on the PPAFO. That effort has been exploring how to improve overall system efficiency by recycling exhaust gas from one portion of the gait cycle (plantarflexion) to drive the other portion (dorsiflexion).

Related Projects

Should a successful prototype be constructed, it would be tested in Test Bed 6 on the portable pneumatic ankle-foot orthosis test platform.

5. Milestones and Deliverables?

The milestones for the project align with the milestones defined by the Bradley ME department's senior design curriculum:

1) 1st Oral Presentation (Gateway 1)	Before September 31, senior year
2) Proposals to the Client	Before October 31, senior year
3) 2nd Oral Presentation (Gateway 2)	Before October 31, senior year
4) Written Progress Report	Due end of Fall semester
5) 3rd Oral Presentation (Gateway 3)	Before February 28, senior year
6) 4th Oral Presentation (Gateway 4)	Before April 31, senior year
7) Written Final Report & Deliverables	Due end of Spring semester

For both teams, a working prototype actuator is the expected primary deliverable at the end of the course. Additional deliverables were interim and final reports. These reports include performance characterization of the actuator at a range of pneumatic pressures, engineering drawings of the components, and details about the actuator construction.

6. Member Company Benefits

This project does not have corporate sponsors, although the students on both teams have worked with Winzler Gear, a plastic gear engineering and manufacturing firm in Chicago, which has worked with the students to design appropriate gear trains. The AY12-13 team has also been working with engineers at Bimba Manufacturing on the linear pneumatic actuator. Should future designs be successful, we would be happy to share with CCEFP or NFPA industry members.

In addition, this project, enables CCEFP member companies to interact on many levels with CCEFP engineering students, some of whom will join their work forces, others of whom will work within the fluid power industry's customer base; and still others who will find their way to the classroom where they will teach a next generation of engineers, instilling in them a knowledge of and interest in fluid power.

EO Project C.3b: Parker Hannifin Chainless Challenge

Project Team

Project Leader:	Brad Bohlmann, University of Minnesota
Other personnel:	Elizabeth Hsiao-Wecksler, University of Illinois, Urbana-Champaign
	Andrea Vacca, Purdue University
Industry partners:	Parker Hannifin

1. Project Goals

The Parker Hannifin Chainless Challenge is a design competition for undergraduate college and university students. The focus is creating a human powered vehicle (typically bicycles or recumbent bikes) in which the conventional mechanical chain drive is replaced with a hydraulic transmission. Elements of the competition include the design (creativity/novelty, functionality, presence of renewable energy systems), fabrication (quality, aesthetics), design process (design report, cost analysis) and a 3 event competition (efficiency, acceleration and distance events).

The goal of this project is to provide students with an opportunity to learn about fluid power, apply their knowledge to a real world design project and compete in a national competition to demonstrate their work.

2. How Project Supports the EO Program Strategy

Engagement in these projects provides undergraduate engineering design students with a hands-on experience in fluid power design and development. It also increases the number of mechanical engineers graduating from Center schools training in fluid power (about 20 students from Center schools per year).

3. Achievements

The Chainless Challenge is a two semester commitment for students and faculty. In the Fall semester, the generally work on the project in their capstone design projects course. A team of 5 undergraduate students learn about fluid power, develop design specifications for the modifications to their bike, complete the design and install the modifications on the bike. In the Spring, the students test and optimize the bike's operation in preparation for the national competition in April.

There are typically about a dozen teams in the Chainless Challenge competition. In 2011-12, CCEFP was represented by Illinois, Illinois Tech (advised by Prof. Jose Garcia, a recent CCEFP PhD from Purdue), Minnesota and Purdue. Minnesota took second place overall in the competition. In the 2012-2013 competition, CCEFP will send teams from Illinois, MSOE, Minnesota and Purdue.

One of the students from the University of Minnesota participating in the 2011-12 Chainless Challenge is currently pursuing a Masters degree in mechatronics at Minnesota. His advisor is Prof. Perry Li.

Most schools have a one semester capstone design course. This doesn't align well with the two semesters required for Chainless Challenge participants. The supplemental funding from CCEFP Education and Outreach helps to provide resources that ease this challenge.

4. Plans

The Chainless Challenge is a fun and educational experience for the students and advisors. It provides a unique opportunity for students to learn about fluid power. We hope to expand CCEFP's participation in Chainless Challenge and have a team in the next competition from each of its seven schools.

5. Member Company Benefits

Capstone projects are a way to connect the Center to the engineering program at a local university. The Chainless Challenge exposes students to fluid power. Even if they don't work in the fluid power industry upon graduation, their knowledge of fluid power makes it a possible solution for engineering challenges they face during their career.

Parker Hannifin benefits directly by meeting and working with the students on the project team. They have an opportunity to observe students in a job-like situation which can help find potential employees. It also provides a way to get bright minds on an engineering problem of interest to the company.

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EO Project C.3c: Hydraulic Fluid Power for Fuel-Efficient School Buses

Project Team

Project Leader: Dr. Michael J. Leamy, Associate Professor, Georgia Institute of Technology

Other Personnel: Dekun Pei, Graduate Student, Georgia Institute of Technology
Laith Gammoh, Undergraduate Student, Georgia Institute of Technology
Brent Barnes, Undergraduate Student, Georgia Institute of Technology
Nathan Sacks, Undergraduate Student, Georgia Institute of Technology

Industrial Partner: Poclain Hydraulics, Inc. (CCEFP Member)
Atlanta Public Schools
Eaton Corporation (CCEFP Member)
Linde America (CCEFP Member)
Evonik Oil Additives (CCEFP Member)
National Instruments

1. Project Goals and Description

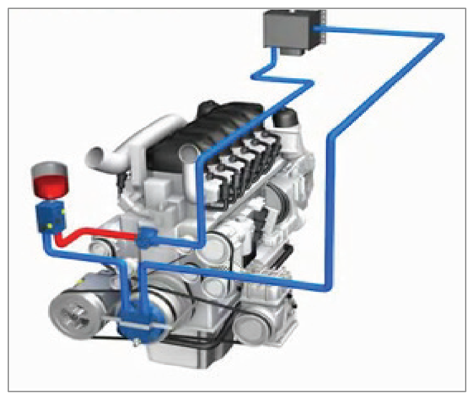

Figure 1. Depiction of Poclain Hydraulic's CleanStart technology for restarting a diesel engine.

The main goal of this project is the implementation of Poclain Hydraulic's *CleanStart* hydraulic stop and start technology (see Fig. 1) on our existing hydraulic hybrid school bus. In its commercially-available form, this technology employs a tank (shown rear of engine in Fig. 1), a heavy-duty hydraulic motor (shown attached to the crankshaft), an auxiliary pump (shown above crankshaft and attached to a power takeoff), and a hydraulic accumulator. During driving, power taken from the engine is used to fill the accumulator. When the vehicle (such as a city bus) makes a stop, the motor is shut off until the driver depresses the accelerator. At this time the accumulator and the hydraulic motor are used to restart the engine in approximately 0.4 seconds. Based on similar fielded systems on city buses, it is believed that this system could save as much as 15% of fuel used by a typical school bus. It should also lead to a significant decrease in emissions, especially in areas where children congregate (bus stops and entrances to schools).

Georgia Tech's existing hydraulic hybrid retrofitted-bus provides an ideal starting point for exploring this complementary technology for saving fuel and reducing emissions of school buses. With the already-present hydraulic accumulator, fluid reservoir, and pump/motor, the *CleanStart* tank, accumulator and auxiliary pump can all be deleted. The only major component necessary to retrofit the technology is the heavy duty hydraulic motor. In addition, control of the system can be accomplished using the existing microcontroller-based system presently being used to control the hydraulic hybrid components. Furthermore, braking energy will be used (instead of engine energy) to charge the accumulator, furthering its efficiency. With assistance from our industrial partner, Poclain Hydraulics, the work is expected to be completed by a team of three undergraduate seniors (Laith Gammoh, Nathan Sacks, Brent Barnes) in the spring of 2013.

2. How Project Supports the EO Program Strategy

This project supports several components of the CCEFP Education and Outreach program, including university education, K12 education, industry education, and public awareness of fluid power. The engineering of the *CleanStart* implementation on the hydraulic hybrid school bus is being carried out primarily by three undergraduate students (Laith Gammoh, Nathan Sacks, Brent Barnes), who had the assistance of a graduate student (Dekun Pei) last semester. These students interact with engineers from the fluid power industry (e.g., Poclain Hydraulics and Eaton Corporation) and gain exposure to fluid power concepts and analysis that they cannot get from classes presently taught at Georgia Tech. The hydraulic hybrid project has in the past, and will continue in the future, directly impacted K12 education through its partnership with Atlanta Public Schools. The PI and his students have attended the Career Day event at Mary Lin Elementary School in Atlanta where they have discussed the underlying technology being developed on the bus with K-5 student groups. There, simple props (like long cylindrical balloons and air pumps) have been used to explain how fluid power can be used to store and transfer energy, and ultimately decrease the amount of diesel fuel used by their buses. It is anticipated that the research team will again attend this event in May, 2013. The work also has the potential for impacting industry education through the sharing of engineering technology and practices being developed by the research team. Two examples are the state of the art hydraulic simulation models and microcontroller algorithms developed in-house and used in component selection and optimal control of the school bus hydraulic hybrid hardware. Public awareness of fluid power has been increased throughout the project through articles appearing in popular press and trade magazines, such as Wired's Autotopia, MotoTrend's Truck Trend, Automotive World, Biodiesel Magazine, and Diesel Progress.

3. Accomplishments

In the past year the project has reached several milestones. First, graduate student Dekun Pei was instrumental in completing the hydraulic hybrid school bus and making it operational. The bus now is able to operate in regenerative braking mode (hydraulic energy storage) and in hydraulic assist mode (hydraulic energy delivery). Small obstacles still exist for efficient operation, such as fast response of the pump/motor's swash plate. This issue will be addressed in the coming year, and may require a reworking of the pump/motor with a swash plate sensor. Dekun also finished his Master's thesis, which describes in detail design, fabrication, operation, and initial testing of the hydraulic hybrid school bus. In the fall semester, Laith Gammoh completed a reworking of the hydraulic controls such that a commercial-grade microcontroller (National Instruments single-board RIO, donated by National Instruments for this purpose) now replaces the hobby-grade Arduino microcontroller. This new microcontroller allows us to remove the need for separate voltage controllers since the board itself can handle the various voltage requirements of the onboard hardware. In addition, the controller operates significantly quicker, has many more input/output channels for future upgrades, and is rugged enough for long term usage.

First graders at Mary Lin Elementary School (Atlanta, GA) paint the school bus, which is being converted by Georgia Tech researchers and students, into a hydraulic hybrid that runs on biofuel.

The past year has seen outreach accomplishments in the form of public awareness of our efforts to make school buses more efficient using fluid power. Three students from the previous year competed in the 2012 ACC Clean Energy Challenge in College Park, MD this past April. The students presented a technology review and business plan for working directly with school bus manufacturers (e.g., Blue Bird) to upfit new buses with hydraulic hybrid power. The team first made the internal Georgia Tech down-select to be the team chosen to represent the Institute. They then competed in Round 1, where they were chosen from 10 teams from across the Eastern and Southeastern United States to advance to the Final Four Round and compete for $100,000 in startup funds. Although they did not win in the final round, they were recognized as a Final Four finisher and were subsequently invited to give a talk on their research at the 2012 World Energy Engineering Congress. Undergraduate student Keong Yeong gave a talk entitled “Clean Hydraulic Hybrid Technology” at this Congress on November 1. Finally, the hydraulic hybrid school bus has continued to receive attention from the general public. The CCEFP issued a press release in June, and the trade magazine *Diesel Progress* ran a two page story on the bus with three color photos in their September, 2012 issue.

The *CleanStart* phase of the project has started successfully by establishing a good collaboration with Mike Scotese, General Manager, and Homer Hawk, Application Engineer, both of Poclain Hydraulics. Mike Scotese visited our research facility on March 27, 2012 and observed the bus first-hand. We discussed at length the current status of the hydraulic hybrid retrofit and plans to implement Poclain’s *CleanStart* technology as an additional means to increase efficiency. Shortly after this meeting, we got the formal commitment from Poclain to donate several hydraulic components needed for the implementation, including a small hydraulic motor, accumulator, control unit, and electric pump. Working with Homer Hawk, we appropriately sized the components and received them in late December. The parts are now in the hands of the undergraduate students, who are working on CAD drawings and calculations to assist in the retrofit.

4. Plans

The proposed project has duration of one year and began in earnest in the fall of 2012. With Poclain’s donated parts having just arrived in the last few weeks, the work plan is for the three undergraduate students to begin designing the hydraulic circuit and component layout, designing and fabricating component mounts, installing the hydraulic and electrical equipment, and completing the project by the end of the spring term. Testing is planned as a follow-up effort, where the retrofitted school bus (hydraulic hybrid and *CleanStart*) are to be tested together to measure their increased efficiency gain. By the end of 2013, the hydraulic school bus will be a completed prototype with testing and further refinement anticipated to be a one to two year effort before commercialization of the technology can commence.

5. Milestones and Deliverables

The primary project milestone remaining is the completion of the *CleanStart* implementation, which is planned for May 2013. Milestones beyond the scope of the present project include full testing and completion of the hydraulic hybrid school bus by the summer of 2015. Deliverables in both cases are working prototypes.

6. Milestones and Deliverables

Several CCEFP-affiliated corporations have contributed to the success of the hydraulic hybrid school bus to date. Eaton Corporation donated the pump/motor presently residing on the bus, as well as provided the team with expertise in the form of interactions with several engineers (Vincent Duray, Ben Hoxie, Robert Isaacs, and Thomas Cleghorn of Linde America). The hydraulic oil used in the bus was donated by Evonik Oil Additives and the present microcontroller was donated by National Instruments. Poclain Hydraulics has donated several *CleanStart* components and will be a partner in the continued development of our own *CleanStart* implementation. Benefits in return to these companies have primarily been exposure to undergraduate and graduate students. However, the research team has developed hydraulic power simulation tools, control algorithms, and other intellectual property that is available to companies sponsoring the work.

