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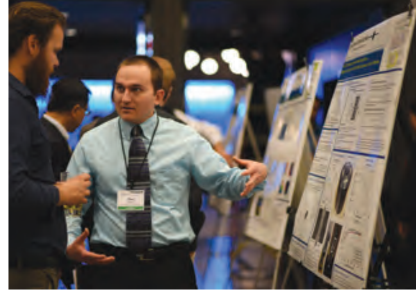
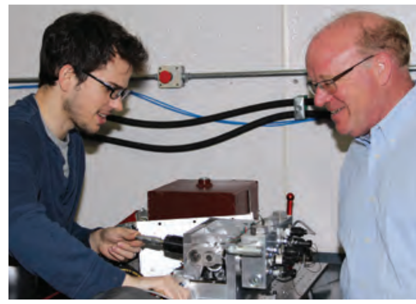
PRELIMINARY FINAL REPORT 2016





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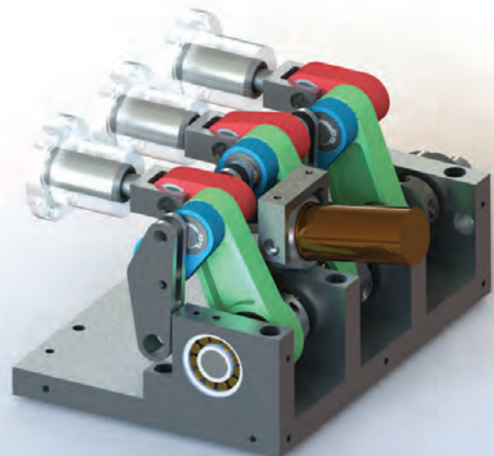
VOLUME 2



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

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Dr. Eric Barth, Co-Deputy Director
Dr. Zongxuan Sun, Co-Deputy Director

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

RESEARCH PROJECTS

Thrust 1 – Efficiency

Project Name	PI / Institution / Sponsor
1B.1: New material combinations and surface shapes for the main tribological systems of piston machines	Monika Ivantysynova, Purdue University
1E.3: High Efficiency, High Bandwidth, Actively Controlled Variable Displacement Pump/Motor	John Lumkes, Purdue University; Monika Ivantysynova, Purdue University
1E.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
1G.3: Rheological Design for Efficient Fluid Power	Randy Ewoldt, University of Illinois at Urbana-Champaign
1J.1: Hydraulic Transmissions for Wind Energy	Kim Stelson, University of Minnesota
1J.2: A Novel Pressure-Controlled Hydro_Mechanical Transmission	Kim Stelson, University of Minnesota
Adjustable Linkage Pump	James Van de Ven, University of Minnesota. *Sponsor: Cat Pumps*
Advanced Hydraulic Systems for Next Generation of Skid Steer Loaders	Monika Ivantysynova, Purdue University. *Sponsor: Confidential*
Aeration and Fluid Efficiency	Paul Michael, Milwaukee School of Engineering. *Sponsor: Confidential*
Building a Hardware-in-the-loop Simulation Testbed and a Living Laboratory for Evaluating Connected Vehicle-Highway Systems	Zongxuan Sun, University of Minnesota *Sponsor: FHWA*
CAREER: Control of Mechatronic Automotive Propulsion Systems	Zongxuan Sun, University of Minnesota *Sponsor: NSF*

Project Name	PI / Institution / Sponsor
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Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump	Andrea Vacca, Purdue University *Sponsor: Dae Jin Hydraulics-TECPOS*
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	Perry Li, University of Minnesota *Sponsor: NSF*
Energy Efficient Fluid Field Trial	Paul Michael, Milwaukee School of Engineering. *Sponsor: Confidential*
Energy Efficient Fluids	Paul Michael, Milwaukee School of Engineering. *Sponsors: Confidential*
Energy Saving Hydraulic System Architecture for Next Generation of Combines Utilizing Displacement Control	Monika Ivantysynova, Purdue University *Sponsor: Confidential*
Evaluation and Design Improvements for a Hydraulic Pump	Monika Ivantysynova, Purdue University *Sponsor: Confidential*
Evaluation and Design Study of the Piston/Cylinder Interface of a Swash Plate Type Hydraulic Motor	Monika Ivantysynova, Purdue University *Sponsor: Confidential*
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Investigation of Alternative Cylinder Block Materials using Fluid Structure Interaction Modeling (FSTI)	Monika Ivantysynova, Purdue University *Sponsor: Confidential*
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Modeling and Analysis of Swash Plate Axial Piston Pump	Monika Ivantysynova, Purdue University *Sponsor: Confidential*
MRI: Development of a Controlled-Trajectory Rapid Compression and Expansion Machine	Zongxuan Sun, University of Minnesota *Sponsor: National Science Foundation*
New Geometries for Gear Machines towards the Reduction of Noise Emissions	Andrea Vacca, Purdue University *Sponsor: Casappa S.p.A.*
Numerical Modeling of GEROTORs Unit	Andrea Vacca, Purdue University *Sponsor: Thomas Magnete GmbH*
Optimal Design of a Fuel Injection Pump	Andrea Vacca, Purdue University *Sponsor: Robert Bosch SpA (Italy)*

Thrust 2 – Compactness

Project Name	PI / Institution / Sponsor
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
2F: MEMS Proportional Pneumatic Valve	Thomas Chase, University of Minnesota
2F.1 Soft Pneumatic Actuator for Arm Orthosis	Elizabeth Hsiao-Wecksler, University of Illinois at Urbana-Champaign
2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems	Robert Webster, Vanderbilt University Jun Ueda, Georgia Institute of Technology

Thrust 3 – Effectiveness

Project Name	PI / Institution / Sponsor
3A.1: Teleoperation Efficiency Improvements by Operator Interface	Wayne Book, Georgia Institute of Technology; Steven Jiang, North Carolina A& T State University
3A.3: Human Performance Modeling and User Centered Design	Steven Jiang, North Carolina A&T State University Zongliang Jiang, North Carolina A&T State University
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 Cunefare, Georgia Institute of Technology
Electrohydraulic Braking System	Andrea Vacca, Purdue University *Sponsor: CNH America, Inc.*
High Pressure Compliant Material Development	Kenneth Cunefare, Georgia Tech *Sponsor: Sauer-Danfoss*
New Generation Of Green, Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology	Monika Ivantysynova, Purdue University *Sponsor: Confidential*
Noise Measurements and Valve Plate Design to Reduce Noise and Maintain Low Control Effort for Tandem Pumps	Monika Ivantysynova, Purdue University *Sponsor: Confidential*
Phase 3: Low Cost Compressed Natural Gas	Perry Li, University of Minnesota *Sponsor: Confidential*
Static Dissipating Hydraulic Filters	Paul Michael, Milwaukee School of Engineering. *Sponsor: Confidential*
Viscosity Measurements of Polymer Solutions at Elevated Temperatures and Pressure	Scott Bair, Georgia Institute of Technology. *Sponsor: Confidential*

Test Beds & General Research

Project Name	PI / Institution / Sponsor
Test Bed 1: Heavy Mobile Equipment – Excavator	Monika Ivantysynova, Purdue University, School of Mechanical Engineering
Test Bed 3: Hydraulic Hybrid Passenger Vehicle	Perry Li, Mechanical Engineering, University of Minnesota
Test Bed 4: Patient Transfer Device – Hydraulics at Human Scale	Wayne J. Book, Mechanical Engineering, Georgia Tech
Test Bed 6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses)	Elizabeth Hsiao-Wecksler, MechSE, UIUC
Controllable Hydraulic Ankle Prosthesis	William Durfee, University of Minnesota *Sponsor: Minneapolis VA Medical Ctr.*
CPS: Synergy: Integrated Modeling, Analysis and Synthesis of Miniature Medical Devices	Pietro Valdastri, Vanderbilt University *Sponsor: National Science Foundation*
Development of a Forearm Simulator to Recreate Abnormal Muscle Tone Due to Brain Lesions	Elizabeth Hsiao-Wecksler, UIUC *Sponsor: Jump Trading Simulation and Education Center*
Passive Hydraulic Medical Training Simulator for Mimicking Joint Spasticity and Rigidity	Elizabeth Hsiao-Wecksler, UIUC *Sponsor: Jump ARCHES*
Wearable eMbots to Induce Recovery of Function	William Durfeee, University of Minnesota *Sponsors: NIH, University of Michigan*
Fluid Power Advanced Manufacturing Technology Consortium	Kim Stelson, University of Minnesota *Sponsors: Georgia Tech, AMT, NFPA*

EDUCATION AND OUTREACH PROJECTS

Project Name	PI / Institution / Sponsor
EO A.1 Interactive Fluid Power Exhibits	J. Newlin, Science Museum 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.4 Fluid Power in Engineering Courses, Curriculum and Capstones	James Van de Ven, Univ. of Minnesota
EO C.4b Parker Hannifin Chainless Challenge	Brad Bohlmann, Univ. of Minnesota
EO D.1 Fluid Power Scholars	Alyssa Burger, University of Minnesota
EO D.2 Industry Student Networking	Alyssa Burger, University of Minnesota Student Leadership Council
EO D.5 CCEFP Webcast Series	Alyssa Burger, University of Minnesota Student Leadership Council
EO E.1 QED External Evaluation	James Van de Ven, Univ. of Minnesota
NSF REU Site Award: Research Experience for Undergraduates in Fluid Power	Kim Stelson, University of Minnesota *Sponsors: National Science Foundation*

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Project 1B.1: New Material Combinations & Surface Shapes for the Main Tribological Systems of Piston Machines

Research Team
Project Leader: Monika Ivantysynova, Department of Agricultural and Biological Engineering and School of Mechanical Engineering, Purdue University
Graduate Student: Ashley Wondergem, PhD student
Industrial Partners: Parker Hannifin, Danfoss, Poclain Hydraulics, Caterpillar, Bosch Rexroth

1. Statement of Project Goals

The goal of this project is to help transform the design of hydraulic pumps and motors from a cumbersome task, requiring significant trial-and-error testing, to a modern approach driven by numerical simulation and digital prototyping. Previous research has developed a fluid-structure-thermal simulation model which is capable of predicting the performance of critical lubricating interfaces inside axial piston machines. The key area of this research is to utilize the latest virtual prototyping and optimization techniques in practical pump design. The focus is to propose surface modifications specifically to the piston/cylinder interface in order to:

1. Improve unit efficiency by reducing the energy dissipation
2. Improve unit performance and reliability by increasing load support
3. Better understand the impacts of surface shaping on the generation of the fluid film of the lubricating interface

Simulated designs will be manufactured and physically tested to validate the computational work.

2. Project Role in Support of Strategic Plan

Piston pumps are often at the heart of many high power hydraulic systems and are especially critical in the energy saving displacement control and hydraulic hybrid architectures, both of which are concepts that have been proposed and developed in the CCEFP. By exploring novel design principles through surface shaping, not only can the efficiency of pumps and motors over a wide range of operating conditions improve, but also the compactness, performance, and reliability. This enables system designs to successfully compete with alternative technologies. This project aims to complete the goal listed above, enabling a digital prototyping approach to a new generation of pumps and motors. Virtual prototyping represents the only practical design method to create improved designs, utilizing new technologies for surface shaping leading to advanced manufacturing technologies.

3. Project/Test Bed Description

A. Description and explanation of research approach

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

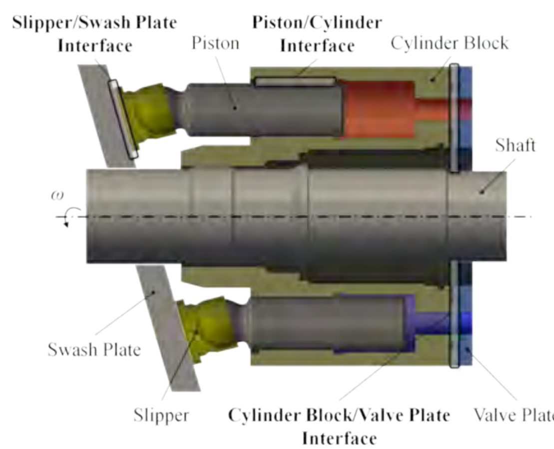

Figure 1: Swashplate axial piston machine cross section and identification of the three lubricating interfaces in red.

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

Previous work again made progress in advancing the accuracy of a model to predict the port and case temperatures as they are critical input parameters for the fluid structure thermal interaction model. Utilizing a large number of measured data from various units an empirical port and case flow temperature prediction model was developed. This model is separated into two parts, in which the temperature variation due to compression and expansion is calculated based on the known fluid properties and the temperature variation due to the heat transfer is calculated empirically resulting in reasonably accuracy predicted temperatures [1]. To support the virtual prototyping of new pumps and motors, the port and case flow temperature prediction model can be coupled with the fluid structure thermal interaction model given the design of the unit, the desired operating conditions including the inlet temperature, and the fluid properties.

Further work was also done to validate the lubrication model of the slipper - swashplate interface of the lubrication model while achieving a better understanding of the impact of solid body deformation and wear. A pump was specially modified to incorporate six high-speed eddy current displacement transducers inside of the swashplate in order to measure the dynamic film thickness between the swashplate and slipper allowing for a direct comparison to simulation results [2]. Confirming the modeling approach used, the simulation was able to predict similar changes in the lubricating fluid film thickness as well as the tilting behavior between nominal and worn slipper designs further validating that the slipper wear has a significant impact on the changing the lubrication operation as well as the deformations [3, 4].

The validated model for the piston – cylinder block interface was utilized to investigate the effect that micro-surface shaping of the piston has specifically on the energy dissipation along with the behavior of the fluid film for various moderate operating conditions in pumping and motoring mode. The surface of the piston was altered from a commercially available nominal piston in a variable displacement swashplate type axial piston machine with a variety of different surface shapes [5]. The simulation predicted improvements of overall energy dissipation of up to 30% at full displacement and 45% at partial displacements for the interface while also improving the overall operation of the machine as the hydrodynamic pressure build up in the fluid due to the surface profile is improved [6].

Achievements during reporting period

Utilizing the formerly developed and validated fluid-structure-thermal interaction simulation model for the piston – cylinder block interface, micro-surface shaping of the piston was further investigated. This investigation specifically focuses on how to reduce energy dissipation between the piston and the cylinder through surface shaping of the piston while improving build-up of the hydrodynamic load to maintain and even improve the robustness of current units. Most recent studies have broadened the operating

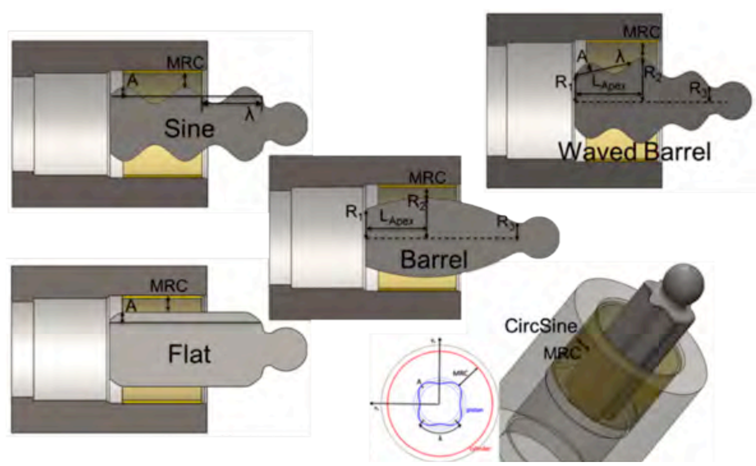

Figure 2: Various micro-surface shapes on the piston surface.

conditions investigated to include higher operating pressures and speeds in order to ensure the performance of the machine over a wide range of applications. This study focused specifically on five surface shape designs on the piston surface in combination with reduced clearances in which previous studies distinguished as shown in Fig. 2.

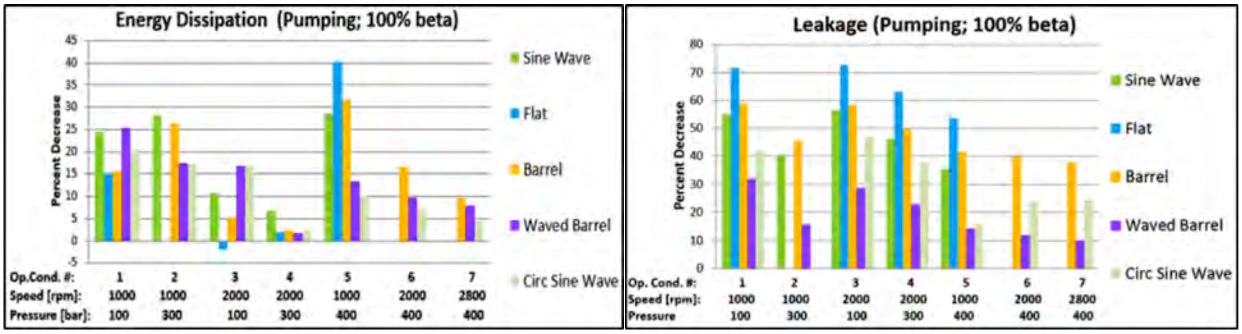

Figure 3: Reduction in losses due to piston micro-surface shaping; energy dissipation: left, leakages: right.

As a reference to quantify the improvement, each design is compared to a baseline design of a nominal wear-in piston-cylinder interface from a 75cc stock variable displacement swashplate type axial piston machine for both energy dissipation, Fig. 3 left, and leakages, Fig. 3 right. The operating conditions shown include a range of speeds and pressures in pumping mode at full displacement. It can be seen that the decrease in energy dissipation can reach up to 40%, strongly dependent on the 70% reduction in leakages due to the reduced clearance, for the flat surface shape. The problem that arises with the flat surface profile is that the results are dependent on the operating conditions, similar for the sine wave, and even fails at higher power operating conditions due to the occurrence of large areas of minimum film thickness across the flat gap surface. Therefore the best surface profile is the barrel surface profile that results in up to around a 30% decrease in energy dissipation, again strongly dependent on the 60% reduction in leakages at the reduced clearance. The reduction in clearance is possible with the surface profiles in which the fluid film can be manipulated to improve the build-up of the hydrodynamic fluid support along with the reduction in deformations. At the reduced clearances, some profiles then also reduce the torque (barrel) while others increase the torque (flat) leading to the trends in the decrease in energy dissipation. Overall, the barrel performs the best, especially at the high power operating conditions whereas the waved barrel and circumferential sine wave perform best at the lower pressure conditionsin which in combination with the decreased leakages, these surface shapes further aid in the fluid support at the reduced clearances [7].

To further establish that the barrel is on average best over all of the operating conditions studied at full displacement in pumping mode, the percent decrease in summation in energy dissipation from the baseline design for each surface profile is shown in Fig. 4. It is clear that the barrel surface profile improves the efficiency most overall as it performs best especially at the higher power operating conditions while sustaining load support. Overall the waved barrel and the circumferential sine wave perform better than the baseline also in terms of energy dissipation. As for the flat and the sine wave profiles, the performance is worse than the baseline overall since they both fail to

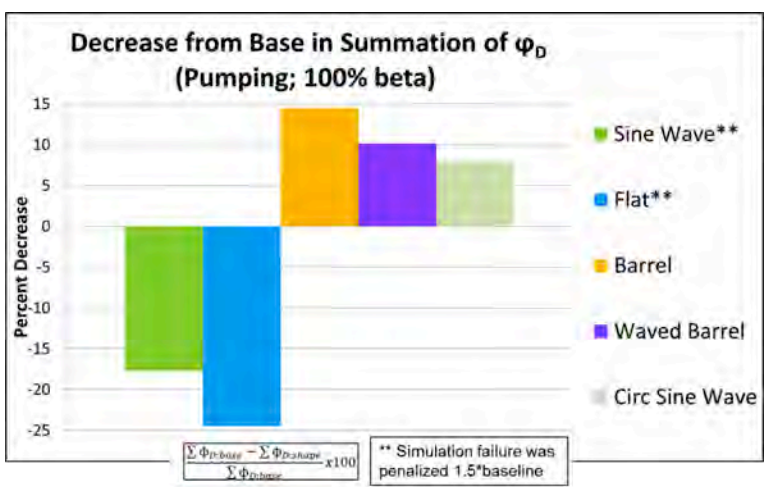

Figure 4: Overall reduction in energy dissipation due to surface shaping of the piston.

operate at the higher power operating condition and are therefore penalized.

Considering the impact of the surface shaping of the piston on the overall machine, the percent of energy dissipation resulting from the piston-cylinder interface on the total energy dissipation from the piston-cylinder, cylinder block-valve plate, and slipper-swashplate interfaces is shown in Fig. 5 for the barrel surface profile in comparison to the baseline. With the addition of the barrel surface profile on the piston, the overall energy dissipation of the unit is predicted to be reduced up to 20%. The barrel surface profile has a larger impact on reducing the losses at the lower speed operating conditions due to the large reduction in losses from the baseline, but in combination with the larger impact that the piston-cylinder interface has on the losses of all three interfaces as the pressure increases, the surface profile has even a larger overall impact.

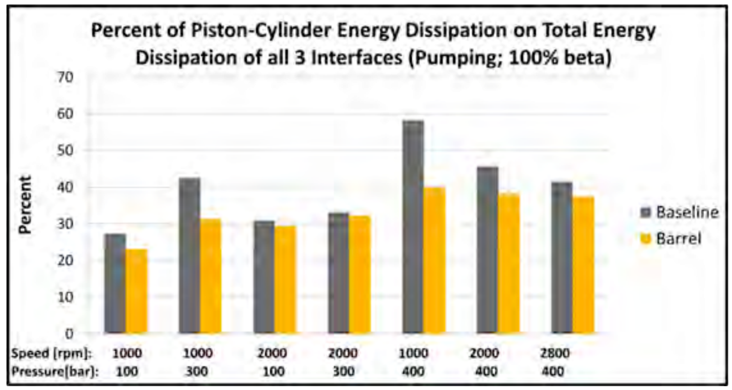

Figure 5: Percent of piston cylinder energy dissipation on total energy dissipation.

Planned Achievements following the report period

With simulation results showing promising improvements, a prototype is to be manufactured utilizing advanced manufacturing technologies. The micro-surface shaped piston can then be tested on a steady state test rig to measure the overall losses of the machine validating the predicted improvement of efficiency. In-house specialized test rigs will also allow for the measurement of the friction forces at the piston/cylinder interface and measurement of the pressure and temperature distribution further validating the models predicted improved load carrying ability at the reduced clearances.

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 on pump and motor operation – predicting up to a 20% overall efficiency improvement of an axial piston pump.
- Fundamental modeling of complex fluid structure interaction enabling further digital prototyping.
- 10% overall efficiency improvement of an axial piston pump using surface shaping techniques demonstrated with prototype waved valve plate measurements [10].
- Preferential patent licensing options for waved pump lubricating surfaces [11, 12].
- Project 1B.1 research has led to seven associated projects on pump modeling with different member companies with a total investment of ~$1.1 million since 2006.

D. References

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Project 1E.3: Digital Pump/Motor System Integration and Control

Research Team

Project Leader:	John Lumkes, Agricultural & Biological Engineering, Purdue
Other Faculty:	Monika Ivantysynova, ABE/ME, Purdue
	Andrea Vacca, ABE/ME, Purdue
Graduate Students:	Farid El Breidi, Tyler Helmus
Industrial Partners:	Airlift, Hydraforce, Moog, Sauer-Danfoss, and Sun Hydraulics

1. Statement of Project Goals

The goal of this project is to develop a high efficiency digital pump/motor capable of pumping oil, water, and corrosive fluids. The goal is to translate the successful fundamental research of the digital pump/motor operating strategies and test bench experimental results of a three piston digital pump/motor to implementation on a test bed (hydraulic vehicle or excavator) for demonstration and industrial commercialization. Mechanically and electrically controlled valves are being investigated to achieve the optimal pump/motor performance along with the control strategies that allow the digital pump/motor to switch seamlessly between operating modes (flow limiting/flow diverting) while maintaining optimal efficiency and minimal noise, and the compact integration of valves and embedded controls to enable mobile operation. Full four-quadrant operation has been demonstrated in all proposed operating modes, and efficiency and noise tradeoffs were characterized for each mode and the mode switching control strategy is being developed. The results have been encouraging and provide motivation for a focused effort to implement a digital pump/motor on a test bed.

2. Project Role in Support of Strategic Plan

The project will overcome a major fluid power system efficiency limitation by improving the efficiency and dynamic performance of piston pump/motors as well as enable pumping a new class of fluids (different types of oil, water, and corrosive fluids). Regardless of the fluid power system, overall efficiency is limited by the efficiency of the primary pump/motor. Project goals will be achieved by leveraging the test bench, simulation, and experimental results to migrate the pump/motor design to a single lever mechanically controlled test bed. Current results have demonstrated higher operating efficiencies at lower displacements, four-quadrant operation, high displacement control bandwidth, and high operating pressures.

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

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

3. Project Description

A. Description and explanation of research approach

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

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

The design of the 1E6 digital pump/motor enables implementation in most fluid power systems. The versatility of this design comes from the ability to independently control the fluid flow of each piston chamber. Individual control allows each piston to act as an independent pump/motor depending on conditions in the hydraulic system. With this type of control and minimal additions, control structures can be implemented to allow for different pressure outputs, energy recovery by motoring on certain pistons and pumping on the others, and energy storage to and recovery from accumulators independently as described in the work of Linjama and Huhtala [4] and experimentally validated by Heikkila *et al* [5]. As mentioned, this outlet control can produce differing pressures from the same pump/motor and could thus be used to replace and improve the dual pump/motors found in the Integrated Energy Recovery system [6].

B. Achievements

Achievements in previous years

Previous work in Project 1E.3 developed a coupled dynamic model of a digital hydraulic pump/motor and an experimental test stand that is crucial for understanding the design tradeoffs and operating characteristics of the digital pump/motor [7-9]. The simulation model was used to characterize and predict the efficiency, define the dynamic response and flow requirements of the on/off valves, and perform design optimization studies. The model has been used to characterize different operating strategies (flow limiting and flow diverting) and the effects on pump/motor efficiency and flow ripple. The three-piston pump/motor unit was used to experimentally validate the model, design, and operating strategies of a digital pump/motor. A schematic of the test bench setup is shown in Figure 1.

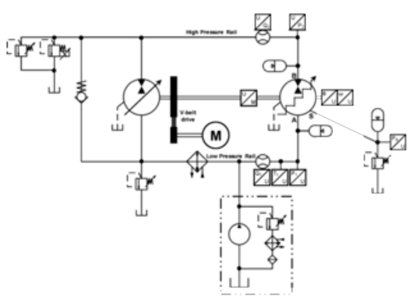

Figure 1: Schematic of test setup

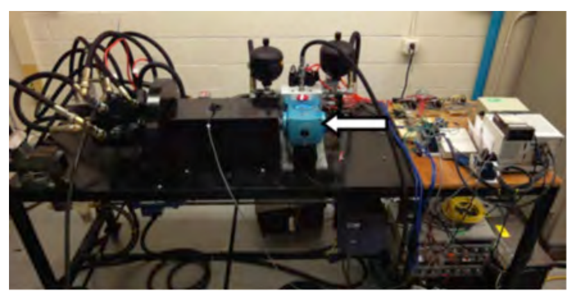

Figure 2: Picture of test setup

The 3-piston digital pump/motor (arrow pointing to it) and test stand is shown in Figure 2. Each piston has two on/off valves, one at the low pressure side and one at the high pressure side. There are three 2,000 Hz pressure transducers measuring the pressure in each of the displacement chambers. A check valve is connected to the displacement chamber to provide a safe release of the displacement chamber pressure in the case of missed valve timing.

There are different methods to achieve partial displacement. These methods, partial flow-diverting and partial flow-limiting, were described by Nieling *et al* [10]. Simulation and experimental tests have successfully characterized the efficiency and noise tradeoffs of the different operating strategies (flow diverting/limited, sequential/partial stroke). Sequential flow-diverting operates on a piston-by-piston cycle, where all the flow from the displacement chamber is either diverted to tank or to system pressure. Another method of operation is sequential flow-limiting. This is similar to the sequential flow-diverting method described, but instead of diverting the piston flow the piston chamber is voided for a complete cycle. This method either completely voids a chamber or the piston does a complete pumping cycle depending on the displacement desired from the sequential algorithm. Construction of the digital pump/motor test stand has allowed the testing of fundamentally new operating strategies in pump/motors, similar to how camless engines in combustion research labs are used to explore new internal combustion strategies. This adds a fundamental contribution to the design of pump/motors beyond the development of a prototype unit (i.e. pump chamber voiding, verified on the test stand, could become the foundation for a new class of variable displacement pump/motors not currently envisioned by conventional designs).

Figure 3 shows the measured results of all 4 operating strategies when the digital pump is running at 700 rpm and 103 bar (1500 psi). The trends of the operating strategies are similar to the simulation results of the four operating strategies seen in Figure 4. The operating strategy with the best efficiency for the conditions and parameters stated in this work is sequential F-L, followed by sequential F-D, next is partial F-L and the worst efficiency is partial F-D.

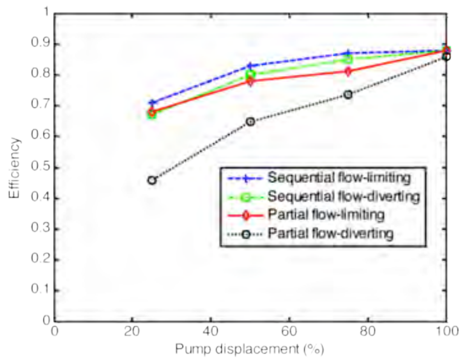

Figure 3: Measured results of 4 operating strategies at 700 rpm and 103 bar

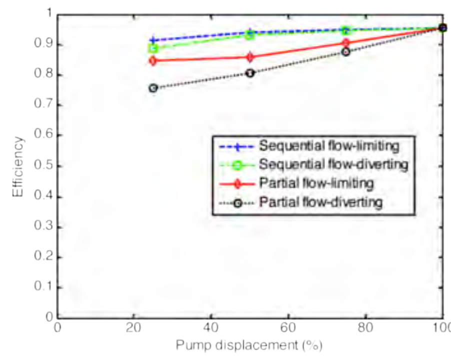

Figure 4: Simulated results of 4 operating strategies at 700 rpm and 103 bar

Given the significance of the valve response times on the performance of the digital pump/motor, we experimentally examined the effect of peak and hold and reverse current strategies on the turn-on and turn-off response of two Sun Hydraulic valves. This involved sending high initial voltage and current to overcome inductance and eddy current lag while generating high flux levels across the air gap. After these effects have been reduced by the peak voltage, a holding current is applied to keep the armature in place.

Experimental results show a decrease of more than 75% in turn-on response time and more than 75% decrease in turn-off response in both valves. The delay time was reduced in both opening and closing phases for both flow directions. The transition time for opening was improved under peak and hold voltage strategies, but stayed relatively constant during closing because it is dependent on the stiffness of the spring. The valve response effects were simulated and experimentally tested on the digital pump/motor. As shown in Figure 5, the simulation model predicts an improvement in efficiency of up to 15% using the flow diverting mode and up to 8% using the sequential flow diverting mode. Experimental testing shown in Figure 6 indicates a considerable improvement in efficiency could be achieved by using faster valves, where an increase of up to 12% was achieved in the partial flow diverting mode and up to 5% in the sequential flow diverting mode.

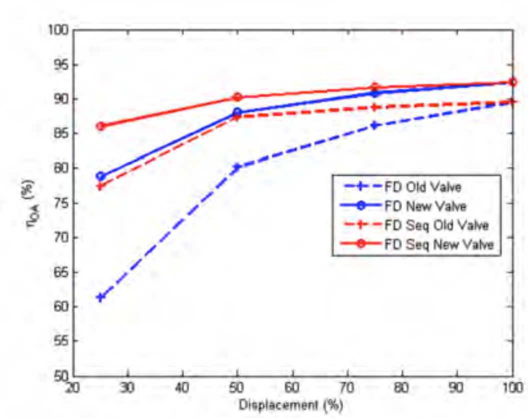

Figure 5: Digital pump/motor simulated valve comparison

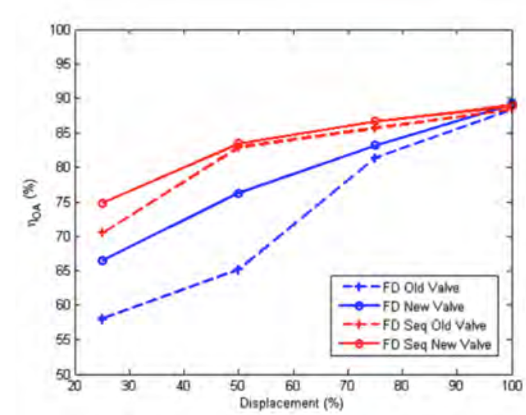

Figure 6: Digital pump/motor measured valve comparison

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

Valve Timing Correction Algorithm

A real-time valve correction algorithm was developed, simulated, and tested on the digital pump/motor. This correction algorithm uses the high and low pressure curves to account for the valve delay. Valve 1 is always connected to port A, so pressure ripples are observed whenever valve 1 is actuated. The ripple represents when the valve started to move, so an algorithm was developed to measure the response time of the valve by measuring the difference in time between the valve signal and the pressure ripple, thus calculating the response time for the valve. Since valve events do not overlap, this algorithm can calculate the response time for all three valves using one pressure transducer at port A. A similar approach was done to measure the response time of the three valves connected to port B. This algorithm runs in real time for speeds up to 700 rpm, and measures the valve transition time for the current cycle, then correcting the input signal to the next cycle to open the valve with optimal timing. More optimization needs to be done for faster speeds.

A comparison between the actual delays and the algorithm calculated delays for one of the chambers are shown in Figure 7. The digital pump/motor was operated at steady state conditions in full displacement at 700 rpm and a differential pressure of 103.4 bar. The algorithm calculated delays are the output values from the correction algorithm, while the actual delays were measured by individually calculating the time it took the pressure ripple to show from the instant the valve signal was sent. It was done manually for each measured data point in figure. The data acquisition system was set to record data at a period of 0.2 milliseconds, but in order to cover a larger period of time, the data points presented were taken at a 200 millisecond intervals. As noticed in the figure, the delay times calculated by the algorithm predicted the delay time in both valve 1 and valve 2 for the on-delay and the off-delay.

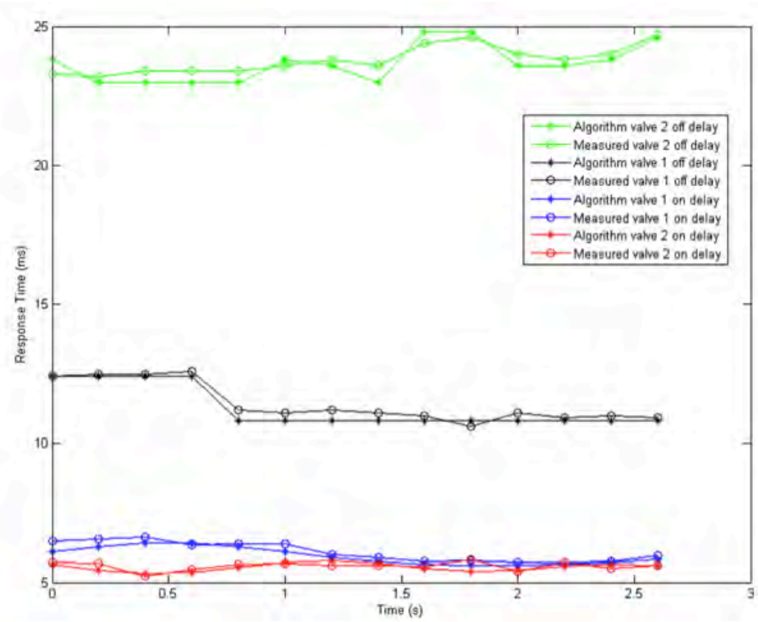

Figure 7: Comparison between the actual delays and the algorithm calculated delays

Mechanically Driven Valve Configurations

Theoretical analysis of the configuration possibilities was completed for a cam based actuation technique. This study analyzed the valve states of 11 different configurations and determined their feasibility and mechanical control requirements. It was determined that a mechanically actuated four quadrant digital pump/motor was feasible for certain configurations. From this, it was determined a simple, pumping-only proof of concept prototype would be the most beneficial configuration to start. This configuration can be found in figure 8 and has one cam actuating on/off poppet valves on the low pressure side and check valves on the high pressure side. As cam based actuation can be implemented on any existing piston pump with stationary pumping chambers, it was decided this simple configuration would be ultimately implemented on the current pump test stand configuration. This allows the performance results to be directly compared to that of the electrically controlled valve digital pump/motor currently in use on the test stand. This configuration was simulated in Matlab and Simulink with promising results.

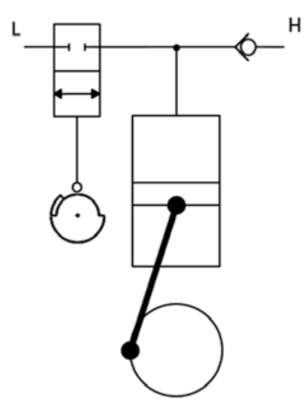

Figure 8: Cam driven valve pump single chamber schematic

C. Plans for the next year

As a result of the previous year's task to investigate different pump driving strategies, we are focusing on the Mechanically Driven Valve configuration. Within the next year we hope to build on theoretical knowledge gained to push this concept to a viable configuration. A working simulation model has been developed and will be used to determine optimal component configurations. Once this is accomplished, the simulation data will be used to help construct the components and in turn a MDV digital pump/motor prototype.

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

Expected milestones and deliverables

Project Tasks:

- Task 1: Determine optimal configuration for MDV pump using simulation [2 months]
- Task 2: Build MDV pump prototype [6 months]
- Task 3: Test MDV pump prototype [5 months]
- Task 4: Investigate and develop mode switching algorithm [6 months]
  Real-time switching between operating strategies (partial flow diverting/limiting and sequential)

Milestones:

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

D. Member company benefits

This project has and will continue to benefit CCEFP member companies by providing new digital pump/motor design tools, on/off valve designs, and digital pump/motor operating strategies for further development and commercialization by member companies. It indirectly benefits member companies through its role as an enabling technology for other CCEFP test beds. Industry partner involvement will be critical while developing the appropriate performance metrics, benchmarking 36 current products, and involvement will be necessary to build (or supply from existing) the various components and sub-assemblies (pumps, valves, sensors, etc.) and help with the fabrication and testing.

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

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

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

Hydraulic transformers are devices that transform hydraulic power conservatively from one pressure/flow combination to another pressure/flow combination. They are hydraulic equivalents of gear-sets (mechanical transformers), and AC magnetic transformers / power converters (electrical transformers). Since pressure transformation does not use throttling, a hydraulic transformer is a potentially efficient means to distribute and control power from a single hydraulic power source to multiple functions that also has energy regeneration capability.

One aim of this project is to gain understanding of how the intrinsic properties of the transformer impact overall system performance and to provide guideline for the future design and optimization of transformer devices. Beside the traditional pump/motor configuration, there is also extensive work focusing on the design proposed by Innas that combines the role of pump and motor into one single rotating group using a rotatable 3-ported valve plate [1-5]. In this project, the performance merits (such as efficiency, size, and ripples) of the various configurations are compared via developing models. From this study, which transformer configuration will be further studied was be determined.

In parallel with the comparison study, this project is developing efficient and precise control strategies and control algorithms for hydraulic transformer based systems. Most literature on transformers focus on transformer designs, few focus on dynamic control performance. Finally, effective and precise control using transformers will be demonstrated experimentally on the lab bench and on the patient mover test bed in a human power amplifier mode.

B. Achievements

Achievements in previous years

<u>Comparison of transformer configurations:</u> A comprehensive comparison between three configurations of the traditional pump/motor (PM) transformer (Fig. 1-3) and the 3-ported Innas Hydraulic Transformer (IHT) configuration has been performed assuming similar axial piston architectures. Comparisons were made by developing average and piston-by-piston dynamic models Friction and leakage within the

piston chambers, between the valve plate and barrel, and piston shoe / swash plate friction, fluid compressibility and throttling loss valve were included based upon models in the literature [6-8].

With these models, it was found that any of the 3 PM transformer configurations would need to have a displacement 33% larger than an IHT to have similar flow capabilities. However if switching is allowed between the different PM configurations for different operating conditions, the PM transformer displacement would only need to be 17% larger than that of IHT. With respect to ripples, the models predict that an IHT would have significantly larger flow and pressure ripples than a pump/motor transformer with the same number of pistons. This is primarily a consequence of the pistons switching ports at locations other than top and bottom dead center, when their flows are non-zero.

Piston-by-piston dynamic models predicted that IHT will be 3~5% more efficient than the 3 PM transformer configurations. However, if PM transformer can switch among three different configurations – PM-1 is good where transformation ratio (output pressure / input pressure) is near 1; PM-2 is most efficient where transformation ratio is near 0.5; and PM-3 is most efficient where transformation ratio is near 2; then a system that is efficient over broader range of operating region can be achieved, making a PM transformer more efficient than IHT.

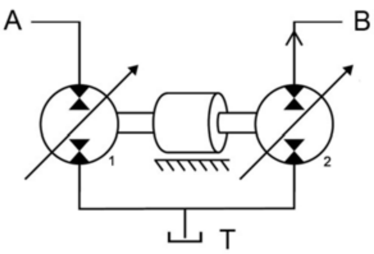

Figure 1: PM Transformer-1 Tank port Shared

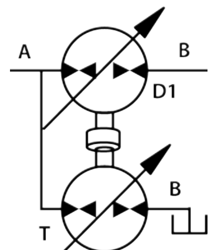

Figure 2: PM Transformer-2 Output Port Shared

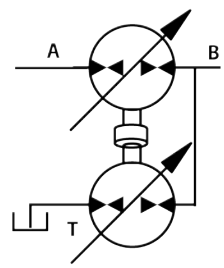

Figure 3: PM Transformer-3 Input Port Shared

Prototype acquisition and testbed construction: It was decided to further study PM transformers with port switching capability because of the sizing and efficiency advantages. Takako Industries has donated a manually controlled pump/motor hydraulic transformer prototype that consists of two variable displacement 3.15 cc/rev micro-piston P/M units in the traditional pump/motor configuration. Design work was done to modify the prototype to allow for computer control. Figure 4 shows the circuit for the prototype which incorporates 3 solenoid 3-way valves and 1 directional control valve to enable switching between the various pump/motor configurations and circuit connections (see below).

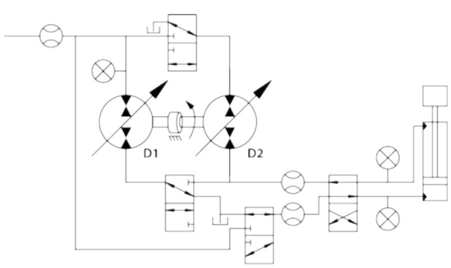

Figure 4: Schematic of experiment setup

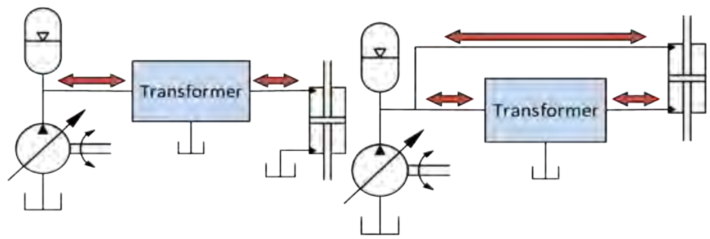

Figure 5: a) Series connection b) Power-Split connection

Achievements in the past year

Mode Switching Characterization and Demonstration: Two different circuits in which a transformer can be used to control a cylinder load have been investigated: the conventional "series" connection in (Fig 5a) and the newly proposed "power-split" connection in (Fig. 5b). The "series" connection has the disadvantage that all power delivered to the load must pass through the transformer thus requiring the transformer to have very high efficiency. In Fig. 8, power is delivered directly to the load with little loss and the transformer is only used to recuperate excess energy. This is analogous to "power-split" transmission in hydrostatic transmission (HST) where the hydraulic T-junction plays the role of the

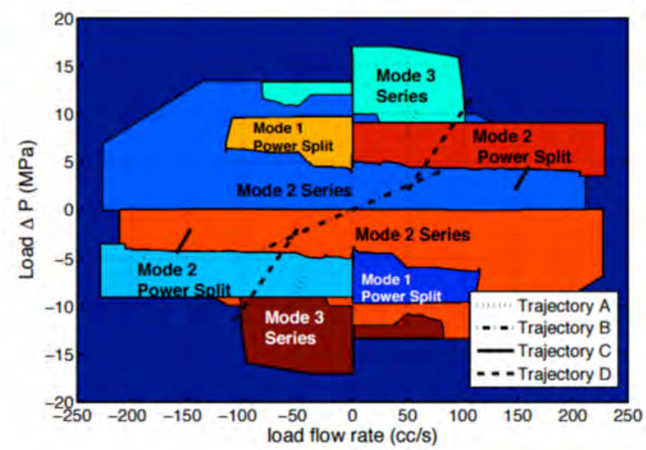

Figure 6: Operating map of a transformer and configuration of the most efficient modes

planetary gear set. Since the transformer can be realized using any of the 3 modes in Figs. 1-3, there are 6 different circuits/transformer configuration combinations (or modes). Using an experimentally determined efficiency map, the portion of the operating regions that benefits most from each of the mode is identified. Fig. 6 shows the partition of the operating region into the most efficient modes for our experimental setup. Compared to any single transformer configuration and circuit, the switch mode transformer circuit increases feasible operating regions (in speed & transformation ratio) and efficiency.

The feasibility to switch between modes while following a desired pressure trajectory (A, B, C, D in Fig. 6) was demonstrated using a simple reactive controller and a needle valve load. Mode switch is successful except for some transient effects where the transformer speed changes rapidly (see Fig. 7 for an example) [9]. It is expected with more sophisticated controller that explicitly considers the switch and anticipates the speed and pressure change will be able to improve the performance and reliability of the mode switch.

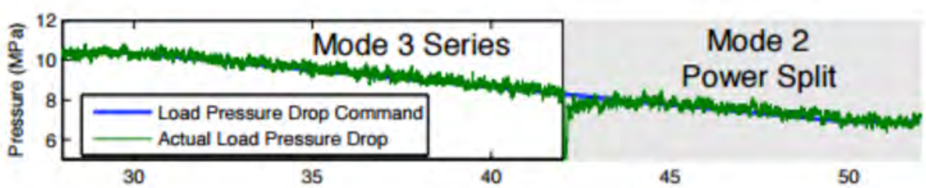

Figure 7: Example mode-switch trajectory corresponding to trajectory D in Fig. 6.