EO Project C.4: Fluid Power Courses

Project Team

Project Leader: Jim Van de Ven, University of Minnesota

Other personnel: Will Durfee, University of Minnesota
All CCEFP faculty

1. Statement of Project Goals

Develop new, semester-length undergraduate and graduate courses in fluid power, and include substantial content on fluid power in existing undergraduate and graduate courses. The expectation is that most CCEFP faculty will find a way to insert fluid power curriculum into their courses.

2. How Project Supports the EO Program Strategy

Developing new courses or making substantial modification to courses in CCEFP universities will help to create a cadre of highly skilled students who will become future fluid power industry professionals and future engineering faculty. Advanced graduate courses with content based on CCEFP research provide a means for knowledge transfer of research results. New courses require significant faculty effort and must be consistent with teaching loads and departments' policies for new course adoption, which are outside the control of the Center.

3. Achievements

- Problem Set for Fluid Power System Dynamics Mini-Book developed by the students at the student leadership retreat in August, 2012. The problem set will be integrated into the next edition of the mini-book, making it easier for instructors to utilize the book in existing courses by being able to assign the problems as homework.
- Developed a Video Lecture Archive from Fluid Power Controls Laboratory taught by Professor James Van de Ven at the University of Minnesota. The videos, available in multiple formats, and the handouts from in-class activities are available on the Fluid Power OpenCourseWare site. New 2012.
- INEN 371: Human Factors Engineering taught by Professor Eui Park & Steven Jiang at NC A&T University, uses outcomes of CCEFP funded projects
- INEN 665: Human Machine Systems taught by Professor Eui Park at NC A&T University uses outcomes of CCEFP funded projects. New 2011.
- ME 271: Introduction to Robotics taught by Robert Webster at Vanderbilt University covers forward and inverse kinetics, dynamics and control of manipulators. Includes a hands-on final project. Some examples are drawn from ERC funded project 2G. New Fall 2012.
- ABE 435: Hydraulic Control Systems taught by Professor Andrea Vacca at Purdue University was prepared using material from his CCEFP research and educational program. New Fall 2012.
- ME 310: Fundamentals of Fluid Dynamics taught by Professor Randy Ewoldt and some material contributed by Andrea Vacca (Purdue U) is the traditional undergraduate fluid mechanics course. Fluid power examples are included in homework to emphasize basic principles. A single lecture is dedicated to fluid power. New Spring 2013.
- ME 236/336: Linear Control Theory taught by Eric Barth at Vanderbilt University includes homework and examination questions related to the control of fluid power systems. Fall 2010.
- ME 351: Nonlinear Control Theory taught by Eric Barth at Vanderbilt University includes great examples of pneumatic systems are included in the course. New Spring 2013.
- ME 340: Dynamics of Mechanical Systems taught by Andrew Alleyne at University of Illinois at Urbana-Champaign, includes a lab that uses fluid power.
- ME 360: Signal Processing taught by Andrew Alleyne at University of Illinois at Urbana-Champaign, includes a lab that uses fluid power.

- ME 236/336: Linear Control Theory taught by Eric Barth at Vanderbilt University includes homework and examination questions related to the control of fluid power systems. Fall 2010.
- ABE 460: Sensors and Process Control taught by Professor John Lumkes at Purdue University utilizes the CCEFP educational activities developed by an REU student during the 2011 summer. New 2011.
- ME309: Fluid Mechanics taught by Professor Andrea Vacca at Purdue University. The traditional introductory class on Fluid Mechanics at Purdue has been modified according to the project "Fluid Power in Fluid Mechanics" supported by CCEFP and NFPA. Two lectures were completely dedicated to fluid power. Moreover, a new lab experience on fluid power has been introduced. The lab experience is based on a high-pressure water hydraulic test rig developed by Dr. Vacca's team at Maha Fluid Power lab. (More information, see project EO Project C.2). New: 2011.
- ME 4803 / ISyE 4803: Model-Based Systems Engineering taught by Professor Christiaan Paredis and Leon McGinnis at Georgia Institute of Technology. Model-Based Systems Engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. New: 2011.
- ME 8287: Passivity & Control of Interactive Mechanical and Fluid Power Systems is a new graduate course at UMN, created and taught by Professor Li. New: 2011.
- ME 460: Industrial Control Systems – Lab taught by CCEFP Graduate Student Tim Deppen, University of Illinois, Urbana-Champaign. Lab portion of a Frequency Domain controls class. Currently offered, ongoing course using ERC related content. New: 2011.
- ME 8287: Design and Control of Automotive Powertrain taught by Professor Sun at the University of Minnesota. Significant content on hydromechanical systems and modeling and control of hydraulic hybrid vehicles CCEFP. New: 2011.
- ME 4012: Motion Control taught by Professor Wayne Book of Georgia Institute of Technology. Existing courses modified to include CCEFP research. New: 2011.
- ME 4232: Fluid Power Control Laboratory taught by Professors Li, Stelson and Van de Ven, includes CCEFP research and guest lectures by engineers from CCEFP member companies. New faculty instructor 2012.
- INEN 371 Human Factors Engineering, INEN 665 Human Machine Systems, INEN 735 Human-Computer Interface taught by Professor Eui Park of North Carolina A&T State University. These are courses at NCAT modified to include CCEFP research.
- ME 597 /ABE 591 Design and Modeling of Fluid Power Systems taught by Professor Ivantysynova at Purdue University. Graduate course, which has substantial content from CCEFP research.
- ME 697/ABE 691 Hydraulic Power Trains and Hybrid Systems taught by Professor Ivantysynova at Purdue University. Graduate course, which has substantial content from CCEFP research.
- ME 3015: System Dynamics and Control, taught by Professor Ueda at Georgia Institute of Technology, used a pneumatic pressure control system as a class project.
- ME 234 System Dynamics taught by Professor Webster at Vanderbilt University includes CCEFP research results and guest lectures by CCEFP graduate student researchers.
- UIUC undergraduate course in system dynamics will include fluid power material based on mini-book on fluid power system dynamics. Taught by Professor Hsiao-Wecksler.

4. Plans

- Continue to encourage the incorporation of fluid power content into existing courses and to develop new lecture and lab courses in fluid power. The Fluid Power OpenCourseWare project (Project C.2) makes it easier for instructors to include college-level fluid power material in their courses.

- Encourage completion of ongoing projects to develop mini-books.
  - Andrea Vacca, Purdue – Fluid Mechanics module
  - Paul Michael, MSOE – Hydraulic Fluids
  - Will Durfee and Zongxuan Sun, UMN – Fluid Power System Dynamics – revision
- Develop problem sets associated with the mini-books to ease course integration.
  - Possibly utilize the SLC for assistance in developing problems & solutions.
- Utilize multiple modes to increase digital repository content.
  - Video capture existing fluid power related courses and course modules.
  - Capture presentations by industry experts aimed at collegiate audience.
  - Capture advanced topic presentations by faculty aimed at academic researchers and industry members.
- Have CCEFP faculty who are teaching core undergraduate classes to write and present papers in the education sections of technical conferences on infusing fluid power modules into existing mechanical engineering classes (system dynamics, fluid mechanics, and thermodynamics).
  - Encourage participation by providing travel support to authors.
  - Publicize presentation among technical conference colleagues to increase exposure.
- Increase awareness of digital repository among industry members through distribution of a brochure at meetings.
- Encourage CCEFP member schools to include fluid power in list of ABET outcome objectives for related core mechanical engineering courses (system dynamics, fluid mechanics, and thermodynamics).

5. Member Company Benefits

Graduate and undergraduate students who are learning fluid power through their courses. These educated students become the new employees of the companies.

EO Project C.5: giiwed’anang North Star Alliance

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	Simone Gbolo, North Star STEM LSAMP Anne Hornickle, North Star STEM LSAMP
Participating Colleges / Universities / Community or Tribal Colleges	*Minnesota Institutions:* University of Minnesota, University of Minnesota-Duluth, University of Minnesota-Morris, Fond du Lac Tribal and Community College, Saint Cloud State University, Leech Lake Tribal College, Bemidji State University, Minneapolis Community Technical College, Century College *Outside Minnesota:* Lac Courte Oreilles Ojibwe Community College (WI), Salish Kootinah Tribal College (MO), University of North Dakota (ND), Michigan Tech (MI)

1. Project Goals

The American Indians in Science and Engineering Society (AISES) is a national organizations with a goal: to increase the number of Native American college students in STEM fields. In conjunction with the University of Minnesota College of Science and Technology Office of Diversity and Outreach, and the North Star (LSAMP) STEM Alliance, and the North Star AISES Professional Chapter, the CCEFP is coordinating, sponsoring and hosting all activities of the giiwed'anang North Star Alliance. This alliance has formed partnerships between the AISES student chapters in Minnesota. It exists to provide tools and resources to assist students of AISES Chapters.

Goals of the Alliance include:

1. engaging students in STEM-related activities
2. encouraging students to pursue their education in STEM-related fields
3. developing a Minnesota student cohort network
4. increasing the number of AISES chapters
5. encourage a greater representation of Native Americans 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 underrepresented 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

- **2012**
  - The giiwed'anang Northstar STEM Alliance continues to provide student support to chapter members in Minnesota, primarily at the University of Minnesota Twin Cities and Morris campuses. Student support includes travel grants, open house grants, sponsored meetings and gatherings.
  - giiwed'anang along with the Northstar STEM LSAMP Alliance (UMN), Northstar AISES Professional Chapter and the University of Minnesota's College of Science and Engineering sponsored over 14 students to attend the AISES National Conference in Anchorage, Alaska, November 1-3, 2012.

  - giiwed'anang hosted a dinner for over 40 student participants in Anchorage, during the AISES National Conferences.
  - giiwed'anang sponsored the travel expenses for four University of Minnesota AISES Chapter students to attend the All-National Rocket Launch workshop in Green Bay, WI, December 2012. Co-sponsorship includes the Minnesota NASA Space Grant Consortium. The past two years, the UMN-TC AISES Chapter has participated in this rocket competition, to score in first and second places.
  - The University of Minnesota AISES Chapter now has over 20 members, 10 highly active members, the highest enrollment the Chapter has ever had on the Twin Cities campus.
  - giiwed'anang will sponsor the attendance of several students at the AISES Leadership Conference in Albuquerque, New Mexico in February 2013.
  - giiwed'anang, along with the Northstar LSAMP (UMN) will sponsor the attendance of the entire UMN-TC AISES Chapter to attend the AISES Regional Meeting in Morris, Minnesota, February 2013.
  - giiwed'anang continues to be a model program for the support of students in AISES.
  - The Northstar AISES Professional Chapter is now heavily engaging professional members in and around the state of Minnesota to the point where they are now offering travel grants to student chapters. Both a potluck and an open house for new chapter recruits will be held in January 2013.
  - In summary, much activity resides around the giiwed'anang Alliance, and all in part of CCEFP's contribution to the AISES organization.
- **2011**
  - The giiwed'anang Northstar STEM Alliance has expanded its number of students from 35 to over 60 Native American undergraduate students participating in at least one giiwed'anang Northstar STEM activity during this current reporting year.
  - The giiwed'anang Alliance was represented on the organizing committee for the National AISES Conference in Minneapolis, Minnesota, November 2011.
  - The University of Minnesota AISES chapter has expanded from six members to over 15. CCEFP Education Outreach Director, Alyssa Burger, serves as the AISES Chapter advisor at UMN.
  - The giiwed'anang Alliance continues to receive financial support from the University of Minnesota Northstar STEM (NSF LSAMP) Program.
  - The giiwed'anang Alliance sponsored 22 students to attend the Region V AISES regional meeting in Souix Falls, SD, in April 2011.

    - The giiwed'anang Alliance sponsored 10 students to attend the National AISES Conference in November 2011.
    - The giiwed'anang Alliance co-sponsored two rocket teams that participated in the All-Nations Launch. One from Fond du Lac Tribal and Community College and the other from the University of Minnesota. Teams earned both first and second place. Co-sponsor was the Minnesota NASA Space Grant Consortium.
    - The giiwed'anang Alliance has helped to launch the Minnesota Region Professional AISES Chapter which is now over 60 members strong and includes Native people in industry, up from 30 just one year ago. The Professional chapter is now eager to begin working with students.
    - The giiwed'anang Alliance is now being accepted as a model for other sub-regions to consider.
    - The giiwed'anang Alliance has successfully established relationships with undergraduate and graduate students in AISES chapters across the states of Minnesota, Wisconsin and North Dakota. Building relationships, mentoring and a support structure is entirely what this Alliance is designed to do.

- Other relevant work: This project is closely aligned with several of the Center's initiatives with the Fond du Lac Indian Reservation, a tribal and community college and the local area schools in Cloquet, Minnesota that foster and mentor the K-14 students of the reservation as well as create programs to bridge middle school to high school to college. The high school students who participate in the gidaa Robotics Program (CCEFP Education Project B.4b) will serve as mentors to the gidaa STEM Camps and the gidaa Robotics day and after-school programs as well as the Robofest teams. Ideally, our graduates of gidaa and gidaa Robotics will continue their education either at a community college or a four-year University and subsequently join the giiwed'anang North Star AISES Alliance and be active undergraduate members of this organization. As noted above, this progressive involvement is illustrative of a very important recipe in making these programs successful: repetition, relationships, trust and a support structure within the community as well as with the Center for Compact and Efficient Fluid Power, the National Center for Earth-surface Dynamics, the North Star STEM LSAMP Alliance, the University of Minnesota and the Fond du Lac Tribal and Community College.