Figure 8: ATLAS robot used in the case study

Robotics Case Study for Efficiency Improvement

To evaluate the efficiency benefits of a switched mode transformer at the system level, a case study comparing the energy use of a walking robot (Fig. 8) with 3 DOF in each leg using the switched mode transformer or the conventional throttling valve was performed. The actuator and transformer sizes were optimized in each case. The dynamics of a walking robot were simulated using published gait data and the hydraulic energy used were compared. Compared to using throttling valves for a constant pressure line, mode switching transformer can achieve 78% reduction in energy consumption [9].

Trajectory Tracking Control and Preliminary Supervisory Control Implemented

A trajectory tracking controller has been implemented for a transformer controlled hydraulic actuator (Fig. 9) [10, 11]. In addition to controlling the actuator trajectory, this controller also regulates the transformer speed at target value. The controller uses a passivity based back-stepping approach [12]. A supervisory control for specifying the transformer speed for the given load condition and minimizes losses has also been developed and implemented. Compared to using a constant transformer speed set to meet the maximum demand, this method can reduce the energy consumption by 18.6%.

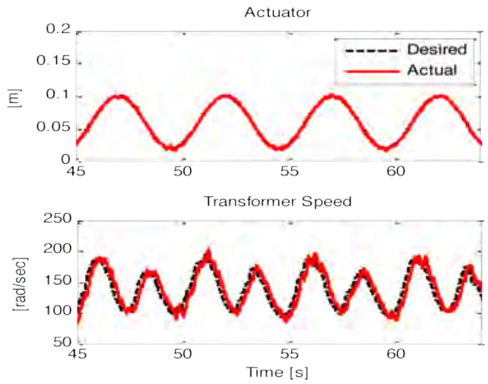

Figure 9: Trajectory Tracking

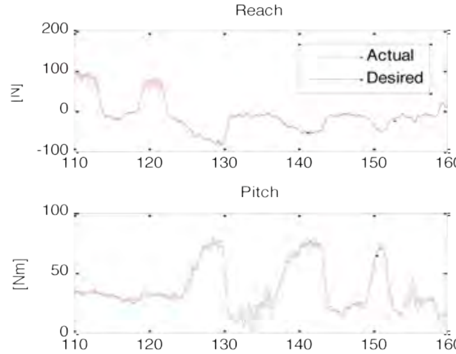

Figure 10: Human Power Amplifier (HPA) Force Tracking. Desired force is 7x the human force.

<u>Control Demonstration on Human Power Amplifier</u> Algorithms to control human power amplifier (HPA, Fig. 11) were developed to demonstrate the control performance using hydraulic transformers. This device is a 2-DOF machine that has a pitch and a reach DOFs to lift and position a load. It also has a force handle to measure the applied force of the human operator. The goal of the virtual coordination controller, in the end, is to amplify the human force and to allow the user to operate the HPA as if it is a simple mechanical tool. The similarity in construction can allow a smooth transition to control demonstration on test bed 4, a patient transfer device at Georgia Tech. In the experimental setup, a pitch movement is controlled by a hydraulic transformer and the reach movement is controlled using a servo-valve.

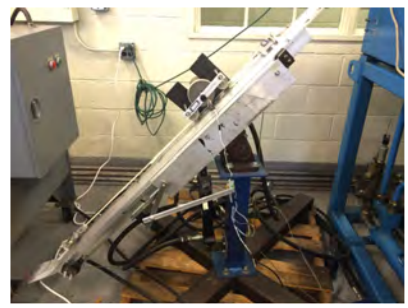

Figure 11: Human Power Amplifier (HPA)

Fig. 10 shows a good force tracking results with RMS error less than 3% of maximum torque or force. This control uses a virtual coordination approach rather than direct force tracking which was found to be not robust due to positive velocity feedback effect [13-14].

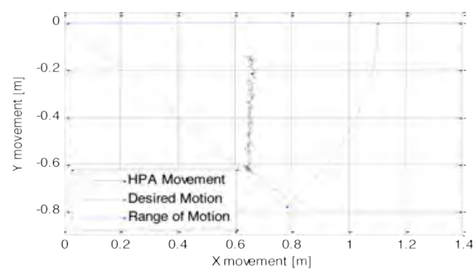

Figure 12: PVFC Straight Path

Additional control strategies that render useful dynamics to assist the human were also demonstrated on the transformer controlled HPA. With the Passive Velocity Field Controller (PVFC) [15,16,17], passive dynamics are incorporated into the machine to guide the operation also a desired path while allowing the machine to remain passive. Results in Fig. 12 shows the velocity guiding the movement towards a vertical path. With the addition of a potential field, obstacle avoidance control [16,17] is achieved. The field repels the machine as it attempts to enter a prohibited zone. Result in Fig. 13 shows the machine prohibited from entering the circle. Both PVFC and potential field controllers ensure passivity so that the machine will be safe to operate. These results and the achieved trajectory tracking performance show that using transformer to improve efficiency does not compromise control performance.

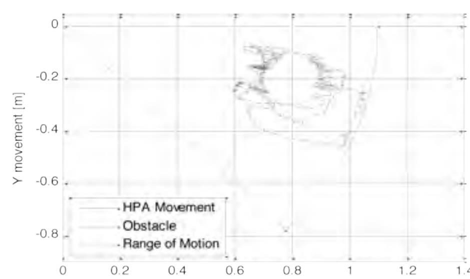

Figure 13: Obstacle Avoidance

C. *Plans for the next year.*

The transformer control strategy will be extended to enable smooth mode transition. In addition, control algorithms will be developed to further improve efficiency. This includes optimizing and controlling the transformer speed (via a supervisory control as shown earlier) and to regenerative energy during braking motion. For the latter, we plan to investigate (1) how to use the recovered energy; (2) how to store the recovered energy; and (3) how to maximize the amount of recovered energy.

Recovered energy can be used to reduce the load on the central hydraulic supply instantaneously or to be stored for later usage. This could be stored external to the transformer by using an accumulator (this case was assumed in preliminary trajectory control studies). Alternatively, recovered energy can be stored internally in a substantial inertia acting as a flywheel. With a flywheel energy storage, each storage phase or regeneration phase needs to go through pump/motor only once as opposed to twice if an accumulator is used. Thus, there may be efficiency advantage with a flywheel energy storage, especially if the energy will be reused quickly. Furthermore, a hybrid operation scheme could be developed to store recovered energy either internally or externally depending on specific operating scenario to maximize amount of recovered energy. Recovered energy can be maximized through optimization of the operating region such that minimal amount of power is consumed when a positive work is required and maximum amount of power is recovered when a negative work is required. We plan to extensively model and simulate various operating scenarios and implement the best algorithm in utilizing regenerative energy.

Expected milestones and deliverables

Control of the mode-switching transformer with efficiency improvement will be complete in the next year. We also expect to publish several papers based on work performed in this project.

D. 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.

E. References Include published literature, patents, etc.

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Project 1E.6: High Performance Valve Actuation Systems

Research Team

Project Leader:	John Lumkes, Agricultural & Biological Engineering, Purdue
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Graduate Students:	Jordan Garrity
Industrial Partner(s):	Moog, Parker-Hannifin, Sun Hydraulics

1. Statement of Project Goals

The goals of the project are to (1) develop the bidirectional proportional control algorithms for the Energy Coupler Actuated Valve (ECAV), (2) integrate the ECAV with both a poppet and a spool valve body and experimentally investigate the pressure-flow-time performance, and (3) develop an integrated electrical systems (driver circuits and sensor), actuator, and valve system that can be easily incorporated into center and industry projects.

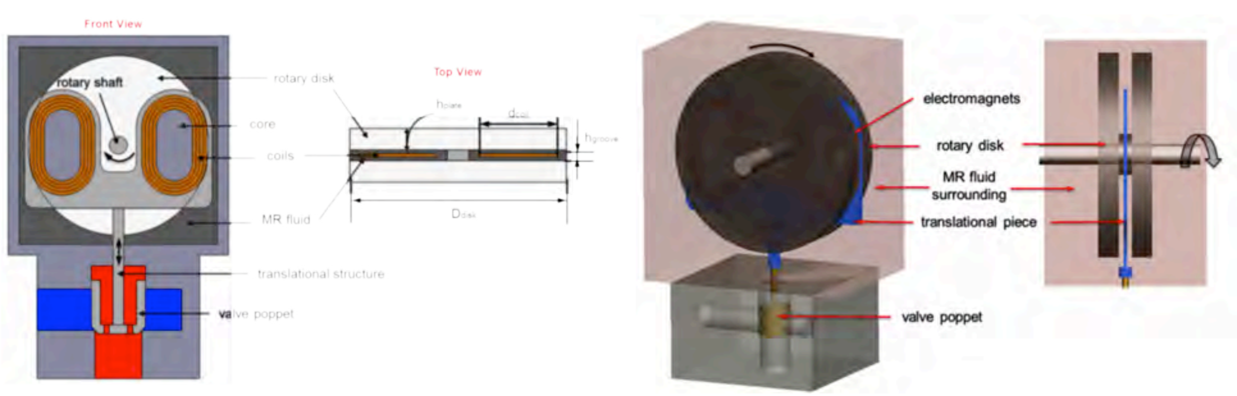
2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

This project continues the development of a promising new valve actuation mechanism concept, the energy coupler actuator (ECA), to solve the trade-off between fast switching and large nominal flow rates in the design of high speed valves. The fundamental principal of the valve actuation system, as successfully tested in the Y7/Y8 project cycle, is to couple a kinetic energy source with a translational valve poppet or spool. Valve positions can be controlled by intermittently coupling or decoupling the translational component from the energy source. Figure 1 illustrates the ECA design. When the MR fluid is not magnetized, the liquid viscous friction forces between the rotary disk and the translational components are small.[1] If the left side coil is energized, magnetic flux will be generated in the gap and will cause the MR fluid to thicken. As the fluid thickens, it creates a shearing force. The rotating (clockwise for the example in figure 1) disk will clutch the translational piece and bring it upwards thereby opening the valve. Similar mechanisms apply to the valve closing.



a) Schematic diagram *b) 3D rendering*

Figure 1: Energy Coupler Actuated Valve

The ECAV has the following design advantages:

- High pressure can be at either port
- Large, bidirectional, and scalable actuation forces
- Large stroke
- Proportional force control
- Small moving mass
- System pressure-independent performance
- Low leakage (with poppet valves)
- Compact axial stacking of valves (Figure 2, valve with multiple MR fluid energy coupler actuators).

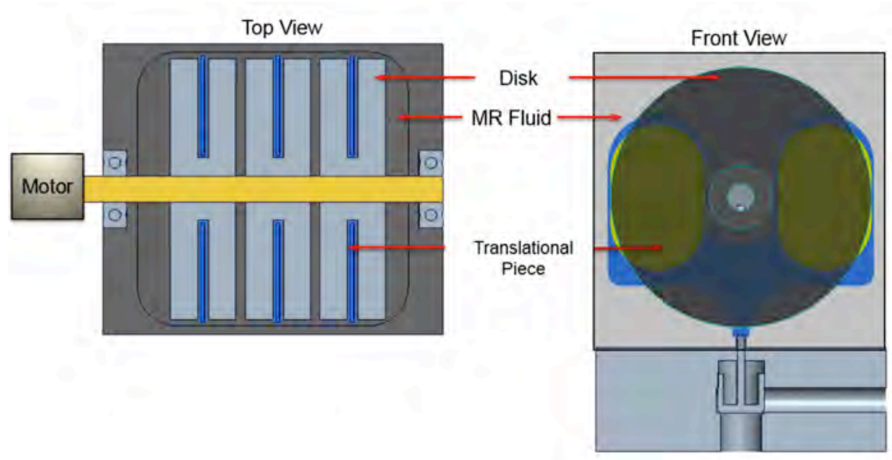


Figure 2: ECAV stacked configuration

B. Achievements

a) Achievements in previous years

Computer modeling of the ECAV across multiple physical domains was created initially to optimize the design and performance of the ECAV. This included a 3D finite element model on electromagnetic field strength, an actuation force model, and a flow domain model within the valve concept. After successful simulation of the computer models, prototyping and experimentation of the design allowed comparison with simulations. Results were generated on measuring displacement over time of the actuation mechanism and improvements to the prototype were made to help enhance the project. Figure 3 shows the dynamic displacement results of the actuator.

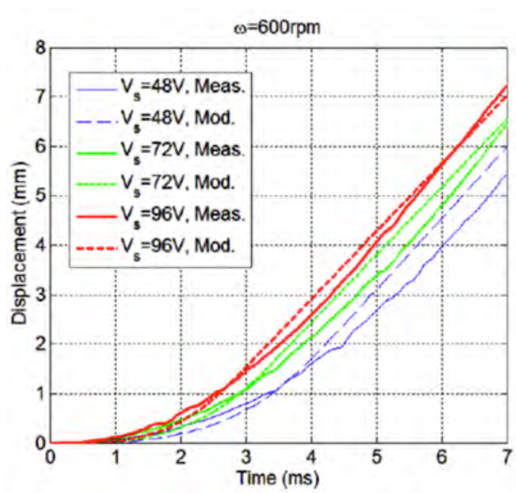


Figure 3: Displacement profile

b) Achievements in the past year

Directly actuated poppet valves are largely impacted by flow forces as the valve cracks open and large (> 50 Lpm) flow begins to occur.[2] CFD modeling was used to accurately predict and minimize flow forces. A 2D, axisymmetric model was developed and is shown in figure 4. The model has reduced simulated forces by over 200 N.

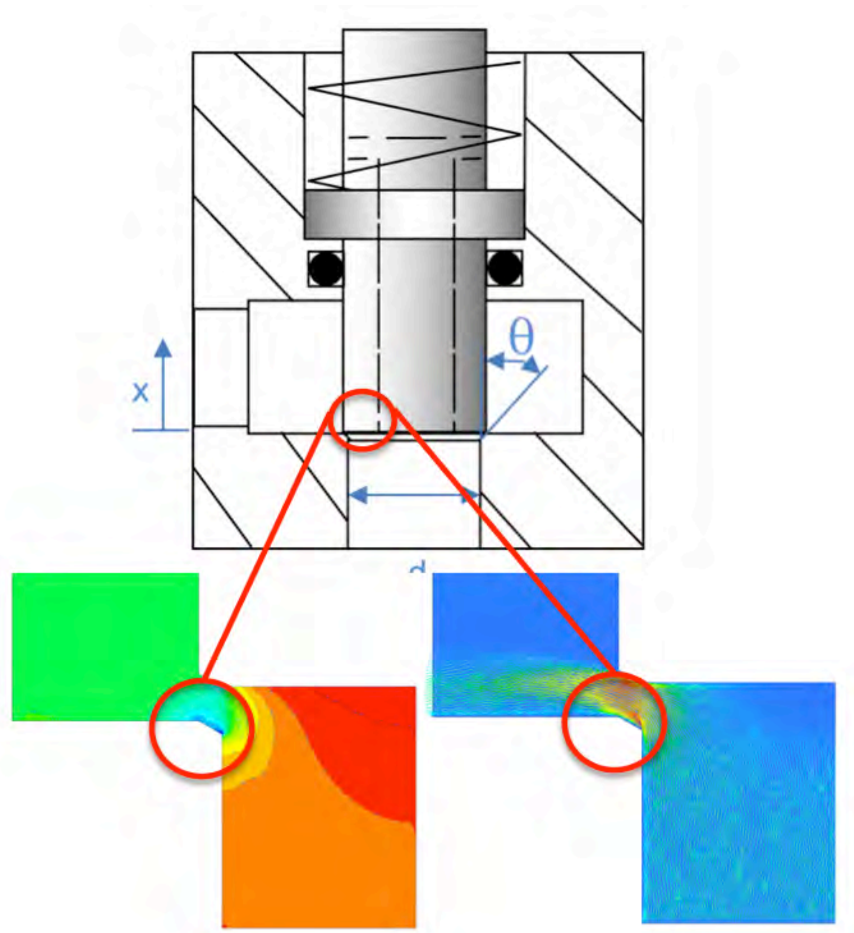
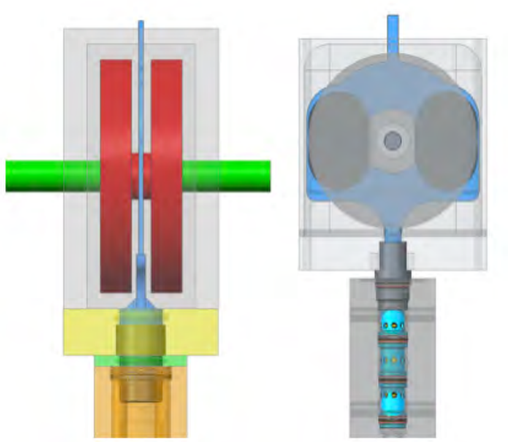


Figure 4: 2D CFD diagram with pressure and velocity profiles



Poppet and spool valve bodies have been designed for implementation of a common actuator on both assemblies. The actuator has been designed to easily interchange between valve bodies for experimental testing. The poppet and spool design is shown in figure 5.

Figure 5: Poppet and spool assemblies

C. Plans

Plans for the next year

The proposed work over the next year includes to develop the bidirectional proportional control algorithms for the Energy Coupler Actuated Valve (ECAV), and investigate experimentally the pressure-flow-time performance of the poppet and spool valve assemblies. The final task will then be to develop an integrated electrical system (driver circuits and sensor), actuator, and valve system that can be easily incorporated into center and industry projects.

Expected milestones and deliverables

The poppet and spool valve, and associated housings will be manufactured and tested while additional work will be spent in developing and testing the integrated valve units with embedded electronics. Work will be done towards the goal of incorporating high performance valves into test bed supporting projects like digital pump/motors, control of swash plate displacement, and for enabling new energy storage configurations.[3] Another outcome and possible application is the integration of the ECAV on the digital pump/motor test stand, as shown in figure 6. This would provide a great multi-valve testing platform while improving the overall efficiency, controllability, and operating envelope of the digital pump/motor

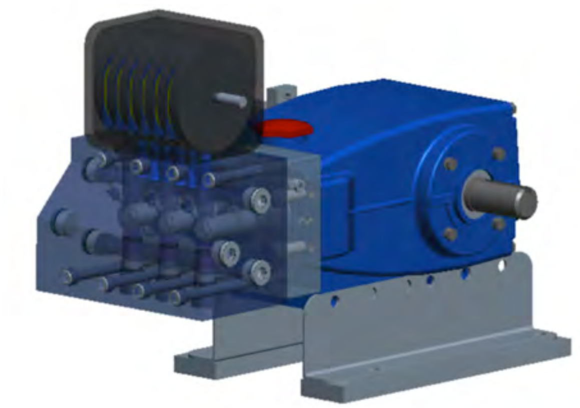


Figure 6: Digital pump/motor

D. Member company benefits

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

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Project 1F.1: Variable Displacement Gear Machine

Research Team

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Undergraduate Student: Karina Bjorklund (REU)

1. Statement of Project Goals

The 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 preserves 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 main 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 research takes into consideration unconventional designs, such as asymmetric gear profiles. Therefore, the goals of the project are:

1. Formulate a new design principle for VD-EGM
2. 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 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 architectures and will permit a wider diffusion on more efficient systems also in low cost hydraulic 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

The well-known advantages of external gear machines (EGMs) such as low cost, compactness, good tolerance to contaminants and cavitation and reasonable operating efficiency, make them as one of the prominently used components in fluid power. Figure 1 shows a typical EGM design for high pressure (up to 300 bar) applications. Despite mentioned advantages, EGMs are fixed displacement and they cannot be used as primary energy conversion units in modern energy efficient layout configurations based on variable flow supplies, such as in load sensing systems, hydrostatic transmissions or in displacement controlled systems [1, 2].

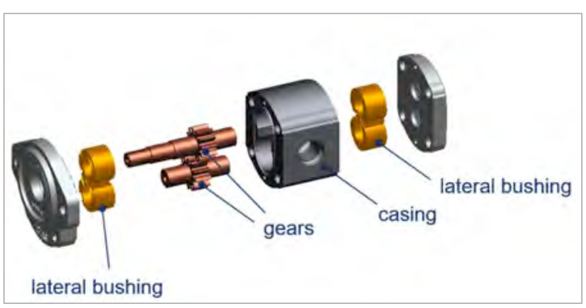

Figure 1: Parts of an external gear machine

With the exception of cases where the unit operates at fixed pressure and flow rate, the energy consumption of fluid power circuits based on fixed displacement units can be as much as 70% higher than standard VD system layouts. For this reason, both industry and academia have been dedicating effort in formulating VD design solutions for EGMs, with the aim of preserving the advantages of limited cost (up to 10 times lower than existing VD units with the same capacity) and reliability.

Representative of the past efforts are given by references [3-11]. All these past efforts share the idea of realizing an axial or radial relative motion between the gears to obtain a variable output flow. However, the motion of the gears, which are the most loaded elements in an EGM, involves major problems such as: sealing the tooth space volume; guaranteeing a smooth meshing process and a good balance of the gears avoiding contacts. A good solution for mentioned aspects generates complexities which increase the cost of the unit and penalize its reliability. For these reasons, none of the solutions proposed for VD-EGMs have found successful commercial application.

The proposed solution for VD-EGM

The novel idea for achieving Variable displacement in EGMs can be obtained by introducing an optimal concept of variable timing of connections between the displacement chambers (tooth space volumes, TSVs) and the inlet and the outlet ports.

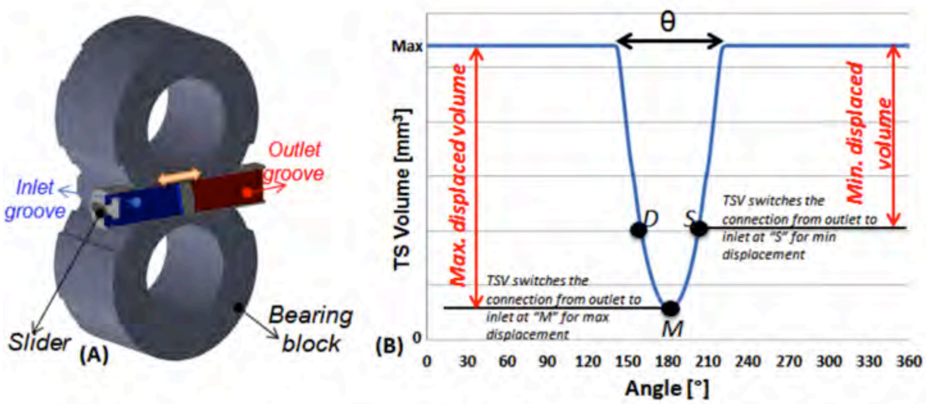

Figure 2: (A) Slider placed within the bearing block of the VD-EGM (B) The progression of TSV as a function of shaft angle. The meshing process realized the displacing action in the angular interval θ, for a portion of the meshing process (between D-S), the volume is trapped between points of contacts.

The variation in the timing of the connections is achieved by the introduction of a movable element called the slider as shown in Figure 2(A). The position of the slider determines the amount of flow displaced by the unit per revolution, for both the cases of pumps and motors.

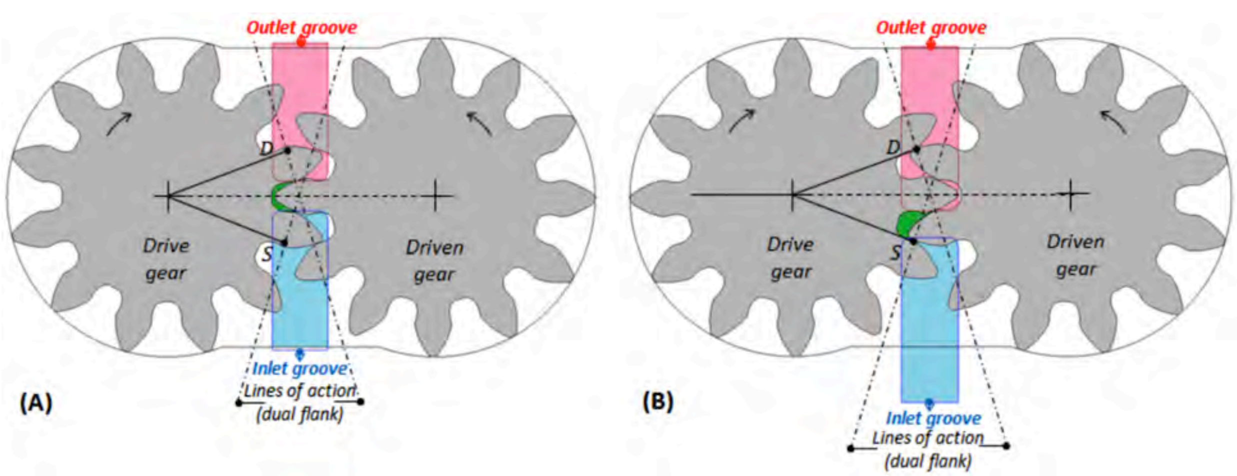

Figure 3: (A) Position of the slider to achieve maximum displacement (B) Position of the slider to achieve minimum displacement

In order to achieve max displacement, the commutation between of the TSVs between inlet and outlet groove (shown in Figure 3(A)) is realized when the volume is at its minimum (represented by "M" in Figure 2(B). Therefore, the max volumetric capacity of the machine is utilized since the TSV is connected to the inlet and outlet for equal intervals of time. A variation of the displaced flow can be achieved by positioning the slider closer to the inlet side as represented in Figure 3(B). In this configuration, each TSV is connected to the outlet for a larger period of time as shown in Figure 2(B), thereby a part of the fluid already delivered to the outlet is taken back into the TSV. Therefore, an effective reduced flow rate is displaced to the outlet.

Design approach of study

A multi-objective optimization algorithm based on the simulation software HYGESim (HYdraulic GEar machines Simulator) developed by Dr. Vacca's team at Purdue [12] was used to study the best geometry of the gears and the slider to achieve the optimal performance of the unit. The optimization flowchart is represented in Figure 4, along with the objective functions considered in this work. The algorithm used was a Fast Multi-Objective Genetic Algorithm.

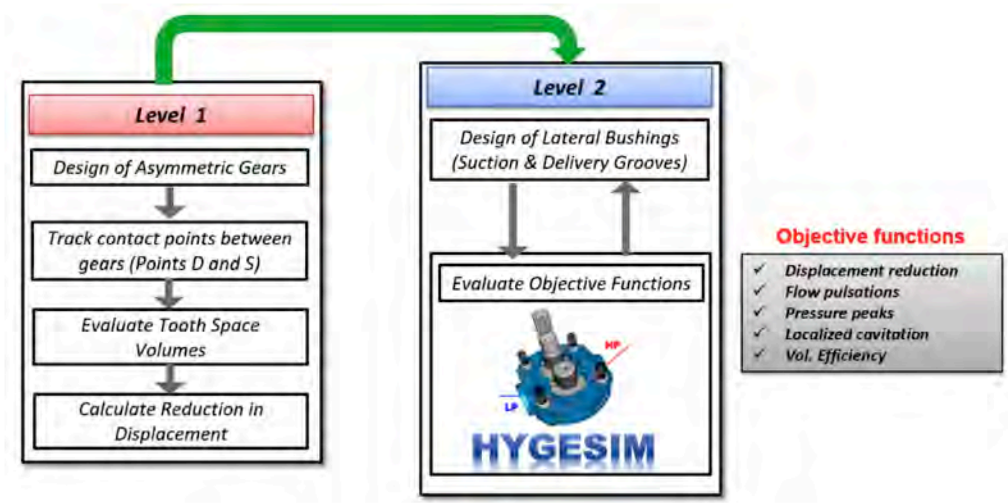

Figure 4: Two-level optimization workflow based on HYGESim to find the optimal VD-EGM design

B. Achievements

Achievements prior to the reporting period:

Prior to the reporting period, the research team has made remarkable progress in this research topic.

1. HYGESIM – HYdraulic GEar machines Simulator [12] was successfully extended to simulate the performance of a VD-EGM. Particularly, HYGESim was successfully used to simulate the VD-EGM in terms of pressure in the displacement chambers, local pressure peaks and cavitation, flow pulsations, forces acting on the gears, input shaft torque etc. The possibility of simulating asymmetric gears was also introduced in HYGESim.
2. A flexible gear generator for asymmetric gears was developed along with a lateral bushings generator [13], to permit optimization studies.
3. The multi-level-multi-objective algorithm of in Figure 4 was executed to find the best design of a VD-EGM capable of operating at 250 bar. An optimal design of the gears and the grooves in the slider was determined at the end of the optimization which offered an impressive displacement variation from 100% to 68% [13].
4. The HYGESim model was validated on the basis of measurements on a prototype EGM that replicates the basic features of the displacing action of a VD-EGM. In particular, the new gears were mounted on in a fixed displacement EGM configuration, but replicating both the max flow and min flow conditions by changing the designs of the lateral plates. It was successfully proved in experiments that variable displacement concept for EGMs is successful in reducing the flow rates as well as the input torque has been reduced proportionally with displacement thereby consuming lower power as compared to that at max displacement [13].

5. A conceptual design for a VD-EGM prototype that introduce the possibility of performing both manual and pilot operated variation of the displacement (according to a pressure compensator concept) was proposed.

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

From summer 2014, the research has made significant progress in addressing the research objective.

Prototype design and realization

The prototype for VD-EGM for high pressure applications initially conceived in 2013 was finalized and manufactured in 2014 (Figure 5). The prototype permits to test the complete VD-EGM functionality according to: a) a *manual control* for the outlet flow; b) a *pressure compensator* which adjust the output flow to limit the maximum pressure at the delivery.

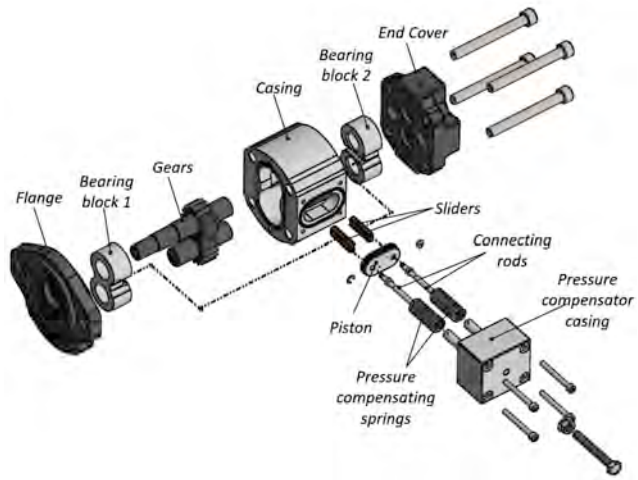

Figure 5: Exploded view and picture of the VD-EGM prototype realized in 2014

Prototype tests

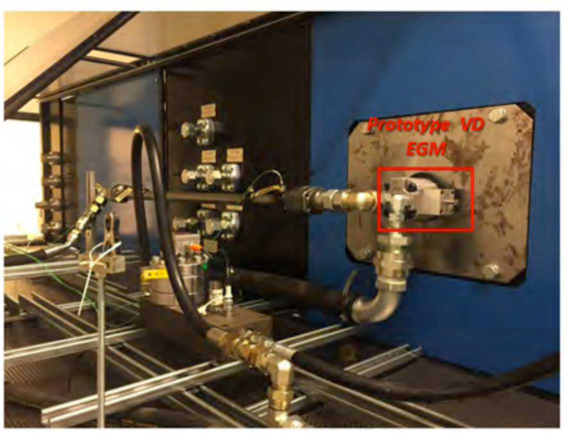

Figure 6: Test set up for the VD-EGM tests

The VD-EGM of Figure 5 was tested at Maha Fluid Power Research Center at Purdue to obtain a complete steady-state and transient characterization. Figure 6 show the test set up used for the measurement of shaft torque, outlet flow and pressure, including pressure oscillations.

Experimental results for both the regulating modes of the prototype were collected. Figure 7 shows the case of manual setting of the displacement. It can be seen how the outlet flow is actually regulated by the prototype with a significant torque reduction.

Since the gears were not properly treated, the pressure during the tests was limited to 100 bar. Measured data show volumetric efficiencies in about 60% at minimum displacement and 85% at maximum displacement.

The reduction of efficiency at maximum displacement is due to the additional leakage path created by the slider (Figure 5), at its back side. This could be reduced by a better machining tolerance of the slider, as well as by a different design concept for the slider that introduce proper sealing.

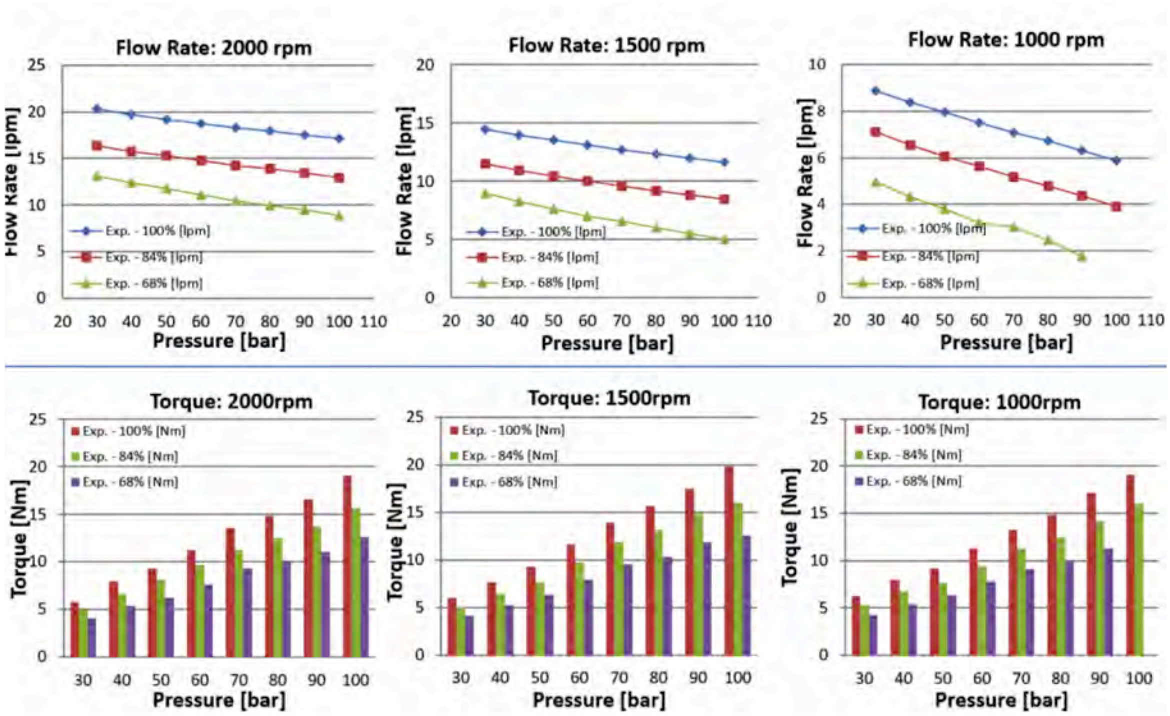

Figure 7: Test results achieved with the manual setting of delivery flow. Flow variation (upper plots) and torque variation (lower plots for different speeds.

Instead, the further reduction of volumetric efficiency at lower displacement is inevitable, due to the higher weight the leakages with respect to the outlet flow. This is a common feature for almost all design of VD positive displacement units.

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

- Deliverables:
  - Complete validation of the HYGESim model on the basis of measurements on the VD-EGM prototype (both manual and pressure compensated results) (Apr 2016)
  - Optimization of VD-EGM to permit a higher flow variation range through a different gear design (May 2016)
  - Creation of a low-pressure version of VD-EGM (up to 30 bar). Prototype design (May 2016)
  - Tests and validation on the low-pressure prototype VD-EGM. Fall 2016, after 1F.1 completion.

C. Member company benefits

- The CCEFP members 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 and can 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 (patent filed).

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Project 1G.1: Energy Efficient Fluids

Research Team

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	Professor Ashley Martini, University of California, Merced
Industrial Partners:	Afton Chemical, Danfoss, Evonik, Idemitsu Kosan, Gates, Poclain Hydraulics

1. Statement of Project Goals

The goal of this project is to bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power systems. This goal is being pursued by characterizing hydraulic fluids in benchtop instruments, analyzing fluid efficiency effects in a hydraulic dynamometer, modeling fluid-component interactions and simulating duty cycles in hydraulic machines. Improvements in the bulk modulus, boundary friction, and shear stability properties of fluids have yielded double-digit reductions in hydraulic motor friction and pump flow losses. These results have been used to develop and validate efficiency models that incorporate fundamental properties of hydraulic fluids. While significant efficiency improvements have been demonstrated, gaps remain with respect to understanding the relationship between fluid properties and hydraulic machine performance.

2. Project Role in Support of Strategic Plan

The CCEFP's strategic call for proposals identified creation of new fluid power technology that improves efficiency, curtails petroleum consumption, and reduces pollution as its top priority. Increased system efficiency also makes possible the use of smaller, more compact valves, pumps, and motors. This project, which combines the high-pressure rheology research of Professor Bair, molecular dynamics simulations of Professor Martini, hydraulic fluid formulation expertise of industry partners and duty cycles obtained from hydraulic machines to bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power systems.

3. Project Description

A. Description and Explanation of Research Approach

This project seeks to improve efficiency by studying fluid properties that impact system-wide efficiency. We will particularly investigate the following hypotheses for how polymer additives can improve efficiency:

- Increased high temperature viscosity decreases internal pump flow losses
- Reduced traction decreases mechanical losses in pumps at high speeds
- Drag reduction reduces pressure drop across valves and through fluid conduits (hoses and tubes)

To explore these hypotheses, dynamometer and fluid property characterizations will be used to investigate how hydraulic system efficiency relates to fluid properties. These results will be used to develop predictive tools that enable the rational design and selection of energy efficient hydraulic fluids.

B. Achievements

Achievements in previous years

Previously we found that the starting and low-speed mechanical efficiencies of orbital, radial piston and axial piston motors were enhanced by using ester base stocks or friction modifier additives that reduce boundary and mixed-film friction. [1,2] Energy-dispersive X-ray spectroscopy analysis of hydraulic motor and tribometer specimen surfaces revealed high concentrations of sulfur and phosphorus from the antiwear additive. The addition of a friction modifier reduced the concentration of sulfur and phosphorus on the surface which underscores the necessity of a well-balanced additive system. [3] Models for the relationship between hydraulic motor efficiency and Stribeck number were developed that are of the Michaelis-Menten chemical kinetics form. [4] These volumetric and mechanical efficiency models utilized the sonic-shear viscosity and yielded a mean standard error of less than 0.5%. These findings are significant because they provide insights toward the development of fluids that enhance hydraulic system efficiency.

Achievements in the current funding period

Dynamometer Evaluations

Five ISO VG 46 hydraulic fluids were evaluated. Pump case drain flow and radial piston motor torque losses were assessed in the hydraulic circuit shown in **Figure 1**. The circuit incorporated a Danfoss Series 45 open-loop variable-displacement axial piston pump. The pump inlet temperature was controlled to 50 or 80^{0}C (±1^0). The pump angular velocity was adjusted to 800, 1200 or 1800 rpm. Pump displacement was controlled by a Parker Denison 4VP01 proportional electrohydraulic valve that adjusted the swash plate angle to maintain a desired pump outlet pressure of 7, 10, 14, 17, 21, 24 or 27.5 MPa. The pump supplied power to a Poclain MS02 radial piston motor to yield rotational frequencies ranging from 1 to 200 rpm. Pump data was collected using modified ISO 4392 and ISO 4409 procedures.

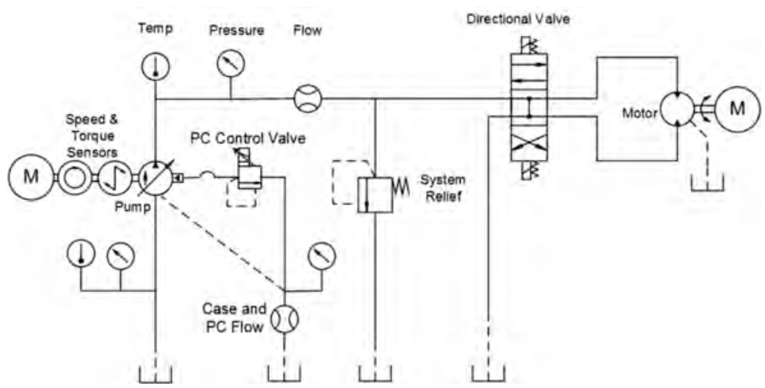

Figure 1: Simplified Circuit Schematic

Model Development

Steady-state models for pump case leakage flow and hydraulic motor torque losses were developed. The pump case drain and compensator leakage flow model was an adaptation of Joeng's flow loss model [5] as described in [6]. The model incorporated viscosity (μ), density (ρ), and bulk modulus (K) as well as rotational frequency (ω), differential pressure (ΔP) and derived displacement (V_E) as shown in **Eqn. 1**. The coefficients (C_P, C_T, C_K C_V, C_O) were derived from experimental data via linear regression.

$$Q_L = C_P(\Delta P / \mu) + C_T\sqrt{\Delta P / \rho} + C_K(\omega\, \Delta P / K) + C_V V_E + C_O \qquad \text{(Eqn. 1)}$$

The torque efficiency (η_{HM}) model was an adaptation of the Michaelis-Menten surface adsorption theory as described in [7]. The model incorporated rotational frequency, fluid viscosity, and motor differential pressure as shown in **Eqn. 2**. The boundary lubrication coefficient (C_{BL}), viscous drag coefficient (C_{SH}) and torque to rotate constants (C_{TTR}) were derived via non-linear regression.

$$\eta_{HM} = \frac{\left(\mu\omega / \Delta P\right)}{\left[C_{BL} + \left(\mu\omega / \Delta P\right)\right]} - C_{SH}\left(\mu\omega / \Delta P\right) - C_{TTR} \qquad \text{(Eqn. 2)}$$

Hydraulic motor torque losses (T_L) were estimated from the mechanical efficiency model and the theoretical torque of the motor (T_o) using Eqn. 3.

$$T_L = T_O\left(1 - \eta_{HM}\right) \qquad \text{(Eqn. 3)}$$

Duty Cycle Analysis

The duty cycle of an agricultural machine that was propelled by radial piston motors was obtained for the purpose of mapping above models to a hydraulic application. As shown in **Figure 2**, the machine operated much of the time at 60 and 140 RPM, and an operating pressure of 10 to 15 MPa. Histograms of the machine operating conditions were integrated using a procedure similar to [8]. These histograms were used to assess the potential benefit of optimizing properties for an agricultural specific duty cycle where the machine primarily operates under constant speed conditions.

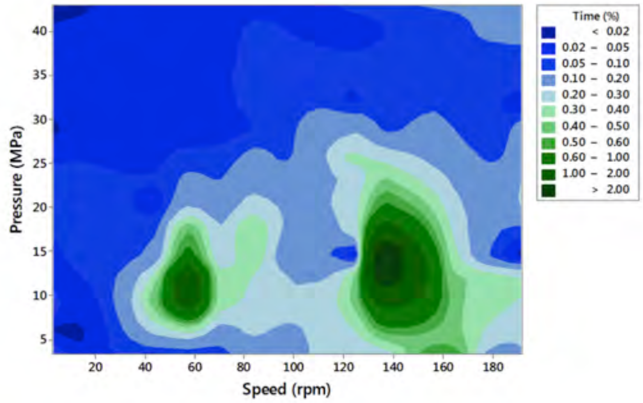

Figure 2: Duty cycle of an agricultural machine

Fluid Testing

The five ISO 46 viscosity grade hydraulic fluids listed in **Table 1** were evaluated. HM46 was a straight-grade Group I mineral oil based hydraulic fluid formulated with a commercial ashless antiwear additive package. HV46 was a multi-grade Group III mineral oil based hydraulic fluid that contained a commercial ashless antiwear additive package and a shear-stable polyalkylmethacrylate viscosity index improver. HEES46 was a Group V synthetic ester based hydraulic fluid formulated with a commercial ashless antiwear additive package. HBMO46 was a Group V phenyl ester based High Bulk Modulus Oil. HBMO46+FM was the Group V phenyl ester plus a friction modifier. The HBMO fluid exhibits a high bulk modulus because phenyl groups pack densely and have a low free volume [9]. In addition, ring structures increase the rotational energy barrier between carbon bonds within the molecule. A higher rotational energy results in a stiffer molecule. Molecular rigidity also affects the shear force transferred across a fluid film. This shear force is known as traction, which is the ratio of traction force to normal load. Base stocks that have a high bulk modulus tend to have a high traction coefficient [10]. Low traction is preferable in fluid power applications. The HBMO fluid evaluated in this investigation is formulated with a polycyclic compound that incorporates ester function groups for reduced traction [11].

Table 1: Test fluid properties

Fluid	HM46	HV46	HEES46	HBMO46	HBMO46+FM
Base stock	mineral oil, solvent ref	mineral oil, hydrocracked	polyol ester	phenyl ester	phenyl ester
Viscosity index	104	197	192	122	Same
KV 40°C, cSt new D445	46.5	50.5	51.1	45.2	Same
KV 100°C, cSt new D445	6.90	10.24	10.12	7.27	Same
KV 40°C, cSt sheared D5621	46.1	48.1	49.0	42.1	Same
KV 100°C, cSt sheared D5621	6.83	9.64	9.67	6.94	Same
Density g/cc @ 15C	0.8772	0.8524	0.9192	1.140	Same
Traction coeff. @ 50N, 20mm/s, 50°C	0.0721	0.0616	0.0482	0.0606	0.0478
Bulk modulus at 80C and 250 bar, /GPa	1.386	1.336	1.457	1.917	Same

Fluid Simulation

A MATLAB program was developed to simulate pump case flow and motor torque losses for the 508 combinations of hydraulic motor speed, pressure and displacement from the machine field study. The program outputs the case flow and torque losses for each combination of pump pressure and motor speed based upon inputs of the fluid properties and equations 1, 2 and 3. In addition to calculating the losses at specific conditions, the results are time-weighted based upon the duty cycle data. Comparisons of the simulated pump case flow rates for the various fluids are shown in **Table 2**. The simulation results predict that at 50, 80 or 100 ºC, the high bulk modulus fluid will reduce pump case flow losses. Somewhat unexpectedly, the simulation also predicts that the HV multigrade hydraulic fluid will increase the pump case flow rate at 50 ºC.

Table 2: Simulated pump case flow losses, percent change relative to baseline fluid HM46

Temp (°C)	HM46	HV46	HEES46	HBMO46	HBMO+FM
50	0	+1.3	-4.5	-16.0	-16.0
80	0	-2.5	-9.1	-18.0	-18.0
100	0	-5.8	-12.7	-19.4	-19.4

Comparisons of the simulated motor torque losses for the various fluids are shown in **Table 3**. The simulations reveal that the HBMO formulations will yield higher relative torque losses at 50 ^{0}C. At 80 and 100 ^{0}C operating temperatures, when viscosities are low and hydrodynamic lubricating films are thin, the low traction coefficient fluids (HEES46 and HBMO46+FM) will reduce motor torque losses. This is a bit surprising because an agricultural machine traversing a field operates at relatively high speed most of the time; only slowing down when it turns to reverse direction.

Table 3: Simulated motor torque losses, percent change relative to baseline fluid HM46

Temp (°C)	HM46	HV46	HEES46	HBMO46	HBMO+FM
50	0	-0.5	-2.4	+2.3	+1.1
80	0	-0.6	-4.6	-0.3	-4.8
100	0	-2.4	-8.7	-2.3	-9.2

These findings demonstrate the potential of combining comprehensive fluid analysis with modelling and simulation to optimize fluids for the efficient transmission of power.

Plans

Plans for this year

A new Danfoss Series 45 axial piston pump with swashplate angle sensing capabilities was installed earlier this year. The pump was broken-in and base-line performance tests were conducted using a straight grade Group III hydraulic fluid that incorporated a zinc dialkyldithiophosphate (ZDDP) antiwear additive. Currently a multigrade Group III hydraulic fluid is being tested. This fluid is formulated with a low-shear stability polyalkylmethacrylate viscosity index improver and ZDDP. The test stand is being operated for an extended period of time at high speeds and maximum rated pressure to shear down the polymer. Efficiency tests are also being conducted on a routine basis to evaluate the effect of shear stability on pump flow losses, motor torque losses and pressure drop through valves and fluid conductors. After the viscosity and efficiency of the low shear stability fluid plateaus, the baseline fluid will be re-evaluated. Thereafter a high shear stability multigrade Group III hydraulic fluid will be will be subjected to the same test regimen as the low shear stability fluid. Viscosity properties will be characterized through a wide range of shear rates to determine the appropriate conditions for modeling the efficiency of multigrade hydraulic oils. In turn, the resulting models will be mapped to duty cycles of hydraulic machines. The collection of the required hydraulic machine duty cycles is funded by an associated project.

Plans for the next year

A research proposal has been submitted to the CCEFP for funding in FY11-12. The proposal broadens the range of polymer chemistries that will be examined and adds molecular dynamic simulation capabilities. Molecular dynamics simulations will be used to predict the molecular conformation and viscosity of model polymers at different temperatures, pressures and shear rates. This effort is expected to yield the following outcomes: (1) Model predictions of polymer conformation and viscosity at a different temperatures, pressures and shear rates; (2) Viscosity measurements at different temperatures and shear rates; (3) Characterization and modeling of pump flow, motor torque and viscous drag losses in dynamometer tests; and (4) Simulations of machine duty cycles to optimize the formulation and selection of hydraulic fluids that reduce transmission losses. The detailed project plan will be developed in collaboration with industrial sponsors. A general description is provided below.

Task 1: Select materials for modeling and experimentation [1-2 months]

Task 2: Ramp up simulation procedures [2-6 months]

Task 3: Formulate test fluids for rheological and dynamometer testing [2-12 months]

Task 4: Conduct simulations, rheometer and dynamometer tests [6-24 months]

Milestones:

Completion of fluid selection process [Q3 2016]

Start of molecular dynamic simulations [Q4 2016]

Complete fluid formulations [Q1 2017]

C. Member Company Benefits

- Hydraulic fluid and additive manufacturers benefit from development of a rational basis for formulating high efficiency hydraulic fluids.
- Hydraulic equipment manufacturers benefit from the opportunity to use smaller power units without compromising performance.
- Hydraulic equipment users benefit from reduced energy costs and enhanced productivity.

D. References

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Project 1G.3: Rheological Design for Efficient Fluid Power

Research Team
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Lakshmi Rao, Industrial and Enterprise Systems Engineering
Yong Hoon Lee, Mechanical Science and Engineering

A. Statement of Project Goals

The overall objective of this project is to increase the efficiency of fluid power components through the rational design of fluids with rheological complexity. We will evaluate the potential of nonlinear viscoelastic fluid properties, coupled with asymmetric surface textures, to meet diverse design objectives for efficiency, such as low friction, high normal stress, and low leakage. These performance enhancements will be achieved through a fundamental understanding of Non-Newtonian lubricant behavior on textured surfaces, utilizing new mathematical techniques to optimize high-dimensional complex fluid properties, and implementation of the fluid and textures in fluid power components. Target applications include reciprocating rods, as well as seals and rotating components. We will fabricate and test textured plates in a novel gap controlled tribo-rheometer. Integration of the designed Non-Newtonian fluids will be applied to the excavator and the orthosis testbeds.

B. Project Role in Support of Strategic Plan

Fluid properties and efficiency are fundamental and applicable broadly to fluid power applications. The target application would be to overcome current barriers to fluid power systems and provide a transformational capability for future fluid power systems. The work constitutes fundamental research in the areas of fluids, tribology, and design. The project will develop expertise in fluid design for the CCEFP, creating new opportunities for engagement with industry. Designs will be validated through collaboration with industry and through application to the excavator and orthosis testbeds.

C. Project Description

1. Description and Explanation of Research Approach

The combination of Non-Newtonian fluids and surface texturing is a transformative design approach for creating efficient fluid power components. The areas of complex fluids, design, and surface texturing have been considered separately, and have not been applied in combination to fluid power efficiency applications. Non-Newtonian fluids can meet diverse design objectives due to their complex function-valued properties [1], and microtextured surfaces can significantly reduce friction, adhesion, and wear [2,3,4,5]. Yet, microtextures with viscoelastic fluids have received limited attention in the open literature. Experimental [6] and computational [7] studies can be found, but they are limited to symmetric textures and/or simplified rheological considerations.

In our approach, we consider the full range of non-linear viscoelastic behavior. Previous work by our team and others with Newtonian fluids show that textured surfaces may offer significant advantages for fluid power including reduced friction and reduced leakage. The long term goal of the project is to introduce the new aspect of fluid design, considering the wide range of rheological complexity and its coupling with surface textures, to produce fluid power components that have lower friction and leakage compared to standard fluid power components.

In order to determine the design of the Non-Newtonian fluids and the surface textures, experimental and numerical work will be performed. A novel experimental setup has been developed in order to mitigate experimental effects than can cause a misinterpretation of the friction reduction of the system and is shown in Figure 1. Several asymmetric plates will be manufactured in order to determine the effect of the asymmetry angle β on the friction reduction. The experimental results will be compared to numerical simulations in order to validate the numerical method. This validated numerical method will then be used to determine the optimal texture configuration and Non-Newtonian rheological properties for reducing friction in fluid power systems.

2. Achievements

Achievements in previous years

We have achieved accurate, reproducible experiments with asymmetric textures, leading to new observations and insight about shear stress reduction and normal force production in fully lubricated sliding contact. The precision-alignment of our system eliminates the risk of misinterpreting shear stress reduction and/or normal force production that is not actually due to textures. By eliminating this issue, our validated setup provides confident experimental observations of the effect of texture profiles and fluid properties.

Achievements in the past year

We manufactured more asymmetric textures with varying asymmetry angle β values and have experimentally tested them with Newtonian fluids. The normal force and effective friction coefficient both show that an optimal β exists for the asymmetric surface textures [8]. We have also developed our own code for solving the Reynolds equation in cylindrical coordinates and have validated our code against our experimental results. From this, we have been able to determine the optimal β value for decreasing friction with asymmetric surface textures. We have also examined other surface texture parameterizations in order to determine the optimal surface texture for decreasing friction in lubricated sliding contact.

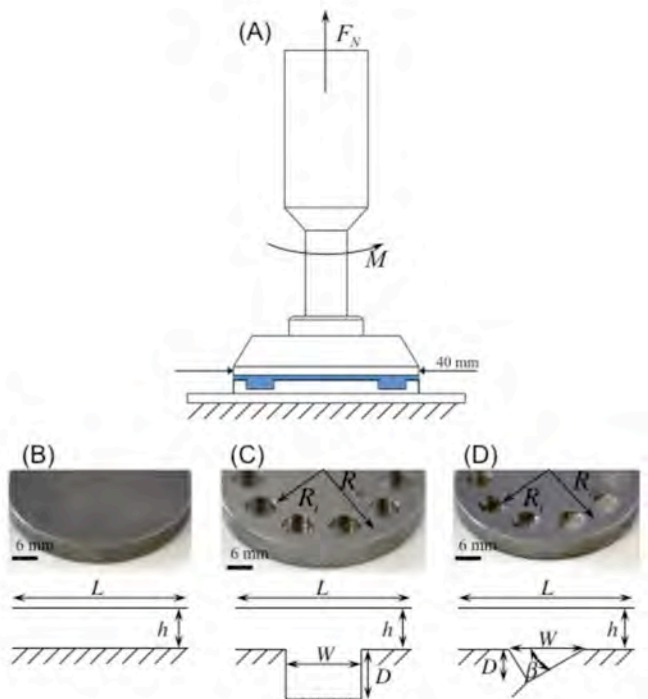

Figure 1: Schematic of experimental setup (modified rotational rheometer) and the three types of textures tested (flat, symmetric, and asymmetric). F_N is the measured normal force and M is the

We used surrogate modeling to decrease the computational complexity needed for determining the optimal geometric parameters for decreasing friction with symmetric surface textures while also minimizing the amount of volume removed by the surface texture [9].

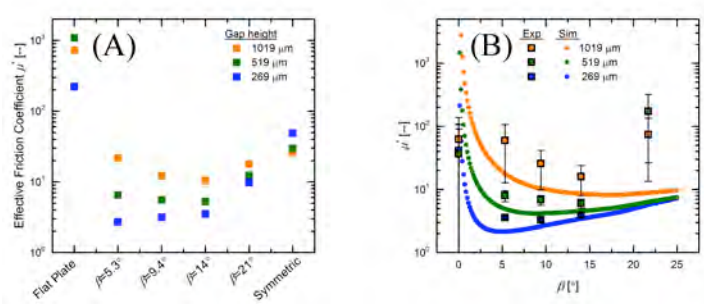

Figure 2: Results of surface textures with a Newtonian fluid (S600, Cannon Instrument Company, η_0=1.4 Pa s at T=20°C).
(A) Experimental results of effective friction coefficient at Ω=100 rad/s.
(B) experimental and numerical results of effective friction coefficient at Ω=10 rad/s. An optimal β is seen in both the experimental and numerical results, and good agreement is seen between the experiments and simulations, validating the numerical method.

We experimentally tested our asymmetric surface textures with a Non-Newtonian lubricant (dilute polymer solution, 0.5 wt% polyisobutylene in mineral oil). We have shown that the normal forces with the Non-Newtonian lubricant are always positive, and that the addition of the surface textures results in a larger normal force than the fluid acting alone. The normal force and effective friction coefficient also show that an optimal β value exists for the asymmetric surface textures. We have also developed code for a restricted set of second order fluids in order to numerically examine the interactions between the surface textures and the Non-Newtonian lubricant.

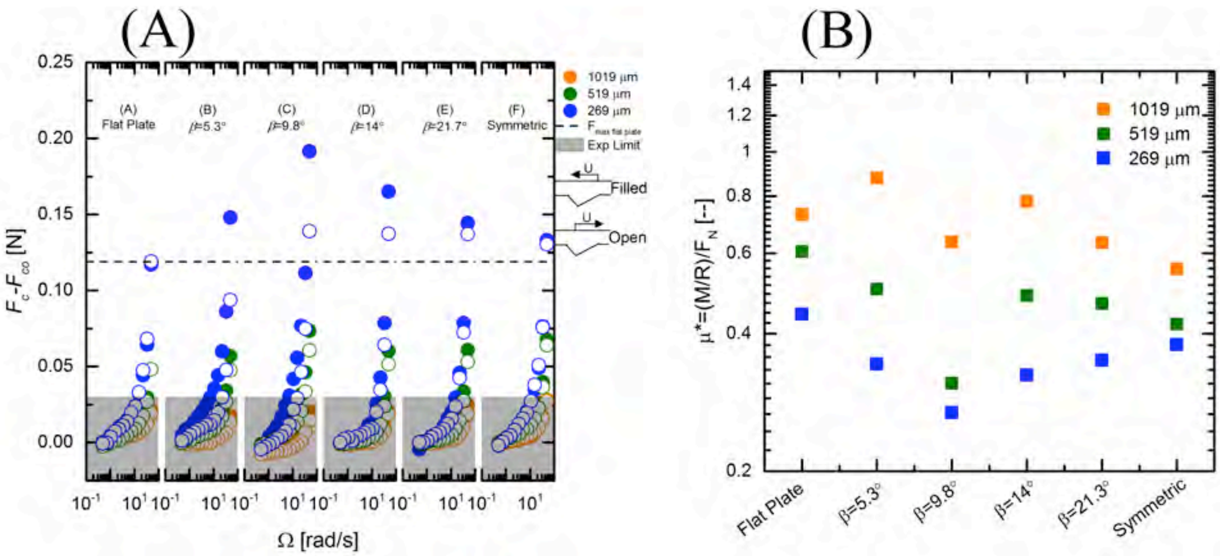

Figure 3: Non-Newtonian fluid experimental results with surface textures (0.5 wt% polyisobutylene in mineral oil). (A) normal forces. (B) effective friction coefficient. Both figures shown an optimal β value exists for increasing normal forces and decreasing friction with surface textures and Non-Newtonian fluids.

3. Plans

Plans for the next year

We will use our developed code for solving the Reynolds equation in cylindrical coordinates to determine the optimal surface texture profile for decreasing friction with a Newtonian fluid. Optimization techniques will be used in order to determine the best surface texture profile, shown in Figure 3. We have also developed code for solving the equations of motion for a restricted set of second order fluids. We will use this code to determine the optimal shape for decreasing friction with Non-Newtonian fluids, shown in Figure 4. Again, optimization techniques will be used in order to determine the best surface texture profile. The optimal profiles from both the Newtonian and Non-Newtonian case will be compared in order to determine how the Non-Newtonian fluid changes the optimal surface texture design.

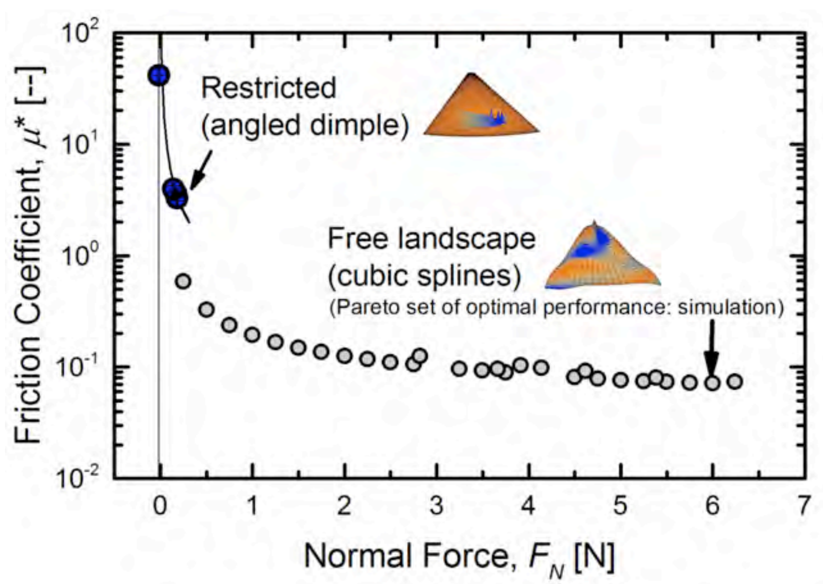

Figure 4. Design optimization results predict improved performance (lower friction, higher normal force) with more general surface topography. These results use the validated Newtonian fluid code [9] and are generated by running a Multi-Objective Optimization with ~200,000 realizations to find the 'Pareto Set' of points at the leading edge of the best performance (gray circles).

We will also develop code for solving the equations of motion for general second order fluids. We will relate the parameters of the second order fluid to microstructural properties (such as length of the polymer chain dissolved in the fluid) in order to design the fluid along with the surface texture. These results will be compared to designing just the surface texture for a given fluid to determine the larger friction reduction when designing both the texture and the fluid.

<u>Expected milestones and deliverables</u>

In the next year, we will deliver the optimal surface texture shape for decreasing friction with Newtonian fluids and the restricted set of second order fluids.

D. Member Company Benefits

Frictional losses occur in every fluid power system. The goal of this project is to help reduce these frictional losses in many applications encountered by the member companies of the CCEFP. The reduction of frictional losses, and thus increased efficiency, will be greatly beneficial through the industry.

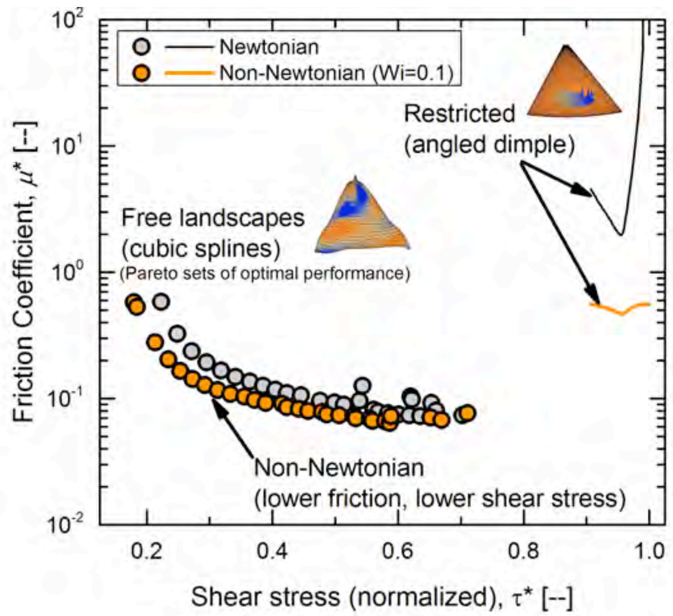

Figure 5. Design optimization with a Non-Newtonian fluid predicts further improvement of performance (lower friction, higher normal force, lower shear stress). A fast computation using the non-Newtonian constitutive model of a Second Order Fluid is used with the Multi-Objective Optimization, with ~200,000 computations, to find the 'Pareto Set' of surface topologies at the leading edge of the best performance (circles).

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Project 1J.1: Hydraulic Transmissions for Wind Power

Research Team

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Undergraduate Student:	Becca Trietch, Yale University
Industrial Partners:	Bosch Rexroth, Sauer-Danfoss, Linde, Eaton, ExxonMobil

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, grid-connected facilities require expensive power transmission lines, typically incur significant construction and maintenance costs, and are highly regulated. A small wind facility can be 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. 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>Modeling and control of hydrostatic wind turbine</u>

To evaluate the performance of the hydrostatic wind turbine, a high fidelity dynamic simulation model was built in Matlab/Simulink. The model is a physical equation based model which simulates both the quasi-static and the dynamic conditions. The rotor aerodynamic data used in the simulation model was generated by using FAST code, NREL's primary CAE tool for simulating the coupled dynamic response of wind turbines. The hydraulic components efficiency data are provided by main hydraulic component manufactures to give the best estimation.

A control strategy based on $K\omega^2$ law is proposed for the control of the hydrostatic wind turbine (figure 1). In the hydrostatic turbine for region 2, torque control using the $K\omega^2$ law is still used. Instead of controlling the generator torque through power electronics, the rotor reaction torque (pump torque) is determined by the line pressure which is controlled by varying the motor displacement. By using a PI controller to track the desired line pressure, the torque can be controlled.

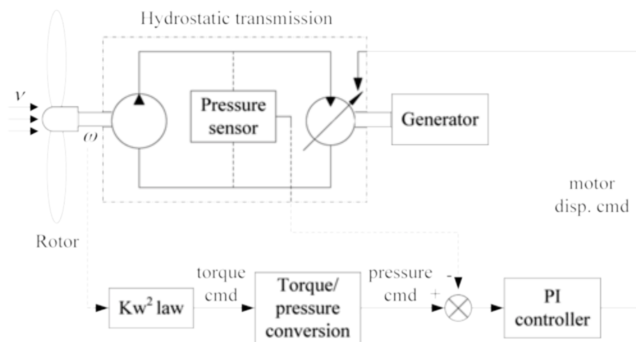
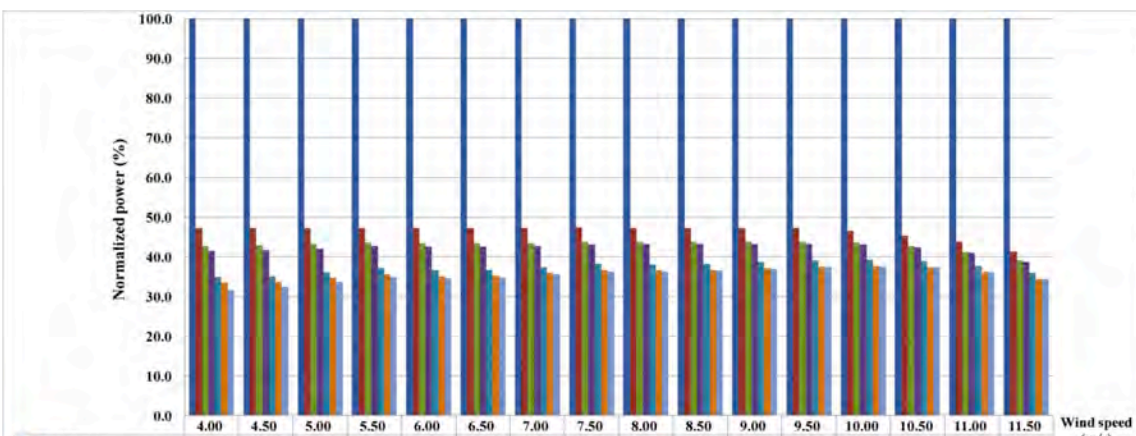


Figure 1: Control schematic of a hydrostatic wind turbine

The normalized power across the turbine drivetrain at different wind speeds was evaluated through the simulation. It clearly shows the power losses across each component in the turbine drivetrain (figure 2). These includes the rotor aerodynamic losses, pump and motor losses, line loss and charge power losses.



Wind speed (m/s)	4.00	4.50	5.00	5.50	6.00	6.50	7.00	7.50	8.00	8.50	9.00	9.50	10.00	10.50	11.00	11.50
Wind power	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Rotor shaft power	47.2	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.2	46.5	45.3	43.7	41.3
Pump hydraulic power	42.7	42.8	43.1	43.6	43.4	43.3	43.4	43.7	43.8	43.8	43.7	43.8	43.5	42.7	41.2	39.0
Motor hydraulic power	41.5	41.7	42.1	42.6	42.6	42.6	42.7	43.1	43.2	43.2	43.2	43.3	43.1	42.3	40.9	38.7
Motor shaft power	34.9	35.0	36.1	37.1	36.6	36.7	37.3	38.1	38.1	38.2	38.6	39.1	39.3	38.9	37.7	35.8
Generator output power	33.5	33.6	34.7	35.6	35.1	35.2	35.9	36.6	36.6	36.7	37.1	37.6	37.7	37.3	36.2	34.4
Net power	31.7	32.4	33.6	34.9	34.6	34.8	35.5	36.3	36.3	36.5	36.9	37.4	37.6	37.2	36.2	34.3

Figure 2: Normalized power across the turbine drivetrain (rated wind speed: 9.5 m/s)

Accomplishments:

1. Evaluated the performance of the proposed turbine control strategy;
2. Evaluated the power losses across the turbine drivetrain at different wind speeds;
3. Identified the control challenges for the hydrostatic turbine.

<u>Short-term energy storage for mid-size hydrostatic wind turbine</u>

To make hydrostatic transmission more attractive, this study investigated a short-term energy storage using hydraulic accumulator to increase the turbine annual energy production (AEP) (figure 3). The working region of the short-term energy storage is the transition region between turbine startup or “cut in” wind speed and rated wind speed.

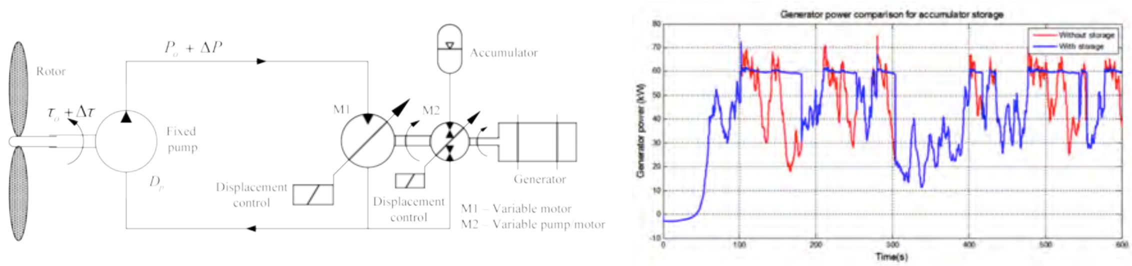


Figure 3: Short-term energy storage for hydrostatic wind turbine

Accomplishments:

1. Proposed a system configuration for the energy storage;
2. Developed a rule-based control strategy for the proposed energy storage system;
3. Conducted a sensitivity study of the accumulator size on the annual energy production;

The target application of this concept study is mid-sized wind turbines. Characteristics of AOC 15/50 (50 kW turbine from Atlantic Orient Corporation) were chosen for blade aerodynamic turbine model. Simulation results show that the AEP increases with the accumulator size until it reaches a point of diminishing return. For a 50 kW wind turbine, the optimum accumulator size was found to be 60 liters which increases the AEP by 4.1% (figure 4).

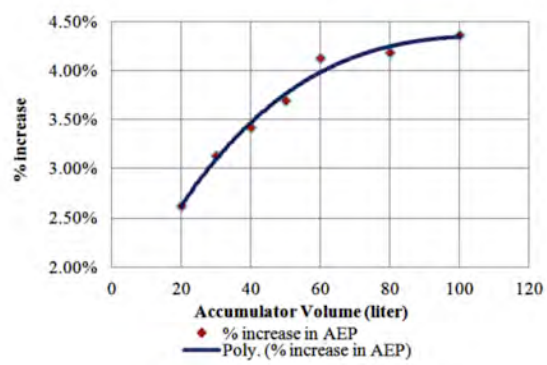


Figure 4: Sensitivity study of accumulator size on turbine AEP

<u>Hydro-mechanical transmission for mid-sized wind turbine</u>

To make the hydrostatic drive more competitive in the wind application, a hydro-mechanical (HMT) transmission combining the planetary gear set and the hydrostatic transmission is proposed (figure 5). By combining the high efficiency of a gearbox and the variable transmission function of an HST, the HMT offers a competitive solution for mid-size turbines.

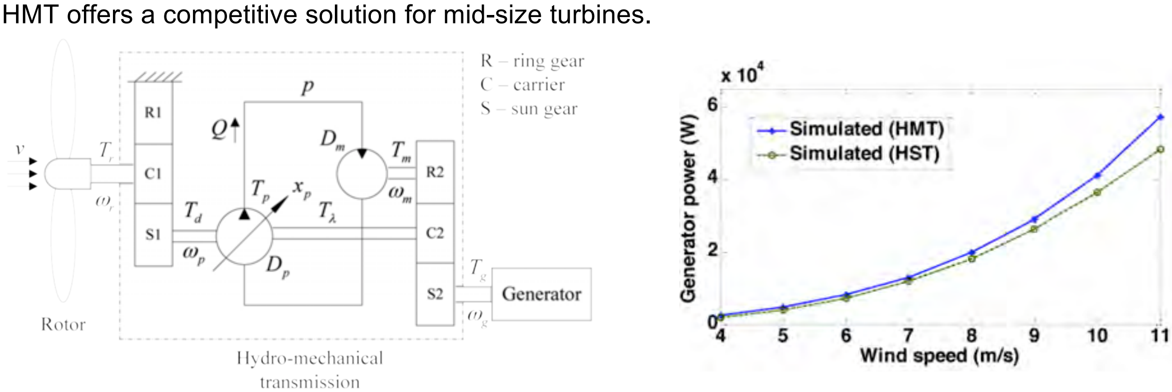


Figure 5: Hydro-mechanical transmission for mid-size wind

Accomplishments:

1. Proposed a hydro-mechanical transmission drivetrain configuration;
2. Compared the drivetrain efficiency and generator power between HMT and HST turbines.

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

<u>Power regenerative research platform for hydrostatic wind turbine</u>

To validate the proposed ideas, a power regenerative midsize hydrostatic turbine test platform is being built at the University of Minnesota, providing a powerful tool for wind research. The platform consists of two closed loop hydrostatic circuit. In Figure 6, the block in dark gray is the hydrostatic transmission under test and the block in light gray is the hydrostatic drive (HSD) simulating the virtual rotor. The virtual rotor is simulated at the input of the hydrostatic transmission (HST) and the turbine output is simulated at the output of HST.

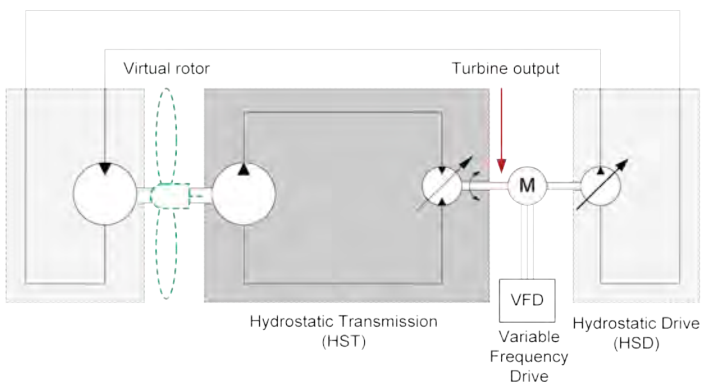
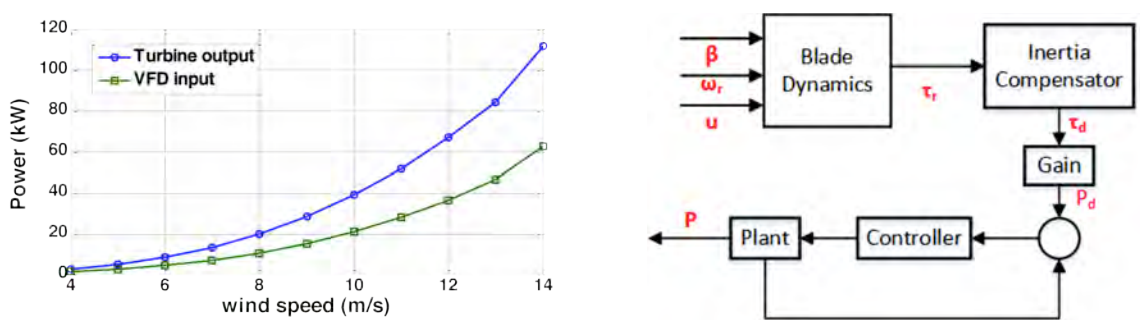


Figure 6: Schematic of power regenerative wind turbine research platform

Instead of dissipating the turbine output power, the power is fed to the HSD along with electric power, thereby allowing power regeneration. A variable frequency drive (VFD) electric motor is coupled on the turbine output shaft in order to compensate the losses of the HST and HSD. Because of power regeneration, the research platform is capable of 105 kW output power with only 55 kW VFD on input power from the electric motor.



(a) Power regeneration of the wind test platform ***(b) Schematic of rotor torque control***

Figure 7: Power regeneration and rotor torque control

One big difference between the research platform and the real wind turbine is the rotor/blade shaft inertia. The rotor/blade shaft inertia in the real turbine is usually large and it is not practical to simulate it in the lab. The large shaft inertia discrepancy between the wind platform and the real turbine makes the rotor shaft react quite differently in both cases. To simulate the rotor shaft dynamics in the real condition, a rotor shaft inertia compensation strategy is proposed for the research platform. The schematic of the rotor torque control with inertia compensation by hydrostatic drive is shown in right hand of figure 7.

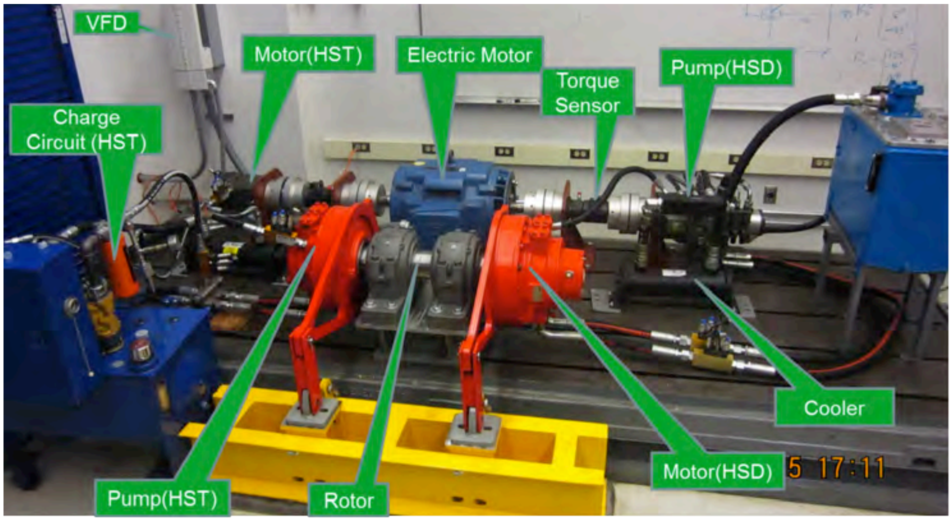


Figure 8: Power regenerative research platform

The research platform is shown in figure 8. It is equipped with pressure, temperature and flow sensor module in the hydraulic line and torque sensor and speed encoder in the mechanical line. The test platform is equipped with 27 sensors to monitor the system performance and three analog inputs to control the displacement of the HST motor, the pump displacement of the HSD and the speed of the electric motor. All I/O are communicated to a computer through a DAQ and controlled through the Matlab XPC target. The research platform provides a powerful tool to investigate the components, systems and advance control strategy.

Accomplishments:

1. The hardware of the research platform has been installed.
2. Hydraulic connection pumps and motors have been done.
3. The Instruments to measure the system performance have been calibrated and installed

B. Achievements

Achievements in previous years:

- Evaluated the performance of the proposed turbine control strategy;
- Evaluated the power losses across the turbine drivetrain at different wind speeds;
- Identified the control challenges for the hydrostatic turbine;
- Conducted the system parameters design for wind turbine research platform;
- Developed a research platform to simulate wind turbine
- Evaluated the proposed rotor/blade shaft inertia compensation strategy through simulation.

Planned future work:

- Design filters to smooth input and output signals of the research platform;
- Simulate the different wind power inputs using the platform;
- Validate the proposed control strategy for HST turbine (region 2);
- Test the transmission efficiency with different oil at different wind speed;

- Investigate dynamic behaviors of the HST turbine during wind turbulence;
- Implement different research ideas through the wind test platform.

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 1J.2: Vane Pump Power Split Transmission

Research Team

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	Emma Frosina, University of Naples Federico II
Industrial Partner:	Mathers Hydraulics

1. Statement of Project Goals

The growing demand for fuel efficient vehicles, low carbon footprint technologies and drivability requires more efficient vehicle powertrains. This creates opportunities to integrate new technologies that simultaneously improve both performance and energy efficiency. The automatic transmission is a widely used drivetrain. However, it is unable to maintain optimal efficiency over the entire engine operating range. In contrast, a continuously variable transmission (CVT) can decouple the engine speed from the vehicle speed, making the engine run more efficiently. The hydraulic form of a CVT is a hydrostatic transmission that uses a hydraulic pump to drive a hydraulic motor. Due to its high power density, durability, continuously variable ratio and smooth operation, the hydrostatic transmission (HST) has been widely used in off-road applications such as agricultural, construction and forestry machinery.

With continuously variable transmission and energy storage, full engine management becomes possible. The high power density of the hydraulic powertrain allows for lower vehicle weight, more regenerative braking and faster acceleration. The EPA's series hydraulic hybrid delivery vehicle has demonstrated 60-70% better fuel economy and 40% or more reduction in CO_2 emissions [1]. Altair's series hydraulic hybrid city bus demonstrated 30% or more fuel efficiency than other diesel-hybrid electric buses available today [2].

The objective of this project is to develop a compact and efficient hydro-mechanical transmission suitable for passenger vehicles and mid-size wind turbines. The main components of the transmission are Vane Power Split Unit (VPSU) and a variable motor. The VPSU is based on a double acting vane pump with a floating ring. The VPSU splits power into a mechanical path and a hydraulic path. The floating ring is coupled to the output shaft and transfers power in the mechanical path. The power of the hydraulic path fed to a variable motor to amplify the torque on the output shaft. The new transmission is projected to be as efficient as a conventional HMT with planetary gears in addition to being quitter, more compact and cost-effective.

2. Project Role in Support of Strategic Plan

Strategic barriers addressed are: (1) efficient components and systems (2) compact integration (3) energy management & efficient control. The outcome of this project could result in a simple, compact, cost-effective, efficient drive with an integral clutch. In addition, it readily accommodates future energy storage for hybridization. This transmission could be integrated into the hydraulic hybrid passenger vehicle test bed (TB 3).

3. Project Description

A. Description and explanation of research approach

The VPSU is based on a balanced designed double acting vane pump. Therefore, it has longer lifetime and quieter operation than a gear pump. The VPSU is more compact, combining both the pumping and motoring functions in one unit, making it function like a conventional HST. But it is more compact. The schematic is shown in left side of figure. The pumping unit consists of input shaft, rotor assembly and floating ring. The motoring unit consists of the floating ring coupled to the output shaft. The exploded view of VPSU is shown in figure 2. [3] [4].

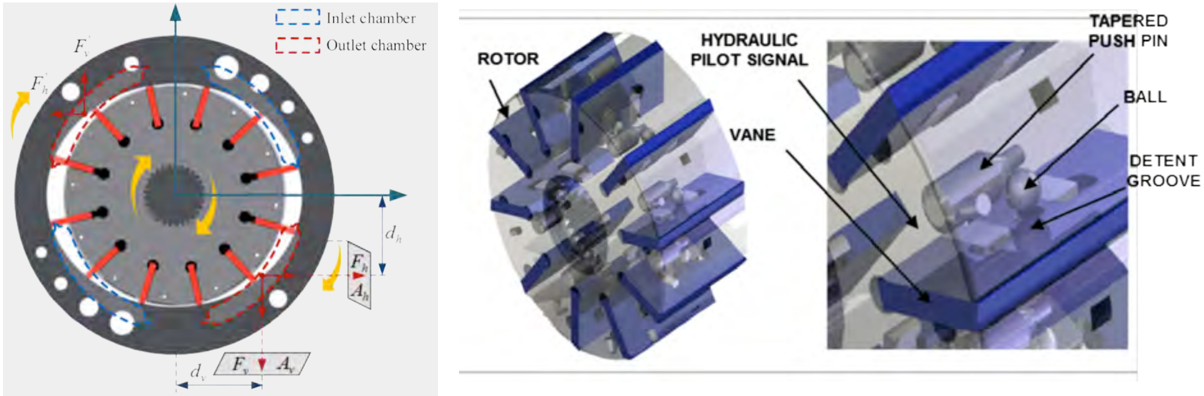


Figure 1: Vane Pump Power Split Unit

The VPSU has an integrated clutch. With the pilot pressure command from the hydraulic system, a tapered pin is hydraulically actuated to retract the vane. This decouples the output shaft from the input shaft, lowering the viscous drag on the rotor, or parasitic loss. The components for the clutch are shown right side of figure 1.

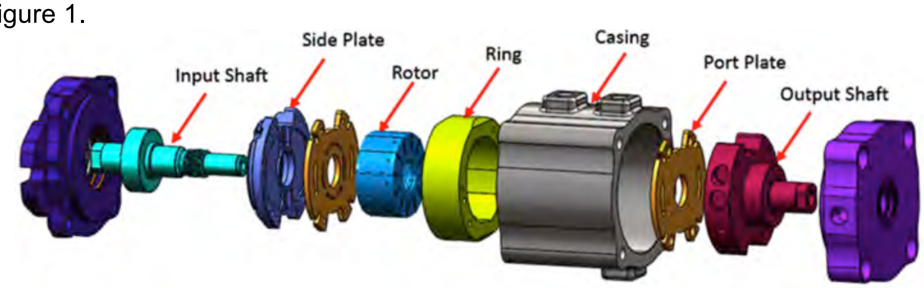


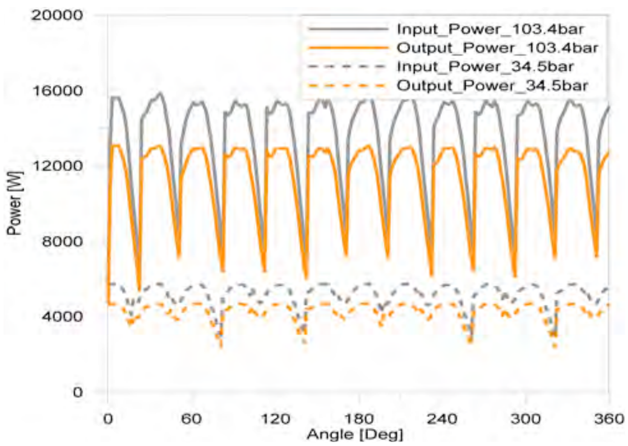
Figure 2: Exploded view of Vane Pump Power Split Unit

Component Study of Vane pump Power Split Unit:

To understand the characteristics of the VPSU, a computational model was developed. The fluid volume and three dimensional mesh for Computational Fluid Dynamics (CFD) analysis is shown in Figure 3. For ease of understanding of the VPSU and its performance, the unit is simulated at different pressure and flow.

Figure 3: CFD simulation of fluid volume of VPSU

Using the 3D CFD model, the performance of the VPSU at different pressure is analyzed. The input shaft power and output shaft power at 35bar and 100 bar pressure is shown in figure 4. In the simulation, the input and output shaft speed kept constant. As expected, by changing the delivery pressure, the input and output powers increase. The efficiency is better at high pressure than low pressure as shown in right of figure 4.



- ❑ Input Speed: 2400 rpm
- ❑ Output Speed: 2000 rpm

$$\eta = \frac{P_{out} + P_{flow}}{P_{in}}$$

PRESSURE (bar)	35	100
P_{in} (W)	5201.2	13541.2
P_{out} (W)	3175.9	11363.0
P_{flow} (W)	1093.9	1103.6
η	0.82	0.92

Figure 4: Efficiency of VPSU with output pressure variation

The CFD model is used to calculate the out power at different out speed and fixed input speed (2400rpm). The result is shown in figure 5. From the results it can be predicted that, with increasing the speed difference between the input and the output shafts, decreases the output power. Also, with increasing output shaft speed, the amplitude of power ripple decreases and mechanical efficiency increases. The mechanical efficiency is expected to be maximum, when input and output speed are same. This is known as lock-up condition and is good for high speed cruising [5].

- ❑ Input Speed: 2400 rpm
- ❑ Output Speed: 400,1200,2000rpm
- ❑ Pressure: 35 bar

OUTPUT SPEED (rpm)	400	1200	2000
P_{in} (W)	6413.7	5748.6	5201.2
P_{out} (W)	1115.1	2947.8	3175.9
P_{flow} (W)	1631	460.8	1093.9
η	0.43	0.59	0.82

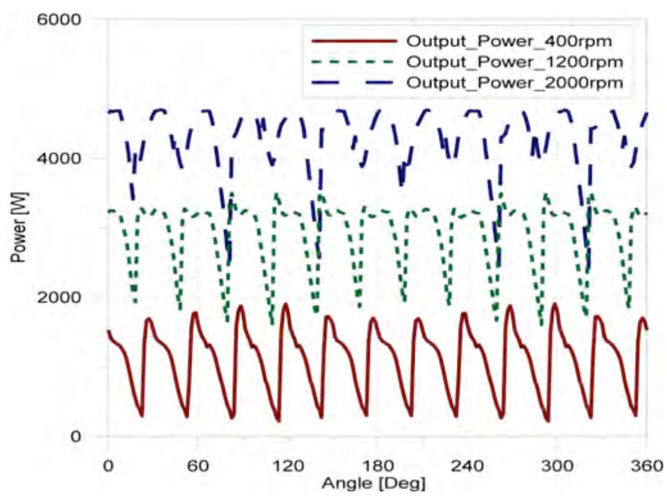


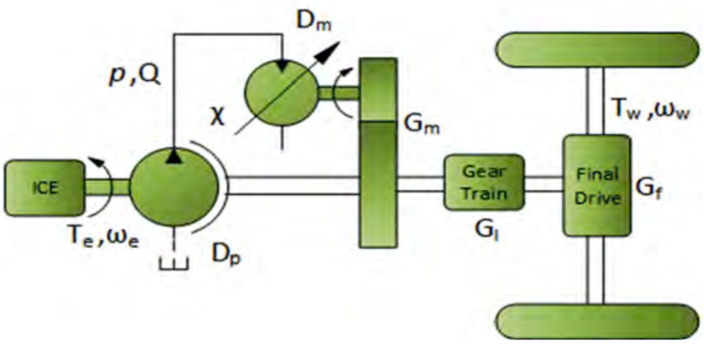
Figure 5: Efficiency of the VPSU with output speed variation

Accomplishments:

1. Developed a 3D CFD model to understand the performance of the VPSU at different operating pressures.
2. Evaluated the shaft torque at different working pressures and at different output shaft speeds.
3. Evaluated input and output shaft torque relationships at different output shaft speeds.
4. Analyzed the performance of the VPSU at different vane tip gap

Vane Pump Power Split Transmission (VPPST)

The transmission consists of a VPSU and a variable motor. The input shaft of the VPSU is coupled to the engine directly. The VPSU has an integral clutch. Therefore the transmission does not require any additional clutch or torque converter. The VPSU splits the power between the mechanical and hydraulic paths. The hydraulic power is fed to the variable displacement motor. The variable motor can be any type of motor appropriate to the application. The motor is mounted on the output shaft of the VPSU through the desired gear ratio to amplify the torque. The resulting torque of the shaft is fed to a gear box. The gear box has a two stage forward gear and one reverse gear. The output shaft of the gear box is connected to the wheels through the final drive. The variable displacement motor and gear ratio of the gear box together define the transmission ratio of the drive train. Due to smooth shifting of displacement of the variable motor, every possible gear ratio can be achieved. It gives more freedom to operate the engine in the most efficient zone. The schematic of the transmission is shown in figure 6. [6] [7].