4. Plans, Milestones and Deliverables

- Every effort will be made to:
    - Increase the number of participants and institutions in the North Star Alliance.
    - Find additional funding for the Alliance and expand its program options.
    - Expand the Alliance network at the community and industry levels.
    - Increase the number of AISES Chapters in Minnesota.
    - Promote the Alliance framework to other states.
    - Increase the number of students participating in research experiences or internships.
- The North Star STEM LSAMP Alliance will continue to serve as the partial funding source for this program, enabling the Alliance to sponsor and/or support student travel to professional conferences, leadership meetings, or academic events.
- The CCEFP needs to determine a vein of support as sustainability of these efforts.
- The Alliance will provide information for educational opportunities such as research experiences for undergraduates, industry internships, mentorships, outreach opportunities, etc.
- The Director of the Alliance will continue to be sources of support and mentorship as AISES Chapter Advisors as giiwed'anang students work towards their undergraduate degrees in STEM.

5. Member Company Benefits

This Alliance will continue to foster STEM education and in turn that will be a direct benefit to society as a whole.

EO Project C.6: Fluid Power Simulator

Project team:

Project Leader: Prof. Will Durfee, University of Minnesota, CCEFP
Other personnel: Prof. Chris Paredis, Georgia Tech, CCEFP

1. Project Goals

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

2. How Project Supports the EO Program Strategy

Not all students have access to fluid power hardware through teaching labs or to professional-grade fluid power simulation applications. Exposing more undergraduate and pre-college students to fluid power engineering can be achieved by providing a high quality simulation package that can be used by anyone without charge. Because Project Lead The Way (PLTW), a national primary and secondary school curriculum that includes year-long courses, for example *Gateway to Technology* and *Principles of Engineering*, has a particular interest in a simulation package for use by PLTW schools that cannot purchase fluid power hardware, the strategy of educating pre-college students in fluid power by embedding fluid power into PLTW courses will be aided by provided a high quality fluid power simulation package to PLTW.

3. Achievements

- Simulator requirements were refined.
- The decision to build the simulator as a front end to the Hopsan simulator was re-visited. Instead, the simulator will likely be built directly on top of Open Modelica.

4. Plans

- Continue development with the goal of a first release during Y8.

5. Milestones and Deliverables

- First release of simulator by May 2014.

6. Member Company Benefits

Increased awareness of fluid power. Increased knowledge of fluid power by PLTW students.

EO Project C.8: Student Leadership Council

Project Team

Project Leader:	Alyssa Burger, Education Outreach Director, CCEFP
Other Personnel:	Cherie Bandy, Education Program Coordinator, CCEFP SLC Officers SLC University Representatives Student Members of the CCEFP

1. Project Goals and Description

The primary role of the CCEFP's Student Leadership Council is to serve as one of five advisory boards to the CCEFP. The SLC also functions as a service organization, a social club, and a student government entity for all students at the CCEFP. The SLC promotes inter-university and industrial collaboration directly with CCEFP students through a travel grant program, provides students with funding opportunities to conduct outreach programs at their local universities through a project grant program, organizes and produces the Center's bi-weekly webcast and is also responsible for planning the annual student retreat.

Each university nominates one graduate student representative to serve on the student leadership council. The SLC members elect four individuals to serve in officer roles: President, Vice President, Secretary, and Treasurer. In addition to university representatives from each CCEFP partner institution. The SLC serves as a liaison between the student body and the senior CCEFP leadership providing guidance, voicing concerns and relaying important information between these two groups.

2. Project Role in Support the EO Program Strategy

The SLC serves a vital role in meeting the EO program’s goal of providing fluid power education and awareness for pre-college, university, and practitioner students. At the university level, the SLC strives to make the education and research resources of each member university accessible to all CCEFP students through the creation of student directed travel grant program. For pre-college students, the SLC supports programs to have current CCEFP students teach basic fluid power concepts to future engineers and students. Due to the age proximity between pre-college students and current CCEFP researchers, it stands to reason that some of the most effective methods of connecting to younger individuals could come through the student body of the CCEFP. Presently the SLC sponsors project grants which allow individuals at member universities to pursue projects that allow them to connect better with and educate the youth of their communities.

3. Achievements

The SLC travel and project grant programs, introduced in CCEFP year 6, were continued in year 7 and represent one of the largest impacts the SLC has back to its student body.

Travel Grants

The SLC Travel Grant Program aims to provide funds for students to travel to another project or industry location, making collaboration more accessible. Two or three times a year the SLC solicits travel proposals, with a call addressed to all CCEFP students. Students submit written grant proposals and the SLC discusses and votes on which travel grants to approve and which to deny. The maximum grant for any trip is $1,000, and preference is generally given to collaboration between projects over collaboration with industry.

This program has proven to be very popular among students and faculty. During year 7 a number of grants submitted in year 6 were utilized, and this past fall another call for proposals was issued awarding five grants. Below are testimonials from two CCEFP students who utilized the travel grant program:

"The goal of the visit to University of Illinois Urban-Champaign (UIUC) was to get hands-on experience with the features and functions of the ankle-foot orthosis (AFO) test bed, and to show our efforts with regards to the clinician-centered interface and serious gaming with the test bed team. A preliminary video game was created for the serious gaming component of our research using Microsoft XNA Game studio. Davorin worked on connecting the game to the hardware used to control the AFO, using the API code provided by the hardware. There were some hurdles to overcome with software/hardware incompatibility. However, Davorin was able to control the game with the device once these issues are resolved. This type of progress was only possible with an actual visit to UIUC." – Ritson Delpish & Davorin Stajsic

In addition to providing an outstanding collaborative opportunity for CCEFP graduate students, it also is a good experience for members of the SLC who must review and vote on a variety of differing proposals.

One issue that has arisen as this program has progressed is awarded proposals that go unused or become postponed. Of the 11 awarded grants in the 2011/2012 year, only six were actually used. The remainder were canceled due to either changes in research direction, or personnel. Additionally, a few of the proposals issued in the fall of 2012 are not for travel scheduled until mid-2013. The SLC understands there is a challenge and balance needed between accommodating long range planning of students and the need for an upper limit to the useful grant award period will be addressed in the next call for proposals.

Project Grants

The SLC project grant program is intended to fund outreach or social activities in which primarily CCEFP students will be involved. This may include activities such as building hydraulic demonstration kits, travel to an elementary school to teach about fluid power, or lunch for biweekly webcast presentations. Projects may be one-time or recurring, but should be presented in a single proposal as long as recurrence occurs in the same fiscal year. Proposals are limited to $500 per request.

During the reporting period of this report, seven project grant proposals were awarded to students at various institutions by the SLC. Two of those grants were utilized, two grants to build demo excavator kits for their institution were canceled, and three were just awarded this past fall. Below is a testimonial from CCEFP students who utilized the project grant program:

"As part of CCEFP's education and outreach program, we exhibited miniature hydraulic excavators (built in Purdue) at the Engineering Open House (EOH) of UIUC each year. For our exhibit, we displayed two different hydraulic excavators each utilizing a different type of valve actuation. To complement the instructions, we had posters explaining the working principle of these excavators. We also provided the students with learning materials and toys to encourage them to learn more about fluid power and the research projects at CCEFP. The SLC project grant money was used to purchase foam giveaway toys, purchase some components needed to repair the toy excavators, and provide lunch to those helping with the exhibit." - Ashwin Ramesh

UIUC Engineering Open House 2012

CCEFP Bi-Weekly Webcasts

The Center estimates between 45 - 60 participants per webcast on a regular basis. Participants include industry, faculty, staff and students. Note that we realize that the Center's seven universities as well as industry often arrange for a conference call and meeting space for multiple listeners. In addition to including an audio feedback component, the Center has greatly improved its efficiency and effectiveness with the CCEFP webcasts. The SLC's vice president hosts each webcast, creating seamless transitions between each presenter.

Presentations are not just project-specific information; they also include information on how each project is aligned with the Center's strategic plan. For research, presentations describe how work is demonstrated on the Center's test beds, how current research aligns with what has been done previously as well as how it is breaking new ground, etc. These inclusions have added important new dimensions to the webcasts and have provided another avenue where students, faculty and Center leadership can continue to strategize on the direction of the research projects across the Center. Additionally, webcasts now include more special topics, education outreach presentations and "State of the CCEFP" discussions presented by Center Leadership.

SLC Social Activities and Student Retreat

In addition to providing all of the previously mentioned resources, the SLC also aims, in part, to foster a positive social atmosphere between its student members. Given the physical separation of much of the student body, time spent together at conferences and meetings is particularly important to forming bonds that will enable greater overall moral and collaboration. One of the goals of the SLC is to set aside one lunch or dinner at future annual meetings just for students to help foster these personal connections.

The 2012 CCEFP student retreat was held in Ames, Iowa at Sauer-Danfoss, a CCEFP member company. The two day event featured team building activities between students, a tour of the Sauer-Danfoss facility, and the SLC General Meeting. Additionally, tours at a few other local companies were organized, along with dinners at an arcade and then a casual dinner with Sauer-Danfoss engineers. The event was well organized and offered a blend of social activities, insight into a fluid power company, and a face-to-face meeting of SLC members. Although the digital age enables instant communication, the SLC's experience is that once students have actually met the SLC leadership, they are far more likely to respond to email communication because of that personal connection.

SLC Student Retreat in Ames, Iowa – 2012

Graduate Internship Program

This year the SLC has taken on the challenge of promoting a graduate student internship program. Summer internships are quite common in undergraduate engineering programs. For a variety of reasons, corporate internships are markedly less common among graduate engineering programs. Nevertheless, the SLC believes that for particular individuals a graduate internship could be a great opportunity. In the past simply soliciting interested students through email seemed unsuccessful, thus the opposite approach is being taken this year. Contacts have already been made with CCEFP member companies through the Industrial Advisory Board. A number of companies expressed interest in having graduate internships and work is underway to list specific company internship postings to CCEFP graduate students. In this way, the SLC does not have responsibilities to manage a program per-say, but rather undertakes efforts to foster the initial communication between companies and interested students.

SLC SWOT Analysis

Every year the SLC conducts a Strengths, Weaknesses, Opportunities, and Threats analysis of the student body to identify what efforts are working and identify what areas need continued improvement. An online survey of CCEFP student members was conducted this past year to gauge how students felt the Center has changed since the last SWOT analysis. The results of this survey and the SLC analysis can be found in the SLC SWOT analysis in section 5 Infrastructure, sub-section 5.1 Configuration and Leadership Effort.

4. Plans, Milestones and Deliverables

The deliverables of the SLC efforts this past year have been clear. Through the hard efforts of many of its members, travel and project grants were awarded and processed, bi-weekly webcasts continue to educate CCEFP student members and external companies of recent research developments, and work is underway to promote graduate student internships. Additionally, the SLC sponsors and promotes social events to encourage the development of strong relationships between fellow researchers at SLC student retreats and any other event where many CCEFP students are present.

Plans for the future continue to promote and expand the travel and project grant programs, enabling CCEFP students to continue collaboration with their colleagues at other institutions. The SLC will work to ensure that a student lunch or dinner is scheduled for CCEFP meetings where students will already be present to take advantage of the opportunity. Finally, the SLC hopes to see some of the first graduate student internships begin in the summer of 2013.

5. Member Company Benefits

- SLC funded travel grants enable CCEFP students to travel to industrial locations for training or further education.
- The SLC organizes industrial tours at locations near-by to conferences or retreats.
- The SLC is looking to promote and foster internships between CCEFP graduate students and member companies.
- The SLC hosted Webcasts continues to be the primary means by which industry members can receive continuous updates on CCEFP research projects and Testbeds.
- Student retreats offer significant networking opportunities for companies wishing to get to know students or hire them.

EO Project C.9: Undergraduate Research Diversity Supplement (URDS)

Project Team

Project Leader: Alyssa Burger, Education Outreach Director, CCEFP

Other Personnel: Paul Imbertson, Education Director
Kim Stelson, Center Director
CCEFP Faculty Advisors

1. Project Goals

The CCEFP is committed to promoting the increased participation of diverse undergraduate students in engineering. The short and long-term goals of this supplement program are:

- to provide CCEFP faculty with the means to involve additional undergraduate students on CCEFP research projects,
- to identify an underrepresented student who might not otherwise consider a research opportunity in CCEFP laboratories,
- to encourage students to consider graduate study or an employment position in the fluid power industry by fostering a learning and career advancement environment,
- to further provide exposure to fluid power technology to a diverse audience, and
- to answer the country's need for greater retention of underrepresented students in engineering.

2. How Project Supports the EO Program Strategy

The Center's Education and Outreach program is committed to providing opportunities to broaden the participation of underrepresented students in undergraduate engineering programs through this Undergraduate Research Diversity Supplement to current CCEFP research projects.

3. Achievements

This program was launched in Year 6 of the CCEFP and the response has been favorable. To date, five supplemental requests have been proposed and/or granted:

- **Spring 2013**: Lashawn Nevins, North Carolina A&T State University. African-American undergraduate student supported on CCEFP affiliated project: Ankle-Foot Orthosis.
    - **Advisor:** Professor Zongliang Jiang, North Carolina A&T State University
    - **Project description:** Within the CCEFP, Test bed 6 is developing a portable and pneumatically powered ankle-foot orthosis (PPAFO) prototype. The human factors research team at NCAT supports this effort by developing a clinician-centered graphical user interface for the PPAFO. Such a user interface is designed around the clinician needs to facilitate their information processing and decision-making. More specifically, the design of the rehabilitation function of the PPAFO centers on the design of serious games (built into the user interface) as the main approach to therapies. With the built-in serious games, clinicians assemble therapy routines using game modules, and patients interact with the game-based routines independently from clinician supervision using the PPAFO as the main controller. The student will assist the research team to conduct experiments on human subjects recruited from the NCAT community. The student will measure user performance using the visual analog scale; analyzing and reporting the data. Student will implement the research findings in the development of the user interface.

- **Spring 2013**: Kali Johnson, University of Minnesota. Caucasian Female undergraduate student supported on CCEFP Testbed 6.
    - **Advisor**: Professor William Durfee, University of Minnesota
    - **Project description**: Develop and test hydraulic ankle foot orthosis system. Specifically will be responsible for developing and conducting performance tests to characterize miniature hydraulic components and to characterize the assembled system.

- **Summer 2012**: Jessica Tello, University of Minnesota. Hispanic Female undergraduate student supported on CCEFP-Affiliated Wind Turbine project.
    - **Advisor**: Brad Bohlmann, Mechanical Engineering, University of Minnesota
    - **Project description**: CCEFP Alternative Test Bed β is a 2.5 MW Clipper Liberty wind turbine owned by the University of Minnesota. It is located on a 5,000 acre site owned by the University in Rosemount, MN and was constructed as a research wind turbine with funding from the Department of Energy. The research on the wind turbine is administered by the University's Eolos Wind Energy Research Consortium of which CCEFP is a partner (http://eolos.umn.edu/).
    - **Outcome Report**: The goal of this URDS project was to add some content and finalize a report on research done by another REU. Wind velocity increases with height above the ground and the amount of energy in wind is proportional to the wind velocity cubed. However, tower cost increases with tower height. The REU's project focused on analyzing the trade-offs in determining the optimal tower height for a wind turbine. Jesse built a wood apparatus to simulate the turbine to determine if the equation the research team was utilizing was accurate. The student was able to verify the rotation across the x-axis and the y-axis, which allowed the research team to apply the data to the accurate equations. The student compared data during low wind speed and high wind speed and found the data to indicate movement far beyond what was reasonably expected. It was determined that the movement in the turbine tower was exaggerating the movement in the foundation. Other variables and use of data is to be determined. The URDS funding to this student covered two weeks. She gathered the REU student's work and started working on the additions and revision, but did not submit a final report.

- **Spring 2012**: Lee Ann Monaghan, University of Illinois, Urbana-Champaign. Caucasian Female undergraduate student supported on CCEFP Testbed 6.
    - **Advisor**: Professor Elizabeth Hsiao-Wecksler. University of Illinois, Urbana-Champaign
    - **Project description**: Under Testbed 6, researchers have developed an untethered powered AFO system, which is called the portable-powered ankle-foot orthosis (PPAFO). This system uses pneumatic power from compressed CO2 to drive a rotary actuator that provides bi-directional assistive torque at the ankle joint: dorsiflexor assistance (toes up) and plantarflexor assistance (toes down).
    - **Outcome Report**: Lee Ann was involved in Test bed 6 on the pneumatic powered ankle-foot orthosis (PPAFO). Her responsibilities were to work with her graduate student mentors, NSF GRDS-supported Morgan Boes and CCEFP-supported David (Yifan) Li, to perform experiments to quantify the efficiency of the PPAFO. Specifically, she had two objectives: (1) analyze the efficiency of the PPAFO pneumatic circuit with different configurations of the components to determine the optimal configuration, and (2) measure the efficiency of each individual component in the circuit to identify the least efficient components. Lee Ann created a benchtop configuration of the PPAFO components for the circuit and individual component analyses. She completed the circuit configuration analysis, but was not able to finish the individual component analysis. The individual component analysis was completed by CCEFP REU summer intern, Megan Hodgson. Lee Ann was also involved in the 2011-2012 Parker Hannifin Chainless Challenge competition (E&O Project C.3b) as part of her Capstone Senior Design course. Lee Ann graduated with her BS in Mechanical Engineering in May 2012. She is now employed at Microsoft in their Kinect hardware group.

- **Spring 2012**: Brianna Benedict, North Carolina A&T State University. African-American Female undergraduate student supported on CCEFP Testbed 6 affiliated project: Ankle-Foot Orthosis.
  - **Advisor**: Professor Zongliang Jiang, North Carolina A&T State University
  - **Project description**: The construction and implementation of a database system is essential to the success of the AFO user interface. The long-term goal of the AFO user interface project is to establish an effective and user-friendly interface for the clinicians to interact with the AFO enabling them to examine a patient's rehab progress and prescribe a new assistance plan or therapy regimen. This proposed database manages patient data (e..g., medical history, past therapy sessions and results) which are crucial pieces of information in the decision-making processes of clinicians during their interaction with the AFO for maximized effectiveness in rehabilitation or daily assistance. How such data is organized and accessed by the clinicians is fundamental to the effectiveness of the entire AFO user interface.
  - **Outcome Report**: Brianna helped design the logical structure of the database that records and manages patient records as an important component of the user interface being developed by the NCAT team for the PPAFO of Testbed 6. The student has reached her research goals and expressed strong interest in seeking further educational opportunities in this area. Brianna was unable to continue to work on the project after the supplemental funding due to other curricular and extracurricular commitments. Currently Brianna is a junior in Industrial and Systems Engineering at North Carolina A & T State University.

- The CCEFP E&O program has an application and proposal process for this URDS which includes the following:
  - **Candidates:**
    - Candidates must be a currently enrolled undergraduate student, in good standing, at CCEFP institution
    - A candidate must be a student of underrepresented status in engineering or other related discipline. This includes students who are women, African American, Native American or Native Alaskan, Pacific Islander, Hispanic or Latino/a, a person with disabilities, or a recent war veteran of the armed services
    - Candidates must be United States citizens, nationals, or permanent residents of the United States.
  - **Supplement request requirements:**
    - **A proposed research project**. A maximum of 2 pages.
    - **Undergraduate student mentoring plan**. Include a brief description of mentoring activities that will be provided for the proposed candidate. This could include a timeline and set of deliverables, career counseling and networking, professional development, presentation opportunities, seminar/conferences or workshops, etc.
    - **Previous CCEFP experience**. Include a brief description of previous CCEFP experience, if applicable. Eligibility requirements of this supplement require that awardees are not current student employees of the CCEFP.
    - **Student statement of purpose**. The candidate indicates interest in undergraduate research including academic and career goals.
    - **Student resume.**
    - **Budget and justification**. Submit a budget that is fully burdened, inclusive of 25% indirect on participant support costs. Maximum request is $2,000.
  - **Award Information:** Awards will be granted based on proposal merit. The Education Outreach Director, in consultation with Center Director, will make decisions on the supplement awards. Anticipated funding for this supplement is $11,250 under the CCEFP Education and Outreach Program. The estimated number of supplements to be awarded will be four to six. The end date of the supplemental award is May 31, 2012.

4. Plans, Milestones and Deliverables

- As usual, a start-up program requires time to gain footing. To date, and as noted above, five awards have been proposed and/or granted to undergraduate underrepresented students in engineering. All females, three racially or ethnically underrepresented.
- The CCEFP E&O program will continue to support this program as long as the research program can sustain it. The CCEFP understands that hands-on research experiences, with the guidance of a mentor, are key to promoting graduate school to underrepresented students in engineering. The CCEFP has the resources, tools and leadership to make significant impacts in fluid power education.
- The CCEFP will continue to support up to six undergraduate students per year beginning in year 7, continuing into year 8. At least half of the URDS awardees will be women and at least half will represent racial or ethnic minorities.
- The CCEFP will inquire into additional and external funding to support this program -- sponsored funding and/or industrial support.
- The E&O program will require advisors to issue a mentoring plan for each student and invite awardees to present at one of the following events: CCEFP Annual Meeting, CCEFP Site Visit, or CCEFP IAB Summit or CCEFP Research Webcast.
- When appropriate, the CCEFP will encourage awardees to apply to the National GEM Consortium, which is a national program committed to promoting graduate student study for racially or ethnically underrepresented students in engineering. The GEM Consortium has a fellowship program, which is supported by its industry members. The GEM Consortium and the ERC membership are key to the CCEFP Diversity strategy.

5. Member Company Benefits

The URDS program contributes to the building of an informed and motivated student group—future leaders for industry and academia.

EO Project C.10: NSF and CCEFP Graduate Research Diversity Supplement (GRDS)

Project Team

Project Leader:	Alyssa Burger, Education Outreach Director, CCEFP
Other Personnel:	Kim Stelson, Center Director, CCEFP Paul Imbertson, Education Director, CCEFP CCEFP Faculty advisors
Industrial Partners:	National GEM Consortium Caterpillar, Inc.

1. Project Goals

The CCEFP is committed to promoting the increased participation of diverse graduate students in engineering. The short and long-term goals of this supplement program are:

- to provide CCEFP faculty with the means to involve additional graduate students on CCEFP research projects,
- to identify a graduate student who might not otherwise consider a research opportunity in CCEFP laboratories,
- to encourage students to consider graduate study or an employment position in the fluid power industry by fostering a learning and career advancement environment,
- to further provide exposure to fluid power technology to a diverse audience, and
- to answer the country's need of greater retention of underrepresented students in engineering.

2. How Project Supports the EO Program Strategy

The Center's Education and Outreach program is committed to broadening the participation of underrepresented students in engineering programs through channels including the NSF Graduate Research Diversity Supplement (GRDS) to current CCEFP research projects. This effort is complimented by the CCEFP's own Graduate and Undergraduate Research Diversity Supplement (GRDS, URDS, respectively). (See E&O Project C.9.) Ideally, the CCEFP's URDS would positively influence a student to enter graduate school within the Center.

3. Achievements

The CCEFP has applied for and been awarded five years of funding under the NSF GRDS supplement and has supported four female graduate students. The CCEFP will not apply for a sixth year of funding, as the NSF GRDS program has been put on hold, as of January 2013. The CCEFP will work to find funds to continue to support the two existing female graduate students in the CCEFP who were supported in the previous NSF GRDS award.

In addition, the CCEFP supplements the funds of the NSF GRDS award to fully support the two GRDS awardees. Funding from the NSF GRDS does not provide sufficient support for full-time academic employment for the graduate students. Typically, the CCEFP contributes over $28,000 between the two GRDS awardees. Finally, the CCEFP has launched a new program under the auspice of the CCEFP GRDS initiatives, which includes a joint graduate student fellowship between CCEFP, the National GEM Consortium and Industry.

<u>CCEFP Graduate Research Diversity Supplement (CCEFP GRDS)</u>

The Center for Compact and Efficient Fluid Power is collaborating closely with the National GEM Consortium to devise a novel interface between NSF Engineering Research Center's, the National GEM Consortium and Industry. The intersection of the three sectors is synergistic – GEM identifies and fosters top diverse talent in the STEM fields; NSF ERCs are responsible for creating a diverse pathway for students of all ages, with a focus in research at the Masters and PhD levels; industry, of course, is interested in a qualified workforce.

The CCEFP has reached an agreement with a corporate member of the Center – Caterpillar, Inc., who is also a corporate member of GEM. The CCEFP and CAT will serve as "Co-Employers" for an identified student at Georgia Institute of Technology. The student, who will be identified as a GEM Fellow, will be a new Masters student, as of the Fall of 2013, and will be identified in Spring 2013. The CCEFP will provide the one-time initial investment of $22,500 to GEM, and CAT will provide two paid graduate level summer internship positions at one of their corporate locations. The student will work on CCEFP research aligned with CAT's initiatives, as the advisee of a CCEFP faculty researcher at GeorgiaTech. GeorgiaTech will contribute the remaining funds to support the GEM Fellow in full.

The CCEFP will utilize core EO funds to offer a GEM Fellowship, which is worth over $150,000 for the GEM Fellow, while leveraging the support of the corporate member and the available GEM grants at GeorgiaTech.

NSF Graduate Research Diversity Supplement (NSF GRDS)

Funded: 2012 - 2013: **Ms. Charreau Bell**, Vanderbilt, GRDS and CCEFP Funding
Ms. Morgan Boes, UIUC, GRDS and CCEFP Funding

Description of Scope of Work (Proposed January 2012, Awarded June 2012)
The supplement will be used to fund two female GRDS awardees, Charreau S. Bell and Morgan K. Boes. The supplement will be a key element in recruiting Charreau Bell, a perspective African-American Ph.D. student in the Department of Mechanical Engineering at Vanderbilt University (VU) beginning in August 2012. Her research mentor will be Professor Pietro Valdastri, a new faculty member in the CCEFP and the Department of Mechanical Engineering at Vanderbilt University, whose limited startup funds, alone, would not allow Charreau's recruitment. The supplement will also be used for a GRDS renewal project for another female student, Morgan Boes who started as a PhD student in the Department of Bioengineering at the University of Illinois, Urbana-Champaign (UIUC) in January 2012, the start-date of her current GRDS support. Morgan's mentor will be Professor Elizabeth Hsiao-Wecksler (UIUC) on CCEFP Test Bed 6, Human Assist Devices. The GRDS funds have allowed Morgan to move to an engineering-based project for her PhD dissertation. Both women's long-term career goals are to obtain positions in major research universities. Morgan is part of the Medical Scholars MD/PhD Program at UIUC. Her career goal is to be a physician-researcher at a research university with a medical school. Charreau's goal is to obtain a tenured faculty position in a major research university.

Outcomes:

- **Charreau Bell** is working on the development of a biocompatible chemical reaction to provide wireless insufflation of the gastrointestinal tract. Adequate tissue distension provided by insufflation will enable wireless capsule endoscopy to become an effective screening technique for colorectal cancer. Charreau started in August 2012. She was able to submit a paper to a peer-reviewed journal, and two publication for workshop that resulted in two poster presentations. As a female African American student, Charreau is deeply involved in outreach activities. She is involved in the Engineering Ambassador program, coordinated by Penn State University, coordinating with Dr. Valdastri the efforts at Vanderbilt University. Charreau is also mentoring a male African American high school student, and one freshman (male) and one sophomore (female) Vanderbilt students, all doing research in Dr. Valdastri's lab. Charreau's future research will focus on the same topic and will move from bench to in vivo animal (porcine model) trials. Charreau's career goal is still to obtain a tenured faculty position in a major research university. The experience she gained during this year in both doing research and mentoring students, made possible by the GRDS funds, will provide a strong foundation toward her goal.