Parameter	Value
Displacement Pump (D_p)	82 cc/rev
Displacement Motor (D_m)	200 cc/rev
Final Drive Ratio (G_f)	2.17
Motor Mounting Gear (G_m)	2.275
Intermediate Gear (G_I)	0.63,1.03

Figure 6: Architectures of the VPPST

The VPPST needs to fulfill the wheels' demand at all operating conditions such as high speed demand during cruising and high torque demand during acceleration, climbing and towing. At high speed, all the power is transmitted through the mechanical path by setting the variable motor displacement to zero. For high torque, most of power is transmitted through the hydraulic path, using full motor displacement to amplify the torque. The equivalent gear ratios during these conditions are shown in a table in figure 6.

The engine torques and speeds using the Urban Dynamometer Driving Schedule (UDDS) with a 200 cc/rev motor are shown in left of figure 7. The plot shows that, most of the time the engine operates on the optimal curve for minimum fuel consumption. The performance of the variable motor is shown in right of figure 7.

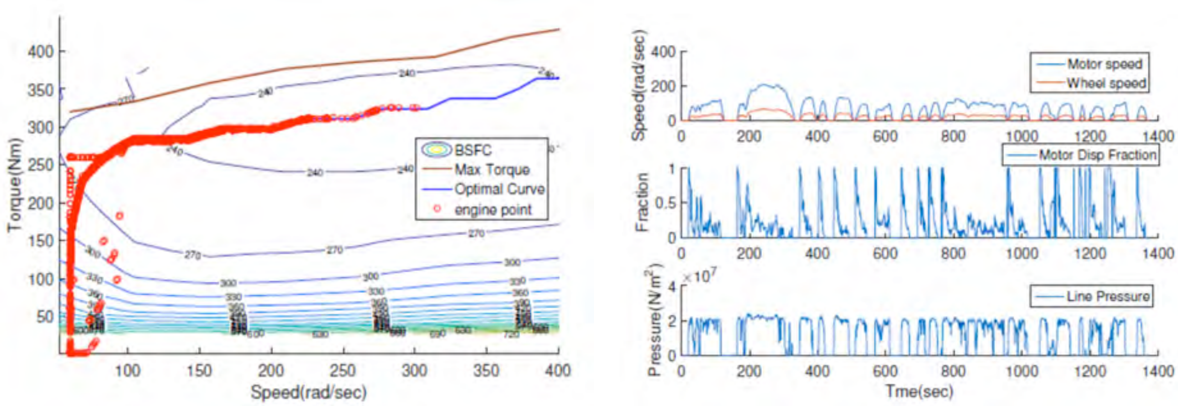


Figure 7: Performance of the engine and drivetrain in UDDS cycle

Accomplishments:

1. Proposed an architectures of the VPPST for a pick-up truck.
2. Evaluated the size of VPSU, variable displacement motor and intermediate gear at static conditions.
3. Performance of the drivetrain during UDDS cycle and highway cycle.

B. Plans

Planned future work:

- Investigate the drag effect of hydraulic oil and vane tip on floating ring.
- Validate the CFD result through component testing.
- Design optimization of the components such as vane tip, rat tail, ring profile and port plate.
- Simulate the VPPST architecture under dynamic conditions.
- Investigate the performance with hybrid VPPST.
- Implement the control strategy for better engine management.

C. Member company benefits

The vane pump power split transmission addresses a very large new potential market for fluid power. It projects to be a more efficient system for on-highway vehicle transmissions than existing automated mechanical or conventional (torque converter) automatic transmission. The compact unit is projected to be cost competitive with existing transmission technologies.

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Project 2B.3: Free Piston Engine Hydraulic Pump

Research Team

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Graduate Student: Chen Zhang
Industrial Partner: Ford Motor Company, Individual Project Champion: John Brevick

1. Statement of Project Goals

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

2. Project Role in Supporting of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

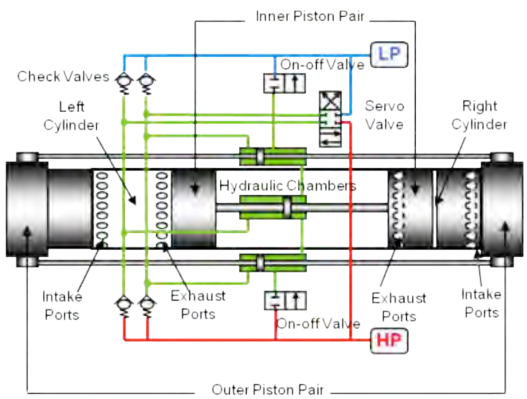

Figure 1: Schematic of the Free Piston Engine Driven Hydraulic Pump

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

B. Achievements

<u>Achievements in previous years – precise piston motion control</u>

Previously, an active controller was designed to act as a “virtual crankshaft”, which regulates the piston to follow any reference trajectory using the energy from the storage element [11-15]. By adjusting the opening of the servo valve, the controller actually controls the hydraulic forces acting on the piston pair, therefore regulat the piston motion. Two feedforward controllers are also investigated to complement the existing virtual crankshaft mechanism and further improve the piston tracking performance. The experimental results demonstrate the effectiveness of the feedforward controllers [16]. Additionally, a transient controller was developed as well and implemented on the HFPE to deal with the transient period when the engine switched from motoring to firing [17]. Figure 2 shows the related experimental results, which demonstrates the effectiveness of the virtual crankshaft mechanism as well as the transient controller.

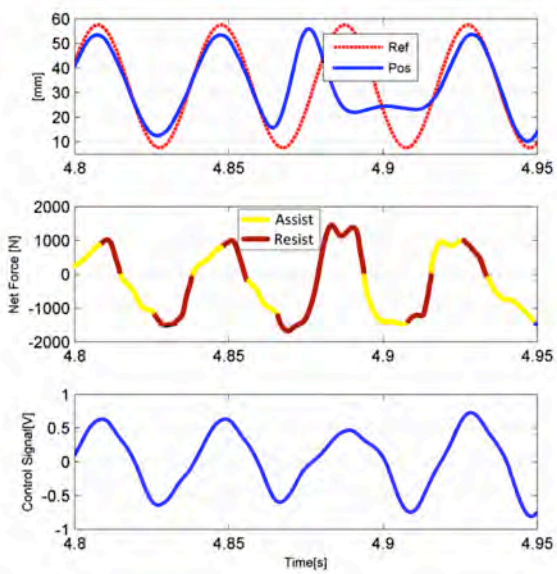

Figure 2(a): Transition when switch from motoring to firing

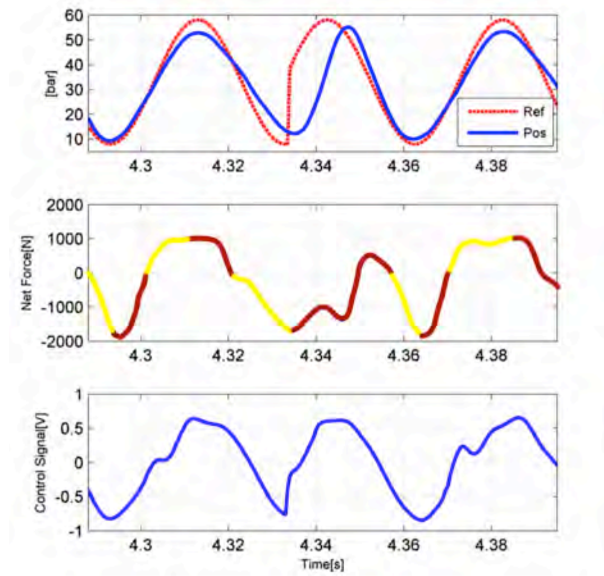

Figure 2(b): Piston motion after applying the transient control

Achievements in the past year

In the past year, a supercharge system has been designed and integrated with the HFPE, which boosts the intake charge pressure from 1.5 bar to 2.5 bar. Such a high intake air pressure not only benefits the scavenging process, but also improves the air fuel mixing inside the combustion chamber and enhances the combustion events.

Attributed to the improvement on piston motion control and the installation of the supercharge system, we have achieved continuous combustion in the HFPE last year. Figure 3 shows the corresponding experimental result, which offers valuable information for future HFPE research, as no previous experimental results have been published in the literature on such a FPE operation with opposed-piston-opposed-cylinder (OPOC) architecture.

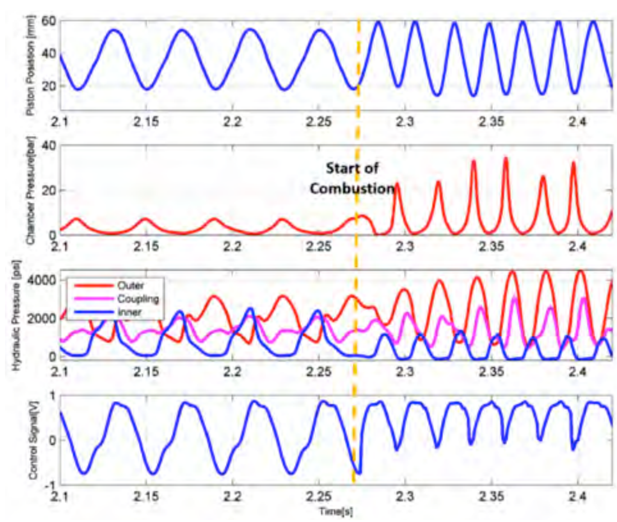

Figure 3: Continuous combustion of the FPE

In addition, a novel combustion control, namely the piston trajectory-based combustion control, was also developed using the ultimate flexibility of the piston motion in the HFPE. By chanigng the piston trajectory in real time, we are able to adjust the combustion chamber volume, affect the pressure, the temperaure and the species concentrations of the in-cylinder gases and therefore tailor the combustion process to maximize the engine efficiency and minimize emssions [18, 19]. The corresponding simulation results validate this idea (Figure. 4) and show that higher indicated thermal efficiency and less NOx emission can be achieved simultaneoulsy if a specific asymetric piston trajectory is deployed. Furthermore, the proposed combustion control offers ultimate fuel

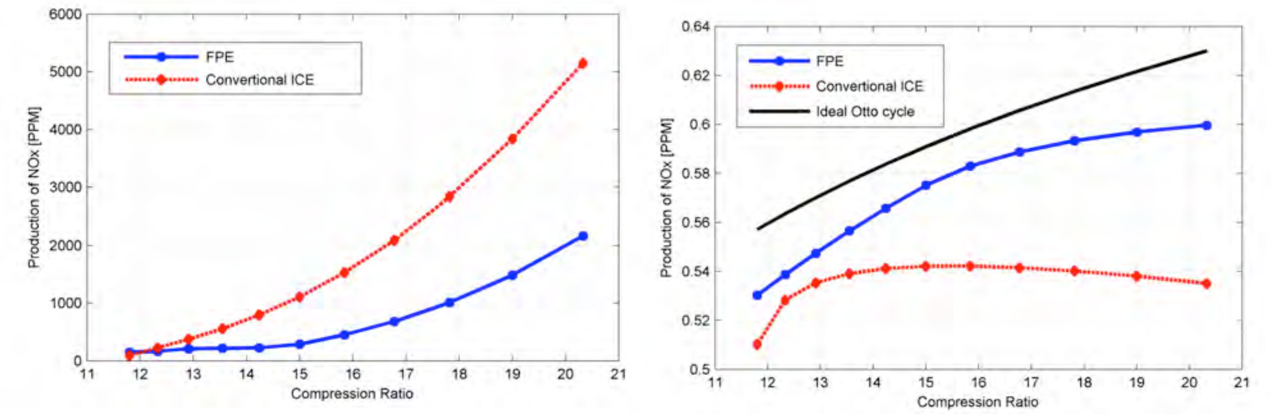

Figure 4: Comparison between FPE and conventional ICE under different compression ratio (left NOx emission; right thermal efficiency)

flexibility since a variety of fuels can be utilized in the HFPE by varying the compression ratios accordinlgy [18].

C. Plans

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

1) *Design of hydraulic actuation system enabled by modular fluid power source to reduce throttling losses*

   Since the FPE is a modular fluid power source, each module can be used for a dedicated function and therefore fluid power can be generated in a distributed manner which will significantly reduce throttling losses compared with the centralized power supply and offer ultimate flexibility in off-road vehicle design and packaging. However, to realize the benefits of the FPE as a modular and on demand fluid power source, an efficient and effective hydraulic actuation and control scheme is required. Due to the stroke by stoke motion, the FPE can be viewed as a digital flow source. The objective of the hydraulic actuation system is to convert the digital flow into linear or rotary motion required by off-road vehicles in real-time with minimal losses.

2) *Controlling the hydraulic free piston engine as a modular fluid power source*

   Based on the required pressure and flow rate for the designed hydraulic actuation system, we need to control the hydraulic FPE as a modular fluid power source accordingly. Due to its ultimate freedom on piston motion and much lower inertia compared with the conventional ICE, the FPE is a perfect candidate with much smaller response time for the load change.

3) *Evaluating the performance of the free piston engine based off-road vehicle*

   The FPE model and the hydraulic actuation model will be integrated and overall system simulation will be conducted. Typical duty cycles of a representative off-road vehicle will be used to evaluate the efficiency and performance of the FPE based off-road vehicle. Benchmark with conventional off-road vehicles will also be conducted. Besides simulation studies, hardware-in-the-loop (HIL) tests will also be conducted to evaluate the proposed system. To prepare for the HIL tests, necessary sensors and new subsystem need to be installed to further improve the engine performance and integrate the FPE into the HIL test.

<u>Expected milestones and deliverables</u>

- Task 1: *Design of hydraulic actuation system to reduce throttling losses* [9 months]

  - Investigate different architectures for hydraulic actuation with a modular and digital fluid power source.
  - Model the hydraulic actuation architectures and derive the optimal configuration.
  - Simulate and analyze the performance of the selected hydraulic actuation system.
- Task 2: *Controlling the hydraulic FPE as a modular fluid power source* [12 months]
  - Implementing the variable frequency control and the variable displacement control of FPE with the virtual crankshaft.
  - Systematic comparison of the control methods to independently regulate the FPE output pressure and flow rate.
- Task 3: *Evaluating the performance of the FPE based off-road vehicle* [9 months]
  - Simulation and analysis of the complete system model including the FPE and the hydraulic actuation system.
  - Improvement of the FPE hardware in the laboratory
  - Conducting the hardware-in-the-loop tests to evaluate the performance of the FPE based off-road vehicle.

Milestones:

- Hydraulic actuation system design for an off-road vehicle [month 9]
- Control of the FPE as modular fluid power sources for an off-road vehicle [month 15]
- Evaluation and Benchmark of the FPE based off-road vehicle [month 24]

D. Member company benefits

The project will benefit the member companies in three areas. First, this project will provide a new fluid power source for series hydraulic hybrid vehicles. 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 create new opportunities for both fluid power components and system integration due to the modular fluid power supply.

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Project 2B.4: Controlled Stirling Thermocompressor

Research Team

Project Leader: Eric Barth, Vanderbilt University, Mechanical Engineering
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Industrial Partner: Enfield Technologies

1. Statement of Project Goals

The goal is to design and build a second generation Stirling thermocompressor as a design evolution of the first generation device that has already been completed with CCEFP funding. The research goals are: (1) design and experimentally validate a Stirling thermocompressor for untethered fluid power applications, as driven by the challenging and representative requirements of the ankle-foot-orthosis test bed (TB6), (2) continue to pursue a dynamic model-based design approach for a Stirling-based thermocompressor based on validated models from the generation 1 device, (3) experimentally characterize the generation 2 device for model validation purposes and performance, and (4) study the scalability of technology developed for the Stirling thermocompressor from miniature pneumatic power supplies up to industrial air compressors, particularly with respect to enhancing heat transfer within the compressor to enhance efficiency. A fifth goal has been added to the project as well: (5) study different power outputs, namely a miniature hydraulic power unit based on the pressurizer portion of the thermocompressor, small-scale electric power generation, or high-pressure water filtration units. The goals of the project will be achieved by paying attention to the lessons learned from the generation 1 device from both a model-based / fundamental standpoint, as well as from an implementation standpoint.

2. Project Role in Support of Strategic Plan

This project contributes to two thrusts within the Center: compactness and efficiency. The compactness and efficiency barrier are addressed by developing a fluid power based, portable, and compact power and actuation system that will provide an order of magnitude greater power and energy density than the current state-of-art batteries. High heat transfer will be achieved by maximizing the heat transfer area and by utilizing pre-pressurized helium as the working fluid within the device; therefore increasing the efficiency and power density. Compactness is essential for a human assist device like the ankle-foot orthosis. By designing this small, compact device, it will be determined whether the energy/weight and power/weight advantages of fluid power will hold for small devices. The ultimate goal of this work is to fulfill the CCEFP's strategic vision of providing a source of power for untethered fluid power devices in a way that will open up whole new applications and whole new markets in robotics.

3. Project Description

A. Description and explanation of research approach

Mobile robots need to be energetically autonomous to be truly effective. The market for personal service robots is estimated to be worth \$10 billion (Japan government Report, March 2005). However, there is no power supply or actuation system capable of powering a portable, untethered human-scale robot for an extended period of time. Although battery powered servomotors have the advantage of lithium-ion (Li-ion) and nickel-metal hydride (NiMH) batteries being relatively cheap and DC servo motors being easily controllable, the mechanical work output and operating time of this power supply and actuator system is very limited. This is due to the low energy density of batteries and the low power density of electric motors. The energetic deficiencies of the state-of-the-art battery-powered servomotors for mobile robots have motivated the development of alternative power supplies and actuation system with improved energetic characteristics.

This research investigates a Stirling device as a high energy density power supply energetically superior to batteries. A Stirling device can run on a flexible fuel/heat sources such as high energy density fuels like propane, butane, solar concentrators or waste energy, among others. The Stirling device will burn a high energy density fuel, such as hydrocarbon fuels with an energy density of about 45,000 kJ/kg, and absorbs the heat to convert it to oscillatory pressure energy which in turn drives a power extraction unit. In order to achieve the same fuel specific work output as a battery-powered system, a Stirling powered actuation system would only need to an overall efficiency of 1.4%. Any efficiency above 1.4% would represent an energetically superior system. It is also important that such a device be relatively silent. Our current prototype shown in Fig 1 operates reliably and completely silently up to 500º C. This prototype is the basis for the reported work.

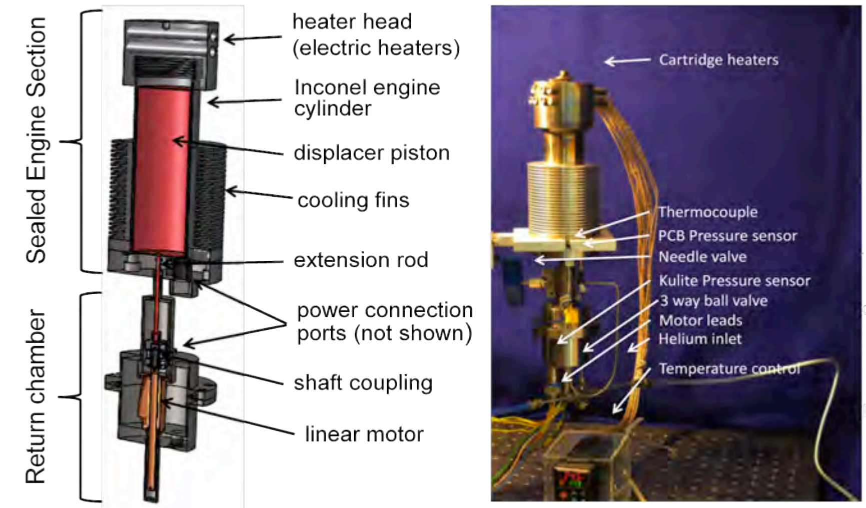

Figure 1. Design of Stirling pressurizer (left) and experimental platform (right)

Primary advantages of a free-piston arrangement such as ours include the ability to completely seal the engine, the elimination of side forces on the piston, and the ability to pressurize then engine to obtain higher power densities [1]. Many free-piston Stirling engines have been built and shown to work, such as Beale's arrangements [2,3], the Harwell Thermomechanical Generator [3,4,5.], or the ingenious liquid piston Fluidyne Stirling engine by West [6,7]. However, none of these machines have been utilized as a prime-mover for fluid power systems.

B. Achievements

Achievements in previous years

Design, modeling, fabrication, and experimental testing of a first-generation controlled Stirling thermocompressor in 2012-2013:

- First generation prototype represented a true thermocompressor – meaning working fluid was the air being pumped
- It was a multistage thermocompressor. Each stage was designed to progressively increased pressure of the working fluid until the target output pressure of 80 psig was reached.
- Displacer within the engine was driven by a DC motor and a linear reciprocating lead screw.
- Engine housing was made from a fused quartz cylinder due to its low thermal conductivity.
- In cylinder heat exchangers were developed to increase the heat transfer area.
- Experimental results showed a pressure ratio of 1.6 at 800°C and 2.8 Hz

These results were lower than expected due to excess dead volume and a slow leak at the high temperature seal. Also the reciprocating lead screw mechanism represented too much friction which resulted in significant losses. Therefore, a second generation prototype had to be designed.

A second generation prototype (shown in Figure 1) was designed, modeled, fabricated and tested beginning in 2014. Achievements from prior years related to this device include:

- Fabrication and testing of a sealed, high-temperature, helium working fluid Stirling pressurizer.
- Successful and reliable tests up to 500°C and 30 bar.
- Silent operation – whisper level acoustic signature.
- Formulation of a system dynamic model appropriate for model-guided design of similar scaled devices.

Achievements in the past year

The prototype was used to experimentally validate the dynamic model. This included: 1) the dynamic pressure in the cold side of the engine as a function of heater head temperature, average engine fill pressure, and various displacer motion profiles and frequencies. These results are summarized in Tables I and II.

TABLE I. Pressure ratio of experimental and modeled data at 1 Hz

1Hz	250°C		350°C		450°C		500°C	
10bar	1.53	-11.75%	1.62	-4.48%	1.78	5.93%	1.79	-5.84%
	1.35		1.55		1.68		1.69	
15bar	1.52	-12.72%	1.63	-8.18%	1.76	0.37%	1.77	1.03%
	1.32		1.49		1.75		1.79	
20bar	1.49	-8.17%	1.56	-11.15%	1.56	3.07%	1.76	-6.67%
	1.36		1.39		1.51		1.62	

TABLE II. Pressure ratio of experimental and modeled data at 2 Hz

1Hz	250°C		350°C		450°C		500°C	
10bar	1.55	-9.84%	1.74	-4.90%	1.89	-2.16%	1.87	6.15%
	1.40		1.66		1.85		1.97	
15bar	1.54	-5.36%	1.70	-2.21%	1.86	1.82%	1.89	6.00%
	1.46		1.66		1.89		1.96	
20bar	1.48	-2.97%	1.66	-1.04%	1.86	0.17%	1.97	0.00%
	1.44		1.64		1.97		1.97	

Key for Tables I and II:

Experimental $\overline{P}_{k,\max} / \overline{P}_{k,\min}$	% Error
Modeled $\overline{P}_{k,\max} / \overline{P}_{k,\min}$	

Our tests demonstrated an excellent device temperature gradient (see Figure 2). Using the validated model, we simulated the device delivering work through a power piston. These simulations verified our basic hypothesis that a controlled displacer motion, as opposed to a sinusoidal displacer motion can substantially impact the efficiency and power output of the device. In the simulation shown in Figure 3, a standard sinusoidal displacer motion profile resulted in a power output of 148W with an efficiency of 22.5%. A more square-wave motion profile resulted in a power output of 220W with an efficiency of 39.8%.

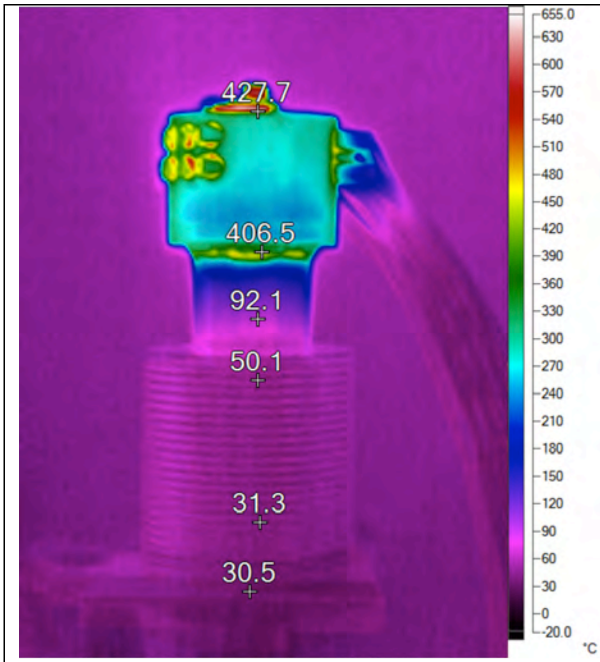

Figure 2: Thermographic image of the engine

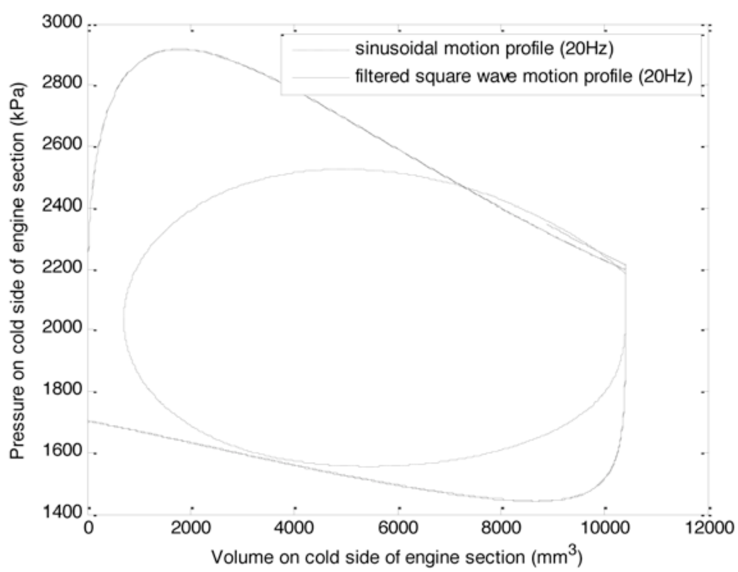

Figure 3: PV diagram for two different displacer motion profiles

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

- *Milestone 1:* Generation 1 device initially designed and constructed. [Completed]
- *Milestone 2*: Generation 1 device pressure ratio experimentally characterized [Completed]
- *Milestone 3*: System Modeled and Validated [Completed]
- *Milestone 4*: Pressurizer and Compressor stage designed and modeled [Completed]
- *Milestone 5*: Pressurizer experimentally characterized [Completed] and dynamic model validated [Completed]

- *Milestone 6*: Power out stage experimentally characterized and dynamic model validated [Completed]
- *Milestone 7*: First full controlled Stirling power unit modeled and validated [Completed]
- *Milestone 8*: Design and fabricate the hydrocarbon fueled heater [04/2016]
- *Milestone 9*: Final full controlled Stirling power unit completed [05/31/2016]

C. Member company benefits

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

D. References

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Project 2C.2: Advanced Pneumatic Strain Energy Accumulator

Research Team

Project Leader:	Prof. Eric Barth, Mechanical Engineering, Vanderbilt University
Graduate Students:	Joshua Cummins
Undergraduate Students:	Christopher Nash, Benjamin Seth Thomas
Industrial Partners:	Enfield Technologies, SMC Corporation, Parker Hannifin, Kolmar Laboratories and Schmalz

1. Statement of Project Goals

The goals of this project are to characterize the efficiency of a power dense pneumatic component and study its impact on system efficiency. In year one, selection of an appropriate rubber compound for the accumulator was completed and proof of concept of conductive elastomers accomplished. In year two, due to budget constraints, focus shifted to modeling and experimentally validating the efficiency of a pneumatic strain energy accumulator (pSEA) and quantification of its impact on system performance when compared with the baseline system without a pSEA.

2. Project Role in Support of Strategic Plan

First, with the recent involvement of Enfield Technologies and SMC Corporation, the project has engaged existing industrial partners and attracted potential new industry members through Kolmar Laboratories and Schmalz thus supporting the sustainability portion of the Center's strategic plan. Next, the project aims to accurately characterize component and system efficiencies, increasing the likelihood of successful transition to commercialization. By modeling and experimentally validating efficiencies of power dense pneumatic components and their impact on system efficiency, the research contributes to the centers goals of compactness and efficiency.

3. Project Description

A. Description and explanation of research approach

Component Efficiency Study

The motivation for the current research has been the development of the advanced strain energy accumulator combined with a 2012 report by Oak Ridge National Labs (ORNL) and the National Fluid Power Association (NFPA) on the efficiency estimates of the fluid power industry.[1] In the study the fluid power industry was estimated to average just 22% efficiency with the pneumatic sector averaging even lower at just 15% efficiency. The strain energy accumulator has long been believed to be a highly efficient energy storage device. The component efficiency studies completed in the past year investigate, validate and quantify this devices efficiency on a component level.

System Efficiency Increases with Implementation of pSEA

In previous work done by Bing *et al.*[2] comparison of two fluid power systems, one with a traditional accumulator and one without, are compared and their efficiencies studied. Their findings estimate system performance improvement for a hydraulic system but lack a formal model and indeed directly identify the need for modeling for efficiency estimation and improvement metrics. The system efficiency increase study develops these models for pneumatic systems, quantifies the energy savings due to the SEA, validates the results and makes projections of energy savings at an industry level.

B. Achievements

Achievements in Previous Years

In previous years a low pressure strain energy accumulator prototype demonstrated nearly constant pressure behavior during charging and discharging of the rubber bladder after the initial radial expansion. While this is desirable, further investigation revealed limitations of the bladder in shroud strain energy accumulator design, primarily the non-uniform strain profile of the bladder wall resulting in underutilization of the power density available in a uniformly strained configuration. The distributed piston accumulator design was developed to overcome the limitations of the bladder in shroud accumulator design.

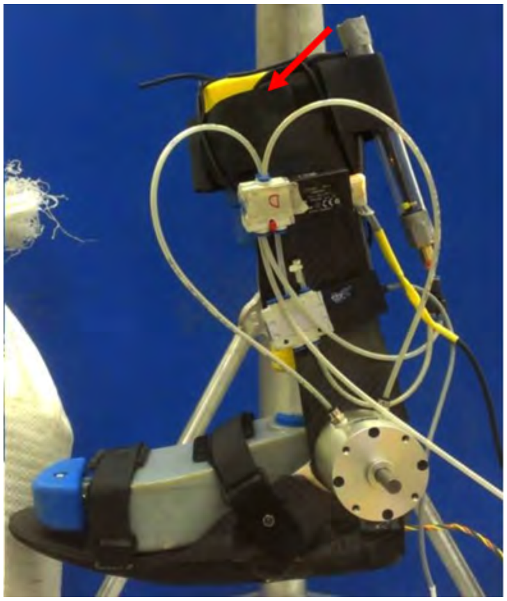

Figure 1: Pneumatic strain energy accumulator implemented on TB6

Much of the early work focused on the distributed piston accumulator because of its energy storage capability that more fully utilized the material by achieving a higher power density while exhibiting a P-V curve similar in shape to the balloon configuration. Work on the Distributed Piston Elastomeric Accumulator (DPEA) approach developed geometry-based design equations.[3] A prototype DPEA accumulator was constructed and experimentally evaluated. Experimental testing of polyurethane bladders and uniaxial tension specimens was conducted. These experimental results were used to make projections for a full scale device and were compared to an idealized gas-charged accumulator. It was shown that the DPEA accumulator has a system energy density many times larger than conventional gas charged accumulator.

Early work primarily focused on a hydraulic SEA which led to the development of a pneumatic strain energy accumulator that was applied the Ankle-Foot Orthosis (AFO) testbed (TB6). The bladder-in-shroud version of the strain energy accumulator was designed and constructed to recycle the exhaust air of the pneumatic rotary actuator of the AFO testbed. Experimentally determined energy savings were reported in excess of 25% relative to operating the AFO with no accumulator. The fully integrated pneumatic accumulator used in the AFO testbed is shown in Figure 1.

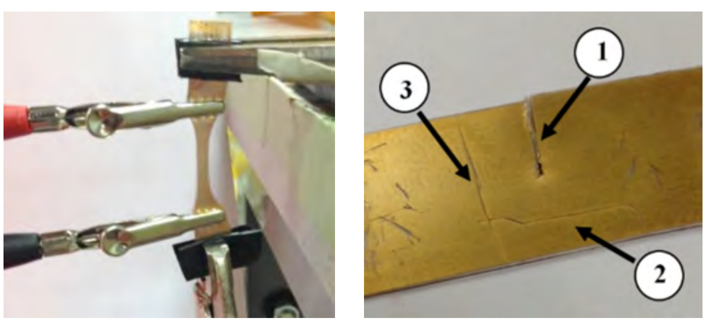

Figure 2: Metal Rubber dogbone specimen used for cyclic load (left) and damage sensing (right) testing

Challenges in obtaining adequate pressures for hydraulic SEAs resulted in the development of concepts for advanced materials with higher elastic moduli with sensing capabilities, leading to investigation of carbon nanotube (CNT) rubber. While budget constraints limited the ability to make CNT rubber a conductive elastomer was acquired and experimentally evaluated for proof of concept as shown in Figure 2. The results indicated that a conductive rubber is feasible and that load measurement and damage detection are possible but only up to strain values of approximately 75% for the material used in the test. A full report of the findings of the tests completed can be found in Cummins et al.[4]

Building off the momentum from previous years where the strain energy accumulator was integrated as a component on the AFO testbed, we continued with development of the breadboard demonstrators shown in Figure 3. These demonstrators are being brought to trade shows where they are being displayed as interactive displays to attract new member companies to the CCEFP. The demonstrators combined with the results from the AFO testing and feedback from interactions at the tradeshows have served as the motivation for the work completed in the past year, work for the remainder of the current year, and future years work pending funding approval.

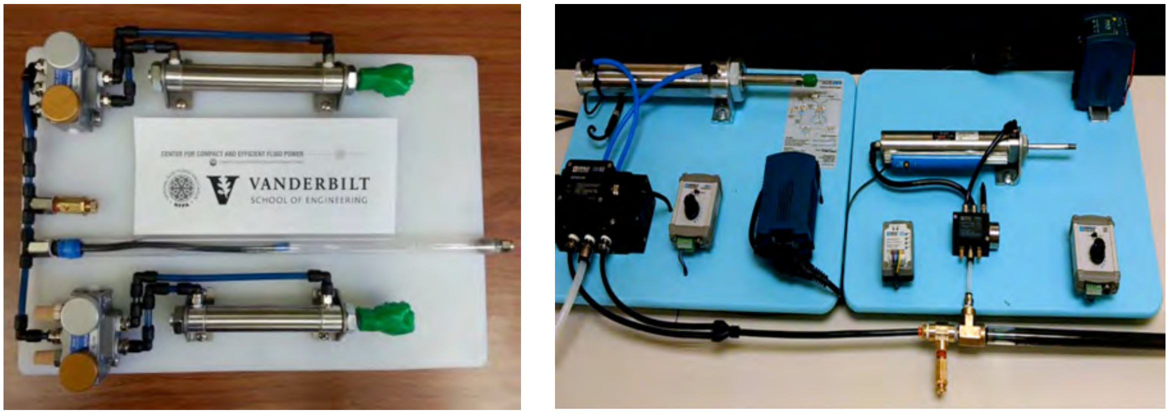

Figure 3: Pneumatic strain energy accumulator implemented on interactive manual demonstrator (left) and industry partner Enfield's automated demonstrator (right).

a) <u>Achievements in Past Year</u>

In the past year the following tasks were accomplished:

- A quick disconnect version of the pSEA was designed, built and sent to U of I where successful testing on the AFO test bed was completed
- Component efficiency testing was completed with an efficiency consistently over 93% in over 2500 cycles of testing
- System efficiency test setup completed in preparation for system efficiency increase testing to quantify savings attributed to pSEA
- Identified two new partners, Schmalz and Kolmar Laboratories who are willing to participate in case studies on manufacturing equipment for pSEA efficiency studies
- Technology selected as part of pilot commercialization course at Vanderbilt University[5] and has recently been featured in three separate fluid power news outlets including NFPA.com[6], FluidPowerWorld.com[7] and PneumaticTips.com[8]

A quick disconnect version of the pSEA was created to improve ease of use and advance the device towards full commercialization and is pictured in Figure 4. Component efficiency (Figure 5) was quantified and found to be consistently over 93% which set the stage for system efficiency projections. Two new industry partners were identified for future case studies, building on the pending results of the current system efficiency benchtop results. Finally the technology has been selected as part commercialization course and has been featured by several fluid power news outlets

Figure 4: Quick disconnect pneumatic strain energy accumulator

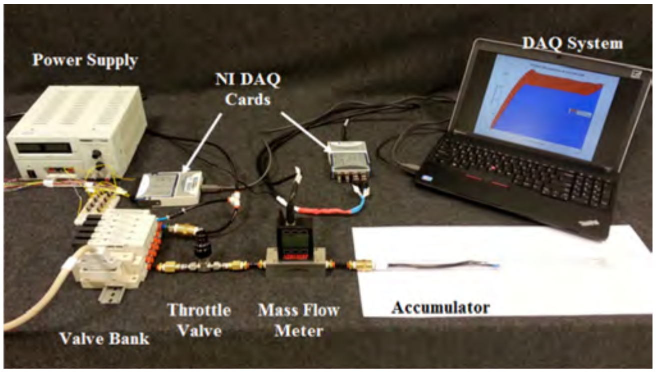

Figure 5: pSEA component efficiency test configuration

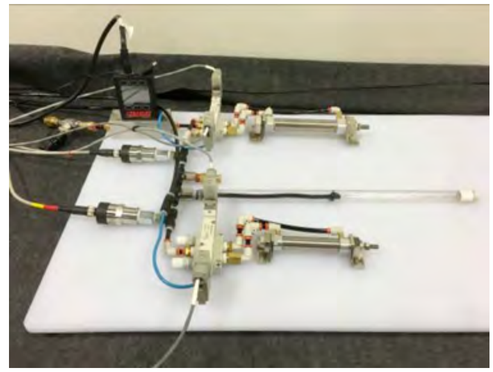

Figure 6: pSEA system efficiency test configuration

C. Plans

Plans for the next year

In the remainder of the current year when current funding expires the following task will be completed:

- System modeling with efficiency increase due to implementation of pSEA will be quantified with industry energy savings projections (Figure 6)

As this is the final year of NSF funding any tasking beyond that listed above is conditional upon future funding.

Expected milestones and deliverables

Milestones and deliverables:

- Quantification of energy savings using pSEA in systems having various configurations
- Pending approval of future funding, case study results for implementing pSEA on industry partners manufacturing equipment will be completed

D. Member company benefits

The pneumatic strain energy accumulator project will improve the advanced strain energy accumulator developed previously, increase the TRL level of the strain energy accumulators and advance the modeing of pneumatic systems and understanding system efficiency increases attributable to the pSEA. Strain energy accumulators have extraordinary energy density, simple configuration, low material costs, are easy to manufacture, less susceptible to leaks, require no pre-charging, and do not experience gas diffusion, making them preferable to traditional accumulators. In addition, member companies such as Enfield Technologies and others will benefit from deeper relationships with Vanderbilt University and extend their pool of potential candidates for future employment. New Industry relationships are forming from the current body of work and include continued talks about case studies with Kolmar Laboratories and Schmalz in implementing the pSEA on their industrial manufacturing equipment. Increasing the TRL level of the pneumatic accumulator from a three to a five has led to increased industry interest and attraction of potential new industry partners as well as additional funding for an exhaust gas recirculation project which kicked off this past August.

E. References

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Project 2F: MEMS Proportional Valve

Research Team

Project Leader: Prof. Thomas Chase, Mechanical Engineering
Graduate Students: Nebiyu Fikru, Alexander Hargus and Erik Hemstad.
Industrial Partners: Enfield Technologies, Parker Hannifin, Bimba, Festo

1. Statement of Project Goals

The goal of this project is to utilize Micro-Electro-Mechanical (MEMS) technology to create extremely efficient proportional valves for pneumatic systems. 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 just 4 cc. Supporting goals of this project include: leveraging the potential of piezoelectric materials such as lead zirconate titanate (PZT), developing MEMS-scale sealing technologies and developing flow control strategies for the MEMS scale devices.

2. Project Role in Support of Strategic Plan

This project has breakthrough potential toward the Center's transformational strategic goal of developing efficient fluid power components. Valves developed in the scope of this project are also expected to be the smallest valves in their class. While we are developing generic proportional valves, their extremely low power requirements and compactness make them especially attractive for human-assist, portable and mobile applications. The project also contributes to the Center's goals of developing leak-free systems by addressing sealing of MEMS-scale devices. The project was inspired by the Ankle-Foot Orthosis of Test Bed 6.

3. Project Description

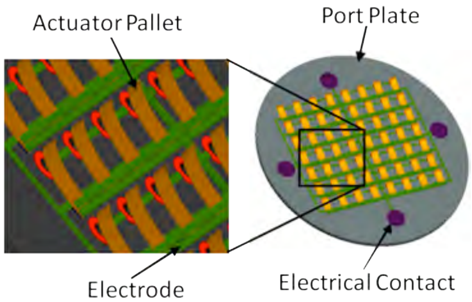
A. Description and explanation of research approach

Microvalves have been under development over the past 30 years. However, previous valves can only deliver flow rates on the scale of milliliters per minute [1]. The basic concept underlying our novel valve design is illustrated in Fig. 1(a). We have overcome the flow limitation by ganging together an array of potentially hundreds of microvalves in parallel. Reducing the size of each individual orifice reduces the force on each actuator. This makes it possible to reduce the actuator size to the MEMS scale.

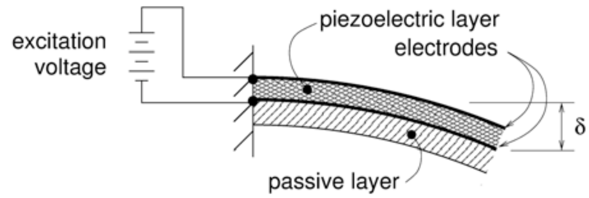
During Year 6, we demonstrated that an array of multiple orifices will yield the same flow rate as a single orifice having equivalent area. Therefore, the concept of parallelizing the flow using multiple miniature orifices and actuators is sound. Since each actuator has extremely low mass, the valves are expected to have exceptional bandwidth. Furthermore, MEMS batch fabrication methods are expected to result in low-cost valves when manufacturing is taken to the commercial scale.

Beams that bend due to piezoelectrically induced strain are called "piezobenders". Our valves will utilize "unimorph" piezobenders, illustrated in Fig. 1(b). A cantilever beam is constructed of one passive layer and one piezoelectric layer. Electrodes are included on each face of the piezoelectric layer. When a voltage is applied across the piezoelectric layer, it elongates, causing the actuator to deflect as a cantilever beam subjected to pure bending. Alternatively, both layers can be active, which is described as a "bimorph" actuator.

The actuators in Fig. 1(a) can be wired so that they all operate in parallel, or so that they open in groups. The first prototypes used the parallel strategy, while the most recent utilize groups (see Section C).



(a) Basic device architecture.



(b) Structure of a "unimorph" piezobender

Figure 1. MEMS valve concept.

Four valves have been identified in the literature which utilize a parallel actuator/orifice strategy similar to our valve. The first uses PZT actuators but has low flow rates, 7.3 mL/min, and high leakage, ~10% [2]. The others are non-piezoelectric and are also characterized by low flow rates: electrostatic actuation of diaphragms, 150 mL/min [3]; membrane valves, 250 mL/min [4]; and high-frequency flap and tether valves, 2.1 L/min [5].

B. Achievements

Achievements in previous years

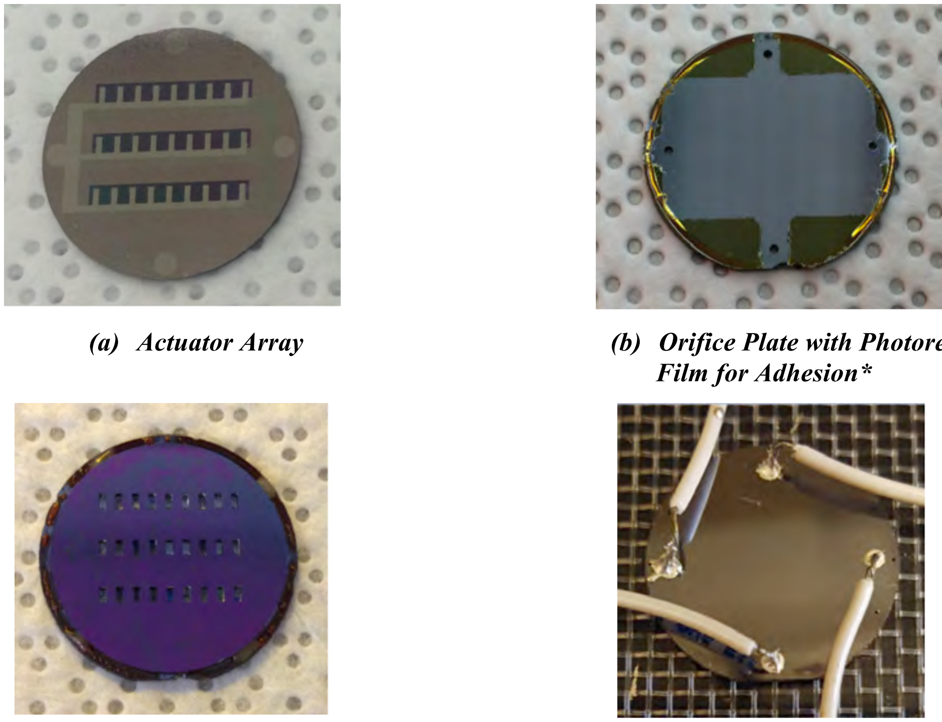
This project was initiated in Year 5-6 and extended twice. Accomplishments during the first four years include: performing a literature review on pneumatic MEMS valves [1], constructing an ISO 6358 compatible [6] test stand to determine flow rate characteristics of valves constructed in the scope of the project, demonstrating the valve concept on a "meso-scale" version of the MEMS valve, integrating a capacitive displacement sensor on the meso-scale valve, developing a compressible flow model which includes friction at low displacements, establishing a contract with Penn State University (the only domestic open research lab where it is possible to fabricate PZT on MEMS devices [7,8]) for actuator fabrication, fabricating and testing early prototype MEMS scale port plates, and fabricating the first functional unimorph actuator array. The meso scale valve, which utilizes a commercially available piezobender, demonstrated the remarkably low power consumed by piezoelectric actuators.