- **Morgan Boes** continues to work on Test Bed 6. During the past year, Morgan has been focusing her efforts on improving the efficiency of the pneumatically powered ankle foot orthosis, which is a continuation of the work by previous GRDS-supported student, Emily Morris. Specifically, Morgan has implemented a pneumatic energy recycling scheme into the portable powered ankle-foot orthosis (PPAFO). Her work has involved benchtop and human subject testing to validate that use of an accumulator to capture exhaust gas from the higher pressure plantarflexion motion can successfully drive the lower pressure dorsiflexion motion during walking. This recycling scheme can result in a fuel savings of 30-35%. She has also been working on designing and implementing an elastomeric pneumatic accumulator into the PPAFO, and is working in conjunction with Vanderbilt which has been working on the elastomeric hydraulic accumulator (Research Project 2C.2). Further, she has been driving the collaboration with NCAT to develop a clinical user interface and rehabilitation robotic gaming interface for stroke rehabilitation using the PPAFO (Research Project 3A.3.). Morgan was mentor to undergraduate students involved in the test bed, including Spring 2012 REU student Lee Ann Monaghan (supported by EO Project C.9 URDS) and Summer 2012 REU student Megan Hodgson, who both worked on experiments to validate Morgan's component efficiency calculations. She also presented the TB6 work during the Spring 2012 NSF site visit oral presentations and at the Fall 2012 CCEFP Annual Meeting, which resulted in getting a top award for best poster presentation.

Funded: 2011 - 2012: **Ms. Katherine (Braun) Houle**, UMN, NSF and CCEFP GRDS Funding
Ms. Emily Morris, UIUC, NSF and CCEFP GRDS Funding
Ms. Morgan Boes, UIUC, NSF and CCEFP GRDS Funding

Outcomes:

- **Morgan Boes** is working on Test Bed 6 (Human Assist Devices: Fluid Power Ankle-Foot Orthosis (AFO)). TB6 is one of four test beds in the CCEFP. Of the four, it is the smallest size scale and is intended to answer the question of whether the energy-to-weight and power-to-weight advantages of fluid power continue to hold for tiny, mobile fluid power systems in the 10 to 100 W range. Test Bed 6 also serves to drive the development of enabling fluid power technologies that are powerful, compact and lightweight and has the practical objective of creating new portable, wearable fluid power assist devices. Test Bed 6 is a joint project between the University of Illinois (UIUC) and the University of Minnesota (UMN) with UIUC integrating the technology and conducting biomechanical testing on low-pressure pneumatic systems and UMN looking at advanced technologies with high-pressure electro-hydraulic solutions.

- **Kathy (Braun) Houle** continues to work at the CCEFP on Test Bed 6. She is part of the UMN team working on a hydraulic version of the powered AFO. Kathy used her expertise in musculoskeletal mechanics to translate biomechanical requirements into engineering designs. She conducted detailed assessments of the torque, velocity and power produced by the ankle during normal walking and translated these into appropriate design requirements for the hydraulic components in the AFO. This was a non-trivial task as informed trade-offs must be made to accommodate realistic hydraulic configurations. She also directed the test plan to evaluate performance of the first version of the hydraulic AFO, which includes comparing performance to computer simulations. In addition, Kathy has taken on leadership roles including presenting the TB6 project for CCEFP project reviews and mentoring a summer REU student.

- **Emily Morris** decided to complete her master's degree and thesis at the end of August 2011. She returned to industry working for Caterpillar in Peoria, IL, a CCEFP Industry member. Caterpillar served as her employer prior to starting her graduate studies. During the spring and summer of 2011, she worked on projects to improve the efficiency of the PPAFO inTB6. She performed computational analyses to assess inefficiencies due to pressure loss. The work was presented at the 2011 International Fluid Power Expo and a journal paper is in preparation. During the summer, she worked with a CCEFP REU to experimentally explore use of thermal regulation of the CO_2 power source bottle or supply line to the rotary actuator to improve system efficiency.Morgan Boes will continue these activities by incorporating Emily's design modifications into the next generation PPAFO. Emily continues to work with the CCEFP and TB6 as an advisor for a Mechanical Engineering senior design team at Bradley University in Peoria, which has a CCEFP Education & Outreach grant for AY11-12 to develop a pancake pneumatic rotary actuator using a novel design. During Emily's master's program, she authored eight abstracts/papers for scholarly or professional conferences (four as first author), and presented at two national technical conferences and multiple UIUC campus and CCEFP events and meetings. Two journal papers are also in preparation from her work.

Funded 2010 - 2011: **Ms. Katherine Braun**, UMN, NSF GRDS Funding
Ms. Emily Morris, UIUC, NSF GRDS Funding
Funded 2009 – 2010: **Ms. Emily Morris**, UIUC, NSF GRDS Funding

4. Plans, Milestones and Deliverables

- The CCEFP E&O and Research program will look for ways to support underrepresented graduate students, utilizing NSF supplemental opportunities, as long as research within the Center can sustain it.
- The CCEFP will continue to request NSF supplemental support for graduate students during CCEFP years 8 and 9, assuming other NSF supplemental funding is available.
- The CCEFP will continue to work with the National GEM Consortium on supporting a GEM Fellow in years 8, 9 and 10.
- The supplement will require advisors to issue a mentoring plan for each student and invite awardees to present at one or more of the following events: CCEFP Annual Meeting, CCEFP Site Visit, or CCEFP IAB Summit or CCEFP Research Webcast.
- Efforts will be made to encourage GRDS awardees to achieve their Masters and PhDs through the CCEFP.

5. Member Company Benefits

Member companies can participate in graduate research projects as mentors. Member companies can also take advantage of the new relationship with the National GEM Consortium. Here, member companies get a first look at a bright, diverse pool of students trained in fluid power who may become future intern or permanent employees. More generally, the GRDS program contributes to the building of an informed and motivated student group—future leaders for industry and academia.

Project C.11: Innovative Engineers (IE) Program

Project Team

Project Leader: Paul Imbertson, CCEFP Education Director

Other Personnel: Alyssa Burger, CCEFP Education and Outreach Director
Student Members of the Innovative Engineers (IE) Student Organization

1. Project Goals and Description

The Innovative Engineers (IE) student group, with support from the Center for Compact and Efficient Fluid Power (CCEFP), is dedicated to providing authentic pedagogical experiences for engineering students, primarily in the area of renewable energy solutions for developing nations. They do this by actively engaging students in the design and implementation aspects of real-world problems in the United States and abroad. The group was formed by engineering students at the University of Minnesota who were inspired to actively pursue renewable energy solutions for people in remote and developing areas. They now have branches at the University of Minnesota and at Universidad Ibero-Americano in Mexico City, Mexico. IE fills a need at the university by providing a space where engineering students can take part in active pedagogy, learning and honing their engineering skills through work on real projects.

2. Project Role in Support of the EO Program Strategy

A core mission of CCEFP Education and Outreach program is to educate university students and to bring awareness of the CCEFP and fluid power to those engineering students. Partnering with the Innovative Engineers student group gives the CCEFP a unique opportunity to address that mission by becoming an integral partner in a large and active group of engineering students. The CCEFP will provide project and organizational support to IE.

3. Achievements

The Innovative Engineers have positively impacted communities, university students, and pre-university students through an assortment of implementation projects and outreach programs in the United States and Nicaragua, involving inner-city schools, American Indian Reservations, technical schools in Nicaragua and remote communities in Nicaragua.

Sustainia100: The Innovative Engineers were honored in 2012 to be listed as one of the top 100 examples of sustainable solutions that show a path to a viable future for our planet. They were included on the Sustainia100 list along with projects from 56 countries and were the only university students group so honored.

Press: Since its formation in 2010, the Innovative Engineers has been very busy as can be seen from articles that have been written about them in the press.

- "International honor for wind energy work in Nicaragua", Revista Eolica y del Vehiculo Electrico (REVE), June 2012
- "U of M Innovative Engineers receives international honor for wind energy work in Nicaragua", Physics.org, June 2012
- "U of M student group honored for wind turbine in Nicaragua", KSTP News, Summer 2012
- "Winds of Change", Inventing Tomorrow, a publication for alumni of the College of Science and Engineering, Winter 2012
- "Wind-Wind Situation", University of Minnesota Foundation, Summer 2011

- “Promueven energia eolica en Jinotega (Promoting Energy in Jinotega)”, La Prensa, May 2011
- “Building turbines and relationships”, College of Science and Engineering”, April 2011
- “U Engineers Aid Nicaraguan Village”, Minnesota Daily, November 2010
- “Innovative Engineers Power Third World”, Minnesota Daily, March 2010

Activities: Much of the work of IE is documented in these publications. These and, as yet unmentioned, activities include:

- IE built and installed a wind turbine in the community of La Hermita in Nicaragua for the BRIDGE Project. The CCEFP supported the final installation efforts.
- IE has designed a turbine and generator for a hydroelectric facility in Bocay, Nicaragua. This work has involved site visits to Nicaragua and installation is planned for 2013. Plans are to use these designs for multiple installations in the Bocay region of Nicaragua.
- Work was started on the design and development of a hybrid electric/hydraulic wind turbine. This work is directly supported by the CCEFP. Major accomplishments to date include mathematical and ProE modeling, major electrical and mechanical component design and fabrication, mock layup, and lab testing. The hybrid electric/hydraulic wind turbine will be field tested in 2013 with subsequent evaluation and modification.
- DC (Developing Nations) Wind Turbine. The goal of this project is to simplify generator designs with the aim to create designs that can be easily constructed by local residents in developing nations. Major accomplishments include characterization of the existing generator design, evaluation of winding shapes, and completion of a cut-in speed study.
- Active collaboration with the National Society of Black Engineers (NSBE) and American Indian Science and Engineering Society (AISES) on outreach efforts to the White Earth Indian Reservation in northern Minnesota. White Earth is located in the poorest county of Minnesota and is often overlooked because of its remote location.

4. Plans

Innovative Engineers is positioned for growth and more efficient project development with its partnership with the CCEFP. Future plans include:

- Identify and begin work with additional communities in Jinotega Department in Nicaragua for collaborative development of wind and hydroelectric energy production systems.
- Expand work with Universidad Ibero Americana in Mexico City.
- Expand BRIDGE project activities to Little Earth Community in inner-city Minneapolis (Largest urban reservation in the United States).
- Continue BRIDGE activities on the White Earth Indian Reservation.
- Testing and verification of hybrid hydraulic/electric wind turbine.
- Test new generator designs for developing nations (DC Wind Turbine).
- Install hydroelectric energy system in Bocay, Nicaragua.

- Coordinate with electrical system officials in Bocay, Nicaragua to discuss further hydroelectric development in the remote Bocay region.

4. Related Projects

The Innovative Engineers work with the National Society of Black Engineers (NSBE), the American Indian Science and Engineering Society (AISES), and the BRIDGE project, which is in turn supported by the CCEFP. The Innovative Engineers also work with the CCEFP on the hybrid hydraulic electric wind turbine.

5. Milestones and Deliverables

6. Member Company Benefits

Benefits to member companies include access to students and projects. Further, member companies may benefit from the public visibility that can come from an association with IE.

EO Project D.1: Fluid Power Scholars/Interns Program

Project Team:

Project Leader:	Alyssa Burger, CCEFP Education Outreach Director
Industry Partners:	Members of the CCEFP Industrial Advisory Board; volunteer sponsors/mentors from the ranks of the Center's industry supporters

1. Project Goals

The Fluid Power Scholars program benefits participating students and the companies that sponsor them. Student participants gain hands-on experience in fluid power technology as they work as summer employees in a "real world" work environment. Sponsoring companies benefit as the students they mentor contribute to workforce productivity, often bringing new perspectives to their tasks based on what they have learned in the classroom. An internship program also provides companies with opportunities to determine whether their scholar/intern might work well as an employee following graduation. Recognizing these benefits, the CCEFP has made a good model even better by adding an intensive orientation to fluid power at the outset of the internship experience in order to enable scholar/interns to make more immediate and effective contributions to their host companies.

2. How Project Supports the EO Program Strategy

Cultivation of cooperative efforts, informed by and of benefit to the academic and corporate world of fluid power, is key to CCEFP education and outreach program strategy. The Fluid Power Scholars/Interns Program rests on partnerships between industry, the Center, and engineering students nationwide. The program also facilitates knowledge transfer between Center constituents--from the classroom to the shop floor.

3. Achievements

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 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:

- Since program launch, Scholars have come from these various institutions: Carnegie Mellon (1), Case Western Reserve (1), Clarkson (1), Iowa State University (2), Kansas State University (1), Illinois Institute of Technology (2), Montana State University (2), Purdue University (2), University of Michigan (1), University of Minnesota (5), University of Minnesota-Duluth (1), University of Missouri-Columbia (4), University of Florida (1), University of South Florida (1).
- The history of the Fluid Power Scholars Program demonstrates that 68% of former participants stay in the fluid power industry; 52% of former participants are hired directly into their host company; others are either still in school or are pursuing graduate education.
- All company sponsors have expressed their satisfaction with the program. Seven of the nine corporate sponsors in 2012 were repeat participants, two companies were new to the program. Those who have elected not to participate are for reasons other than any dissatisfaction with the program.

- The orientation to fluid power offered to scholars/interns at the outset of the program by faculty at the Milwaukee School of Engineering's Fluid Power Institute has been highly reviewed by scholars/interns and their corporate sponsors.
- Recruitment efforts continue to generate interest in the program among students within and outside of the CCEFP university network.
- The CCEFP will expand the method and modes of this program to launch, in Y7, a similar effort for graduate-level internships in CCEFP member companies.

	2010	2011	2012	TOTAL
Number of Students	8	8	9	25
Males	6	8	8	22
Female	2	0	1	3
% of students from underrepresented groups 1) racial minority 2) gender minority 3) disability	13% 25% 0%	0% 0% 0%	0% 11% 11%	.04% 12% .04%

2012 Fluid Power Scholars Program

- Scholar/Intern positions: nine companies offered to support nine scholars in the summer of 2012: Caterpillar, John Deere, Case New Holland, Sauer-Danfoss, Parker Hannifin, Deltrol Fluid Products, Eaton Corporation, HUSCO International and Sun Hydraulics.
- Fluid Power Scholars were from the following institutions: University of Missouri-Columbia (2), Iowa State University (2), Kansas State University, Illinois Institute of Technology, University of Minnesota, University of Minnesota-Duluth, Purdue University
- Since the summer experience, five Fluid Power Scholars were hired by their host company, one student was hired into the fluid power industry, two continue their undergraduate studies and two have pursued graduate study.