Five significant achievements were reported during the fifth year of the project. First, a prototype MEMS-scale bimorph actuator array was fabricated. Second, three wafers each containing 14 bimorph actuator arrays of five different styles were fabricated. Third, the first port plates which were matched to actuator arrays were fabricated; each port plate could be paired with multiple styles of actuator array. Fourth, the electronics which couple sensors to the data acquisition card of the ISO-compatible test stand were rebuilt to eliminate drift problems. Fifth, etching processes for the actuators were refined to improve releasing actuator beams from the underlying silicon wafers. In summary, at the end of the fifth year, separate actuator arrays and matching orifice arrays had been fabricated, but they had not yet been packaged into a complete MEMS valve.

Achievements in the past year

Achievements in the time period between February 1, 2015 and January 31, 2016 include:

- A preliminary process to assemble actuator arrays to port plates, creating the first complete packaged valves, was developed. MEMS assembly is traditionally performed on full wafers, which typically contain multiple devices. Special processes were necessary to assemble individual devices. A Karl Suss FC150 "flip chip bonding" machine, which is capable of aligning the actuator array to the port plate with the necessary tolerances, was located at local company (arcnano.com); the prototype assembly was done there. The actuator array was tack-bonded to the port plate using photoresist (see Fig. 2), then the resulting assembly was mechanically clamped in a clam shell package in the test stand.



(a) Actuator Array

(b) Orifice Plate with Photoresist Film for Adhesion*

(c) Assembled Prototype on Actuator Array Side

(d) Assembled Prototype on Orifice Plate Side with Lead Wires*

Figure 2: A Complete MEMS Valve: Components and Assembled Views
****Micro-orifices may not be visible in photo***

- The above process was used to bond three devices having various actuator geometries and styles. Two devices had 27 piezobenders with dimensions of 1000x250 micron and one device had 130 piezobenders with dimensions of 400x100 micron. Two devices had fixed-fixed piezobenders and one device had cantilever piezobenders. All devices utilize bimorph piezobenders.
- Each of the three devices was installed into the test stand for flow analysis. Unfortunately, all three suffered from shorting upon installation. Inspection of the failed devices revealed the likely cause to be a growth of a contaminant between electrode layers on the actuator arrays, apparently originating from the environment.
- A new set of devices were designed to address the problems encountered with the above devices. A processing step was added to deposit an insulating layer over the electrodes of the actuator array to avoid contamination. Improved assembly methods will be applied at the wafer level rather than the device level. We have returned to unimorph actuators, as they simplify processing and are likely to improve device reliability. The new devices implement digital proportional control for reasons discussed in Section C. Fabrication of new orifice arrays was commenced.
- A design disclosure and provisional patent [9] for a new type of hybrid valve which combines elements of the MEMS- and meso-scale valves were filed. While no development was done on the new concept in the scope of this project, the provisional patent protects the concept for the future.

C. Plans

Plans for next year

Figure 3 illustrates a refined plot of flow versus actuation voltage for the meso-scale valve, which eliminates the effects of drift that formerly afflicted the sensing circuits. Note that when operated at low differential pressures (say less than 4 bar), the slope of the flow versus voltage curves is reasonably gentle. This suggests that individual piezobenders may be partially opened to enable the valve to function as a proportional valve. However, at high differential pressures, the slope of the flow versus voltage curve becomes steep; e.g., the piezobender tends to "snap" open. In consequence, partially displacing the piezobenders for proportional flow control would likely be difficult for higher pressures.

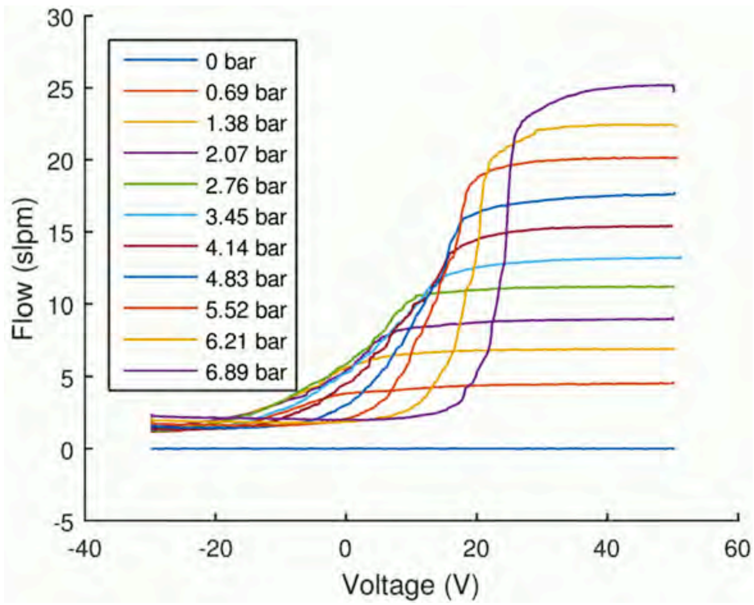


Figure 3. Meso Scale Flow vs. Actuation Voltage for Varying Pressures

As a result, we have designed our newest MEMS actuator arrays to implement digital rather than analog proportional control. Digital flow control is achieved by dividing the array of actuators into independent groups, each group containing twice as many actuators as the last. All actuators in a group are fully opened rather than partially opened. By actuating each group individually and in combinations, proportional control can be approximated digitally. The combinations can achieve 2^n different flow rates between zero flow and full flow, where n is the number of separate groups in the array.

Plans for February 2016-May 2016 are listed in chronological order below:

- Finish fabricating MEMS valves based on designs outlined and commenced in year 10, including the continued collaboration with the Nanofabrication Lab at PSU.
- Map the performance of completed MEMS valves on the UMN test stand to determine flow for varied actuator voltages and supply pressures. In addition, develop and analyze the digital control strategy.
- If time permits, use results from above tests to adjust designs accordingly. Then, fabricate another iteration of MEMS valve prototypes.

Expected milestones and deliverables

- Demonstrate first complete and functional packaged MEMS device [3/1/16]

- Demonstrate final MEMS valve embodiment developed within the scope of the original CCEFP project [5/31/16]

D. Member company benefits

CCEFP member companies will benefit from a new concept for constructing miniature flow control valves with significant market potential. In addition, developing the valves provides opportunities for member companies to become familiar with MEMS fabrication techniques, which are likely to play a growing role in valve manufacturing technology.

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Project 2F.1: Soft Pneumatic Actuator for Arm Orthosis

Research Team

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1. Statement of Project Goals

This project has two main goals: to develop novel high-force, energy storing, miniature soft pneumatic actuators, and to integrate them into soft robotic upper extremity orthoses for patients that use Lofstrand, or forearm, crutches for ambulation. We seek to develop a light-weight (< 1 kg), pliable (tunable modulus of rigidity), powered (by <100 psi) wrist orthosis and integrated compact actuators to reduce transient loads and associated wrist stresses by 50% and improve wrist posture to a more neutral position. To this end, we will develop new knowledge and tools for the design-for-manufacturability of soft pneumatic actuators known as Fiber Reinforced Elastomeric Enclosures (FREE). We will develop a robust analysis framework to generalize the construction and operating principles for FREE actuators to yield different deformation patterns. Further, we will develop new manufacturing processes to fabricate miniature pneumatic actuators.

2. Project Role in Support of Strategic Plan

The development of miniature soft pneumatic actuators and soft pneumatic arm orthosis directly address one of four major goals of the Center, namely the development of “new miniature fluid power components and systems … that are one to two orders of magnitude smaller than anything currently available”. This project will also address at least four of nine technical barriers to fluid power: compact energy storage (5), compact integration (6), safe and easy-to-use (7), and quiet (9). Further, the wrist orthosis would be an added test bed platform that complements the work being accomplished on the pneumatic ankle-foot orthosis of Test Bed 6 (Human Assist Devices) at the University of Illinois. The development of compact, light-weight, high-force, energy storing, soft fluid powered actuators has the potential to revolutionize the creation of portable medical assistive devices such as powered prosthetics and orthotics.

3. Project Description

A. Description and explanation of research approach

In this project, we aim to design, manufacture and test soft pneumatic actuation concepts for wearable flexible orthoses. The testbed for this application will focus on developing a lightweight soft wrist orthosis for patients that use forearm crutches for ambulation. This project will conduct the research necessary to develop working prototypes of soft pneumatic actuators and wrist orthosis.

B. **Achievements** (This project started in 6/1/14.)

This project has resulted in one US provisional patent application [1], one invention disclosure [[2]], three conference presentations [3,4,5], and one MS thesis [6].

Figure 1: Prototype of the pneumatic sleeve orthosis

<u>FREE Actuator</u>

The pneumatic sleeve orthosis prevents wrist hyperextension and reduces/redirects the loads acting on the wrist and palm by generating a constricting force around the forearm. A custom made soft pneumatic actuator (FREE) is used in the orthosis to generate this constricting force (Fig 1). To design an actuator that generates the desired force, we need an analysis model that predicts pressure dependent deformation of the FREEs under external loading conditions. We have developed a model [7] that solves a calculus of variations problem to analyze the deformation behavior of FREEs. This problem formulation is based on the principle that any inflatable device such as a balloon or a bellow assumes a deformed shape that tends to maximize its enclosed volume subject to a physical constraint. A FREE is made of a cylindrical hyperelastic membrane with two families of inextensible fibers wound helically on the surface. Maximizing the enclosed volume of the FREE subject to the constraint enforced due to the inextensibility of fibers gives the locked shape of the FREE beyond which no further deformation is possible (Fig. 2 right).

We are interested in all the intermediate deformation shapes that a FREE attains when actuated at different pressures before it reaches the locked shape. By applying an additional kinetostatics constraint on the strain energy of the elastomer membrane to the original problem, we can obtain all the intermediate deformation shapes (Fig. 2). The hyper-elastic behavior is governed by the Mooney-Rivlin model. The Lagrange multiplier of the Euler-Lagrange equation is related to the actuation pressure by a simple relationship. This gives a measure of actuation pressure for all the intermediate deformed configurations. We have experimentally verified the deformed shapes and corresponding actuation pressures (Fig. 3).

The constrained maximization can be extended to accommodate for applied axial forces and moments at the end of the actuator. This requires additional constraints that fix values of the stroke length and angular rotation, respectively. Similar to the strain energy constraint, the Lagrange multiplier of stroke length and angular rotation gives a measure of axial force and moment, respectively.

<u>Modeling sleeve constriction force</u>: The sleeve design (Fig. 1) is a coiled contracting FREE actuator wrapped around two rigid slpints attached to the crutch cuff. When pressurized, the FREE actuator's contraction in length and minor radial expansion leads to constriction force on the forearm. The sleeve is pressurized prior to beginning a walk and depressurized when the crutches are removed, such as when seated for extended periods.

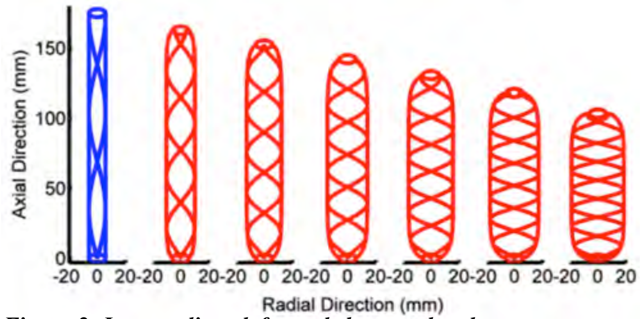

Figure 2: Intermediate deformed shapes taken by an increasingly pressurized and contracting FREE before reaching the locked configuration (right).

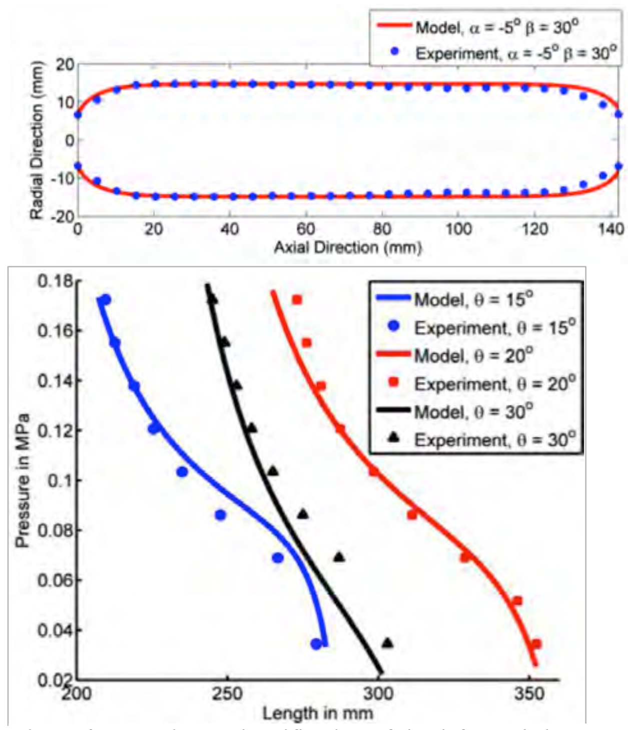

Figure 3: Experimental verification of the deformed shape and relation to the applied pressure.

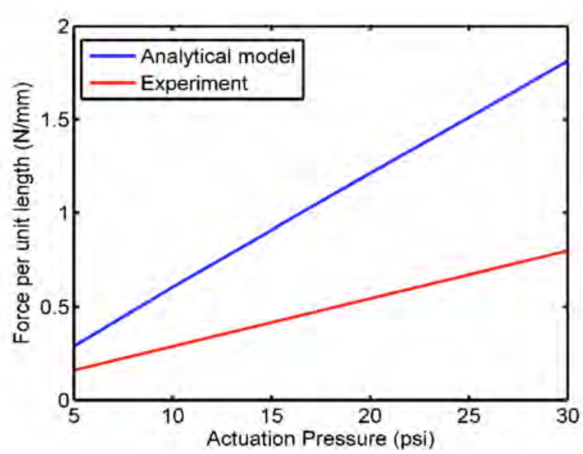

Figure 4: Comparison between experimental constriction force and analytical results using the string model.

One of the major tasks involved is modeling the constriction force exerted by the helical FREE on the splint attached to cuff and the forearm. The cylindrical shell of the sleeve had an outer diameter of 87 mm and height of 99 mm. The FREE actuator was found to have negligible bending stiffness, and hence it was modeled as a string. Since both ends of the actuator are fixed on the sleeve, pitch and number of coils remained constant, thereby allowing a change only in the coil diameter. Upon pressurization, the actuator reduces in length resulting in a change in the coil diameter, which is resisted by the cylindrical shell. This leads to a constriction force, which can be evaluated by knowing the axial tensile force in the actuator. This is known from the constrained maximization formulation. The string model relates this axial tension T to the constriction force f through the formula $f = T \sin \alpha / r$, where α is the helix angle of the coil and r is the outer radius of the shell. The constriction force per unit length of the FREE actuator is plotted in Fig. 4. For the actuator length of 500 mm and pressure of 10 psi (0.7 bar), it is seen that a constriction force of about 250 N is obtained. This contributes to load reduction in the wrist (~ 20 kg).

Figure 5: Experimental setup using FREE actuator, 3D printed shells and air bladder and cylinder

To validate this simplified analytical model, an experiment was conducted to obtain the relationship between the actuation pressure and the measured normal pressure inside the shell (Fig. 5). 3D-printed cylindrical shells were placed around an air bladder. After inflating the FREE actuator to a given actuation pressure, the air bladder was pressurized until the shells separated (Fig. 5b). The release valve for the bladder was gradually opened until the shells just contacted (Fig. 5c). This bladder pressure was considered to be the normal pressure generated by the helical FREE. An analytical expression converted normal pressure to normal reaction force per unit length. Approximately linear relationships between reaction force and actuation pressure were observed for both simulation and experimental results (Fig. 4). Revised experimental protocol and modeling assumptions are being considered to address differences between simulation and experimental results. Furthermore, finite element simulations are being considered to capture realistic bending stiffness and elastic properties. Once refined and validated for its accuracy, this modeling method will be extended to explain the behavior of other FREE architectures.

Pneumatic Sleeve Orthosis

The sleeve is pressurized prior to beginning a walk and depressurized when the crutches are removed, such as when seated for extended periods. We exploit the energetics of walking to harvest pneumatic energy via a piston pump at the crutch tip. This pneumatic energy is stored in an elastomeric accumulator and used in the subsequent pressurization of the sleeve; thus, this powered orthotic device requires no external power supply.

To produce a self-contained pressurization system, we will harvest pneumatic energy from the crutch during walking by using a custom piston pump (Fig. 6). A stroke length of 12.7 mm was selected for user comfort. When loading the crutch, the crutch shaft and piston will compress air in the lower air chamber which will be forced through a one-way valve in the piston head and stored in an accumulator. A pressure relief valve prevents overfilling of the accumulator. When the crutch tip leaves the ground, conical springs in the lower air chamber will extend the crutch tip back to its original position, in preparation for a second pump. The springs and compressible gas also provide an added benefit of shock absorption to the crutch user. (Compliant passive tips are sold for this purpose.) An analytical model, based on the ideal gas law and assuming isothermal condition, has been developed to determine optimal pump and accumulator design sizing to minimize number of gait cycles to charge the accumulator and fill the FREE actuator.

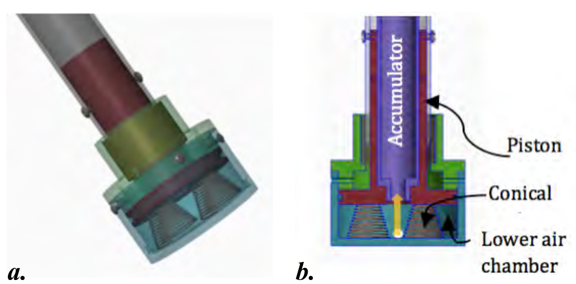

Fig 6. (a) Overview of piston pump in tip of crutch. (b) Cross-section view and air flow (yellow arrow) during pumping.

The analytical pump accumulator model predicts 4~5 gait cycles to fully charge a FREE actuator with length of 650 mm from 0 psig to 30 psig, without considering leakage and other sources of energy loss. The maximum pressure in the accumulator was determined to be 79 psig, which is endurable for the pneumatic circuit components.

Passive wrist orthosis

During our initial work on the pneumatic sleeve concept, we thought that separate design components were necessary to reduce loads to the hand and to prevent hyperextension of the wrist. Once the pneumatic sleeve prototype (Fig. 1) was assembled, it was determined that the one design could achieve both goals. However, before completing assembly of the prototype, a passive wrist orthosis was developed to reduce wrist extension (Fig 7). The design can be easily attached to any Lofstrand crutch or modified for underarm crutch, and has a strap to allow for gentle compliance to accommodate some wrist movement during crutch gait. The design allows for the hand and forearm to have free range of motion when not holding the grip. Ten healthy adults were tested. Preliminary analysis from two subjects found that the orthosis reduced total force, maximum force, contact area, mean pressure of the hand, and wrist extension. Peak pressure was observed to increase with orthosis use. Peak pressure moved toward the adductor pollicis (palm area near the thumb's distal joint) and away from the carpal tunnel region.

Figure 7: Passive wrist support

Micro-pneumatic cilia design: A new class of soft micro-pneumatic actuators is being designed and fabricated. The goal of this task is to study how micro-scale surface features can be actuated with moderate air pressures (<20 kPa), and create micro motions inspired by eukaryotic cell motile cilia; and we are exploring its utility in applications ranging from cell culture scaffolds, to motile cilia for controlling the flow patterns and boundary layer on wind turbines.

The current design is shown in Fig. 8 and comprises straight pillars (cilia) of 1-3 μm diameter and 100 μm height fixed on the surface of inflatable micro-channels of 100 μm. By actuating the pressure, the inclination angle of the cilia can be changed as shown in the calculations of Fig. 8. The membranes have a rectangular cross section, and the angles and patterns of the inclination will be determined by the organization of the cilia on the membrane.

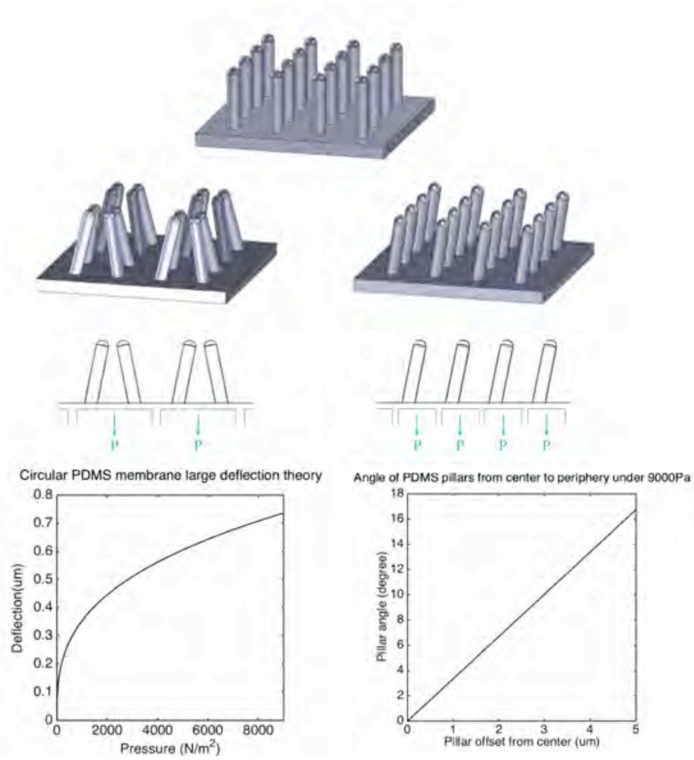

Figure 8: Design of micro-pneumatic cilia consisting of circular high aspect ratio pillars on rectangular inflatable channels. Depending on the location of the cilia on the channel, they can change their inclination angle when the top-membrane of the channel is inflated. Our analytical model demonstrates a deflection of angle of 17° at 8 kPa.

Micro-fabrication progress: We used photolithography and Si deep reactive ion etching (DRIE) to fabricate silicon masters having the inflatable micro-channels geometry. A novel fabrication method was developed where two silicon molds were fabricated and aligned sandwiching a thin layer of poly dimethyl siloxane (PDMS) diluted with 60% hexane. We used capillary forces to align the channels with an angle in-plane rotation misalignment of less than 0.1° followed by baking on a hot plate at 60 °C for 4 hours. The results are hollow square shaped profile channels as shown in Fig. 9. As shown in Fig. 9, the membrane thickness is close to 15 μm.

We are currently working on integrating the micropillars (the cilia) on these channels to test their inclination actuation as a function of pressure.

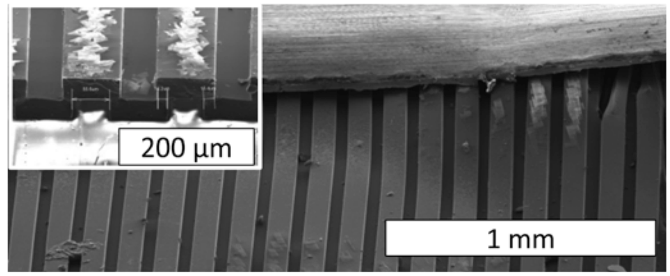

Figure 9: Inflatable micro-channels made from PDMS elastomers by a new sandwich molding technique.

Plans for the next year.

<u>FREE actuators</u>

- Verify simulation and experimental results of constriction force
- Apply model to other FREE architectures

<u>Micro-pneumatic cilia design</u>

- Finish the fabrication of the cilia and the molds
- Test the pneumatic actuation and prepare manuscript

<u>Pneumatic sleeve orthosis</u>

- Finalize fabrication of piston pump and elastomeric accumulator
- Finalize and assemble pneumatic circuit connecting accumulator and actuator
- Test on bench and healthy subjects
- Understand impact of constriction force on skin strength

C. Member company benefits

CCEFP member companies can benefit from this project through the development of a robust framework for realizing high-force, energy storing, miniature soft pneumatic actuators that can produce a variety of motion patterns. In addition to possible applications in orthotics and prosthetics, these FREE actuators could be applicable to a number of other applications that could use soft robots such as healthcare as assistive feeders, manufacturing automation, agricultural crop harvesting, or even space exploration.

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

Research Team

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Industrial Partners:	Enfield Technologies, KYB Corporation

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

We aim to break the Major Technical Barriers relating to 1) Compact integrated systems (by designing systems where actuators, mechanisms, and sensors are not separate entities), and 2) making fluid-power systems safe and easy to use (new force sensors will ensure human safety when interacting with machines in an MRI). Furthermore, we will break a Transformational Barrier by applying fluid power in medicine.

3. Project Description

A. Description and explanation of research approach

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

Intraoperative image guidance, and particularly use of MRI images which have far better soft tissue imaging capability than other modalities, has the potential to fundamentally change the fact that the success of any modern surgery relies entirely on the experience, memory, spatial reasoning, judgment, and hand-eye coordination of the surgeon. To break this barrier and move surgical accuracy beyond the limits of human skill and perception, what is needed is real-time image feedback during surgery, combined with precise machines able to accomplish the surgeon's objectives accurately. Such feedback can enable the surgeon to visualize the position of instruments in relation to sensitive subsurface blood vessels, nerves, tumors, etc. and enable the robot to directly position a tool at a desired target specified in a medical image. Both have the potential to make surgery safer and to improve clinical outcomes by enhancing the accuracy of treatment delivery. MRI is a key enabler of this due to its ability to clearly show soft-tissue boundaries and structures that 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. To achieve compact and MRI-compatible actuation, we have developed a fail-safe pneumatic stepper using new geometries of inflatable bellows that are enabled by a design for additive manufacturing approach.

MRI is one of the most useful methods available to study neuromotor functions, evaluate rehabilitation therapies and perform image-guided interventions and surgeries. Functional MRI (fMRI) is a new technique that can observe brain activity by measuring blood flow in a certain area. Research on brain-hand coordination in fMRI is an emerging area. Actuation and sensing technologies that can be used in MRI/fMRI would provide a wide variety of applications and research opportunities such as studies on neuroplasticity after stroke, somatosensory and motor functions, and sympathetic nerve activity during motor task learning. The study requires non-magnetic, compact, low-noise, highly accurate haptic interfaces with pneumatic actuators. The limitation in the selection of materials requires methodologies to design, develop, and analyze mechanical systems that can be used in fMRI. To achieve accurate sensing in fMRI, we have developed a new design method based on 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 in Year 10

MRI-Compatible Actuators and Surgical Robots

The focusing application for our work in surgical robotics have been the development of a novel, minimally invasive, MRI-guided, needle-based surgical treatment for epilepsy, illustrated in Fig 1. Our new intervention is designed to access the deep brain through a straight needle inserted through the patient's cheek and into the foramen ovale, a natural opening in the skull base [3]. From the straight docking needle, a robotically actuated, helically curved, superelastic, steerable needle can guide an ablation probe to the hippocampus—the structure near the center of the brain from which epileptic seizures originate. The ablation probe delivers thermal energy to the hippocampus, destroying the tissue, and achieving the same objective as surgical resection. Work in Year 10 has focused on system validation and improved design and control of the functional hardware prototypes developed in Year 9, including the precision pneumatic robot and steerable needle, shown in Fig 2.

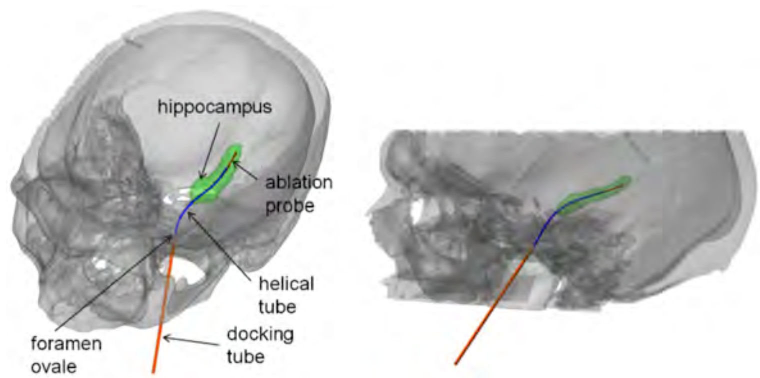


Figure 1: Accessing the hippocampus via the foramen ovale with a steerable needle

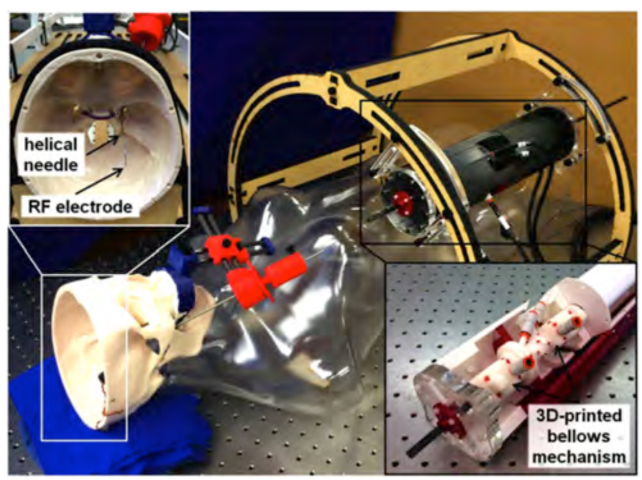
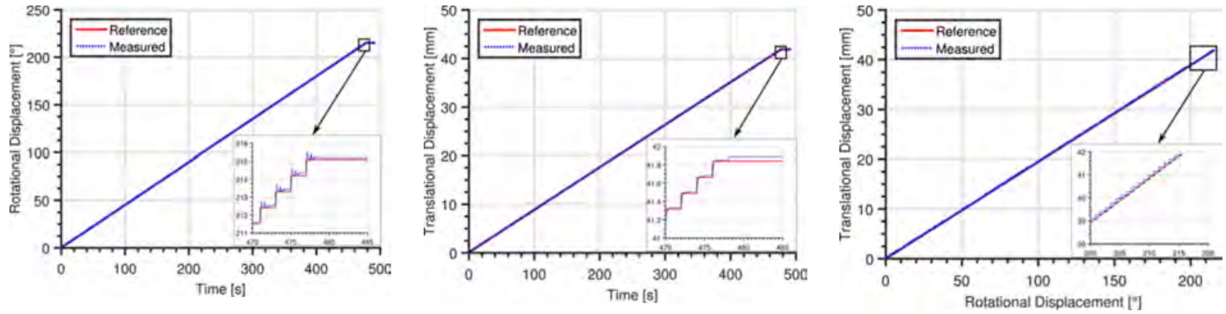


Figure 2: 3D-printed robot and outer cannula fixture are compactly positioned with a patient manikin. This layout fits inside an MRI magnet opening of 60 cm.

Avoiding shearing tissue when driving curved needles in soft tissue requires precise coordination of the needle rotation and insertion in order to achieve "follow-the-leader" (FTL) deployment in which the needle backbone follows the same trajectory as the needle tip. We have developed a technique to achieve the corkscrew-like deployment of our helical needles using our intrinsically safe, pneumatic, stepper actuators [4]. Unlike previous control approaches, this new technique allows us to simultaneously track desired translational and rotational displacements of the stepper actuator, as illustrated in Fig. 3. Moreover, the new controls architecture prevents the accumulation of errors from step-to-step, even as the desired displacements increase. Ultimately the improved control architecture has achieve actuator accuracy of 0.046mm (translation) and 0.072° (rotation).



(a) *(b)* *(c)*

Figure 3: Follow-the-leader trajectory tracking using a pneumatic stepper actuator. (a) translation displacement (b) rotational displacement (c) coordination of translation and rotation

Additional hardware characterization in an MRI scanner (Fig. 4) has validated our MRI-compatible hardware design. Even with the robot in full motion, no discernable reduction in the signal-to-noise ratio of the MR images could be observed, indicating that the robot system causes no imaging interference. Furthermore, the strong magnetic field in the scanner did not adversely affect the performance of the robot. Fig. 5 shows the accuracy of needle placement in a gelatin phantom in the MRI scanner. During multiple trials, tip placement accuracy ranged from 1 mm to 3 mm, sufficiently accurate for the intended clinical application.

Figure 4: Experimental validation of MRI-compatibility

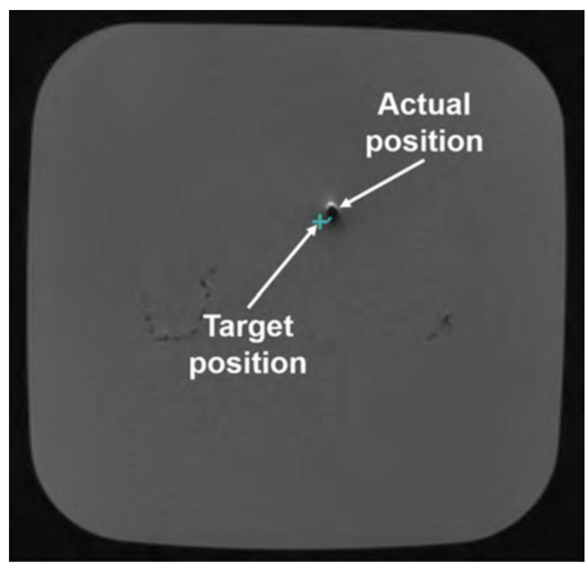


Figure 5: Needle placement accuracy in an MRI scanner

<u>Pressure Observer Based Impedance Control of Tele-Operated Pneumatic Actuators</u>

Prior studies at Georgia Tech have provided crucial tools and methods for observing the pressure states in a tele-operated pneumatic actuator. A non-linear, asymptotically stable pressure observer that utilizes interaction force measurements for error correction have been proposed and tested in Y9. An MRI-compatible, optical force sensor had been developed in Y6-Y7 to realize the force exerted at the tip of the actuator piston without any dynamic or transportation delays [1,2].

In Y10, the developed pressure observation algorithm was used to compensate for the lack of direct pressure reading. The proof of stability in the observer dynamics has been provided by the authors in an earlier study [6]. The observed pressure states are provided to a sliding-mode based non-linear controller. The suitability of this control scheme is tested on a 1-DOF pneumatic system with sufficiently long transmission lines for MRI related applications.

Figure 6 illustrates the benefit of the described observer both in pressure estimation and the impedance control performance with a reference force of 0.5 Hz. The improvement in control accuracy is more significant at higher frequencies -%25 on the 1.5 Hz force tracking experiment- where the demand for the

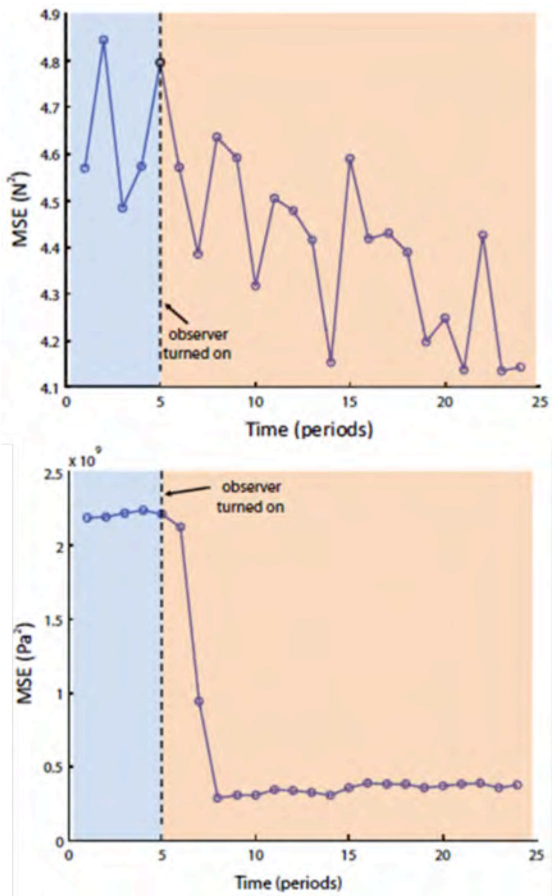


Figure 6. Mean squared error (MSE) for 0.5 Hz sinusoidal reference. Error in the output force (upper) and the error in pressure estimation (below) [6]

valve flow is greater. Pressure states are involved in the equivalent valve input; hence, they are more effective when the magnitude of the ideal flow rate is higher. On the other hand, the improvement in the pressure estimation may not follow the same trend. The described observer substantially reduced the pressure estimation errors in this study. Yet, the magnitude of the improvement depends on the quality of the valve calibration within the given interval of valve inputs for a specific operation. The advantage of utilizing the observer can also be viewed by the rate of error convergences, shown in Fig. 6. A rapid improvement in the pressure estimation initiates a downward slope in the force error when the observation is turned on. The motivation for the developed algorithm comes from the potential of pneumatically driven systems for robotic rehabilitation in MRI. The described algorithm will be applied on an MRI-compatible haptic interface with long transmission lines in the future.

<u>Timing Analysis of Robotic Neuromodulatory Rehabilitation System for Paired Associative Stimulation</u>

A Robotic Neuro-modulatory Rehabilitation System (RNRS) in Fig. 7 has been developed and discussed by the authors in the previous studies in order to understand the timing and characteristics of PAS with mechanical stimulation [7]. RNRS targets the flexor carpi radialis (FCR) muscle and provides mechanical stimulation in the form of tendon tapping, mimicking what therapists do in real RFE.

In Y10, further studies have been made on the timing accuracy of the mechanical stimulation of RNRS [8]. RNRS shows a steady delay for tapping action with high repeatability. The tendon hitting time of RNRS was repeatable under 5ms STD for all of the experiments. This 5ms is accurate enough to give repeatability in tendon tapping with regard to the 50ms the overlapping time window for mechanical stimulation. As mentioned earlier, the most important thing in PAS is precise timing between TMS and peripheral stimulation, not the speed of stimulation which is related to delay. Therefore, if this system accounts for delay, RNRS can perform tendon tapping at the right timing. Also, mechanical stimulation shows wide range of overlapping time window 50ms which is longer compared to electrical stimulation (20ms). It is expected that the timing requirements for PAS procedure can be relaxed by using mechanical stimulation. In addition to that, fMRI compatible RNRS will allow further research on how mechanical stimulation itself affects on brain by observing brain activity through fMRI, where use of an electrical stimulation device and TMS are not allowed.

<u>Vane Actuator for Neuromuscular Facilitation in Hemiparetic Limbs</u>

As an extension to the RNRS in Fig. 7, an MRI compatible mechanism for wrist rotation was introduced and dynamically analyzed in Y10. The rotation of the wrist joint follows the tendon tapping step in the targeted rehabilitation procedure: PAS; hence, an active device that can accomplish wrist supination/pronation of a desired range within a suitable time frame is necessary to perform robotic PAS properly. The results of the analysis revealed important details on the feasibility of wrist rotation for the treatment, using MRI compatible vane actuators. The analysis was made for a specific range of rotor height and depth, constrained by the spatial requirements of MR scanner. In that range, a bigger actuator

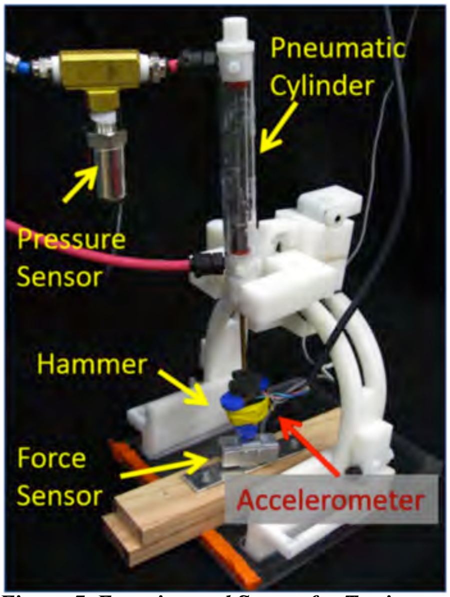


Figure 7. Experimental Setups for Testing of Timing Delays [8]

does not always yield a better dynamic performance. Moreover, for a fixed value of actuator depth, there is no monotone relation between the speed of the actuation and rotor height as well. The actuator can be designed to serve better without occupying all the available radial space in the bore. This can be explained by considering the effects of rotor dimensions on the chamber volumes; hence, the inertia in the pressure dynamics. A higher volume can kill the advantages of having a greater maximum torque, by slowing down the pressure build-up in the chambers [9].

A pneumatically driven, tele-operated vane actuator could realize the targeted rehabilitation procedure. The inertia in the pressure dynamics of the system plays a dominant role against the rotational dynamics of the actuator shaft, making a more compact actuator chamber more effective. The rotor size of the actuator can be adjusted for a very comfortable fit into MR-scanners. The outcomes of this study, made in Y10, will be experimentally validated.

C. Member Company Benefits

The success of this project will lead to strong commercialization potential that would expand the role of fluid power in the medical industry, which accounted for 17.5% of gross domestic product in the United States in 2014 [5]. This fact was underscored by the CCEFP's Scientific Advisory Board, whose 2015 report encouraged the Center to increase its research efforts in biomedical applications for fluid power—in particular, “small-size MRI compatible componentry”—because “continued/expanded research in this area could be beneficial financially” for the fluid power industry.

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

Research Team

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

1. Statement of Project Goals

This project will consolidate results on multi degree of freedom interfaces over the range of speeds, dimensions, numbers of interfaces, extent of automation and interface modalities found with hydraulic actuation. Experimentation via excavator simulation and simple displays has been the principle source of data up to this point. Studies performed on the Georgia Tech excavator simulator have illustrated a potential double-digit percentage improvement in efficiency and economy when using advanced hand controllers, however these studies have been inconsistent. Another goal for this project is to determine the root of these inconsistencies, providing a better understanding of how user interface drives performance. The intuitiveness of hand controllers, position versus velocity control, and the effectiveness of selected data presentation modes will be evaluated.

2. Project Role in Support of Strategic Plan

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

3. Project/Test Bed Description

A. Description and explanation of research approach

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

Traditional excavator control is done along the kinematic joints. Using dual two degree of freedom joysticks, excavator operators control the pump flow to each joint piston. Flow induces a torque on the joint, which induces motion. The boom, arm, and bucket joints control the end effector height, depth, and rotation. The swing joint controls the horizontal positioning of the bucket relative to the operator. The traditional two-joystick interface was adopted by industry because it was easy to implement from a hardware perspective. There is a steep learning curve associated with this interface due to the mental load it places on the operator. Human operators naturally break down tasks into Cartesian coordinate commands: emptying a bucket load requires moving the bucket up, then forward. The concept of Cartesian direction is lost on traditional excavator control. Operators are forced to do inverse kinematics, a process of translating Cartesian commands to joint angles and angular velocities, to determine the necessary joystick positions required to induce the desired end effector movement. Skilled operators can do the inverse kinematics in near real time, however it requires many hours of training to reach this skill level. Difficulty of performing inverse kinematics suggests that the operator and excavator system would perform better if the command channel from the operator to the excavator were in Cartesian space, because it would be more intuitive to the operator. This research has explored several non-traditional control interfaces that alleviate the need for the operator to mentally perform inverse kinematics.

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

Data acquisition for this research has been performed on the Georgia Tech excavator simulator. Previous teleoperation of TB1 in Purdue suggests that the simulator is a realistic substitute to a live excavator. However, verification of the simulator results on an outdoor excavator is envisioned. The Georgia Tech simulator is housed in a Bobcat 435 compact excavator. The excavator cab rotates with the simulation environment, but the excavator arm has been removed and replaced by a large screen TV. The arm of the vehicle, the soil and the state of the excavator are displayed to the operator on the TV, and an audio signal mimics engine noise.

B. Achievements

Achievements in previous years

This research has explored several ways of eliminating the need for the operator to perform inverse kinematics. One such implementation involved a position controller that was kinematically identical to the excavator arm. With this controller, the excavator would mimic any manipulation of the controller joints. By manipulating the end effector of the controller in Cartesian space, the operator could easily move the bucket up, down, forward, or backward with little cognitive load. This control method performed the inverse kinematics mechanically, as the desired excavator angles are identical to the controller joint angles due to the kinematic similarity. Other controllers that have been tested eliminated the need for the operator to perform inverse kinematics through computation. Unlike humans, computers can perform the inverse kinematics required to move an end effector to a desired location or in a desired direction in real time, without error. Using a Phantom Omni 6 degree of freedom controller, several variations of coordinated control (commands sent in Cartesian space) were implemented. This research has shown that both the kinematically similar position controller and the coordinated control implemented with the Omni Phantom perform better than the traditional dual joystick flow control, increasing operator effectiveness by up to 81% and fuel efficiency by 18% [2, 3]. While the alternative control strategies reduced operator errors and decreased task completion time, both the phantom and kinematically identical controller increased operator fatigue making them unfit for prolonged use. For the kinematically identical controller, the ergonomics were improved by rotating the mini excavator arm on its side, allowing the operator to rest their weight on an armrest [7]. This horizontal configuration eliminated the performance drop off seen by previous (fatigue inducing) controllers when used on sessions lasting 10 minutes or more in length.

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

Last year a correction algorithm was developed to compensate for the distortion caused by the simulator operator's proximity to the TV. This algorithm was crucial to creating an immersive 3D environment, and was used with the recently installed 3D TV. This algorithm returns a projection matrix that the graphics pipeline uses to render simulation objects onscreen in the position and orientation the operator would naturally observe them in. The operator's head position is an input parameter to this algorithm, and was originally set to be a constant position somewhere above the excavator chair. This methodology provides reasonable looking geometry only when the users head is near the set point. Very tall or short operators, or operators that move their head during operation will experience a discontinuity where the TV image should change, but does not. To alleviate this problem and to make the simulator more immersive, head-tracking hardware was added to the excavator and integrated with the simulation software. With the current implementation, operators of any size can get the proper visual environment, and operators can move their head around the cab to get a better view of obstructed objects.

There was a simplification in the simulation that was tainting results. The simplification was the lack of physical constraints between the excavator arm and the environment: users could (and did) swing the arm through objects that would be hard stops in real life. The solution implements a hard stop: if the operator swings the excavator into a bin or other obstacle, the excavator ceases movement, and the operator has to *back out* and go around the obstacle. With the system, any advantages with the 3D display should show in the task time and fuel efficiency figures. This system was implemented using PhysX, a robust physics simulator and collision detection library maintained by NVidia and primarily used for video games. Work was done connecting the excavator's hydraulic model (developed in Simulink) to the PhysX engine.

User Study on Efficacy of 3D Display, Coordinated Rate Control

A 50-person study was completed in December 2014. This study had two goals: quantify difference between 2D and 3D display modes on the excavator simulator, and test the performance of a coordinated rate control joystick user interface. Previous studies performed on the excavator simulator were done on a 2D TV screen. There were questions as to whether or not the lack of depth tainted those results. By comparing operator performance in 2D and 3D environments, we are able to quantify operational differences for the 3D setup. During the study, each participant operated the excavator simulator during three half hour sessions. The 50 participants were randomly split into two groups, one group operated the simulator in 2D mode during session 1 and 3D mode during session 2, and the other group did the opposite. Session 3 was used to introduce a new controller to the participants, and was ignored for the 2D-3D comparison. Each session comprised 4 five-minute trials during which the participants were instructed to perform a trenching task. The first trial was a warm up, and all data from warm ups was ignored. Participants were instructed to remove as much soil as possible in the allotted time while keeping the excavator under control. They were scored on how much soil was removed and how much fuel was consumed at the end of each trial.

The experiment illustrated that there was no conclusive difference between operator performance on 2D and 3D screens. The soil removed per unit time and soil removed per unit fuel numbers for 2D and 3D were nearly identical. This implies that 3D projection had little effect on operator performance, and our previous data that was acquired on 2D screens remains valid.

Performed simultaneously with the 2D-3D study was a study on excavator user interface. Each group from the 2D-3D split was split again into two more equally sized groups. The first of which operated the simulator with a traditional control interface for sessions 1 and 2, and the second did the same with a coordinated rate controller. For session 3, everyone switched controllers: people using the coordinated rate controller went to traditional, and vice versa. The coordinated rate controller was implemented with the standard excavator joystick hardware. The four degrees of freedom corresponded to the Cartesian position of the end effector and the end effector rotation (bucket dump). The layout was identical to the high performing, rotated, kinematically similar arm that was tested by Winck previously on this project using position rather than rate control.

Figure 1 compares the two control styles. The left to right increase trend illustrates learning; participants perform better with practice. The drop between trials 6 and 7 corresponds to when the study participants switched control styles. The different drop off magnitudes indicates that it is easier to switch from the traditional control style to the coordinated rate control style than it is to go the other way. Standard deviations for this dataset are large, which again indicates the widely varying skill level of study participants. When asked about interface preference, 26 subjects preferred coordinated control, 6 preferred traditional control, and 18 made no distinction. Unlike coordinated control of position that has been tested previously, coordinated rate control on the joystick interface underperformed the traditional control style although the difference does not meet tests of statistical significance. At this point it is unclear why, and one of the project goals going forward is to determine a cause for this discrepancy. The difference between the maximum speeds permitted in the two approaches and the correspondence between joystick position and bucket direction will be considered in seeking an explanation.

Achievements in the past year

Further data analysis was completed for the previous experiment. Figure 2 shows the amount of time users were idle during the experiment. This time was defined as any time when the user was not issuing any commands. In other words, the time users spent thinking about the next command. Using coordinated rate control the users consistently spent less idle time. This suggests that the coordinated rate control user interface is a more intuitive interface. While this did not correlate to better user performance, it demonstrates the potential benefits of coordinated control with an optimal mapping configuration.

The excavator was moved to a new location on the Georgia Tech campus during the summer of 2015. This transition required the reinstallation of the hydraulic connections, causing a slight delay in the progression of the project. After the excavator simulator was operational, an IRB proposal for another human subject experiment was submitted and approved, and a pilot experiment implementing new joystick mappings was conducted.

Simulation Improvement: Bucket Glitch

During a pilot study to test a new coordinated rate control user interface against traditional control, it became apparent that there was a simulation glitch. The glitch occurred when users commanded the bucket to achieve the maximum attainable angle, and then forced the bucket into the soil. After the maneuver, the bucket would become stuck in this configuration. The glitch could be resolved by

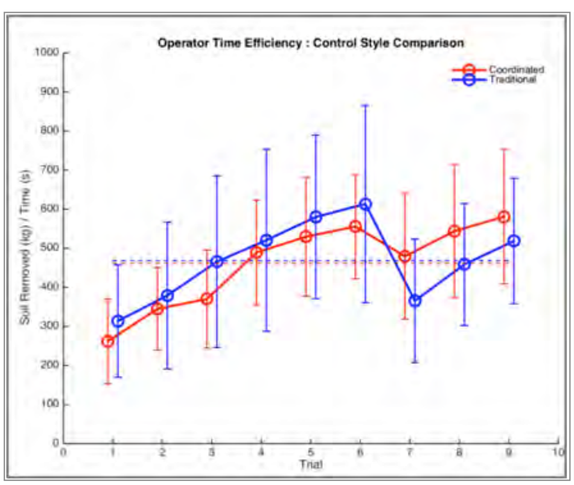

Figure 1: Control Style Comparison

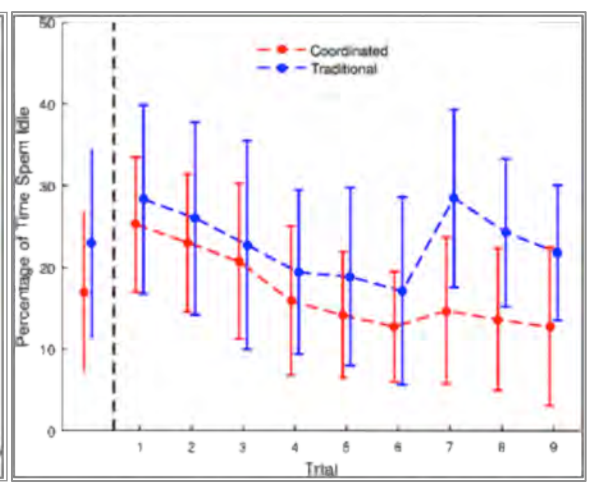

Figure 2: Control Style Idle Time Comparison

toggling the joystick controlling the bucket, but it would often waste the user's time during a trial. It was found that by slightly varying the range of motion of the bucket, the glitch was resolved. The slight change in the range of motion does not affect performance during the trenching operation.

Simulation: Coordinated Rate Control Constraints

During the same pilot study, participants noted an unexpected behavior of the end effector when using coordinated rate control. In specific configurations, when the user would input a forward command the end effector would move forward, but would eventually encounter a kinematic constraint and begin to descend. Figure 3 shows this kinematic constraint. The dotted radius shows the end effector's range of motion with the arm at the maximum angle. In the configuration depicted by the red and blue links, the end effector would follow this radius when being commanded forward until it met a critical point in the center, and could no longer move forward. In practice, unexpected motions of the end effector would be dangerous. The solution ensures that the end effector motion matches the operator input. In other words, if the operator is commanding forward, the end effector is limited to moving strictly forward. In the future, some form of feedback to the operator will be included in the simulation to alert the operator that they are on this boundary.

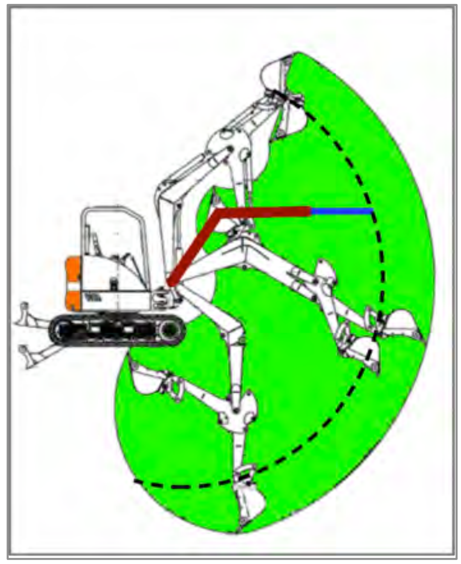

Figure 3: Kinematic Constraint

C. Plans

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

The coordinated rate control joystick user interface did not yield the same increased performance as the other user interfaces implementing coordinated control. One hypothesis to possibly explain this discrepancy is that the mapping adopted from the kinematically similar joystick is sub optimal. Future work and experiments will be used to evaluate this hypothesis.

A new coordinated rate control user interface is to be evaluated through another user study. The new user interface implements a different mapping between the joysticks and end effector motion, while a joystick rocker (continuous button) is used to control the bucket. The new mapping, along with the addition of a rocker for bucket control, is hoped to provide a more intuitive user interface.

<u>Expected milestones and deliverables</u>

1. Complete user study to evaluate new user interface
2. Complete the evaluation of selected coordinated control interfaces
3. Paper on coordinated rate control constraints
4. Paper on coordinated rate control of an excavator
5. Completion of experiments on actual hardware (dependent on coordination with industry and CCEFP test beds)
6. Generalization of results to other machines with similar characteristics

D. Member company benefits

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

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

Research Team

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1. Statement of Project Goals

The goal of the project is to investigate human performance in complex fluid power 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 barriers by comprehensively assessing fluid power 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 fluid power systems both in simulated laboratory environment and in real world scenarios.

3. Project Description

A. Description and explanation of research approach

Human factors and ergonomic practitioners play a critical role in fluid power systems design to help asses and solve performance, quality and safety problems. Several factors and the interaction among them contribute to work system complexity and poses unique challenges to the people involved when doing work [1]. In this project, we investigated the impact of various factors on nurses operating a patient transfer device (PTD). In recent years, work related musculoskeletal disorders (MSDs) have become one of the leading and most expensive occupational hazards in the United Sates [2, 5]. In the healthcare profession, MSDs have been identified as one of the primary occupational hazards among workers. Patient handling remains the top cause of injuries to caregivers [3, 5]. Engineering solutions such as ergonomic interventions technologies are developed and used as preventive methods to reduce or avoid injuries caused by handling patients [4]. Unfortunately, the functions of many current market technologies for patient handling assistance are inadequate and insufficient for achieving one of the main goals of ergonomics, which is safety of workers and patient's needs [4]. To help resolve these issues, a new patient transfer device using fluid power is under development (Test bed 4). This study intends to identify significant factors and their impacts on nurses operating the patient transfer device and incorporate the findings in the design as part of the user centered design process. Furthermore, researchers' expectations are that engineering solutions will address and resolve the MSD issues among caregivers, but this is only half of the solution. Caregivers have to be accepting of these ergonomic interventions and willing to use this new technology when it is introduced in the workplace. The objective of this study is to use the user-centered design (UCD) approach and The Systems Engineering Initiative for Patient Safety (SEIPS) Model of a healthcare work system, to assess a caregiver's work system and its interacting elements. This will help researchers gain knowledge about healthcare personnel's work system during nursing task to improve patient care, caregiver safety and performance, and ergonomic intervention design and adoption. This research will bridge a gap and address the need in ergonomic intervention research, specifically in the intervention development, implementation, and adoption stages.

B. Achievements

Achievements prior to February 2016:

1. A user-centered design approach was applied:

- Conducted task analysis to gain a thorough understanding of tasks performed
- Established usability goals
- Conducted usability study on existing patient transfer device
- Conducted time study
- Conducted Feedback Survey
- Conducted video recordings for motion capture
- Identified limitations and capabilities for modeling purposes
- Conducted benchmark test for Test Bed 4

2. Digital human models were developed to mimic caregivers performing a transfer task:

- Building Jack Models : A caregiver was created to represent Weights and Heights: 5%, 50%, 95% percentile of the population; a patient was created to represent 50th Percentile of the male population
- Animating Jack: Task Simulation Builder and Kinect were used to build the animation; TSB was used to creating poses that were identified from the task analysis; Customized movements were made using Microsoft Connect

Figure 1: Simulation of Kinect capturing postures in Jack software

- Import CAD drawings of two lift designs
- Create Environments: Environment 1: contains one caregiver, a patient and a hospital bed in a standard hospital room; Environment 2: contains one caregiver, a patient, a wheel chair, a hospital bed, and Hoyer lift design in standard hospital room.

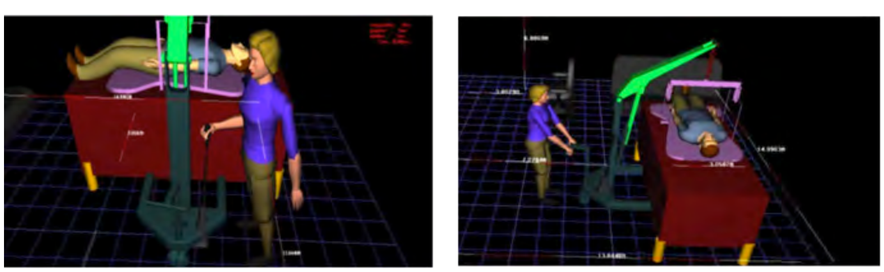

Figure 2: Simulation of caregiver transferring patient from bed using Hoyer lift

3. Use Tool Kit to Collect Data

- Low back Analysis Lower Back Analysis- evaluates the strain on different parts of the lower back as a job is being performed
- SSP - predicts strength requirements for tasks such as lifts, presses, pushes and pulls and the percentage of men and women who can perform the task

Achievements in this reporting period:

- The SEIPS model was applied to asses a healthcare environment and gain an understanding of the work system and interaction among them the following components: the organization, person, environment, technology/tools, processes, and outcomes. The work system components will help address the factors that contribute to the adoption of ergonomic interventions.
- Four caregivers were interviewed for this study.
- Categories for each question were generated from the SEIPS model. To analyze the responses chunks of data were identified that reflected similar responses and keywords from participant's responses. Tables 2-5 provide a sample of the responses collected from the four participants

Table 2: Responses to questions related healthcare worker's individual knowledge about MSD

Questions	Participants Comments	Common Themes/Words
Do you feel educated enough about the work factors that potentially lead to MSD problems?	• "I feel I am knowledgeable about MSD, and I know the patient's weight is the main/greatest factor that can contribute to MSD problems" • "I feel knowledgeable, but would like to be more educated on the topic"	• All respondents felt knowledgeable about MSD, but wanted more quantitative data explaining the risk associated with different task.
Do your managers or educational department provide literature about MSD and the importance of safe patient handling?	• " we have periodic meetings were it is mentioned and encouraged, but not always enforced" • " flyers and safe practice reminders are visible in working area" • " I typically work in homecare so a lot of my literature comes from school"	• The caregiver working in a homecare environment was not provided with literature or reminders about safe patient handling. • Flyers and reminders are very important in a hectic environment
Do you feel you are at risk of having MSD Problems if you continue use the method you are currently using to perform work?	• " I feel my method is safe even during manual handling" • "to much of a bad thing will eventually have a negative impact on my body" • "no, I always use some type of technology assistance when I am handling patients"	• Two caregivers felt it will impact them as they get older if they continued to handle "heavy loads" • One nurse felt "Technology" will improve over time and their job will become safer and easier

Table 3: Responses to questions related healthcare worker's task and training processes

Questions	Participants Comments	Common Themes/Words
List the factors you feel are related to caregiver injuries when handling patients	• manual patient handling • unforeseen circumstances • patient behavior, medical conditions, and unpredictability • staffing, workload, and time constraints • inadequate training • Space constraints • lack of use of patient handling equipment • performing care on low patient beds and awkward postures • difficulty moving and maneuvering lifts • Caregiver age and physical fitness	
What type of training method is typically used in your unit or facility?	• "no training was provided in the homecare work environment, my experience and certification wad the training" • "we typically use a train the trainer Model, I feel this method is most effective from past experiences"	• Train the trainer method was felt to be the most used and effective. • Homecare training was based from experience and certification completion
Do you periodically interact with an human factors/ergonomic specialist to discuss personal and environmental risk factors within your job"	• " No not directly, our educational department provides training and best practice meetings" • "yes, they visit monthly and we are informed about body mechanics and possible risk factors in the overall profession"	• Caregiver's expressed they would like more direct contact with someone knowledgeable about human factors in their work system • Overall, more awareness is needed about their specific working environment.

Table 4: Responses to questions related healthcare worker's technology and tools

Questions	Participants Comments	Common themes/words
In your opinion what are the reasons caregivers may not use patient handling equipment?	• time constraints • inadequate training • accessibility • equipment design factors (user-friendliness, space constraints) • maintenance and repair issues • sling attachment • battery • Patient medical conditions and wishes	
Do you always have patient handling technology available to use?	• "no, patients may not have the equipment available in the home" • "might be available, but no time to use or patient request not to use"	• Technology is limited in homecare settings • Technology is available, but time constraints limit use.
Do you always feel safe and comfortable using the technology?	• "Not alone, but if the patient is able to assist I am more comfortable" • "don't know if the device is strong enough to handle patient"	• The patient's size and weight is a safety concern
Do you have enough training about the proper usage of technology, and How can it be improved?	• " I don't have any experience using patient handling technology(lift), and never been trained" • "I think the more you use the faster you catch on, unless it is completely new or if I am a new nurse with little experience."	• Many caregiver's felt training is useful, but proper usage was mastered from continuous use.

Table 5: Responses to questions related healthcare worker's organization

Questions	Participants Comments	
How do your managers or charge nurse motivate you to use patient handling (PH) technology ?	• "typically in a homecare agency you work alone so you have to motivate yourself" • "meetings with the charge nurse and during training classes use strategies to encourage PH technology usage"	• More teamwork is needed in the homecare setting • Overall felt their managers or the charge nurse were motivating
Are you included in the decision making process for implementing intervention strategies?	• " no typically we are told the strategies and how to follow them" • " no, I wish I could be more involved because I am doing the job"	• Involve staff in the equipment selection process and process improvement projects
What are some Recommendations you feel will help decrease risk of injury in your organization?	• increase ceiling lift coverage and presence of other types of innovative patient handling equipment • provide more training on equipment • promote teamwork • involve staff in the equipment selection process • Encourage staff safety on the same level as patient safety • Incentives for safe practices	

This study provided baseline data and insight for a future large scale questionnaire survey study. Interview questions and the study will be modified and expanded and more subjects will be interviewed. Workers from the educational department were not included in this analysis, but are needed for additional studies, also more homecare nurses are needed to interview. To enhance the study, an observation study during RN lectures, training classes, and daily nursing processes will be conducted.

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

- Collaborate with TB4 designers to conduct a usability study for TB4.
- Interview and observe more expert operators (healthcare workers) to study operator decision making process when performing transfer task
- Develop cognitive task analysis
- Conduct an Psychophysical assessment
- Use Jack simulation to model TB4 with different design parameters to achieve the most efficient and effective lift design.
- Investigate sling design to improve overall human performance

<u>Expected Milestones and Deliverables</u>

- Usability studies of the patient transfer device
- Development of prototype interface for the patient transfer device
- Human performance models for patient transfer device
- Empirical experiments studying operator performance for patient transfer device
- Develop an integrated intervention adoption model to understand and predict the factors that impact the adoption of ergonomic interventions in a complex system.

4. 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. Human digital modeling provides the capability to evaluate designs before prototype is development, test multiple designs with a reduction in time and experimentation, and predict system performance under extreme conditions that are undesirable for human subjects. 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 3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems

Research Team

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

1. Statement of Project Goals

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

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

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

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

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

2. Project Role in Support of Strategic Plan

<u>Compactness</u>

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

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

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

<u>Efficiency</u>

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

3. Project Description

A. Description and explanation of research approach

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

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

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

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

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

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

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

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

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

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

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

B. Achievements

PUBLICATIONS

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

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

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

3. Bair, S. and Cassalini, R., "A Scaling Parameter and Function for the Accurate Correlation of Viscosity with Temperature and Pressure across Eight Orders-of-Magnitude of Viscosity", J. Tribology, Vol.130, 2008, 041802.

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

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

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

PROGRESS DURING THIS PERIOD

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

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

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

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

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

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

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

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

PLANNED PROGRESS

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

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

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

C. Member company benefits

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

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Project 3E.1: Pressure Ripple Energy Harvester

Research Team

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Undergraduate Students:	Jeremy Savor, Nalin Verma, Daniel Kim, Aaron Kranc, Karthika Poonammalle Venkatasubramanian, Brian Hults, Zachary Koontz, Chong Woo (John) Han, Tanya Johnson, Tri Nguyen, John David Cavanaugh II, Zachary Hussin, Bradley M. Argauer, Mark Cops, Forest Schwartz, Charles Xiao
Industrial Partners:	Parker-Hannifin, Danfoss Power Solutions

1. Statement of Project Goals

The goal of this project is to model, develop and prototype energy harvester devices capable of producing useful power from pressure ripple in high-pressure hydraulic systems. The application of the devices is for powering sensor nodes within a fluid hydraulic system, as may be used for health monitoring or data acquisition applications. This project has fulfilled all of its initial project goals, including proof-of-concept devices with demonstrated performance for powering of wireless sensor nodes. In addition, detailed design models have been developed and validated. Current research goals include exploration of means to increase the power conversion efficiency at low hydraulic noise levels, as well as developing means to improve efficacy at high static pressures. Full funding of this project ended in May, 2014; year 10 funding was for graduate student support, only.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

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

While there are numerous publications on energy harvesting from low density sources such as thermal, vibration, wind turbulence, flow turbulence, we have found no citations to work that directly exploits the pressure ripple directly as we consider here. There has been some work on energy harvesting from air borne noise by various means, but the low energy density of such fields has led to the use of techniques and devices that would not be appropriate in a pressurized hydraulic system [6-17]. If one seeks to harvest energy from a typical low level acoustic signal in the environment, either one must have a large device, or a means of achieving an efficient focusing of the available energy, or have a need for only very low power levels (microwatt or less). In pumped fluids, however, the situation is significantly different, as the use of positive displacement pumps can lead to high intensities within fluid systems, with intensities on the order of kW/m^2 being possible.

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

B. Achievements

Achievements in previous years

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

Figure 1 depicts the key elements of an HPEH-powered wireless sensor mounted on a fluid hydraulic system. The housing of the HPEH retains a piezoelectric multilayer stack or single crystal, and has a connection to the fluid system. The piezoelectric element is exposed to pressure forces in the fluid system through an interface that serves to isolate the element from the fluid, while permitting pressure forces to be coupled into the element.

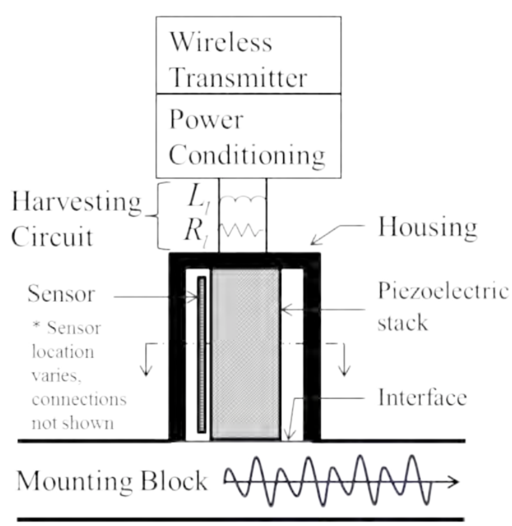


Figure 1: Simplified schematic of self-powered wireless hydraulic pressure energy harvester sensor, where the interface implements fluid-mechanical coupling between the piezoelectric element and pressure ripple in a pressurized fluid.

Modeling

An advanced power production model was developed that enables performance prediction of HPEH designs. The electrical equivalent model for a HPEH is depicted in Figure 2, where the active element, a piezoelectric stack or single crystal, is represented as a current source in parallel with a capacitance.

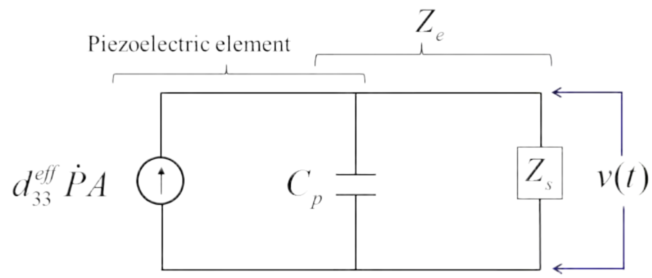


Figure 2: Equivalent electrical circuit with the piezoelectric element modeled as a current source in parallel with a capacitance.

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

$$\Pi_{avg,l} = \frac{v_{rms}^2}{R_l} = \frac{|Z_e|^2 \left(\omega d_{33}^{eff} A P_0\right)^2}{2R_l} \tag{1}$$

where the electrical impedance is represented as

$$Z_e = \left(j\omega C_p + \frac{1}{Z_s}\right)^{-1} . \tag{2}$$

The optimal loads to maximize the power response for a resistive only or a parallel resistive-inductive load for a given excitation frequency has been solved, details of which can be found in [2, 3]. This enabled design analysis and optimization of HPEH devices for particular applications and available pressure ripple. Prototypes have been developed and tested, with much of the design work performed by REU students.

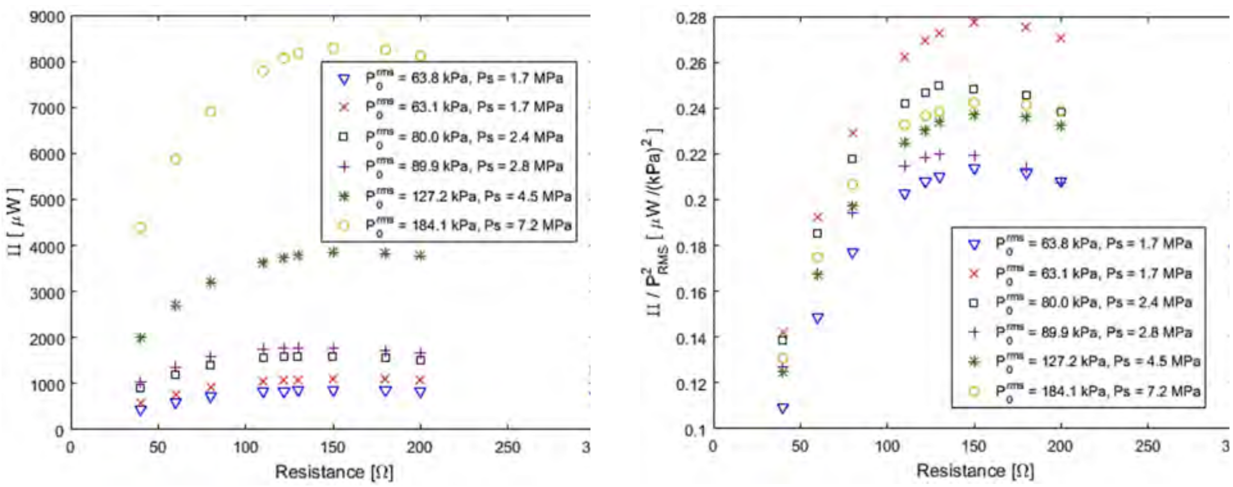
Achievements in the past year

Two main topics were addressed during the past year: 1) alleviating the mean stress on the piezoelectric element and 2) amplifying the acoustic pressure applied to the piezoelectric element.

Force Shunt HPEH

The validity of the electromechanical model above is dependent on the integrity of the piezoelectric material and conversion efficiency, which can be compromised if exposed to high stresses derived from hydraulic system mean pressure. The linear piezoelectric constitutive equations are typically valid for low excitation levels, excitation far from resonance, and low pre-compressive stress and electric field levels [18]. While HPEH devices operate far from piezoelectric element resonance, the pre-compressive stresses caused by the static pressure can be high, especially if area amplification of the interface is included in the HPEH. It has been shown that nonlinearities can occur when exceeding these conditions [19]. Cao and Evans [20] observed that when a piezoelectric element undergoes high compressive stress levels, the linear constitutive equations are no longer valid. Krueger [21] and Zhang et al. [22] present the change of piezoelectric parameters (such as piezoelectric strain constant and permittivity) when undergoing high stresses. If the piezoelectric element is exposed to an exceedingly high stress for a period of time, then depolarization of the piezoelectric material may occur. A decrease in power normalized by square pressure amplitude for various static pressures was observed when testing a HPEH device, and therefore a method, referred to as force shunt, to alleviate the static pressure exposed to the piezoelectric element was designed and tested.

The force shunt (FS) HPEH device allows a certain mean pressure testing range to be set prior to use, and then protects the piezoelectric element from the system mean pressure of interest, while only fractionally reducing the dynamic pressure applied. This allows the HPEH devices to safely operate in a larger mean system pressure range. The test results for the HPEH-FS prototype developed as proof-of-concept are shown in Figure 3. While the normalized power is in a comparable range, the system mean pressure applied to the device range from 1.7 MPa to 7.2 MPa; however, without the FS implementation, the stress on the piezoelectric stack at 7.2 MPa would be over 50 MPa, which is considered beyond safe operation limits for a soft PZT element. This device has produced over 13 mW of power when tested with over 230 kPa pressure amplitude at 10 MPa static pressure.



a) *b)*

Figure 3: HPEH test results for a force shunt device with a 7.4 area amplification of a 25 mm^2 stack electrode area a) power test results; b) power normalized by dynamic pressure amplitude.

The HPEH-FS concept allows HPEH devices to be safely used for the full static pressure range of interest within hydraulic systems. It also allows area amplification to be used to increase the power response for a given dynamic pressure input without limiting the maximum system mean pressure that a HPEH device can be used.

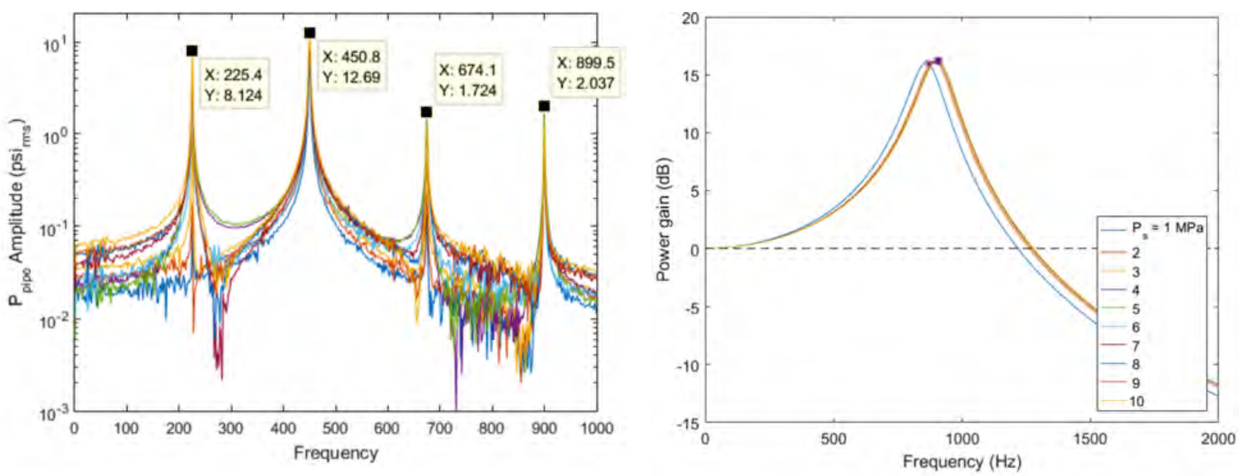
<u>*Helmholtz Resonator HPEH*</u>

As seen in Eq. 1, the power produced by a HPEH device is proportional to the squared pressure amplitude and excitation frequency. A Helmholtz resonator is well established in acoustic literature for absorbing or amplifying pressures within a narrowband, and has been incorporated into other acoustic energy harvesting devices [23-27]. A model of a Helmholtz resonator (HR) was developed and tested using HPEH-sized HR test bodies that used a dynamic pressure sensor rather than a piezoelectric stack to measure the power gain within the HR cavity [28]. The power gain is represented as

$$G = 20\log_{10}\left(\left|\frac{P_{HPEH}}{P_{pipe}}\right|\right), \tag{2}$$

which compares the pressure amplitude within a HPEH device compared to within the pipe. To reduce the size of the Helmholtz resonator, a syntactic foam was added to the cavity of the HR test body. This allows the body to be smaller; however the trade-off requires the device to be designed for a specific static pressure value due to the change in foam volume as static pressure increases.

Another way to reduce device size is to target a higher resonant frequency. Since HPEH power is also a function of squared frequency, a HPEH-HR device was designed to amplify the acoustic pressure at a higher frequency. For example, on the GT hydraulic test rig, the first and second harmonic contain the highest pressure amplitudes for a given frequency, as seen in Figure 4a, and thus typically a harvesting circuit is optimized to match one of those frequencies. However, there is pressure excitation at higher harmonics, and if a HPEH-HR amplifies the pressure at those harmonics, then a HPEH with a matched electrical circuit will have high power response due to the amplified pressure response and the higher excitation frequency. Therefore a HPEH-HR device was designed to target the system's fourth harmonic to test this hypothesis, with the expected power gain modeled in Figure 4b. Note the power gain modeled is only showing the power gain from the amplified pressure, and is not including the power gain from a circuit matched to a higher excitation frequency.



a) *b)*

Figure 4: a) Acoustic pressure response in GT hydraulic rig in frequency domain; b) modeled HPEH-HR device power gain that targets the fourth harmonic of a Georgia Tech hydraulic testing rig.

C. Plans

The plans for the next half-year include implementing and testing designs developed during year 10, in addition to further wireless sensor network demonstrations. This includes incorporation of a Helmholtz resonator targeting the fourth harmonic of GT fluid power testing rig, utilizing a material phase changing single crystal within a HPEH device, and power conditioning of low-voltage piezoelectric stacks. The first two are expected to further increase the normalized power output of a HPEH device. The last is intended to allow HPEH devices to be efficiently used with electrical energy storage devices and circuits currently available.

D. Member company benefits

This project has yielded very positive results that are strongly rooted in practical application and the development of new technology. 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.

Two companies (Parker-Hannifin and Danfoss) have notified Georgia Tech that they will participate in the patenting and licensing of the technology through the Center's IP agreement.

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

Research Team

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Industrial Partners:	Bobcat, Sun Hydraulics, Caterpillar, Parker Hannifin, Moog, Husco, Danfoss.

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) promises fuel savings for various 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. Over the past few years, efforts have been focused on demonstrating a novel hydraulic hybrid configuration with pump switching. The series-hybrid architecture introduces 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 up to 50% engine downsizing. The pump switching architecture introduces a distributing manifold that acts as a logic element to minimize the installed pump power while maximizing the number of actuators available to the operator. This architecture leverages fuel savings above those demonstrated with the non-hybrid DC excavator prototype and the reduction of production costs and improved reliability.

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 and through advanced power management strategies. Past and present work has been developed to evaluate and ultimately implement 1) throttle-less DC actuation, 2) a novel highly efficient hydraulic hybrid swing drive and 3) pump switching, a reliable and cost effective solution for the reduction of the installed pump power. The test bed has also been used for the demonstration of a novel human-machine interface as part of project 3A.1 at Georgia Tech.

The test bed is well positioned for testing of energy-efficient fluids researched at MSOE (Project 1G.1), and for evaluation of high efficiency, virtually variable displacement pump/motors that utilize high-speed on-off valves (Projects 1E.3 and 1E.6), at Purdue University. With the transmission 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).

3. Project/Test Bed Description

The current state-of-the-art in hydraulic drive and actuation technology involves the use of different forms of resistance control through the utilization of valves. Most mobile applications use load-sensing), negative flow control, positive flow control architectures or variations of these architectures. In those systems one or two hydraulically controlled variable displacement pumps provide the required 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 (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 wasted or recovered very inefficiently, through these architectures.
Displacement controlled (DC) actuation is a highly efficient throttle-less actuation with simultaneous utilization of energy recovery without energy storage. The basic circuit for linear single rod cylinders has been introduced by Rahmfeld & Ivantysynova (1998). 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 initial challenge was to demonstrate that pump control could compete with the performance of valve controlled systems with respect to bandwidth and accuracy. Another challenge was to define the maximum required pumps in multi-actuator machines by introducing pump switching architectures and new control concepts. This complete new hydraulic actuation technology has been demonstrated in the past on a wheel loader where measurements showed 20% higher fuel efficiency.[1] 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 were 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 affiliated project, energy efficient active vibration damping of the boom and machine cabin has been demonstrated on a skid-steer loader.[2] Competing throttle-less actuation technologies are open-circuit DC actuation and hydraulic transformers.[3,4] Open-circuit DC actuation is a feasible alternative, however it involves the use of several logic valves per actuator and accompanying control laws, which greatly complicates the actuator control. The INNAS Hydraulic Transformer (IHT) concept is not yet a proven technology that has been demonstrated on mobile multi-actuator machines.

The DC hydraulic hybrid prototype captures the swing drive braking energy in a hydraulic accumulator. Through the use of a secondary-controlled variable displacement motor for the swing drive, both the energy recovery concept and the manipulation of the excavator cabin motion are possible. 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. 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. In such scenario, 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.

Achievements Prior to Reporting Period

- Four variable displacement pumps were installed on TB1 along with associated sensors and electronic control hardware and position and actuator velocity algorithms to retrofit the prototype with DC actuation.
- Simulation and measurement results on TB1 determined that up to 50% of the cooling power capacity in the system could be reduced.
- Productivity and fuel test for TB1 with DC hydraulics was conducted in cooperation with Caterpillar; 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 using a pipe-laying cycle. Results showed 56.4% fuel efficiency improvement over the non-optimally managed.
- In April 2011, TB1 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 1A.2, 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.

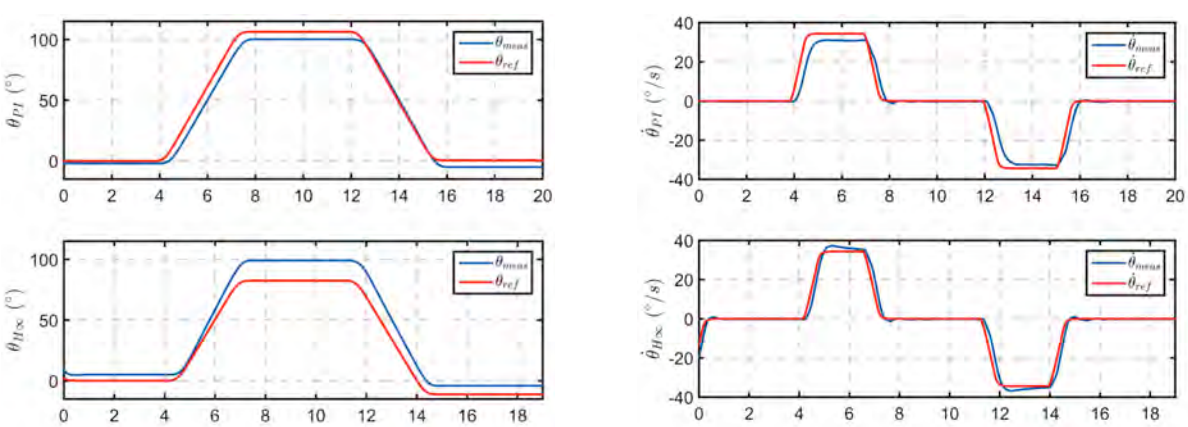
- Through 1A.2 in 2011, a conservative power management strategy demonstrated that the proposed TB1 hybrid configuration together with downsized engine, can achieve 52% fuel savings compared to the standard machine (> 20% over the prototype DC excavator).
- Also through 1A.2, optimal power management strategies were developed to achieve up to 27% fuel savings over the non-hybrid DC excavator.
- Optimal sizing studies using dynamic programming were undertaken to evaluate various possible unit and accumulator sizes as well as accumulator pre-charge pressures.
- The hydraulic hybrid swing was successfully implemented on TB1 and control strategies were implemented with the goal of demonstrating the hydraulic hybrid functionality.
- Actuator level controls were developed and successfully tested for pump switching.
- Two actuator level controllers were proposed for the hydraulic hybrid swing drive to improve operability and performance.
- A general and effective electronic anti-stall controller was proposed and implemented.

Achievements During the Reporting Period

Hydraulic Hybrid Actuator Level Control

Since the conception of secondary-controlled drives, many advances in the control of the actuator position, velocity and torque have been developed. Efforts in this area for TB1 focused on determining a control strategy that would maximize performance and achieve conventional drive operability, which is a challenging control problem due to the large and rapidly-changing inertial load s to which the machine is subjected to. For this purpose, two linear control strategies, a PI controller and a robust multi-input multi-output controller (developed in the previous reporting period) were compared to a newly developed nonlinear adaptive robust technique.

Measurements of these control strategies demonstrated that the proposed nonlinear controller outperforms the previously developed control strategies, tracking the commanded drive velocity and position very closely. Measurements with low and high inertia loads were conducted on testbed 1 by extending and retracting the excavator arm. All controllers were tested under the same conditions. To obtain a controlled experiment for a fair comparison of the measured controllers, most of the human element was extracted from the commanded signal. Instead, an artificial joystick command was created using a constant, a rate limiter and a first-order discrete transfer function combination. This in turn allows for repetitive measurements in terms of command rates and for comfortable excavator operation. In doing so, measurements of an expert operator cycle were utilized to realistically set the parameters of both the rate limiter and the first-order discrete transfer function. Figure 1 shows the velocity and position excavator swing drive measurements for a low inertia 90° cycle.[5]



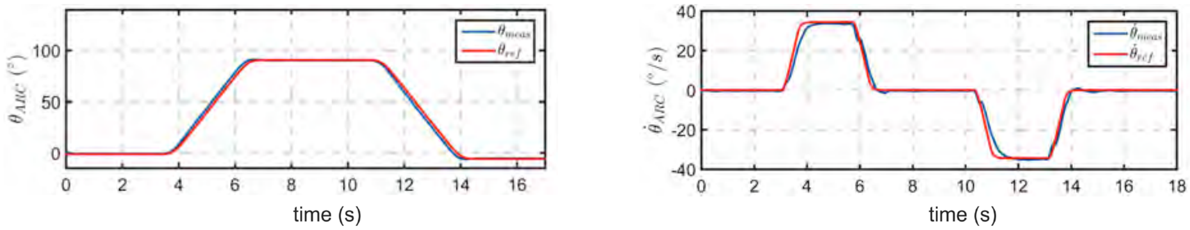


Figure 1: Hydraulic hybrid swing drive measurements for three control strategies for a 90° cycle under low inertia

Hydraulic Hybrid Supervisory Level Control

A constant pressure net is unreasonable for a secondary-controlled hydraulic hybrid drive. With this in mind, TB1 has been utilized as a platform to develop a minimum speed and a rule-based control strategy for the power management of a hydraulic hybrid swing drive. Nonetheless, these strategies were not able to achieve the previously predicted engine downsizing in implementation. During the reporting period, an effective and general power management supervisory-level controller was developed for displacement-controlled hydraulic hybrid machines. The control strategy proves that, through the proper management of the primary unit, the system is able to perform as a conventional machine while operating with a downsized engine.

The proposed supervisory controller comprises two parts, 1) an instantaneous optimization for the minimization of fuel consumption and maximization of actuator performance and 2) a feedforward controller for the hydraulic hybrid primary unit based on the system power flows. In conjunction, these two parts optimize the usage of engine power and allow the hybrid to provide complementary power to the common shaft. Measurement results of TB1 with a stock-sized engine (shown in Figure 2 to Figure 6) show that the control strategy maintains the engine at or below the prescribed engine power for a truck-loading cycle.

It is important to note that the developed control algorithm does not seek to achieve machine optimal operation. In order to achieve this, the operator commands must be known a priori or a learning or model-based algorithm must be implemented to focus on maintaining the mean accumulator pressure at the lowest possible while still maintaining operability. This then would allow the engine to operate at lower speeds and the primary and secondary units to operate at lower pressures thereby incurring in lower losses. Nonetheless, the derived algorithms demonstrate that the hydraulic hybrid architecture in combination with DC actuation allows engine downsizing by up to 55% for an excavator.

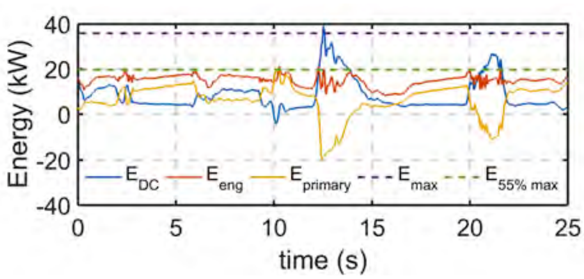


Figure 2: System power

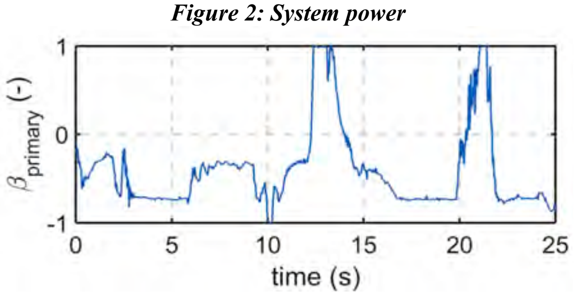


Figure 3: Primary unit displacement

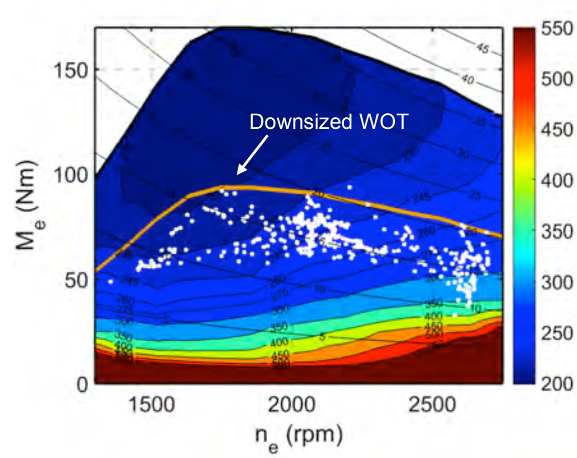


Figure 4: Engine Operation

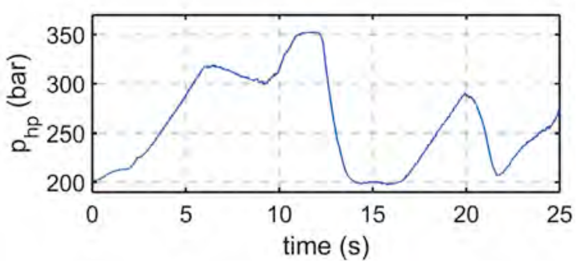


Figure 5: Accumulator pressure

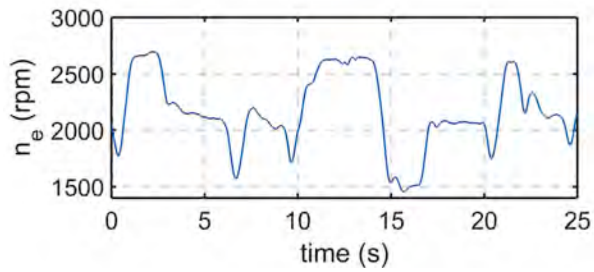


Figure 6: Engine speed

Pump Switching

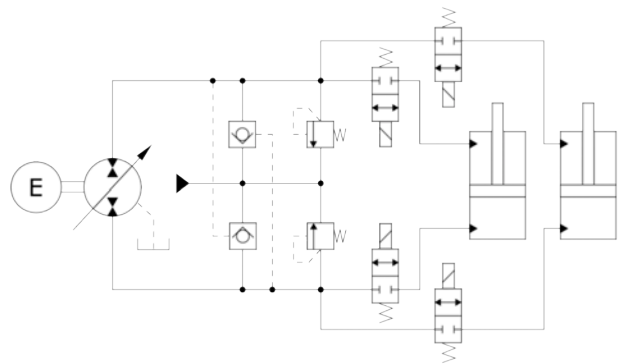


Figure 7: Basic pump switching hydraulic circuit

With the developments from project 1A.2, the concept of pump switching was realized in TB1. For illustration purposes, the hydraulic circuit of TB1 is shown in Figure 7. As demonstrated in project 1A.2, pump switching has the potential to minimize the number of pumps in a DC hydraulic system. During the previous reporting period, a distributing manifold as well as actuator level controls were developed for TB1. The need now arises to develop a supervisory level controller that would allow for the effective management of the operator commands, the hydraulic units and the switching valves. In order to achieve this tasks, a priority-based supervisory controller was developed. The advantage of using a priority-based approach is that the controller will select certain actuators by default and, using predefined joystick signal weights, allow the operator to switch to lower priority actuators in a seamless manner. The impediment is obviously the fact that not all actuators are available at all times; nonetheless, through the use of DC actuation with pump switching the possibility to complete tasks in a reduced amount of time relative to VC systems is a big advantage.