2012 Fluid Power Scholars

2011 Fluid Power Scholars Program

- The set up of the 2010 program was so workable by all accounts, that the same promotion, recruitment and selection procedures were followed again in this, the program's second year.
- Scholar/Intern positions: Seven companies offered to support eight scholars in the summer of 2011: Caterpillar, Deltrol Fluid Products, John Deere, Case New Holland (2), Parker Hannifin Corporation, Sun Hydraulics, and HUSCO International. Their internship positions were posted at the Fluid Power Scholars section of the Center website.
- Student recruitment: The CCEFP received applications from 60 students at __ universities. Students representing universities within and outside of the Center applied through an on-line process at the Center website. (Note that the Scholars/Interns Program is open to undergraduate students who have successfully completed at least two years in an accredited engineering program anywhere in the United States.)
- Matching process: All sponsoring companies had access to a secured section of the CCEFP website where student applications were posted. Company personnel studied these applications and selected their top choices for the internships they had posted. While they informed CCEFP staff of these choices, companies were solely responsible for contacting students to set up and conduct telephone interviews and to subsequently make internship offers. 2011 scholars/interns represented Case Western Reserve (1), University of Florida (1), Purdue (1), Clarkson (1), University of Minnesota (2), and University of Missouri-Columbia (2). (The "myriad of differences" in company choices, noted above, was manifested in the selection process. None of the companies named the same student as their top choice.)
- Ongoing evaluations: Following an evaluation model established and conducted by the Center for Applied Research and Educational Improvement (CAREI) in 2010 as well as reference to CAREI's relevant background work in 2008 and 2009, CCEFP staff evaluated the 2011 program through surveys and telephone interviews with student scholar/interns and their corporate sponsors.

2010 Fluid Power Scholars Program

- 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 Educational 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.

4. Plans, Milestones and Deliverables

- As of this writing, company and student recruitment for the 2013 Fluid Power Scholars/Interns Program is still in process. CNH, Parker Hannifin, Deltrol, Sun Hydraulics, HUSCO International and Eaton Corp.

- The orientation to fluid power offered by MSOE to scholars/interns was lengthened by a day in 2012 and the existing program will follow this trend. The change follows recommendations by students and industry.

- Given student and corporate interest, the Fluid Power Scholars/Interns program will continue beyond 2013, potentially with added scholar/intern opportunities in 2013 and thereafter. The CCEFP is implementing expanding this program to graduate student internship positions, minus the fluid power orientation at MSOE.

- The CCEFP's website page that provides links to internships within the fluid power industry outside of the Scholars Program will continue to be maintained. Though complementary to Center goals, these internship programs are independent of the Scholars/Interns Program. See http://www.ccefp.org/get-involved/internships.
- A thorough evaluation of the Scholars/Interns Program will be conducted at the launch and at the end of summer 2013 with the help of Quality Evaluation Designs. New data, along with comparisons with the old, will help to shape the Fluid Power Scholars/Interns Program going forward.

5. Member Benefits

- Internships provide companies with opportunities to directly participate in educating and training a next generation of engineers.
- Fluid power interns provide an excellent way to locate motivated, short-term engineering help.
- Long term, internships are viewed by many in industry as an invaluable tool for identifying talented candidates for future full-time employment. And the program has proven to do just that; sponsoring companies have established a track record of hiring fluid power scholars.

Project D.2: Industry Student Networking

Project Team

Project Leader: Alyssa A. Burger, Education Outreach Director

Other Personnel: Student Leadership Council
CCEFP Graduate Students
Industrial Advisory Board

Industrial Partner: All CCEFP Industry Members

1. Project Goals and Description

The goal of this project is to provide CCEFP students with opportunities to network with industry representatives through a variety of channels. In doing so, there are multiple benefits: all students will better understand the fluid power industry's needs and its markets; interested students will be able to find internships and later job opportunities upon graduating; companies will be able to meet, interact, and discuss potential employment opportunities with students. Channels utilized in this project include company tours, poster sessions, and resume exchanges as well as additional opportunities that extend the Center's outreach to more students and companies.

2. Project Role in Support the EO Program Strategy

This program aligns well with the goals, mission, and strategy of the CCEFP by engaging students in the fluid power industry, often offering them opportunities to stay in this industry so they can have an impact in fluid power research and applications. This project also provides industry with mechanisms to contact and interact with students (possibly prospective employees) who have become familiar with fluid power through the Center's work.

3. Achievements

- Student Retreats: Each year a student retreat is held for all CCEFP students. These have been held at member institutions, as well as in conjunction with the National Fluid Power Association's (NFPA) 2009 and 2011 Industry and Economic Outlook Conference. Retreats provide students with the opportunity to expand their networking connections as they present their research to company representatives, some of whom are not members of the CCEFP but work in fluid power.
  - In 2012, the Student Leadership Council held it's annual Student Retreat in August at Sauer-Danfoss in Ames, Iowa. The experience was mutually benefitting for students and for industry members at Sauer-Danfoss. The company expressed interest in hosting the Student Retreat again. Agenda at the Retreat included a welcome, overview and orientation to the company followed by creative team-building exercises for CCEFP students. The students were given a facility plant tour, had lunch with a number of hydraulic engineers and had various social arrangements around the Ames geographic area. On the departure day, students were tasked with creating problem sets for the CCEFP's System Dynamics and Control mini-book, which will eventually be integrated into the individual chapters. Subsequently, Caterpillar has approached the Center in hosting the next CCEFP Student Retreat.
- CCEFP Annual Meetings: Since 2006, the CCEFP has held an annual meeting at each of the following locations: the University of Minnesota, MSOE, Georgia Tech, North Carolina A&T, Purdue, University of Illinois, Urbana-Champaign and in conjunction with the International Fluid Power Expo in Las Vegas. Representatives of the Center's industry members attended each of these meetings. The next Annual Meeting will be in partnership with the Bath Fluid Power Symposium in Sarasota, Florida.
  - In the Fall of 2012, the CCEFP partnered with NFPA in hosting the first NFPA Workforce Summit and CCEFP Annual Meeting at the University of Illinois, Urbana-Champaign. The event was a synergistic combination of networking among industry and students with a student poster session and competition followed by an industry networking kiosk session where all attendees were able to mingle over appetizers and beverages. Over 17 companies hosted a kiosk during the reception. The event hosted a resume exchange for students and industry as well as panel presentations and discussions by fluid power

leaders. Immediately after the "Workforce Summit", CCEFP launched into the traditional Annual Meeting where students presented on CCEFP research, had UIUC laboratory tours as well as closed-door meetings between the Industry Advisory Board and the Scientific Advisory Board regarding the sustainability of the Center. Overall, a powerful meeting achieved by NFPA and CCEFP.

- Resume Exchanges: At the CCEFP Annual Meeting in 2011, a resume exchange session was held between Center students and representatives of its member companies. Each company had its own designated table, and students could rotate around the tables to speak to as many representatives as they wished. The representatives gave a brief background and introduction to their company, along with providing details about the projects they are currently pursuing. Students were encouraged to bring their resumes to share with companies representatives to discuss internship and job opportunities. This event provided students the opportunity to talk with industry representatives one-on-one in a more personal setting.
- Research Poster Sessions: A poster session has been held at each of the CCEFP's Annual Meetings. These events allow students to enhance their presentation and professional skills as they describe their research to industry members, while industry members can stay informed of research being done in the Center. A poster competition was added at the 2011 NSF Site Visit and Annual Meeting. Industry members served as judges, awarding prizes to presenters of the top three posters. A poster session competition was also held at the 2012 NFPA Workforce Summit and CCEFP Annual Meeting at the University of Illinois, Urbana-Champaign.
- The Fluid Power Scholars Program was launched in 2010. The goal is to introduce and interest undergraduate engineering students to the possibility of working in the fluid power industry. This is a highly selective program for undergraduates nationwide. Prior to beginning an internship in a member company, each scholar attends an intensive Fluid Power Bootcamp program at MSOE. To date, 24 Fluid Power Scholars have been supported through the program. For more information, please refer to EO Project D.1.
- The CCEFP supports the Parker Chainless Challenge Competition for undergraduate engineering students interested in fluid power.
  - In 2012, teams participated from University of Minnesota, advised by Brad Bohlmann; University of Illinois, Urbana-Champaign, advised by Elizabeth Hsiao-Wecksler; Purdue University, advised by Andrea Vacca; and Milwaukee School of Engineering, advised by Vincent Prantil. Over 20 students had direct exposure to fluid power through their capstone design course via the Parker Hannifin Chainless Challenge. For more information, please refer to EO Project C.3a.
- Industry members have provided their knowledge and expertise to senior design capstone projects. Project examples include a hydraulic pedicab, a chainless bicycle powered by hydraulics, and numerous demonstrations, on display at the Science Museum of Minnesota.
- The CCEFP supports the NFPA Fluid Power Challenge Competition for 8th grade students, a competition in which students had to design a device to accomplish a task using fluid power (see EO Project B.7). Competition judges included representatives from local industries who invited students to ask them questions about their careers. CCEFP has hosted the Challenge at the University of Minnesota in 2009 and 2012. Over 200 students have participated between each competition.
- The Student Leadership Council (SLC) hosts a Research Webcast every other Wednesday afternoon. Students and faculty from CCEFP institutions participate, along with representatives from affiliated industrial member companies. These webcasts are intended to keep everyone in the Center informed about research progress, give and receive suggestions, and generally promote inter-university collaboration as well as cooperation between academia and industry. Research presentations are 20 minutes long with up to 10 minutes for discussion. Occasionally, officers from the CCEFP administration present about topics of general interest (strategy, overall progress, education & outreach, and so on). These webcasts are typically very well attended with approximately 180 members from CCEFP's 52 member companies requesting invites.

4. Plans, Milestones and Deliverables

- Following a successful student retreat hosted at a corporate member facility, future retreats will be held at CCEFP member companies. Holding retreats at company facilities will provide more students the chance to interact with practicing engineers and will facilitate opportunities for knowledge transfer.
- Given positive feedback from both the students and the industry members, future poster sessions at CCEFP Annual Meetings will continue to include a competition, with industry representatives

as judges. This guarantees that some representatives from industry will be visiting each poster, while providing students with additional incentive to put together a good poster and presentation.

- Resume exchange/roundtable discussions and Industry Kiosks will continue at future CCEFP Annual Meetings. Students will have a chance to visit the booths and see which companies are of particular interest. A resume exchange session will follow, where industry representatives will sit one-on-one with students to meet, conduct something of an informal interview, and explore mentoring and research project sponsorship opportunities. This event provides students with a more private atmosphere to talk with company representatives, one-on-one.
- Industry sponsorships will be encouraged as a way of getting middle and high school students interested in fluid power.
- An education committee of industry representatives will be formed to brainstorm and develop new activities within this project. The goal is to have 3-5 representatives from industry work with Center staff to help devise additional strategies for networking. Committee members would also become "points of contact" for students who are looking for a career in fluid power or assistance on a project, but are not sure of where to begin.
- The Student Leadership Council is exploring the challenges student face when trying to enter into internships in Industry. The SLC will identify ways to encourage students to take advantage of industry internships during their graduate study. See EO Project C.8.

5. Member Company Benefits

This project, with its current and planned programs and activities, enables CCEFP member companies to interact on many levels with engineering students, some of whom will join their work forces, others of whom will work within the fluid power industry's customer base; and still others who will find their way to the classroom where they will teach a next generation of engineers, instilling in them a knowledge of and interest in fluid power.

EO Project D.5: CCEFP Webcasts

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	Cherie Bandy, Education Program Coordinator SLC President and Vice President CCEFP graduate students Invited speakers outside the CCEFP network
Industrial Partners:	All CCEFP Industry Members

1. Project Goals and Description

The goal of the webcast series is to maintain a consistent means of technology transfer throughout the Center—students, faculty and industry supporters. On a regular basis, the CCEFP hosts a webcast featuring two presentations, each discussing either research projects or other Center-wide programs (e.g., special topics, strategic planning, education and outreach, project evaluation, etc.). These webcasts are open to all CCEFP students, faculty, and CCEFP member companies. The webcasts are presentation based, with audio and visual capabilities. A brief question and answer session after each presentation allows the audience to ask for clarifications and give feedback to the presenter. Each webcast is recorded and archived for retrieval and is posted and available on a members-only secured section of the Center's web site.

2. Project Role in Support the EO Program Strategy

This program aligns well with the mission, vision, and strategy of the CCEFP by creating widespread awareness of its research and education projects as well as the Center's administrative and evaluative work. Since many of the webcast presentations are made by Center students, participation in this project fosters professional development as they "learn by doing" how best to communicate—describing their work and also responding to and benefiting from the input of faculty, their peers and industry.

3. Achievements

- Each research project funded through the CCEFP presents once per year. The CCEFP hosts "State of the Center" addresses by the Center Director each year. Approximately once a quarter special topics webcasts are scheduled which may include education and outreach, or invited talks from Industry as well as from experts on matters such as intellectual property, patents, ethics, etc.
- The Center estimates between 45 - 60 participants join the webcast on a regular basis. Participants include industry, faculty, staff, and students including special invitations to the Scientific Advisory Board.
- The Center continues to find ways to improve the efficiency and effectiveness of the webcasts. In addition to including an audio feedback component, the Student Leadership Council emcees each webcast, making for seamless transitions between presenters.
- The Student Leadership Council has provided funding to CCEFP sites to host lunch to encourage participation and attendance.
- Presentations are not just project-specific information; they also include information on how each project is aligned with the Center's strategic plan. For research, presentations describe how work is demonstrated on the Center's test beds, how current research aligns with what has been done previously as well as how it is breaking new ground, etc. These inclusions have added important new dimensions to the webcasts and have provided another avenue where students, faculty and Center leadership can continue to strategize on the direction of the research projects across the Center.
- With the initiation of the travel grant and project grant programs through the SLC this past year (EO Project C.8), students who were awarded these funds are invited to present to give a brief description of where they went, why they went there, and what was achieved. This not only gives

the CCEFP industry members a chance to see collaborations with other research projects or industry, but it also allows students to see how others have used these funds and generate ideas for how they could utilize the SLC travel grant with their own research projects.