For validation of the proposed supervisory control, a cycle involving the use of 6 actuators has been chosen. In this case, the operator commands the tracks to position the excavator aligned with a trench. Then, the boom arm and bucket are used to dig the trench. A swing motion is commanded to dump the dug material at a location 90° away from its original position. As the 90° mark is reached the operator dumps the dirt in the bucket and returns to its original position. As the excavator is swung back to its original position, the operator commands the track motors to move further along the trench. The cycle is then repeated. The measurement results are shown in Figures 8-11. Unfortunately, the excavator longitudinal position or the tracks position have not been measured. To show where the travel function was commanded, the integrated displacement command is plotted.[6]

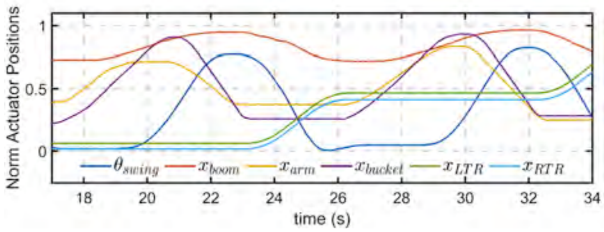


Figure 8: Measured trench-digging cycle actuator positions

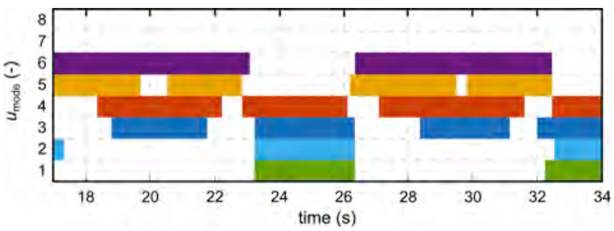


Figure 9: Supervisory controller output for the trench-digging cycle labelled by the color scheme for each actuator

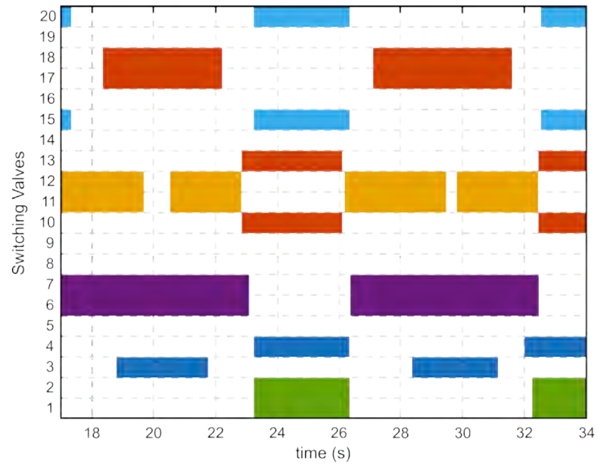


Figure 10: Corresponding switching valves to achieve the trench-digging actuator combinations

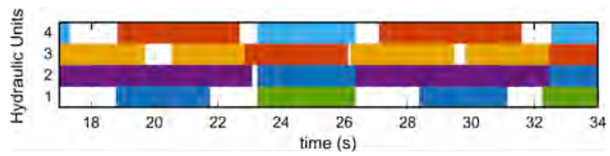


Figure 11: Hydraulic units providing flow for the commanded motion labelled by the color scheme for each actuator

Planned Achievements following the reporting period

- Synthesize controllers to optimize the energy usage of the hydraulic hybrid swing drive through learning algorithms
- Develop learning controllers to determine operator driving patterns with the goal to override operator commands and effectively manage the DC architecture with pump switching

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: TB1 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 regulations under the TIER emissions standards, together with providing the resulting monetary benefits.

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Test Bed 3: Hydraulic Hybrid Passenger Vehicle

Research Team

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Undergraduate Students:	John Pullar, Christian Wollner
Industrial Partners:	Bosch-Rexroth, Eaton, Parker, 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 excellent fuel economy and good performance. As a test bed project, it also drives and integrates associated projects by identifying the technological barriers to achieving that goal. The design specifications for the vehicle include: (i) fuel economy of 70 mpg under the federal drive cycles; (ii) an acceleration rate of 0-60 mph in 8 seconds; (iii) the ability to climb a continuous road elevation of 8%; (iv) exhaust emissions meeting California standards; and (v) size, weight, noise, vibration and harshness comparable to similar passenger vehicles on the market. Powertrains produced in the scope of this project must demonstrate advantages over electric hybrids to be competitive.

2. Test Bed Role in Support of Strategic Plan

Test Bed 3 directly supports goal 2: improving the efficiency of transportation. Efficiency is achieved by utilizing hydraulic assist to enable operating the engine at or near its “sweet spot” and regenerating brake energy. The power trains integrate high efficiency components, hydraulic fluids and energy management algorithms (thrust 1), compact energy storage (thrust 2) and methodologies for achieving quiet operation (thrust 3) from related CCEFP projects.

3. Test Bed Description

A. Description and explanation of research approach

The high power density of hydraulics makes them an attractive technology for hybrid vehicles, since both fuel economy and high performance is achievable. Hydraulic hybrids provide an intriguing alternative to electric hybrids because the large battery required for electric hybrids can be eliminated. A few hydraulic hybrid vehicles have been developed for heavy, frequent stop-and-go applications such as garbage or delivery trucks. However, hydraulic hybrids have not yet reached the much larger passenger vehicle market. In order to succeed in this market, hydraulic hybrid drive trains must overcome limitations in component efficiency, energy storage density, and noise. These barriers represent worthwhile challenges that stretch the envelopes of existing fluid power technologies.

TB3 focuses on power split architectures, which combine the positive aspects of the series and parallel drive train. They are not as well studied as the simpler architectures. Two hydraulic hybrid passenger vehicles are being developed in the scope of this test bed, each of which offers unique research benefits. The “Generation 1” vehicle **(**Figure 1**)** was built in-house using the platform of a utility vehicle (a Polaris “Ranger”). It is connected to an in-house built hydrostatic dynamometer, which allows for testing of the vehicle without a test track. The vehicle has been outfitted with a modular power train. This enables experimenting with different pump, motor and energy storage technologies, including those developed in complementary CCEFP projects.

The “Generation 2” vehicle is being developed in partnership with Folsom Technologies International (FTI). It is built on the platform of a Ford F-150 pickup truck, which has refined vehicle dynamics capable of highway speeds. Its power train utilizes a prototype continuously variable power split hydraulic transmission developed by FTI. Adding hydraulic accumulators to the CVT enables hybrid operation. The power train is built as a compact, integrated, self-contained package. However, the integrated package prevents changing out the hydraulic pump/motors or instrumenting them individually. Development for the last three years has focused on the Generation 1 vehicle, although development of the Generation 2 vehicle has continued as resources permit. The Generation 2 vehicle was recently moved to the Ford Research & Innovation Center in Dearborn, MI following the shut-down of Folsom Technologies International.

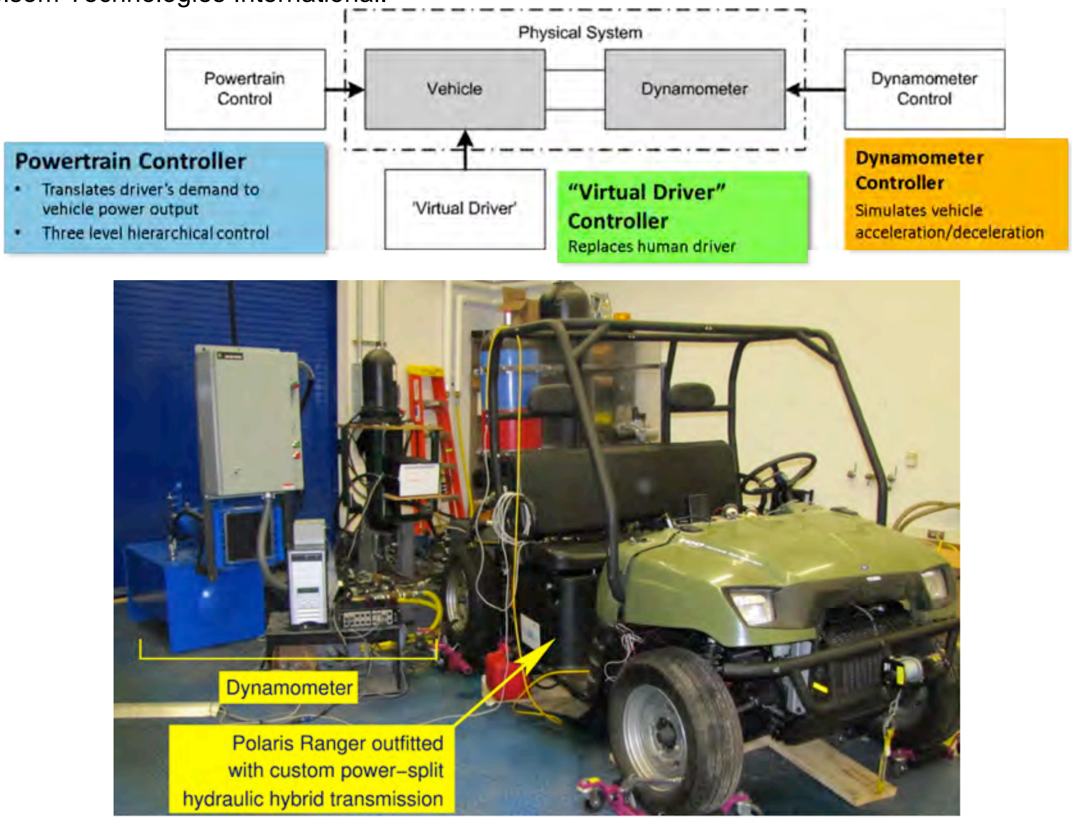

Figure 1: Overview of Test Bed 3 HHPV Generation 1 with hydro-static dynamometer.

B. Achievements

Achievements are separated according to the two platforms: the Generation 1 vehicle and Generation 2 vehicle. Within each category, achievements in previous years are briefly summarized first, followed by more detailed descriptions of achievements in the past year (2015).

<u>Achievements Applicable to the Generation 1 Vehicle</u>

Recent years' major achievements:

(i) *Drive train rebuild:* The first hydraulic hybrid transmission was completely rebuilt in 2011-2012 to use only gears to transmit power to and from the hydraulic pump/motors. The all-gear design improved the power capacity, the efficiency and the reliability of the power train.

(ii) *Dynamometer:* The vehicle was coupled to a hydrostatic dynamometer in 2012, eliminating the need to drive the vehicle on a test track. The dynamometer was designed and constructed in house to enable it to motor as well as load the vehicle, thereby enabling it to simulate braking events. In December of 2014 a new power supply was installed to help simulate the full weight of the vehicle, and an electric motor for the charge pump was added to allow for the full range of output shaft speeds.

(iii) *New engine installation and characterization:* The vehicle's engine was discovered to be inadequate to take the vehicle through all planned drive cycles, so it was replaced with larger and more efficient engine in 2013. The new engine was characterized using the dynamometer described above.

(iv) *Powertrain and dynamometer control systems:* Three controllers have been designed and implemented on the vehicle-dynamometer system (see Fig. 1). The first, the "powertrain controller", is integrated with the hybrid vehicle itself. It utilizes a three-level hierarchical strategy, which was described in previous years. The second is the dynamometer controller. This controller simulates the inertia of the vehicle, which requires monitoring the torque applied to the drive shaft. The third, described as the "virtual driver" controller, interfaces with both the dynamometer and the vehicle's throttle controller. It makes it possible to track arbitrary drive cycles repeatably for testing purposes. These control systems aid in the reliable operation of the vehicle in CVT mode.

Major achievements in year 2015:

- *High level Energy management strategy:* The three level control program for the vehicle has been modified to allow for the testing of different high level energy management strategies other than CVT. Dynamic Programming (DP) and Modified Lagrangian Multiplier (MLM) control programs have been created for testing.

- *Internal Friction Characterization:* When testing the vehicle in CVT mode, a consistent difference between the expected torque and the measured vehicle torque was observed. Investigation revealed that significant friction existed within the drive train that was not included in the system model. Extensive tests were done to characterize the friction at different output shaft speeds, vehicle torques, and pump/motor speeds and directions to enable modeling it.

  To characterize the friction, the engine speed, the speed of pump S, and the output shaft speed were held constant while the dynamometer was used to change the load on the vehicle and, by extension, change the commanded vehicle torque. The friction contributed by each branch of the modular transmission was then quantified by independently changing the speed of pump S, the engine speed, and the load on the vehicle.

  Figure 2 shows an example result from the friction characterization tests. The top graph shows the displacement of the dynamometer pumps, which translates directly to load on the vehicle. The second graph plots the displacement of the Speeder pump. The lower graph plots the vehicle torque being commanded (T_{veh}) and the measured torque (T_{meas}). The difference between the commanded and measured torque is easily visible. Figure 3 shows the improvement to tracking due to implementing a friction model. The bottom graph is the original, showing a significant difference between commanded and measured torques. The top graph includes the friction model: little difference exists between the commanded and measured torques.

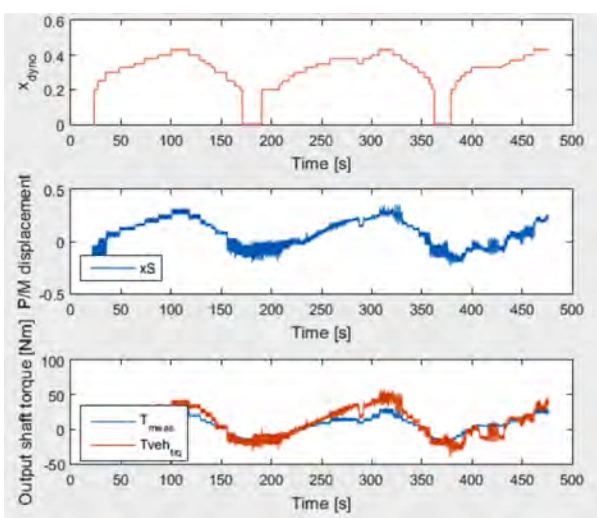

Figure 2: Example results from friction characterization testing.

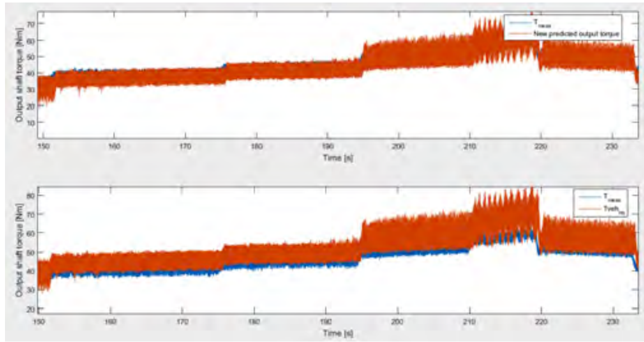

Figure 3: Improvement in torque command tracking due to adding a friction model. The top graph shows tracking with a friction model and the bottom shows tracking with no friction.

- *Pump/Motor map update:* After the friction was characterized, the output torque of the Speeder pump (pump S) was observed to be significantly less than that estimated by the pump/motor map. The map for pump S was then updated to account for the friction and further close the gap between the expected and measured vehicle torques. Figure 4 shows the results of the new pump map. The x-axis maps the displacement of S, while the y-axis shows the difference between the measured torque of pump S and the calculated torque using the pump map. As shown, the new pump map is accurate to within 1-2 Nm over the range of normal Pump S displacements.

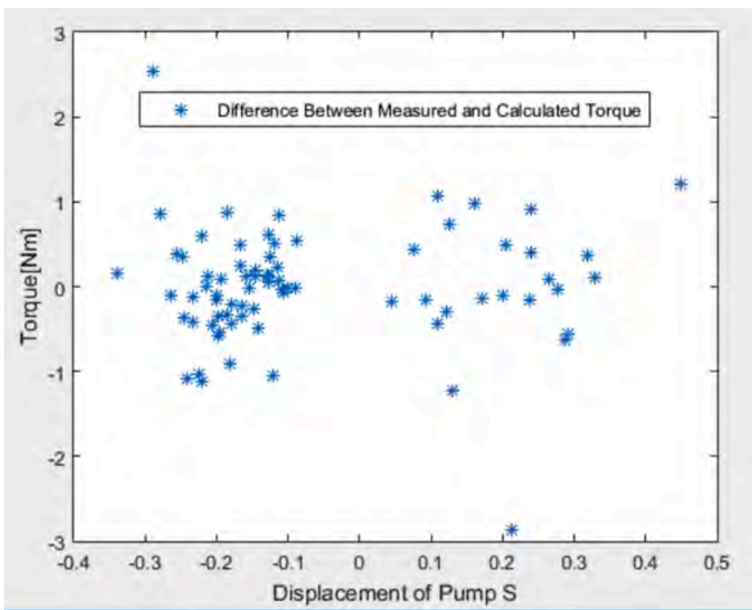

Figure 4: Difference between the experimental Measured Torque of the vehicle, and the calculated Pump Map Torque for difference pump S displacements

C. Plans

<u>Plans for the Generation 1 Vehicle</u>

(1) Additional high level hybrid energy management control strategies will be tested. Dynamic Programming (DP) and Modified Lagrangian Multiplier (MLM) methods will be the first energy management strategies to be integrated into the control system and tested. The fuel efficiency of the vehicle under federal drive cycles with each energy management strategy will be determined.

(2) As mentioned, the Vehicle has exhibited significant amounts of friction in the hydromechanical transmission. Once the current system state is fully quantified, the transmission oil will be changed to a low-friction oil supplied by Exxon-Mobil. The friction of the system will then be re-characterized and the friction results will be compared

(3) To serve as a test bed for Project 1G.1 (Energy Efficient Fluids), a synthetic biodegradable ester will be utilized as the hydraulic fluid. This fluid is expected to exhibit higher efficiency at low speeds [10]. The new oil will be compared with a baseline shear stable high viscosity index hydraulic fluid. The modified Lagrange hybrid control strategy will be used if it shows improvement over CVT control.

(4) The vehicle has been designed such that the hydro-mechanical transmission and hardware of the system fits on the frame of the Ranger vehicle. At the end of the funding period, the team will decouple the vehicle from the dynamometer and install the rear differential so that the vehicle can be driven for autonomous demonstrations.

<u>Milestones and Deliverables</u>

Generation I:

- Task 1: Integrate and then test the Modified Lagrangian and Dynamic Programming methods [2/16]
- Task 2: Replace and test the transmission oil to the low-friction oil supplied by Exxon-Mobil. [3/16]
- Task 3: Baseline Generation I vehicle performance by running it through the EPA urban drive cycle in a hybrid mode using mineral oil based hydraulic fluid. Compare performance of biodegradable synthetic hydraulic oil using identical drive cycle and mode. [4/16]
- Task 4: Prepare the vehicle for autonomous demonstrations. [5/16]

D. Member company benefits

Development of practical hydraulic hybrid passenger vehicles creates a new and lucrative market for hydraulic products. In addition, development of the HHPV enables member companies to gain experience in a potential market segment where they have not traditionally worked which requires very high efficiency at relatively low power. Finally, the test bed provides an ideal application for testing the efficiency of alternative hydraulic fluids intended for use in powertrains.

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Test Bed 4: Patient Transfer Assist Device

Research Team

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Industrial Partners:	Bosch Rexroth, Deltrol Fluid Products

1. Statement of Test Bed Goals

The high level goals of the patient transfer assist device (PTAD) project are to explore ways to expand and improve the use of fluid power to meet needs in human scale applications. Through our needs assessment, we have identified a significant market need for an improved assist device for transferring mobility limited patients, particularly those who are very heavy. This device is designed to provide a way for caregivers to move patients more efficiently and effectively, without injury. To benefit from the force density of fluid power, effective human interfaces and control are crucial. It must be safe for humans in its workspace, allow for simple and intuitive operation, have smooth motion without oscillation, be highly maneuverable, and have sufficient energy on-board to last all day, even in a clinical setting.

While the testbed device itself is a new concept, the main scientific insight and research contributions lie in two areas. First, interesting problems lie in developing control strategies for the device using newly available sensors, both higher level prevention of undesirable conditions and lower level control of non-ideal components. One area of research contributions is in strategies to safely utilize fluid power capabilities with a complex multiple degree of freedom device, with humans in the workspace. Also, while not a new concept, the control of hydraulic systems using separate electric motors driving individual hydraulic pumps in a multiple DOF system is neither common nor well-documented.

2. Test Bed Role in Support of Strategic Plan

In order to expand the use of fluid power into more human scale and medical applications, the power of hydraulics must be adapted to uses in the delicate situations which are epitomized by patient care. Affordable, quality patient care is currently hampered by the high personnel requirement for transfers. The needs for the PTAD application exemplify some primary CCEFP goals, such as the need for a safe and effective operator interface, a compact and mobile design, all in a multi-DOF system. This testbed provides an opportunity to explore how fluid power can be used in non-traditional environments such as homes and clinical institutions, and to explore ways to improve the efficiency of hydraulic actuation systems at this scale. It also provides a system in which to test integrations of various CCEFP subsystem projects/components. Earlier stages of this project involved collaboration with several projects, including those on passivity based control (3A.2), control of vibration/swing (3B.3), multi-modal human machine interfaces (3A.1), and user-centered design (3A.3). Other likely candidates for collaboration include the hydraulic transformer (1E.5), strain energy accumulator (2C.2), and potentially others. Plans are in place to test patient payload oscillation control (3B.3) within the next few weeks. The capabilities developed for patient transfer will be relevant to construction, personal services and other areas.

3. Test Bed Description

<u>Overview</u>

A significant market need has been identified for a better device to aid in moving mobility limited people, particularly those who are very heavy. Typical patient transfers include moving between a bed, gurney, wheelchair, chair/couch, toileting chair or toilet, car seat, and the floor. The developments can also be relevant in other applications, such as human-collaborative hydraulic industrial robots, or machines to aid construction workers in moving building supplies. The National Public Radio recently published a set of articles investigating the high rate of serious injuries to clinicians resulting from patient transfers, noting that clinicians are injured at an even higher annual rate than construction workers [1]. Because of the frequency of injuries to caretakers, the Veterans Health Administration has issued guidelines for safe patient handling [2]. Occupational Safety and Health Administration data from a range of industries in 1991 showed that back injuries afflicted over 600,000 workers and cost around $50 billion per year [3]. A transfer operation today often requires multiple personnel for as much as 10-20 minutes. This problem provides an opportunity to explore ways to make hydraulic machines collaborate with humans, sharing a task and a workspace. Electrohydraulic actuation has the advantage of providing large force capability in a compact package, with the power source located at the base of the device. A needs assessment was performed early in the project, which led to a set of design requirements and technical challenges to be addressed.

Challenges

There are a number of primary scientific research challenges, focused primarily in two areas, control and efficiency, including the following.

- Development of a compact, maneuverable, powerful device to aid patient transfers.
- Control strategies to obtain desired dynamic response using separate DC electric motors driving small hydraulic pumps, with compensation for nonlinear and non-ideal features of low cost components, such as stiction in the gear pump, switching required for a series wound motor, and overall slow plant dynamics.
- Control strategies to manage both motion and interaction forces using a powerful, complex, multiple DOF system operating in a relatively delicate environment with humans in the workspace.
- Modeling and evaluation of efficiency in electro-hydraulic pump control, compared with other forms of actuation and potential improvements from modifications to the hydraulic circuit, such as regeneration, in simulation.
- Hardware implementation and performance evaluation for various efficiency improvements in a functional human scale system.

Also, in order to have a simple and intuitive interface and allow the caretaker to focus on the patient, the higher level control algorithms need to manage certain aspects and prevent undesirable conditions, such as preventing tipping, limiting interaction forces, coordinating DOFs, managing redundancy, adapting to varying patient weights, and compensating for oscillation.

A. **Achievements**

<u>Achievements in Previous Years</u>

Needs Assessment

A needs assessment was performed, including input from all major stakeholders. Individual interviews and a focus group were held with a range of users: clinicians, home caregivers, and patients. Engineers and salespeople in the lift device industry and a nursing home administrator were also interviewed. A set of benchmark operator experiments was performed using current market lifts, utilizing a task analysis and time study developed by NCAT (3A.3). More details can be found in [4]. The assessment indicated several primary needed improvements over current market patient lifts, as described earlier.

Hardware, Modeling and System Integration

In past years, the first two degrees of freedom of the machine were fabricated, the main lifting scissor and the horizontal boom extension. The machine was designed to meet a set of key design requirements, and the concept design was reviewed in a design review meeting, which included experts in fluid power, human factors, current market patient lifts, and others stakeholders. Each actuator is powered by a separate reversible brushed DC motor and a small hydraulic bidirectional gear pump; for actuator feedback control, the control input is a reference signal to the servo drive, operating in current control mode. Available measurements include electric motor current and voltage, actuator pressure and position, and various measurements of forces and proximity to obstacles. Feedback control is implemented on a real time NI CompactRIO. All power, control and actuation are onboard. A schematic and an image of the associated physical components for the horizontal boom actuation system are shown in Figure 1. The hardware system is described in detail in [5].

Figure 1. Boom extension actuation system

Caretaker Interface Design

The caretaker interface and control for this machine present significant challenges. The machine must be safely and easily operable by a single caregiver with one hand. A coordinated rate control scheme has been implemented on all four degrees of freedom, using an operator input from a force sensing handle mounted near the patient. This provides capability for the operator to simultaneously control the machine while fine tuning patient position/orientation by hand.

Achievements in the Past Year

Hardware, Modeling and System Integration

The current first prototype hardware system has four actuated degrees of freedom (DOFs), a main lifting scissor, a horizontal boom extension, and two differential drive wheels (Figure 2). The focus of the work has been on the actuation, control and operator interface design; the overall mechanical design is not yet optimized. The prototype device was made with a larger frame and scissors for modularity and ease of component integration. A set of differential drive wheels has been added, which utilize the same electro-hydraulic pump controlled actuation as the other two degrees of freedom. Initially, a test cart was built for implementing and evaluating various wheel control designs. The cart included the full actuation and control system, force sensing operator input, wheels, ultrasonic sensors for obstacle avoidance, and a National Instruments single board Rio for control. After the wheel control testing on the test cart was complete, the cart was disassembled in order to be transferred to the main machine. At this stage, the wheels have now been mounted on the full machine, and integration of the electronics and control is in process.

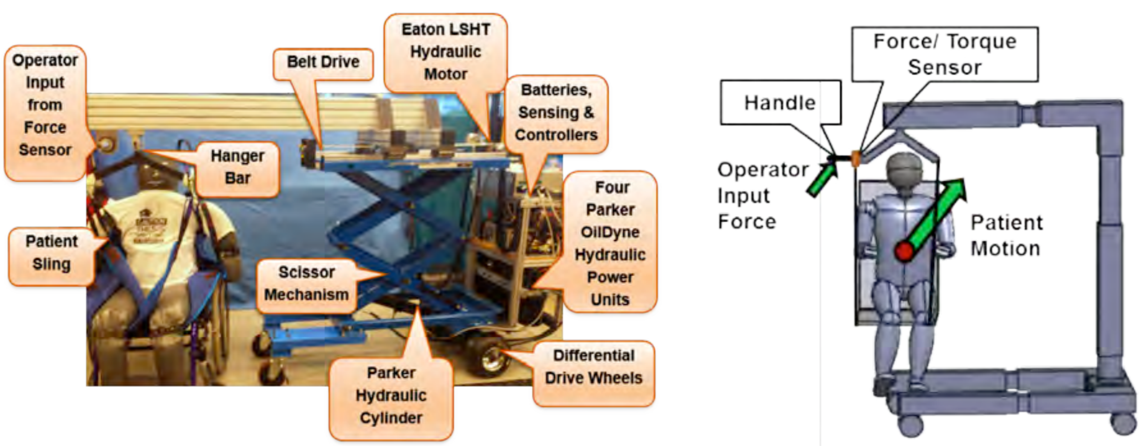

Figure 2. First prototype patient transfer assist device with powered wheels

Control and Caretaker Interface

The control and caretaker interface design has been the main research focus in the past year. Several versions of advanced algorithms to manage any potential environment interaction while also controlling motion have been implemented on all four degrees of freedom of the machine.

Wheel Control

Also, for the mobile base, an obstacle avoidance algorithm has been developed, implemented and tested on the separate wheel test cart, using ultrasonic sensors for proximity sensing. The force sensing operator input maps to a desired velocity in free space. The control scheme utilizes twelve ultrasonic sensors to measure proximity to obstacles in the environment. The algorithm computes a virtual force field, such that the closer it is to an obstacle, the higher the operator input force required to make it move in that direction. Preliminary operator experiments were performed using the wheeled base obstacle avoidance.

Interaction Control

To help ensure safety and effective control with such a powerful device working in a relatively delicate and unstructured environment, and with both the caregiver and patient in the workspace, a form of interaction control to manage external interaction forces is needed. For example, in the difficult case of a car transfer, the machine needs to get as close as possible to the car frame and the patient's head, moving in a very constricted space, while holding up the patient's weight and applying only minimal forces to its environment. Several types of interaction control have been investigated. Forms of impedance control were implemented and tested on the current prototype PTAD [4], which aim to control the machine output impedance, or the relation between any external interaction forces and velocity [6]. Impedance control is often used in machines that work with humans in the workspace. In systems with such high intrinsic stiffness as hydraulics, feedback of external forces is needed [7], but in high speed collisions, control of interaction forces is limited by the speed of response to measured external forces. So an additional virtual force term based on a proximity measurement was added to the impedance control framework to provide earlier information about potential collisions. Sensing both force and proximity provides redundancy and gives the operator the ability to maximize utilization of the restricted environment, and even push lightly against obstacles.

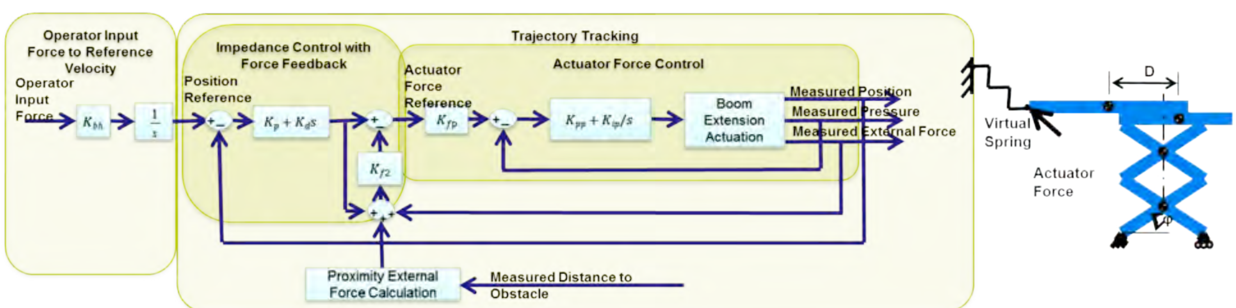

Figure 3. Interaction control; left: current impedance control with proximity based virtual force implementation on boom extension, right: interaction concept of virtual spring in task space

This impedance control framework with an additional proximity-based virtual force feedback term was implemented and tested on the horizontal boom extension, with software and human inputs [8]. Experiments were performed with a stiff obstacle in the path of the boom, and the resulting collision forces were measured. The experiment was performed four times with the same controller, with the following forms of force feedback: none, only proximity-based virtual force, only measured external force, and both proximity and measured external force. As shown in Figure 4, the collision force is reduced by more than 60% using either measured external force or measured proximity and by more than 85% using both measurements, all while maintaining sufficient tracking performance in free space. Early in the project, a passivity based human power amplifier controller was also implemented on a pre-prototype hydraulic lift device and tested with human operators, based on work from Dr. Perry Li's project 3A.2 [9], and published in [10].

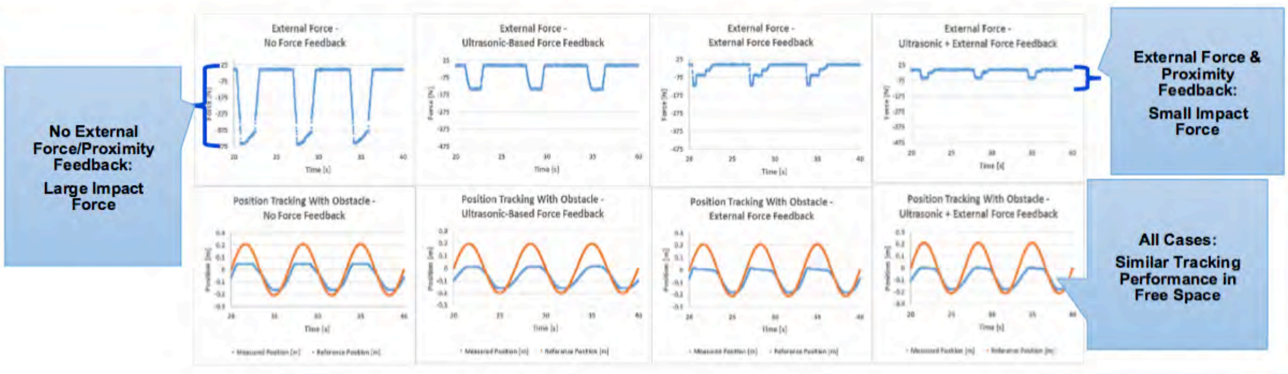

Figure 4: Boom extension interaction control experiment results: impedance control with additional proximity-based virtual force term.

Implementation of a similar form of impedance control is underway on the main lifting scissor. Preliminary experiments show significant reductions in forces applied to the environment using the impedance control. The lifting scissor presents several additional challenges in this control approach. First, the forces involved in the lifting operation are much larger, and the controller must account for gravitational loads from the machine itself and the patient payload. The conversion between task space and actuator space is more complex. And the circuit is designed to be powered off and held in place by check valves when the machine is not moving in order to prevent damage to the electric motor; this must be accounted for in the controller. All control algorithms have been integrated into an operator control from the force sensing handle. Further improvements on the impedance control are underway on the main lifting scissor, and preliminary results show significant reductions in external interaction forces. Integration of the wheels and their actuation and control into the main PTAD is also underway; the wheels and their actuation systems have been integrated into the full hardware assembly, and integration of the electrical and software subsystems are in process.

B. **Plans**

<u>Plans for the Next Year</u>

System Integration and Modeling

Integration of all four DOFs and their associated controllers is expected to be complete in early spring 2016, within the next two months. The impedance control algorithm with proximity based virtual force feedback will be tested on the lifting scissor, and further testing on the similar algorithm for the horizontal boom extension will also be tested. Some changes to the original proposed timeline have occurred. The proximity based virtual force feedback has been added to the research plan, while setbacks have occurred in the areas of force estimation from pressure measurements and unexpected corruption of some National Instruments software. System integration and operator tests will be performed before the end of the current funding cycle.

Operator Interface and Control Design and Testing

A first set of operator experiments is planned for late spring, which will involve a set of transfer operations between a bed, chair and couch, similar to a set of benchmark experiments performed earlier. The results will be statistically analyzed, and any needed modifications to the operator interface that are revealed during testing will be made.

Longer Term Vision

A first prototype electrohydraulic PTAD with human-interactive control has been developed; it is now possible to capitalize on this opportunity to analyze efficiencies of hydraulic circuits, test various CCEFP component projects, improve operator interface and control designs, and make steps toward a commercializable device. These developments can also be utilized in human-collaborative hydraulic machines to assist workers with complex maneuvers of heavy materials in industrial and construction applications. In later stages, more thorough human operator testing will be performed, and any resulting issues will be addressed. Also, a study on efficiency of the electro-hydraulic pump control system will be performed, with hardware implementation of efficiency improvements such as energy recovery and storage and alternative hydraulic circuits. Limitations of the current mechanical design will be assessed and alternatives proposed and studied for feasibility. Steps toward a commercializable device will be made with cognizance of cost limitations for the consumer.

Expected milestones and deliverables

- Testing of impedance control with proximity based external force feedback performed on main lifting scissor and horizontal boom extension [Month 21]
- Hardware and software integration of wheels with main lifting scissor and horizontal boom extension completed [Month 22]
- First round of human operator studies completed [Month 23]
- Statistical analyses for operator experiments completed [Month 23]
- Final reporting and journal publication [Month 24]

C. **Member Company Benefits**

This project provides several potential benefits to member companies. It exemplifies a significant market need where fluid power technology can be utilized, to expand the use of fluid power in home and healthcare applications. This has potential to combat any negative perceptions of fluid power in these areas (e.g. noisy, leaky, unsafe, etc.), paving a way for further expansion into these domains. It also provides an opportunity to develop more effective operator interface concepts for multiple degrees of freedom that work well with humans in the workspace. Furthermore, it is expected to demonstrate methods for effective small scale closed loop electro-hydraulic pump control from electric motors. The methods developed in this research present marketing opportunities for applications in a range of types of machines, such as human-collaborative robots for maneuvering heavy materials in industrial and construction applications.

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

Research Team

Project Leader:	Prof. Elizabeth Hsiao-Wecksler, MechSE UIUC;
Other Faculty:	Prof. Will Durfee, ME Minnesota; Dr. Geza Kogler, Applied Physiology Georgia Tech
Graduate Students:	UIUC: Morgan Boes, Mazharul Islam, Ziming Wang, Matt Petrucci (affiliated project using PPAFO on persons with Parkinson's disease) UMN: Jicheng Xia, Brett Neubauer, Jon Nath
Undergraduate Students:	UIUC: Aaron Benjamin, Montana State University (CCEFP summer REU); UMN: Andres Campos, Karen Gu, Kim Gustafson, Tyler Matijevich (REU)
Industrial Partner(s):	Parker Hannifin

1. Statement of Testbed Goals

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

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

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

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

2. Project Role in Support of Strategic Plan

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

3. Test Bed Description

A. Description and explanation of research approach

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.

Powered AFO 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 < 400 g and provide ideally 50% of normal healthy ankle torque (35-50 Nm; 70-100 Nm would be needed for an 85 kg adult) at a reasonable efficiency. The structural shell must weigh < 500 g, be wearable within a standard pair of slacks (fit inside a cylinder with 18 cm OD), and operate in direct contact with the body. The control system must control the deceleration of the foot at the start of stance, permit free ankle plantarflexion up to mid stance, generate a propulsive torque at terminal stance, and block plantarflexion during swing to prevent foot drop; all in a robust and user friendly manner.

B. Achievements

Portable Pneumatic AFO (PPAFO) UIUC

During 2015, we worked on issues related to runtime efficiency, increased torque output, systems control, and clinical application.

To address runtime efficiency, we evaluated the use of fixed volume compressed gas tanks with carbon dioxide or nitrogen as fuel [1]. A test bench model of the PPAFO and walking trials (treadmill and over-ground) were used to evaluate each tank and gas, investigating normalized run time, minimum tank temperature, and rate of cooling. The CO_2 tanks had much colder minimum temperatures (-53C vs. 8C), much faster rates of cooling (-9C/min vs. -1C/min), and shorter runtimes (1.1 min/oz vs. 1.4 min/oz) than the N_2 tanks. However, the benefits of CO_2 are the commercial availability of refilling the tanks, lighter weight tanks, and the relatively low tank cost compared to high pressure air (HPA) tanks needed for compressed N_2.

To address increased torque output, we further optimized the Gen 3 design (figure 1), which replaced the dual-vane bidirectional rotary actuator with dual linear actuators and gear train [2]. Although the overall weight increased 20% compared with previous design (680 vs. 560 g), it is capable of generating 190% more torque (32 vs. 11 Nm @ 110 psig) which can now enable us to test the system at various torque settings. The current design also had a significant reduction in lateral profile (7.9 vs. 4.3 cm). Decreasing lateral profile enables the possibility of fitting inside the wearer's pants, as well as reducing the risk of interfering with the surrounding environment. The new system has only been tested on a bench; subject testing is needed to evaluate torque and power performance during walking.

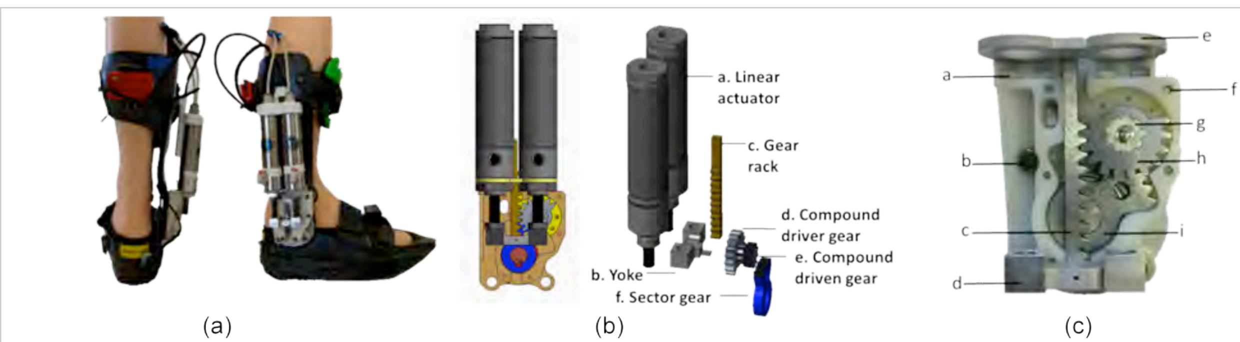

Figure 1: Gen 3 PPAFO (a) prototype, (b) CAD renderings of actuation system, (c) printed compact

To address control of the PPAFO, we have examined different actuation-timing control strategies, and recognition different gait modes (stairs/ramps/level). Two studies that addressed actuation control were completed. In the first study, two improved and reliable state estimators (Modified Fractional Time (MFT) and Artificial Neural Network (ANN)) were proposed to for identifying when the limb with the PPAFO was at a certain percentage of the gait cycle or gait state [3-5]. A correct estimation of gait state will assist with detecting specific gait events more accurately. Their performance was compared to our previously developed Fractional Time state estimator. The MFT estimator is recommended for research work if compactness and energy consumption of the device are critical concerns. Properly timed control of powered assistance during walking is a crucial task to prevent tripping or fall risk. In the second study, a supervised learner algorithm to classify the appropriate start timing for plantarflexor actuation was proposed [3, 6]. This classifier algorithm was able to determine the optimal actuation timing that best matched healthy ankle joint kinematics with high accuracy (average error of <1% of a gait cycle) and after 5 to 6 30s walking trials. Previous optimization methods based on minimizing metabolic cost typically require 10s of minutes. Another study used Bayesian regularized artificial neural networks with an added inertial measurement unit (IMU) sensor to improve our previous gait mode recognition algorithm [3].

Clinical studies with the Gen 2 PPAFO were completed. We finished a study on 16 subjects with moderate to severe multiple sclerosis (MS) [1, 7]. PPAFO use did not overcome gait impairment. Yet, the PPAFO did not negatively impact O2 cost of walking or joint kinematics. The hypothesized impact was not realized and could be due to any number of factors, such as a need for more training and experience walking with the PPAFO, fatigue, or a need for improved device design. In an associated project with collaborators in Neurology at the U Minnesota, we concluded a study to the use of the PPAFO as a gait initiation device for people with Parkinson's disease (PD) [8]. Results suggested that modest mechanical assistance at the ankle could enhance diminished or absent force production and lateral weight shift while preparing for the start of a step in people with PD and symptoms of freezing of gait.

Hydraulic AFO (HAFO) UMN

During 2015 efforts on the HAFO centered on (1) furthering our system level modeling work to predict weight and efficiency of small hydraulic systems and (2) using these principals to drive the preliminary design of a second generation HAFO that can be worn by children (figure 2).