4. Plans, Milestones and Deliverables

- A proposed expansion of the Center's webcast series includes a fluid power training webcast series lead by industry experts provided on the opposite schedule of the regularly scheduled webcast series. Following the webcast model, Sustainability Director, Brad Bohlmann, proposes recruiting industry instructors to present a fluid power training program for CCEFP graduate and undergraduate students. The training series would be archived and available for review; however, each year, presentations will be live for each topic presented. Presentation ideas include topics covered in the traditional training manuals headquartered at many of our fluid power companies. An initial concern is ensuring participation by CCEFP students and faculty. The SLC will explore options to encourage participation. Finally, a certification of completion could be issued by the CCEFP to students who review all training sessions. This proposal is open for exploration for Y8 in the CCEFP. Anticipated launch date is June 2013.
- Presentations will continue to include collaborations and results from awarded proposals from the Student Leadership Council's travel grant program. As the Center matures, more projects will be incorporated into testbeds and industrial applications, and this will provide an opportunity for all members of the CCEFP to see these collaborations.
- The Student Leadership Council is adding funding for graduate student internships in industry. To generate interest, those students who have already held an internship in industry will be invited to present why they took an internships, projects they worked on during their internship, and lessons learned from the experience. Once the program is launched, students that have received funding will be invited to talk about their experience.
- Every effort will be made to expand participation among all audiences. The Center will continue to gather input from current and potential participants as we seek out ways to enhance this key Center project.
- The CCEFP will continue to host the webcasts, which are a proven success, popular within the Center network and among its industrial members. They will continue to be recorded and archived on a secure portion of the website so they are accessible to all members. As the Center matures, so will the research and education outreach projects, and the webcasts will reflect the impact of these initiatives.

5. Member Company Benefits

All Center participants—faculty, SAB, students, industry, and staff—have opportunities to get first-hand updates on research, education, and management level activities from project leaders. Webcasts also foster a sense of "community" throughout the Center network as all constituents regularly have opportunities to hear and learn from each other.

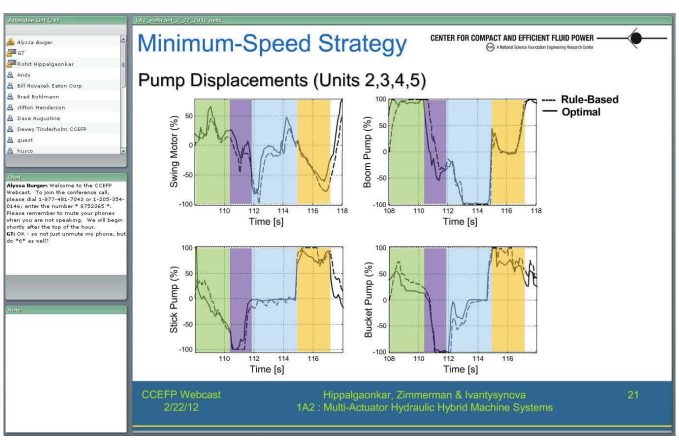

Figure 1: Screenshot of a webcast presentation

EO Project E.1: External Evaluation of Education and Outreach Program

Project Team

Project Leader:	Quality Evaluation Designs (QED)
Other Personnel:	Gary Lichtenstein, Principal, Quality Evaluation Designs Jenifer Helms, Senior Research Associate, Quality Evaluation Designs Aran Glancy, Research Associate, Quality Evaluation Designs Maggie Miller, Project Manager, Quality Evaluation Designs Paul Imbertson, Education Director, CCEFP Alyssa Burger, Education Outreach Director, CCEFP

1. Project Goals

Quality Evaluation Designs (QED) is the new, contracted external evaluator of CCEFP Education and Outreach projects. (QED replaces CAREI, the Center's initial external evaluator.) The overall goal of the QED external evaluation is to collect data that have the potential to promote sustainability of E&O beyond NSF funding of CCEFP. To do this, QED will pursue the following objectives:

1. Anticipate in the evaluation design a new administrative/organizational CCEFP structure that supports and integrates E&O goals and objectives.
2. Identify current and potential stakeholders who could sustain E&O goals and/or programs during and after the current funding cycle.
3. Collect data and draft reports that address the value-added of E&O to CCEFP goals and programs.

2. How Project Supports the EO Program Strategy

Partnership with QED is an application of a key E&O strategy--identifying and working with a strong partner in order to maximize results. Specifically, QED will assist E&O staff in clarifying program objectives, quantifying results, and achieving success in critical ERC goals for E&O.

3. Achievements

QED principal (Dr. Gary Lichtenstein) and project manager (Maggie Miller) visited CCEFP in March, 2012 for an all day briefing about CCEFP and E&O projects and goals. Based on that, QED created an evaluation design and presented the proposed design at the NSF site visit of CCEFP in April 2012. The evaluation design was then modified, based upon email discussions with the NSF Program Officer. The revised proposal was approved in May, pending release of program funds. CCEFP funding issues and summer vacations at the University of Minnesota delayed completion of the subaward. The subaward was finalized on October 23, 2012. QED then initiated an IRB application, which was approved on November 26, upon which data collection could begin.

Goals for the 2012-13 evaluation are to complete a sponsor study that will determine the motivations and goals corporate and non-profit organizations have for partnering with CCEFP. Determining these motivations can help E&O design programs likely to attract sponsorship beyond the ERC funding. Second, QED will work closely with E&O staff to design program-wide metrics that will help E&O quantify participation across projects. In 2013-14, QED will help E&O in defining/clarifying program goals and objectives, and begin assessing projects within E&O for their success in meeting those objectives.

QED Senior Research Associate, Dr. Jenifer Helms, traveled to UMN and met with E&O and CCEFP leadership in August, to gain deeper understanding about E&O goals and operations. Based on that, the implementation plan was refined and the Sponsor Study designed. QED attended the NFPA/CCEFP Annual Meeting on Sept 24-26 at UIUC. Aran Glancy was able to make personal contact with several sponsors and gain insights that sharpened the sponsor study. In December, Mr. Glancy met with Alyssa Burger to get contact information for sponsors. Interviews will begin in early January. Approximately 25-40 sponsors will be contacted for telephone interviews lasting about 30 minutes. Those who prefer completing the information via an online survey will have that opportunity. Interviews will be completed by mid-February and results analyzed and reported by early May.

A draft version of a participant information form to be used across E&O projects has been created. It will be finalized in mid-January, whereupon it will be deployed across all E&O project events. Data will be aggregated to assess a fine-grained profile the populations that participate in E&O and in what contexts and activities they are involved.

4. 2012-13 Implementation and Deliverables

- Scope of the project work with QED will began with a visit to CCEFP Headquarters in March 2012.
- QED attended and presented at the NSF site visit in April, 2012.
- QED senior research associate, Jenifer Helms, met with E&O and CCEFP leadership to design the Sponsor Study.
- QED Research Associate, Aran Glancy, attended the NFPA/CCEFP Annual Sponsor Meeting on September 24-26, 2012 at UIUC.
- The QED subaward was finalized on October 23, 2012.
- The IRB was approved on November 26, 2012 (QED projects were considered exempt).
- The QED Sponsor Study was initiated in mid-December, with interviews taking place January through mid-February.
- QED is working with E&O leadership to put into place reporting forms that will help summarize participant demographics across projects. This work will become the basis for in-depth project evaluation in 2013-14
- QED will attend the May 2012 NSF Site Visit at the University of Minnesota.
- The results of QED's 2012-13 will be presented in the Center's next Annual Report.

5. Member Company Benefits

QED's evaluation efforts with CCEFP indirectly benefit member companies and the entire industry as CCEFP works to increase the numbers and diversity of new engineers in fluid power. The main point of all the evaluation efforts is to assist CCEFP to work smarter, achieve program goals and determine plans for sustainability.

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Associated Project Abstracts: Research

Thrust 1 – Efficiency

<u>Advanced Energy Saving Hydraulic System Architecture for a Wheel Loader</u>
Project Leader: Monika Ivantysynova
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

<u>Advances in External Gear Machines Modeling</u>
Project Leader: Andrea Vacca
Sponsors: Casappa S.p.A.

Abstract: This project is aimed to develop new modeling techniques for external gear pumps and motors. Particular focus is on the sealing gaps within the machine, in particular the lateral gap, between gears and lateral bushes. This gap strongly affects losses and reliability of the unit.

<u>Advances in Modeling External Spur Gear Machines and Development of Innovative Solutions*</u>
Project Leader: Andrea Vacca
Sponsors: Casappa S.p.A.

Abstract: Development of proprietary solutions and related models for new designs of gear pumps.

<u>Design of low noise emission internal gear machines</u>
Project Leader: Andrea Vacca
Sponsors: Confidential

Abstract: Unavailable due to confidentiality of project.

<u>Design of positive displacement machines for SCR automotive applications</u>
Project Leader: Andrea Vacca
Sponsors: Confidential

Abstract: Unavailable due to confidentiality of project.

<u>Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump*</u>
Project Leader: Andrea Vacca
Sponsors: Confidential

Abstract: Unavailable due to confidentiality of project.

<u>Effect of Various Oils on the Efficiency of a Series Hydraulic Hybrid*</u>
Project Leader: Monika Ivantysynova
Sponsors: confidential

Abstract: Unavailable due to confidentiality of project.

<u>EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage</u>
Project Leader: Perry Li
Sponsors: National Science Foundation (NSF)

Abstract: "The goal of this project is to develop an efficient, powerful and cost effective localized energy storage concept for off-shore wind power using high pressure compressed air. The system is to be capable of storing several hours' worth of wind energy. Research involves heat transfer improvement, efficient machine element, and system optimization and control."

<u>Energy Saving Hydraulic System Architecture Utilizing Displacement*</u>
Project Leader: Monika Ivantysynova
Sponsors: **confidential**

Abstract: Unavailable due to confidentiality of project.

Evaluation and Design Improvements for a Hydraulic Pump*
Project Leader: Monika Ivantysynova
Sponsors: Confidential
Abstract: Unavailable due to confidentiality of project.

Evaluation of a Proprietary Gear Pump*
Project Leader: Andrea Vacca
Sponsors: Confidential
Abstract: Unavailable due to confidentiality of project.

Evaluation and Design Improvements for a Hydraulic Pump*
Project Leader: Monika Ivantysynova
Sponsors: **confidential**
Abstract: Unavailable due to confidentiality of project.

Modeling and Analysis of Axial Piston Pump*
Project Leader: Monika Ivantysynova
Sponsors: **confidential**
Abstract: Unavailable due to confidentiality of project.

Modeling and Analysis of Swash Plate Type Axial Piston Pump (Interface)
Project Leader: Monika Ivantysynova
Sponsors: **confidential**
Abstract: Unavailable due to confidentiality of project.

Modeling of Axial Piston Pumps and Motors*
Project Leader: Monika Ivantysynova
Sponsors: **confidential**
Abstract: Unavailable due to confidentiality of project.

PCA Mule- System Implementation and Testing
Project Leader: Monika Ivantysynova
Sponsors: **confidential**
Abstract: Unavailable due to confidentiality of project.

Performance Prediction and System Control through Coupled Multi-domain Models: A Comparison Study
Project Leader: Monika Ivantysynova
Sponsors: **confidential**
Abstract: Unavailable due to confidentiality of project.

Pump Dynamic Model Development
Project Leader: Monika Ivantysynova
Sponsors: **confidential**
Abstract: Unavailable due to confidentiality of project.

Reliable Lightweight Transmission of Off-shore Utility Scale Wind Turbines
Project Leader: Kim Stelson
Sponsors: Eaton Corporation
Abstract: "The US Department of Energy (DOE) has goal of 20% of US energy from wind by 2030. In order to achieve this goal, off-shore wind sites will need to be developed. This requires the development of wind turbines that are 2-3+ times higher in output than current land sited wind turbines. One of the major reliability concerns in current utility scale wind turbines is the failure of the mechanical gearbox. This problem will be exacerbated as wind turbines grow in size and output. Increased reliability is especially important in off-shore wind turbines given their size and

the logistical challenges associated with maintenance and repair. Even beyond the reliability challenges of ever larger gearboxes, the mass of the gearbox and its components and subsystems increase with higher power throughput, thus making construction, maintenance and repair more difficult. This project is focused on developing an advanced hydrostatic transmission (HST) drivetrain concept which considerably reduces the weight in the nacelle and replaces the gearbox with a much more reliable solution. The goal is to reduce the cost of energy (COE) and lower lifetime costs of a large off-shore wind turbine (6 MW=).
UMN's work on this DOE funded project was a continuation of the work initiated in the IREE funded project ""Hydrostatic Transmission for Wind Power Generation""."

Thrust 2 – Compactness

Functionally Graded Metallic Lattice Components for Advanced Propulsion Components
Project Leader: Vito Gervasi
Sponsors: DARPA Associated

Abstract: This DARPA funded project is aimed at producing advanced harsh environment components by leveraging additive manufacturing technologies and two-phase intertwined lattice structures to produce functionally graded materials. Applications include advanced non-eroding propulsion systems, armor, and some effort in the area of composite fluid power components.

Open Accumulator Compressed Air Storage Concept for Wind Power
Project Leader: Perry Li
Sponsors: University of MN; IonE and IREE

Abstract: The goal of this project is to determine appropriate methods to achieve adequate heat transfer during the compression and expansion of air in a compressed air energy storage system.

Thrust 3: Effectiveness

Adaptive Control for Oscillation Damping
Project Leader: Andrea Vacca
Sponsors: CNH America, Inc.

Abstract: Unavailable due to confidentiality of project.

Analysis of transmission noise sources
Project Leader: Monika Ivantysynova
Sponsors: Confidential

Abstract: Unavailable due to confidentiality of project.

Development of an Experimental Pressurized Thin-film Couette Viscometer and Consultation
Project Leader: Scott Bair
Sponsors: Total Oil Company

Abstract: The shear-dependent viscosity of organic liquids at high pressures is of intense interest to the fields of hydrodynamic and elastohydrodynamic lubrication. Many lubricants, however, do not display shear-dependency until the applied shear stress is quite large-greater than 0.3 MPa. The Center for High Pressure Rheology at Georgia Tech has developed six different pressurized, thin-film Couette viscometers of increasing capability. These instruments are not routine viscometers; they are experimental devices for which mechanical and electrical failures may be unforeseen and may occur often. This project involves construction and assistance in the operation of a pressurized, thin-film Couette viscometer very similar to one in use in the Center for High Pressure Rheology at the George W. Woodruff School of Mechanical Engineering of Georgia Institute of Technology.

Evaluation of the High Pressure, High Shear Stress Capability at Georgia Tech
Project Leader: Scott Bair
Sponsors: Georgia Tech Center for High Pressure Rheology

Abstract: The Georgia Tech Center for High Pressure Rheology will characterize liquids, a base oil and some base oil plus viscosity modifier solutions to evaluate whether or not shear-thinning behavior can be demonstrated and if the techniques can differentiate the onset and extent of shear thinning. The eventual goal is to relate shear-thinning to polymer structure and concentration. The techniques to be employed are high-pressure, thin-film Couette viscometry and falling cylinder viscometry. These instruments provide the capability to measure viscosity across seven orders-of-magnitude, 1 to 10^7 Pa.

Multimodal Human-Machine Interface design with Augmented Reality and Ergonomics*
Project Leader: Silvanus J. Udoka
Sponsors: confidential

Abstract: This project sought to use augmented interaction techniques for designing a hybrid user interface that integrates 3D visualization and interaction devices in a mixed-reality environment. The project develops a platform to accommodate models developed through Human Performance Modeling and User Centered Design studies, to develop a user interface extended through augmentation by registering computer generated graphics onto real images that are coming from the work environment to mimic real life scenarios. By conducting experiments in a realistic environment provided by mixed reality, significant input can be provided to designers to develop interfaces that make the operation of the fluid power system on which it is implemented safe, easy to use, and effective.

Optimization of Valve Plate to Reduce Noise and Control Effort for Axial Piston Pump*
Project Leader: Monika Ivantysynova
Sponsors: University of Stuttgart/German Research Foundation

Abstract: Unavailable due to confidentiality of project.

Shaft Pumping by Laser Structured Shafts with Rotary Lip Seals*
Project Leader: Richard Salant
Sponsors: University of Stuttgart/German Research Foundation

Abstract: A simulation model to predict pumping by shafts with various surface finishes, in combination with a rotary lip seal, has been developed and validated by experiment. The model consists of a fluid mechanics analysis of the flow in the sealing zone coupled with a deformation analysis of the seal. The experimental validation consists of pumping measurements with shafts whose surface structures contain laser generated oblique grooves. Plots of pumping rate versus various parameters show good agreement between the model and experiment. Plots of torque vs. speed, as well, show good agreement between the model and experiment.
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Suppressor System Development*
Project Leader: Kenneth Cunefare
Sponsors: Eaton Corporation

Abstract: Develop an optimized noise suppressor configuration using off-the-shelf bladder-style noise suppressor devices for control of noise, vibration, and harshness issues. Develop numerical model for individual suppressor transmission loss performance based on suppressor configuration and charge pressure. Validate the model performance against experimental data obtained on the Georgia Tech ISO 15086 test rig. Integrate suppressor model into basic network model. Use integrated model to develop optimized suppressor configuration (number, connectivity, and charge pressure) for specified performance.

Understanding and Reducing the Adverse Effects of Biodynamic Feedthrough
Project Leader: Wayne Book
Sponsors: National Defense Science and Engineering Graduate Fellowship (NDSEG)

Abstract: This research investigates and seeks to mitigate the undesirable effects of biodynamic feedthrough in backhoe operation. Biodynamic feedthrough occurs when motion of the controlled machine excites motion of the human operator, which is fed back into the control input device. This unwanted input can cause significant performance degradation, which can include limit cycles or even instability. Backhoe user interface designers indicate that this is a problem in many conventional machines, and it has also proved to significantly degrade performance in the test bed used for this research. Dynamic models of this particular backhoe control system, including the biodynamic feedthrough, have been developed. Cab vibration control was selected as a means to mitigate the biodynamic feedthrough effect. Several variations of controllers were developed and tested in simulations, including both active and passive vibration compensation. Both use the working implement itself to reduce the cab motion, rather than adding additional hardware. In this case, the backhoe arm has dual functionality, to perform excavation operations and to cancel cab vibration. Both input shaping and active damping approaches proved to significantly reduce cab vibration both in simulation and in hardware, with minimal cylinder tracking performance degradation and without additional actuators. Extensive testing with human subjects and statistical analysis has confirmed the efficacy of this approach. The results show that both the input shaper and LOR with active vibration compensation can considerably reduce cab vibration. However, this correlates with more significant improvement in operator tracking performance with the LQR controller and active vibration compensation. The operator survey results give some clues about this difference.

<u>CPS: Synergy: Integrated Modeling, Analysis and Synthesis of Miniature Medical Devices*</u>
Project Leader: Pietro Valdastri
Sponsors: National Science Foundation (NSF)

Abstract: The objective of this project is to create a focused cyber-physical design environment to accelerate the development of miniature medical devices in general and swallowable systems in particular. The project develops new models and tools including a web-based integrated simulation environment, capturing the interacting dynamics of the computational and physical components of devices designed to work inside the human body, to enable wider design space exploration, and, ultimately, to lower the barriers which have thus far impeded system engineering of miniature medical devices. Currently, a few select individuals with deep domain expertise create these systems. The goal is to open this field to a wider community and at the same time create better designs through advanced tool support. The project defines a component model and corresponding domain-specific modeling language to provide a common framework for design capture, design space exploration, analysis and automated synthesis of all hardware and software artifacts. The project also develops a rich and extensible component and design template library that designers can reuse. The online design environment will provide early feedback and hence, it will lower the cost of experimentation with alternatives. The potential benefit is not just incremental (in time and cost), but can lead to novel ideas by mitigating the risk of trying unconventional solutions.

*Newly added in year 7

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Associated Project Abstracts: Education & Outreach

Through cooperation and collaboration, the CCEFP leverages its work with the following university and organizational programs and the funding each has received. These efforts follow from the CCEFP's strategy of seeking out strong partners in developing its educational and outreach programs.

EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Bases Targeted Mathematics-Science Partnership
Lead Personnel: Tamara Moore, Paul Imbertson (CCEFP), Gil Roehrig, Martin Davis, Siddika Guzey
Grant: National Science Foundation - Math and Science Partnership (NSF-MSP)
Funding: $8,000,000 over 5 years

The EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Based Targeted Mathematics-Science Partnership vision is to increase grade 4-8 student learning of science concepts, as well as the mathematics concepts related to data analysis and measurement, by using an engineering design-based approach to teacher professional development and curricular development. The partnership involves the University of Minnesota's Science, Technology, Engineering, and Mathematics (STEMEdCtr) Education Center (Lead Partner) and the Center for Compact and Efficient Fluid Power (CCEFP) (Core Partner), the Saint Paul Public Schools (Core Partner), the North Saint Paul-Maplewood-Oakdale School District (Supporting Partner), and the South Washington County Schools (Supporting Partner). A sixth partner is the ECSU/GRO Leadership Council (Supporting Partner) who is uniquely qualified to provide research-based professional development. Together these six partners will explore the overarching research question: What are the effects of engineering design pedagogies and curricula combined with a coaching model on student learning in science, data analysis, measurement, and critical thinking?

This project is designed to help 200 teachers develop engineering design curricular units for each of the major science topic areas within the Minnesota State Academic Science Standards for grades 4-8 with a focus on vertical alignment and transition from upper elementary to middle-level. This will impact 15,000 students over the life of the grant. The alignment will be in both the scaffolding of the concepts and the pedagogy used in these grades. The partnership is using summer professional development and curriculum writing workshops paired with a cognitive coaching model to allow teachers to design engineering design-based curricular units focused on science concepts, meaningful data analysis, and measurement. These curricular units will go through an extensive design research cycle to ensure a quality product and then will be submitted to an online peer-reviewed NSF-funded digital library TeachEngineering (teachengineering.org) for use across the United States and beyond. An external advisory board consisting of recognized experts in engineering, science education, engineering education, mathematics education, science assessment, and cognitive coaching will meet annually to provide guidance to the project.

The research findings will provide directions for designing effective curriculum and learning of STEM. The dissemination of the curriculum modules on the peer-reviewed NSF websites and the findings of the dissemination of the curriculum modules on the peer-reviewed NSF websites and the findings of the research studies will inform practitioners, administrators, researchers, and policy makers who aim to improve student achievement and interest in STEM careers.

CCEFP role: The CCEFP serves as a partner to this project providing technical content experts and direction in engineering pedagogy. Paul Imbertson (CCEFP) serves as the Content Director for the project.

<u>gidaa: The *manoomin* (Wild Rice) Project</u>
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.

<u>Hand Powered Water Pumps for Developing Countries</u>
Lead Personnel: Gary Werner, John Lumkes, Isaac Zama, Vincent Kitio McCutcheon High School/Purdue University
Sponsor: CCEFP, Purdue University, McCutcheon HS, African Centre for Renewable Energy and Sustainable Technologies (ACREST)
Funding: $11,000 in RET Support

This project was initiated during the summer 2011 CCEFP RET program. Gary Werner, a technology and pre-engineering teacher at McCutcheon HS, and John Lumkes, while discussing Purdue's involvement in international service learning and how to get students interested in fluid power, proposed combining real needs for pumping water in Africa with giving the students a real world fluid power design problem. During the summer the researchers contacted a Purdue partner NGO (ACREST) in Bangang, Africa and the project definition took shape. After the conclusion of the summer RET experience Gary incorporated the water pumping problem into his pre-engineering class. There are currently four high-school students planning a trip in May 2012, accompanied by Gary, to ACREST in Bangang, Africa to begin the implementation phase of their project, develop ideas for new projects, and get an early glimpse of engineering solutions to real problems.

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).

NC A&T State University Regional Collaborations for Excellence in STEM
Lead Personnel: Eui Park
Funding: $500,000 over 2 years
Abstract: The North Carolina A&T State University Regional Collaborative for Excellence in STEM is a comprehensive and inclusive project that targets the enhancement of STEM education and learning outcomes for middle school aged children in five counties in Eastern North Carolina: Bertie, Edgecombe, Gates, Pitt, Wilson. In particular, this project focuses on cohorts of 6th grade students 2012. The project will follow these students with programming until high school graduation. In each year following the first cohort, an additional 6th Grade cohort will be added to the project creating a pipeline into high school and post-secondary education.

The approach to this project is to collaboratively assess design and implement programs focused on STEM education tailored to the needs and capacities of the identified rural areas. The needs and the capacities of these localities will differ; however, given the array of partners, the resources in this collaborative, coupled with its comprehensive approach, each locality will be able to improve the educational experience and outcomes in STEM areas, particularly in math and science.

North Star STEM LSAMP Alliance
Lead Personnel: Anne Hornickel, Program Director
Grant: LSAMP - Louis Stokes' Alliance for Minority Participation
LSAMP Funding: $293,025 / year
CCEFP Received: $5,000

Abstract: The Louis Stokes Alliance for Minority Participation (LSAMP) is an initiative funded by the National Science Foundation (NSF) which is intended to double the number of African-American, Hispanic/Latino, and Native American students receiving baccalaureate degrees in science, technology, engineering and math (STEM). In Minnesota, the LSAMP program is called the North Star STEM Alliance, a partnership of sixteen higher education institutions and two community partners, the Science Museum of Minnesota and Minnesota High Tech Association. The academic institutions represent the breadth of higher education institutions in Minnesota, and include both public and private colleges and universities, as well as technical colleges, and a tribal college. North Star STEM Alliance goals include: 1) doubling the number of underrepresented students receiving bachelor's degrees in science, technology, engineering, and mathematics among partner institutions; 2) developing an alliance of collegiate institutions and community organizations working toward increasing the likelihood of success of underrepresented students working toward their bachelor's degree.

CCEFP role: The CCEFP is the lead facilitator of the giiwed'anang Northstar Alliance which is sponsored in part by the North Star STEM Alliance. The giiwed'anang Alliance is considered an official undergraduate program under the North Star STEM LSAMP Alliance.

Purdue University - SURF REU Program
Sponsor: Purdue University
Funding: $16,000 in SURF REU Supplement (recurring)

Abstract: The SURF program provides students across all engineering, science and technology disciplines with an intensive research experience, allowing them to work closely with graduate students and professors in their respective schools. The interdisciplinary nature of the projects allows students to learn and work across other disciplines while still applying the concepts and skills from their own programs. This setting provides undergraduate students with an avenue to perform research in an academic environment while exploring future graduate study options.

CCEFP role: The Center hosts its own REU program at its seven participating universities. However at Purdue, the REU Program leverages the local REU efforts by receiving a 2:1 matching REU supplement award with the local program. In 2009, 2010 and 2011, the CCEFP hosted six REUs at Purdue; two were sponsored by SURF.

Universal Fluid Power Trainer
Lead Personnel: Medhat Khalil, Milwaukee School of Engineering
Sponsor: MSOE's Maha Fund
Funding: $366,000

Abstract: Universal Fluid Power Trainer will be the main training stands for the Professional Education Department at MSOE. After successful development of the prototype unit that was been funded by the CCEFP, MSOE invested $336,000 to develop three additional units to replace the existing and outdated fluid power training units. Presently, the three additional units are under fabrication. The four units of the Universal Trainer are expected to be in full operation. In tandem, Dr. Khalil is working to develop the new lab manual to make a smooth transition from the old to the new trainers.

CCEFP role: The Center provided the seed funding for this project in Years 2 and 3.

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