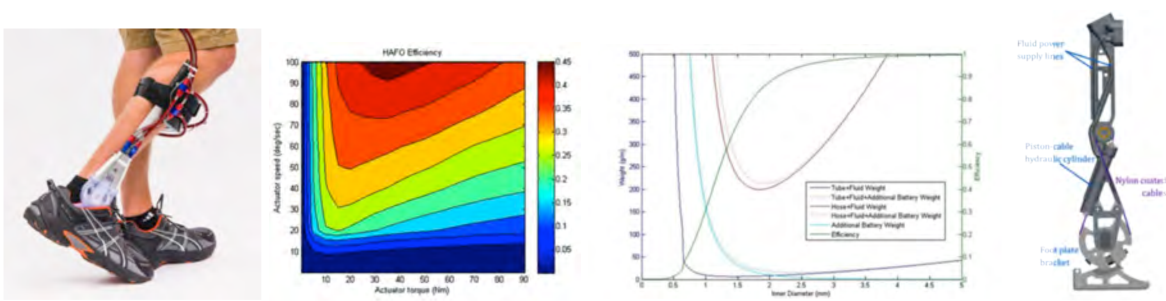

Figure 2: Left to right: (a) Generation 1 HAFO. (b) Simulation of steady state system efficiency as a function of output torque and velocity. (c) Prediction of system weight as a function of hose diameter, taking efficiency into account. (d) Rendering of actuator component of child-size HAFO, to be 3D printed in titanium.

Using analytical models for each component of the HAFO we extended our previous work on weight and efficiency analysis from just the actuator and hose to the complete system including battery, electric motor and pump [11]. More recently we extended the model from static operating conditions to a fully dynamic model so that efficiency over an operating cycle can be examined. Part c of the figure above shows one example of a system level analysis. As the hose diameter decreases, the hose weight goes down but pressure loss across the hose goes up and system efficiency goes down requiring a heavier battery for equal run time. As hose diameter increases, efficiency goes up and a lighter battery is needed, although the hose and the oil contained in the hose is heavier. As shown in the chart, the minimum system weight occurs at a hose diameter of about 2 mm.

In 2015 we started an associated TB6 project which involves applying the HAFO to study walking in children with cerebral palsy, a collaborative project with Gillette Children's Medical Center in St. Paul MN. This means creating an HAFO that can be worn by children ages 8 to 11. Our goal is to cut the HAFO weight by 50%. The key technology for doing this is 3D printed titanium parts with internal fluid passageways and integrated cylinders. The prototype concept is shown in part d of the figure. This furthers the goal of creating lightweight wearable robots powered by hydraulics. Our intent is to use the project as a vehicle for developing design guides for creating hydraulic systems using metal additive manufacturing.

Publications: During 2015, work associated with the PPAFO in Testbed 6 resulted in 8 conference papers or abstracts [2, 4-10]. It will also result in 3 PhD dissertations [1, 3, Petrucci] and 1 MS thesis [Wang] in 2016.The HAFO project resulted in 1 PhD dissertation [12].

Plans, Milestones and Deliverables for Next Year

PPAFO: Implement higher torque Gen 3.0 PPAFO in walking studies. Explore state estimation algorithms that minimize number of sensors needed: currently 3 sensors (heel contact, toe contact, ankle angle); investigating 2 (IMU, 1 heel contact). Explore development of new lighter weight AFO design.

HAFO: Complete system level modeling. Complete the child-size HAFO. Start a new thrust to reduce by 50% the weight of the wearable hydraulic power supply by integrating components and using additive manufacturing.

Plans, Milestones and Deliverables for Next Two-Five Years

PPAFO: Explore development of new lighter weight AFO design. Explore use of soft fiber re-enforced elastomeric enclosure (FREE) actuators for new orthotic and exoskeleton design applications.

HAFO: Continue to develop new guidelines for lightweight, integrated component wearable hydraulic robots using additive manufacturing. Understand and implement systems controlled by pump control and by servovalve control examining performance, weight and efficiency tradeoffs.

C. Member company benefits

New technologies that miniaturize current components such as power sources, actuators, and valves will be developed. This could spawn new markets for miniature fluid power systems.

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CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

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

CCEFP Y10 Thrusts, Projects and Program Objectives	Participant Level	Promote STEM learning to diverse people	Promote awareness of fluid power	Fluid power dissemination	Culture of research and education integration	Increase fluid power workforce	Strengthen ties between higher ed and industry
Thrust A: Public Outreach -- Bringing the message of fluid power to the general public							
A.1 Interactive Fluid Power Exhibits	All	■	■		■		■
Thrust B: Outreach – Bringing fluid power education to K12 students with a focus on middle and high school							
B.7 NFPA Fluid Power Challenge Competition	K12	■	■			■	■
Thrust C: College Education – Bringing fluid power education to undergraduate and graduate students							
C.1 CCEFP REU Program	BS	■	■	■	■	■	
C.4 Fluid Power in Courses, Curriculum and Capstones	BS, MS	■	■	■	■	■	■
C.4B Parker Hannifin Chainless Challenge	BS	■	■	■	■	■	■
C.8 CCEFP Student Leadership Council	MS, PhD		■		■	■	■
Affiliated Project: Excavator Cab Design Competition	BS		■			■	
Thrust D: Industry Engagement – Making connections between CCEFP and industry							
D.1 Fluid Power Scholars Program	BS	■	■			■	■
D.2 CCEFP Engagement Programs	All		■	■	■	■	■
D.5 CCEFP Webinar Series	All		■	■	■	■	■
Thrust E: Program Assessment and Impact							

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 all diverse citizens to navigate the STEM pathway in order to expand and promote a talented STEM workforce.
2. Promote awareness and excitement of fluid power among technical college, undergraduate and graduate students.
3. Disseminate fluid power fundamentals, research, and innovation through evaluated fluid power curricula, projects and programs that highlight fluid power concepts and applications.
4. Create a culture that integrates research and education for technical college, undergraduate and graduate students, as well as industry professionals across CCEFP and NFPA partner institutions
5. Increase the number of students well prepared to pursue fluid power research, jobs and careers.
6. Strengthen ties between higher education and the fluid power industry.

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, those with disabilities and recent war veterans. 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.

Administration of the Education and Outreach Program: The E&O Program is lead and coordinated by Education Program Director James Van De Ven and Education and Administrative Director Alyssa Burger. The Directors report to CCEFP Director Kim Stelson. Additionally, Principal Investigators of specific projects contribute to program direction and implementation. Responsibility for fluid power education and outreach rests with every CCEFP participant. CCEFP research and test bed projects are considered a method of education and workforce development. The E&O activities of individual research projects are reported in the project update reports.

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 Museum of Minnesota (SMM) is creating, field-testing and displaying exhibits that demonstrate basic attributes of fluid power and highlight CCEFP research. Fluid Power exhibits currently on display at SMM include an axial piston pump, hydraulic hybrid car, hydraulic transmission, super-mileage car, pneumatic ball chase 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 also includes a mentoring component 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. Prototypes developed by graduating seniors will be further developed by SMM staff to be incorporated into the Experiment Gallery, for permanent display, at the Science Museum of Minnesota.

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.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. During the two day event, 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 and finally compete. After the initial workshop day, 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. On Competition Day, the students return 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.

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 C.4 Fluid Power in Engineering Courses, Curriculum and Capstones To provide a strategy and goals for 1) developing new, semester-length undergraduate and graduate courses in fluid power, and include substantial content on fluid power in existing undergraduate and graduate courses; 2) developing curriculum modules and tools for broad dissemination; 3) leverage industry supporters to sponsor capstone design projects with fluid power content.

C.4b Parker Hannifin Chainless Challenge In partnership with the National Fluid Power Association (NFPA), CCEFP plays a coordinating and sponsorship role in this program. The Parker Hannifin Chainless Challenge is an engineering design competition for undergraduates to design and create the most efficient and effective human-assisted green energy vehicle. The students are required to design and build the drive system for their vehicles, as well as participate in the final demonstration competition. They can utilize either off-the-shelf components provided by Parker Hannifin or design their own. The demonstration event includes a judging criterion, a straight sprint race, and distance/performance race. This final event is conducted over a two day period. Cash awards were given to the winning team in each specified category.

Project C.8 Student Leadership Council (SLC) The Student Leadership Council is an independent board of the CCEFP. The SLC's current and proposed activities support the education and outreach program of the Center and impact all students within the CCEFP. The SLC is managing a travel 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 webinar program, and provide recommendations and guidance for other Center programs including a student retreat and various networking opportunities with industry.

Affiliated Project Additive Manufactured Excavator Cab Design Competition The Additive Manufactured Excavator Cab Design Competition has one goal -- to design and print a futuristic excavator cab and human-machine interface. The CCEFP is motivated to enlist student engineering teams from across the country to propose an aesthetic and functional design. Additive (3D) manufacturing stands to revolutionize the way things are designed and produced in the not-so-distant future. Raising awareness of advancements in technology to the next generation of engineers is of utmost importance. A panel of industry experts will judge the competition; the winning team will receive a $2,000 cash prize, sponsored by NFPA, and will be offered the opportunity to travel to Oak Ridge National Laboratory (ORNL) in Tennessee to observe the printing of the selected design. Y10 project only.

THRUST D: INDUSTRY ENGAGEMENT

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 Program 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 Fluid Power Scholars/Intern program and launched it in the summer of 2010. Fluid Power Scholars/Interns receive a scholarship to an intensive three and one half-day instructional program in fluid power, taught at the Milwaukee School of Engineering's Fluid Power Institute, and then join a corporate supporter of the CCEFP for a paid summer internship. [Project Leader: Alyssa Burger, CCEFP]

Project D.2 CCEFP Engagement The Fluid Power Innovation and Research Conference (FPIRC) and the Industry Summits exist to provide industry supporters and CCEFP students with opportunities to network. 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 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 D.5 CCEFP Webinar Series The CCEFP hosts monthly webinars on research, education or administrative topics. The webinars are open to the public. The webinars are an important means for Center-wide communication and knowledge transfer.

THRUST E: PROGRAM ASSESSMENT AND IMPACT

The purpose of the assessment and impact analysis 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.

Graduated E&O Programs and Projects

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

Project A.3 Multimedia Educational Materials. The CCEFP leverages the use of multimedia to inform, train, educate and interest the general public in fluid power technology. Utilizing audiovisual 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 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.1 Research Experiences for Teachers (RET). As a part of the National Science Foundation's RET program aimed at improving science, technology, engineering and mathematics (STEM) education, the CCEFP's RET program enables teachers in pre-college schools to introduce fluid power to their students, drawing on their summer-long experiences in CCEFP research labs. A special CCEFP RET focus is recruiting teachers from high schools participating in the Project Lead The Way program.

Project 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. The newest cooperative effort in this partnership is the development of a fluid power simulator.

Project B.3 Hands-On Fluid Power Workshops. Fluid power is most easily understood by students of all ages when accompanied by hands-on experiments. Targeted audiences for the workshops, all of whom can lead various student groups in these learning experiences, include CCEFP faculty and students, SMM staff, CCEFP industry member engineers and technical college and pre-college classroom teachers.

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. Workshops and kits will be disseminated nationwide through engineers from CCEFP member companies and CCEFP faculty.

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.

Project B.4 gidaa STEM Programs. The gidaa K-12 STEM Camps are offered for students in 3rd through 10th grade. Offered as a day-camp, once per month, the camps provide students with a mix of lab science and field science experiences. Program highlights include an introduction to the scientific method and a focus on Native American Indian culture. The gidaa K-12 Robotics Program is offered day and after-school for interested students at South Ridge (K12 school within the Fond du Lac reservation) and Cloquet Middle and High School, Cloquet, MN. South Ridge hosts the only regional RoboFest Competition in the state.

Project 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. 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 C.2 Fluid Power College Level Curriculum. The purpose of the Fluid Power College Level Curriculum project is to create, digitally publish, disseminate and use high quality college level teaching materials in fluid power.

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.

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.

C.4a Capstone Senior Design Project: A Third-Generation Pneumatic Rotary Actuator Driven by Planetary Gear Train. The primary educational impact of this project is to expose a team of undergraduate engineering students to concepts of fluid power design, specifically rotary torque generation using a pneumatic power source. All of the students participating in the capstone design course will be exposed to fluid power issues as they participate in the gated review process which includes four oral progress report presentations by the design team. The project has exposed the student teams to first-hand experiences with fluid power through pneumatic design issues such as torque generation, leakage and seals, fluid dynamics, and also thermodynamic analysis of dealing with expansion of compressed gas (CO2).

Project C.5 giiwed'anang North Star Alliance. The CCEFP launched the giiwed'anang North Star Alliance. Primary goals include student support of local AISES chapters. The project also strives to grow and nurture the student and professional regional chapters of the American Indian Science and Engineering Society (AISES).

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 C.9/10 Research Diversity Supplements (RDS). The Center's Education and Outreach program is committed to providing opportunities to broaden the participation of underrepresented students in undergraduate and graduate engineering programs through this Research Diversity Supplement to current CCEFP research projects.

Project 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.

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

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, 2012, 2014 and 2015 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 seventh (2014) was an exhibit that let visitors compare two forms of air compression – adiabatic and isothermal. 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. The seventh is now undergoing modifications to make it suitable for long term display. Plans for this coming year include a new Capstone project that will focus on introducing visitors to a liquid piston Stirling Engine.

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.

Spring of 2014. 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. In this case, it will focus on efficient compression of air for energy storage.

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.

Spring of 2015. 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. SMM will construct at least one exhibit to complement the product of the Capstone Design team.

Figure 1: Hydraulic Hybrid Car

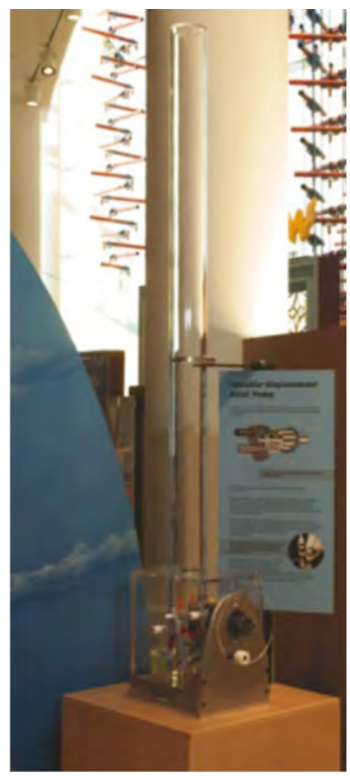


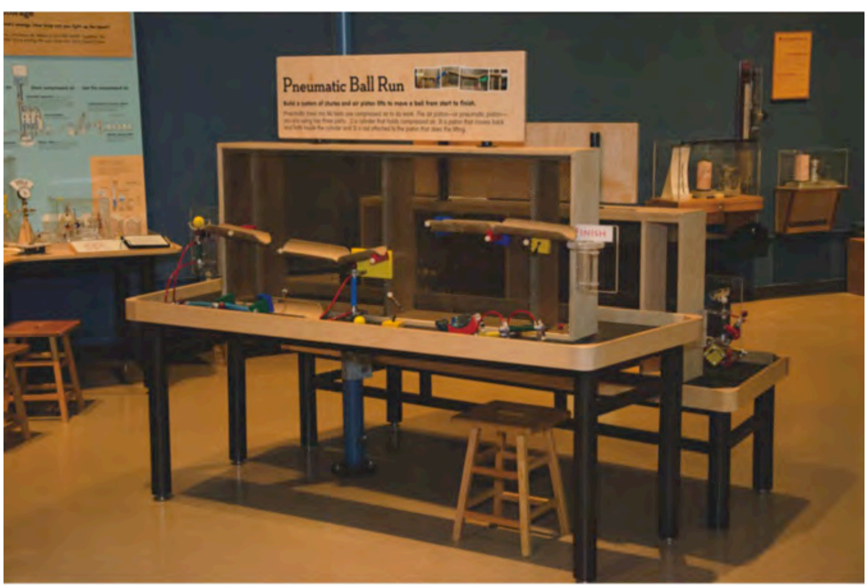
Figure 2: Axial Piston Pump

Figure 3: Hydraulics Lab (Left)

Figure 4: Hydraulics Lab Touch Screen Instructions (Above)

Figure 5: Simple Hydraulic Circuits

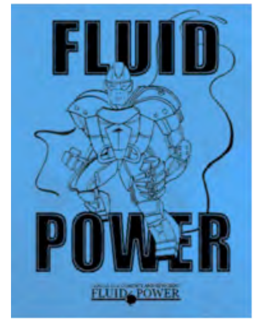
Figures 6 - 7: Compressed Air Wind Energy Storage



Figures 8: Pneumatic Ball Run

EO Project B.7 Fluid Power Challenge Competition

1. Project Goals and Description



The Fluid Power Challenge, offered and promoted by the National Fluid Power Association (NFPA), is an event for eighth grade students to learn how to solve an engineering problem using fluid power. The event is two days. The first - 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, and learn engineering design principles and strategy. The students return to their schools to work in teams to design and build their fluid power device, along with documenting their plans in a portfolio. A little over 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

- The CCEFP has successfully hosted nine Fluid Power Challenge Competitions at three of our partner institutions – University of Minnesota, Purdue University and Georgia Institute of Technology. Milwaukee School of Engineering regularly offers the program, however, not sponsored by the CCEFP. MSOE was the host to the very first Fluid Power Challenge.

- Over 2,000 middle school students have participated in CCEFP Fluid Power Challenge events.

- CCEFP graduate students are the technical facilitators of the events.

- The CCEFP was granted a $10,000 award in 2014-2015 from the National Fluid Power Association to launch two new competitions at Purdue and GeorgiaTech.

- Industry supporters regularly donate funds to sponsor the event.

- Listen to what students have to say about the Fluid Power Challenge: https://www.youtube.com/watch?v=4yp7svoHB0Y

- Most teachers recruited to participate are Project Lead The Way (PLTW) teachers who have a fluid power module in their PLTW Principles of Engineering curriculum.

- Typically, over half of the 8th grade student participants are female. Secondly, by observation, a highly diverse student body.

Highlights

- CCEFP hosted Fluid Power Challenge events at University of Minnesota (21 teams) , Georgia Institute of Technology (20 teams) and Purdue University (15 teams). Nearly 300 students and teachers participated in events hosted by CCEFP in 2015/2016.

- In 2015/2016 the CCEFP served as a mentor to two start-up competitions in Minnesota – at Hennepin Technical and Community College and Alexandria Technical and Community College.

- Nearly $5,000 in sponsorship was raised through university and industry sponsorship.

- Event coordinators at Purdue University have partnered with Purdue Extension / 4-H office to recruit participants and expand the program across Indiana.

- CCEFP and NFPA leadership met with the Associate Dean of University of Minnesota Extension Youth Development Program to explore opportunities to incorporate fluid power and the challenge into their Rube Goldberg Engineering Design Competition.

- CCEFP headquarters created an online best practices manual for other host sites to utilize.

- 2014/2015 NFPA provided a $10,000 sponsorship for the launch of two additional events this year. Other companies (listed above) provided $3,500 in corporate sponsorship.

- 2014/2015 UMN recruited 22 teams, over 90 8th grade students and GT recruited 18 teams, just over 80 students. PU's goal is 20 teams. Yearly goal of 300+ students and teachers impacted by the event and introduced to fluid power technology, engineering design and teamwork.

- 2014/2015 Fluid Power Challenge student participants share their excitement over the competition: https://www.youtube.com/watch?v=4yp7svoHB0Y

- In early 2013, a local news station, NBC's KARE 11 highlighted the Fluid Power Challenge on their 5 pm newscast. It can be viewed at YouTube: http://www.youtube.com/watch?v=_IdvGyWxnTo.

4. Plans

In CCEFP's state of transition, post NSF-funding, the Center does not have core support to host the program. Rather, CCEFP will work with the National Fluid Power Association to identify a corporate candidate to adopt the program in a location geographically situated. CCEFP faculty, staff and graduate students can assist in the coordination and facilitation of future events held at an industry partner location.

- Shift hosting of the event at UMN, PU and GT to a corporate supporter

5. Milestones and Deliverables?

- Shift hosting of the event at UMN, PU and GT to a corporate supporter

6. Member Company Benefits

The 2015-2016 Fluid Power Challenge corporate sponsors include Eaton Corporation, FORCE America, Bosch Rexroth, National Fluid Power Association (NFPA), University of Minnesota's College of Science and Engineering and Department of Mechanical Engineering. This program is closely aligned with industry's hope for and support of efforts that prepare for a talented and diverse pool of leaders in academia and in our future workforce.

Project Team

Project Leader: Alyssa A. Burger, Education Outreach Director

Other Personnel:
Don Haney, Communications Director
Ben Adams, Post Doc, Mechanical Engineering, University of Minnesota
Alex Yudell and Ryan Han, Graduate Students, University of Minnesota
Jose Garcia, faculty, Purdue University
Erika Bennett, staff, Purdue University
Michael Leamy, faculty, Georgia Institute of Technology
Christine Esposito, staff, Georgia Institute of Technology
Justin Wilbanks, Graduate Student, Georgia Institute of Technology

Industrial Partner:
FORCE America
Eaton Corporation
Bosch Rexroth
National Fluid Power Association (NFPA)
University of Minnesota’s College of Science and Engineering
University of Minnesota’s Department of Mechanical Engineering

UMN Fluid Power Challenge

GT Fluid Power Challenge

EO Project C.1: Research Experiences for Undergraduates (REU)

1. Project Goals

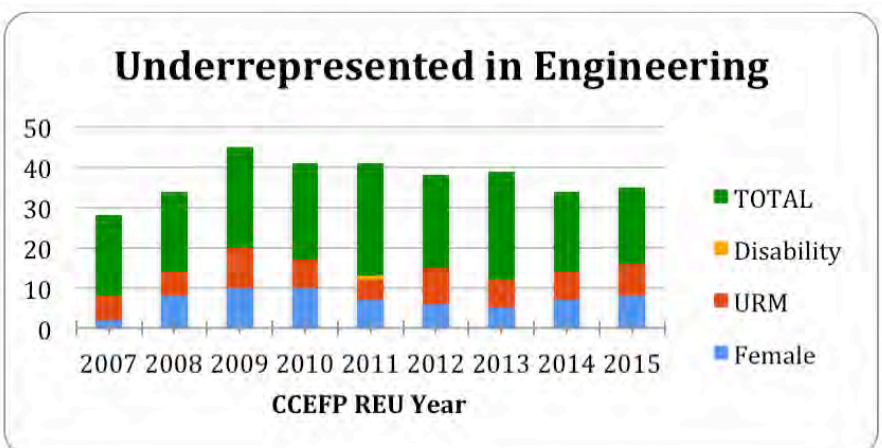
The CCEFP Research Experiences for Undergraduates (REU) program is designed to exposure and interest diverse students into pursuing graduate school and consider fluid power as an area of focus. The REU program is aligned with several CCEFP goals: developing research inspired, industry practice directed 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

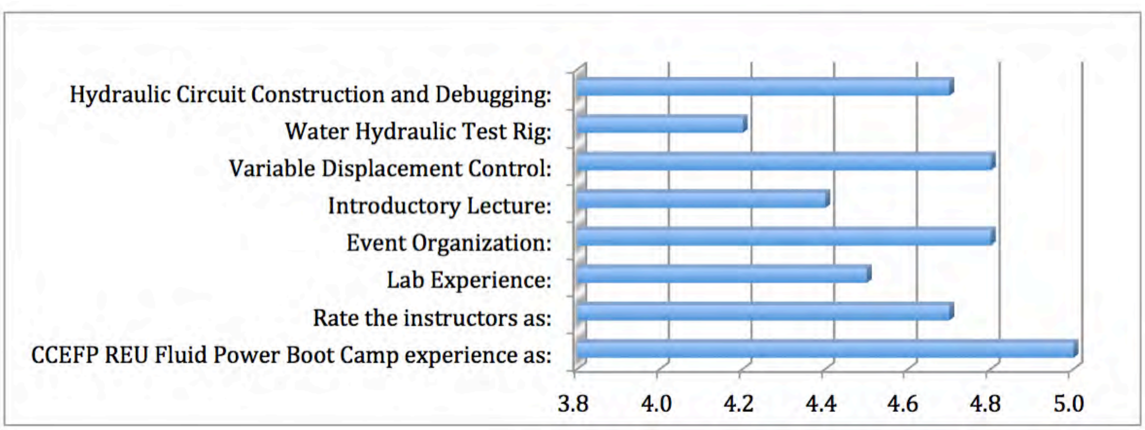
- To date, the CCEFP has hosted over 185 undergraduate students in the highly successful REU program. The CCEFP completed an internal longitudinal study of past participants in early 2014. At the time of the report, 60% of all former CCEFP undergraduate researchers enter graduate school, and 25% of those are PhD candidates. Extremely positive statistics!
- The CCEFP was granted an NSF REU Site Award for 2013 – 2015, years 8, 9 and 10 for $390,000. Subsequently, the CCEFP has applied for a new REU Site Award to provide the means to continue the program into years 11 and beyond. CCEFP does not have sufficient core funding to maintain the program in the post-NSF award years.
- 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.



2015 REU Program:

CCEFP 2015 REU Students at Fluid Power Bootcamp

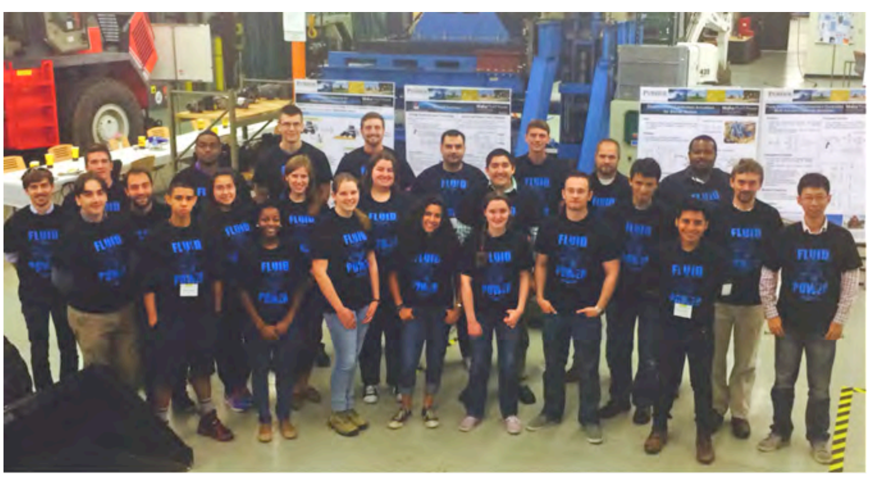
- Nineteen REU students participated in summer 2015, the ninth year of the program. Twelve of the students were recruited from outside the seven institutions of the CCEFP. These institutions include Montana State University–Bozeman, University of Wisconsin-Platteville, Binghamton State University of New York, University of Southern California, St. John's University, University of Michigan-Ann Arbor, University of California-Merced, the College of Idaho, and the University of Central Arkansas.
- Four 2015 REUs were granted travel scholarships to attend CCEFP's Fluid Power Innovation and Research Conference (FPIRC) in Chicago, IL, October 2015. All presented their research during the FPIRC Poster Show and participated in the Industry-Student Speed Meeting session. To date, two are confirmed to be offered internship positions and will be named a CCEFP Fluid Power Scholar in 2016.
- All REUs authored a successful research blog, regularly. They were incentivized by a $25 Amazon gift card to complete at least 80% of the blog topics. The archive is here: http://ccefpreu2015.blogspot.com/.
- Most REUs participated in the Fluid Power Bootcamp at Purdue University, lead by over 10 faculty and graduate student lecturers and laboratory leaders. The bootcamp is coordinated and orchestrated by Professor Andrea Vacca, Purdue University.
  - Results of the 2015 Fluid Power Bootcamp survey: Overall experience rated a 5.0/5.0 scale.




2015 REU Bootcamp at Purdue University

2014 REU Program:

- Twenty REU students participated in summer 2014, the eighth year of the program. Thirteen of the students were recruited from outside the CCEFP seven institutions.
- Four 2014 REU and one 2013 REU attended the CCEFP's Fluid Power Innovation and Research Conference 2014 (FPIRC14) at Vanderbilt University in Nashville, TN, where they participated and presented their research at the FPIRC14 Poster Show and Competition. One REU, an undergraduate from North Carolina A&T State University, won the overall 1st Place Prize of $500.
- All REUs participated in the Fluid Power Bootcamp at Purdue University, lead by over 10 faculty and graduate student lecturers and laboratory leaders. Given the experience from the previous three years, Professor Andrea Vacca, Purdue University, continues to improve upon the instruction.
- The 2014 REU program hosted a successful research blog, in which all REU students contributed to, regularly. They were incentivized by a $25 Amazon gift card to complete at least 80% of the blog topics.
- The 2014 REU Program held a diverse professional development webcast series. Topics included: Everything You Needed to Know About Graduate School; Everything You Needed to Know about How to Get a Job in Industry; Everything You Need to Know About How to Present Research; Everything You Need to Know about Research and Ethics, among other special topics given by CCEFP industry members.


2014 REU at Purdue Fluid Power Bootcamp

4. Plans, Milestones and Deliverables

- An NSF REU Site Proposal was successfully submitted August 2015 to support the CCEFP REU Program in Years 11, 12 and 13.
- If the NSF REU Site Award is successful, the Center is committed to host 10-14 REU students each summer. Students will participate in the Fluid Power Bootcamp at Purdue University.
- 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 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.

Project Team

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

Other Personnel: CCEFP REU faculty advisors
CCEFP REU graduate student mentors

EO Project C.4: Fluid Power in Engineering Courses, Curriculum and Capstones

1. Statement of Project Goals

To provide a strategy and goals for 1) developing new, semester-length undergraduate and graduate courses in fluid power, and include substantial content on fluid power in existing undergraduate and graduate courses; 2) developing curriculum modules and tools for broad dissemination; 3) leverage industry supporters to sponsor capstone design projects with fluid power content.

Fluid Power in Engineering Courses

The expectation is that most CCEFP faculty will design new courses or find a way to insert fluid power curriculum into their courses.

Fluid Power Curriculum and Dissemination

The purpose of the Fluid Power OpenCourseWare (FPOCW) 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.

Fluid Power in Capstone Projects

All senior-level engineering students, traditionally, complete their undergraduate education with a capstone project. Utilizing this infrastructure, partnering with fluid power companies to sponsor and actively engage with students in capstone design projects with fluid power content is a natural fit. Long-term, this project may be a collaborative project with the National Fluid Power Association (NFPA).

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. A way to incorporate fluid power into standard engineering courses is not only achievable with curriculum modules and problem sets but also the most direct route towards increasing the number of engineering students trained in the basics of fluid power.

Engagement in these capstone design 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

Fluid Power in Engineering Courses:

- ABE 435: Hydraulic Control Systems. Purdue University. New 2015.
- Fundamentals of Fluid Power MOOC (Massive Open Online Course) taught by Professors James Van de Ven and William Durfee at the University of Minnesota. In this six-week online course students learn 1) the benefits and limitations of fluid power compared with other power transmission technologies, 2) the function of common hydraulic components, 3) how to formulate and analyze models of hydraulic components and circuits, and 4) how to design hydraulic circuits for specific system requirements. New Fall 2014. Offered Fall 2015.
- Problem Set for Fluid Power System Dynamics Mini-Book. CCEFP SLC. New 2012.
- Developed a Video Lecture Archive from Fluid Power Controls Laboratory. UMN. New 2012.
- INEN 371: Human Factors Engineering NCA&T University. New 2012.
- INEN 665: Human Machine Systems NCA&T University. New 2011.
- ME 271: Introduction to Robotics. Vanderbilt University. New Fall 2012.
- ABE 435: Hydraulic Control Systems. Purdue University. New Fall 2012.
- ME 310: Fundamentals of Fluid Dynamics. UIUC. New Spring 2013.
- ME 236/336: Linear Control Theory. Vanderbilt University. Fall 2010.
- ME 351: Nonlinear Control Theory. Vanderbilt University. New Spring 2013.
- ME 340: Dynamics of Mechanical Systems. UIUC.
- ME 360: Signal Processing. UIUC.
- ME 236/336: Linear Control Theory. Vanderbilt University. Fall 2010.
- ABE 460: Sensors and Process Control. Purdue University. New 2011.
- ME309: Fluid Mechanics. Purdue University. New: 2011.
- ME 4803 / ISyE 4803: Model-Based Systems Engineering. GeorgiaTech. New: 2011.
- ME 8287: Passivity & Control of Interactive Mechanical and FP Systems. UMN. New: 2011.
- ME 460: Industrial Control Systems. UIUC. New: 2011.
- ME 8287: Design and Control of Automotive Powertrain. UMN New: 2011.
- ME 4012: Motion Control. GeorgiaTech. New: 2011.
- ME 4232: Fluid Power Control Laboratory. UMN. 2012.
- INEN 371 Human Factors Engineering, INEN 665 Human Machine Systems, INEN 735 Human-Computer Interface. NCAT.
- ME 597 /ABE 591 Design and Modeling of Fluid Power Systems. Purdue.
- ME 697/ABE 691 Hydraulic Power Trains and Hybrid Systems. Purdue.
- ME 3015: System Dynamics and Control. GeorgiaTech.
- ME 234 System Dynamics. Vanderbilt.

Fluid Power Curriculum and Dissemination:

- Fundamentals of Fluid Power MOOC (Massive Open Online Course) developed and delivered on Coursera fall 2014 and 2015 by Profs. Jim Van de Ven and Will Durfee. The course used the content on the FPOCW including mini-books, problem sets, and slides.
- 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.

Fluid Power in Capstone Projects:
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.

CCEFP EO Supplemental Funding Awards:

University	Year	EO Funding	Project Title
University of Minnesota	AY13-14	CCEFP Supp Award	"Compressed Air Energy Storage Exhibit for the Science Museum of Minnesota" Advisors: J. Newlin, SMM and Jim Van de Ven, UMN
Bradley University	AY13-14	CCEFP Supp Award	"Designing new Linear pneumatic actuator for PPAFO" CCEFP Advisor: Elizabeth Hsiao-Wecksler, UIUC
Bradley University	AY12-13	CCEFP Supp Award	"A Second-Generation Pneumatic Rotary Actuator Driven by Plantery Gear Train" CCEFP Advisor: Elizabeth Hsiao-Wecksler, UIUC
GeorgiaTech	AY12-13	CCEFP Supp Award	"Noise Control Device for Plumbing" CCEFP Advisor: Kenneth Cunefare, GT
Purdue University	AY12-13	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	AY12-13	CCEFP Supp Award	UMN Parker Hannifin Chainless Challenge Capstone Team CCEFP Advisor: Brad Bohlmann, UMN
AY12-13	AY12-13	CCEFP Supp Award	UIUC Parker Hannifin Chainless Challenge Capstone Team CCEFP Advisor: Elizabeth Hsiao-Wecksler, UIUC

Capstone Projects with Other Funding Sources:

University	Year	Sponsor	Project Title
GT	AY 15-16	CCEFP and Other	Additive Manufactured Excavator Cab Design Competition
MN (x 2)	AY 15-16	CCEFP and Other	Additive Manufactured Excavator Cab Design Competition
UIUC	AY 15-16	CCEFP and Other	Additive Manufactured Excavator Cab Design Competition
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

4. Plans

Fluid power in courses, curriculum sets, capstone projects and dissemination protocols will be one of the top priorities of the emerging NFPA and CCEFP workforce development program. Plans include:

- Administer NFPA's Curriculum Grant Program, which provides two $25,000 grants to faculty willing to 1) to create awareness and engage undergraduates in fluid power, 2) to engage faculty in the development and teaching of fluid power, 3) to develop, replicate and disseminate high-quality, high-impact university level fluid power curriculum.
- Continue to encourage the incorporation of fluid power content into existing courses and to develop new lecture and lab courses in fluid power.
- Continue working on mini-books. Continue to develop problem sets, video lectures and lecture slides.
- Promote the Fluid Power OpenCourseWare, which makes it easier for instructors to include college-level fluid power material in courses.
- Encourage completion of ongoing projects to develop mini-books and develop problem sets.
    - Andrea Vacca, Purdue – Fluid Mechanics module
    - Paul Michael, MSOE – Hydraulic Fluids
    - Will Durfee and Zongxuan Sun, UMN – Fluid Power System Dynamics – revision
- 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).
- Partnership with NFPA to promote capstone design projects in fluid power to corporate supporters. 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.

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. Member companies can use the Fluid Power MOOC and/or 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. 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.4b: Parker Hannifin Chainless Challenge

1. Project Goals

In partnership with the National Fluid Power Association (NFPA), CCEFP plays a coordinating and sponsorship role in this program. The Parker Hannifin Chainless Challenge is an engineering design competition for undergraduates to design and create the most efficient and effective human-assisted green energy vehicle. The students are required to design and build the drive system for their vehicles, as well as participate in the final demonstration competition. They can utilize either off-the-shelf components provided by Parker Hannifin or design their own. The demonstration event includes a judging criterion, a straight sprint race, and distance/performance race. This final event is conducted over a two-day period. Cash awards were given to the winning team in each specified category. The goal of this project is to provide students with an opportunity to learn about fluid power, apply their knowledge to a real world open-ended design project and compete in a national competition to demonstrate their work.

2. How Project Supports the EO Program Strategy

The Challenge 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 both CCEFP and non-CCEFP schools with training and experience in fluid power (over 35 student participants).

3. Achievements

The Chainless Challenge is a two-semester commitment. In Fall semester, the students work on the project in their capstone design projects course. A team of 5-6 undergraduate students learn about fluid power, develop design specifications for their bike, complete the design, and fabricate and install their design on the bike. In Spring, the students test and optimize the bike's operation in preparation for the national competition in April.

In Y10, there are ten teams in the competition. Teams are represented by Cleveland State University, Cal Poly San Luis Obispo, University of Central Arkansas, Illinois Institute of Technology, University of Cincinnati, Purdue University, University of Illinois, Urbana-Champaign, University of Akron, Murray State University and Ohio University.

4. Plans

The Chainless Challenge is a fun and educational experience for the students and advisors. It provides a unique opportunity for students to learn about fluid power. All of the schools currently participating have found it to be a meaningful experience for their students and they plan to continue fielding teams for the competition.

The National Fluid Power Association (NFPA) has formally adopted the program from Parker Hannifin, the program's creator and original sponsor. The CCEFP has provided co-sponsorship of the program in Y10. In the future, it will be re-branded to be the NFPA Fluid Power Vehicle Challenge, sponsored and administered by the NFPA and serve as a cornerstone of the strategic university-level education strategies. The NFPA Board of Directors is incredibly supportive of the investment in this hands-on engineering program for undergraduate students.

5. Member Company Benefits

Capstone design projects are a way to connect the Center to the engineering program at a local university. The Chainless Challenge provides an in-depth exposure of students to fluid power. Even if their career path doesn't take them into the fluid power industry upon graduation, their knowledge of fluid power makes it a possible solution for the engineering challenges they will face during their career.

Project Team

Project Leader:	Sandy Harper, AirPegusus (formerly of Parker Hannifin)
Other personnel:	Alyssa Burger, University of Minnesota
Industry partners:	National Fluid Power Association (NFPA)

EO Project D.1: Fluid Power Scholars Program

1. Project Goals

The Fluid Power Scholars program is a sponsorship of an industry intern to a fluid power immersion program at the outset of the internship experience. Student participants gain hands-on experience in fluid power technology as they work as summer employees in a “real world” work environment. Sponsoring companies benefit as the students they mentor contribute to workforce productivity, often bringing new perspectives to their tasks based on what they have learned in the classroom. An internship program also provides companies with opportunities to determine whether their scholar/intern might work well as an employee following graduation. Recognizing these benefits, the CCEFP has made a good model even better by adding an intensive orientation to fluid power at the outset of the internship experience in order to enable scholar/interns to make more immediate and effective contributions to their host companies.

2. How Project Supports the EO Program Strategy

Cultivation of cooperative efforts, informed by and of benefit to the academic and corporate world of fluid power, is key to CCEFP education and outreach program strategy. The Fluid Power Scholars/Interns Program rests on partnerships between industry, the Center, and engineering students nationwide. The program also facilitates knowledge transfer between Center constituents--from the classroom to the shop floor.

3. Achievements

Drawing upon three years of an established program, yet still convinced there was a more efficient way to reach the same objective, the CCEFP has modified the Fluid Power Scholar’s Program yet again.

The History: As interns, students learn about hydraulics and pneumatics through hands-on experiences while companies with whom they work learn about them. Though the benefits to everyone were clearly apparent, developing a successful internship program through the CCEFP proved to be very difficult. For some companies, Center intervention wasn't necessary; they already had established internship programs. For others, the Center's help was welcomed, but within this group there were (still are) a myriad of differences.

- The history of the Fluid Power Scholars Program demonstrates that 75% of former participants stay in the fluid power industry; 68% of former participants are hired directly into their host company; others are either still in school or are pursuing graduate education.
- 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.

The Change: Over the years, several companies asked if they could name their “Fluid Power Scholar” from existing leadership intern programs within their company, or otherwise utilize their own hiring infrastructure and systems to recruit and employ the intern they would name as the "Fluid Power Scholar". Eventually, it was becoming clear the procedures we established (posting a position electronically, recruitment, application process, etc.) were laborious for all parties involved (Center staff, company staff, company human resources, student applicants). It was also clear the original procedures were not the element of the program that industry needed our help. What we could provide, in which the companies may not, was a short fluid power-training program. In fact, the "rigmarole" was actually a deterrent for some companies, as they had to create a "special" process to work with us. Thus, the Center has eliminated the efforts of providing the recruitment of students and asked companies to utilize their own infrastructure to recruit, identify and hire their intern, whom is to be named the CCEFP Fluid Power Scholar. Instead, the CCEFP recruits the companies to commit to hiring one or two interns to be named Fluid Power Scholars and provide the sponsorship to the MSOE fluid power-training workshop.

2015 Fluid Power Scholars Program:

- Seventeen students were named Fluid Power Scholars, which exceeded capacity of the MSOE short-course, nearly doubling the corporate participation from year's past. This is attributed, in part, by success of the program and word of mouth, and secondly, by the launch of the NFPA Pascal Society, in which more industry supporters are directly connected to the CCEFP and NFPA workforce development programs.
- The companies who have committed, to date, for 2015 are: Bobcat Company (2), Caterpillar, Inc.(1), Danfoss (3), Deere & Company (2), Deltrol Inc.(1), FORCE America (1), HUSCO International (3), Poclain Hydraulics (2), SunHydraulics (1) and Pall Corporation (1).

2014 Fluid Power Scholars Program

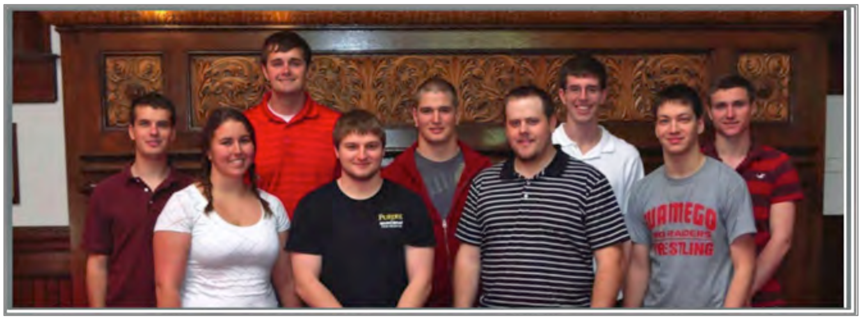
- Scholar/Intern positions: eight companies offered to support nine Fluid Power Scholars in the summer of 2014: SunHydraulics, Danfoss, Deltrol, HUSCO International, CNH, Bosch Rexroth, FORCE America, Deere & Company.

2013 Fluid Power Scholars Program

- Scholar/Intern positions: six companies offered to support Fluid Power Scholars in the summer of 2013: Case New Holland, Sauer-Danfoss, Parker Hannifin, Deltrol Fluid Products, HUSCO International and Sun Hydraulics. HUSCO was unable to identify a candidate.

2012 Fluid Power Scholars Program

- Scholar/Intern positions: nine companies offered to support nine scholars in the summer of 2012: Caterpillar, John Deere, Case New Holland, Sauer-Danfoss, Parker Hannifin, Deltrol Fluid Products, Eaton Corporation, HUSCO International and Sun Hydraulics.
- Fluid Power Scholars were from the following institutions: University of Missouri-Columbia (2), Iowa State University (2), Kansas State University, Illinois Institute of Technology, University of Minnesota, University of Minnesota-Duluth, Purdue University
- Since the summer experience, five Fluid Power Scholars were hired by their host company, one student was hired into the fluid power industry, two continue their undergraduate studies and two have pursued graduate study.



2012 Fluid Power Scholars

4. Plans, Milestones and Deliverables

- The Fluid Power Scholars program will remain a cornerstone of the joint CCEFP and NFPA Workforce Development Program as the Center enters into Year 10 and beyond.

- The goals of this program are to continue to expand and grow as needed and to track the careers of participants. The upcoming 2015 program is full to capacity; there will be negotiations to expand into two short-courses in future years.

- The CCEFP and NFPA intend on increasing the number of corporate participants.

- NFPA will assume the sponsorship of the MSOE course-fee in future years.

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 Team:

Project Leader: Alyssa Burger, CCEFP Education Outreach Director

Industry Partners: Members of the CCEFP Industry Engagement Commitee

Project D.2: CCEFP Engagement

1. Project Goals and Description

The Fluid Power Innovation and Research Conference (FPIRC) and the Industry Summits exist to provide industry supporters and CCEFP students with opportunities to network. 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 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.

2. Project Role in Support the EO Program Strategy

This program aligns well with the goals, mission, and strategy of the CCEFP by engaging students in the fluid power industry, often offering them opportunities to stay in this industry so they can have an impact in fluid power research and applications.

3. Achievements

- Fluid Power Innovation and Research Conference (FPIRC) (formerly CCEFP Annual Meetings): Since 2006, the CCEFP has held an annual meeting at each Center's partner institutions. A growing number of industry and academic supporters attend the event. Corporate kiosks and "speed meetings", poster sessions and presentations allow for regular networking opportunities for industry and students.
    - Fall of 2016, FPIRC planning is underway, to be held in Minneapolis, Minnesota in conjunction with the ASME Dynamic Systems and Controls Conference.
    - Fall of 2015, FPIRC held in Chicago, IL in conjunction with the Bath/ASME Fluid Power Symposium.
    - Fall of 2014, the CCEFP's Fluid Power Innovation & Research Conference (FPIRC) is borne, held at Vanderbilt University in Nashville, TN.
    - Fall 2013, CCEFP Annual Meeting, Sarasota, FL, in conjunction with the BATH/ASME Fluid Power Symposium.
    - Fall of 2012, NFPA Workforce Summit and CCEFP Annual Meeting held at the University of Illinois, Urbana-Champaign.

- Industry Summits (formerly IAB Summits): Added to the Center's agenda in 2012, the CCEFP hosts Industry Summits at one of Center's partner institutions two times each year. The Summits exist to provide a more intimate knowledge transfer between CCEFP research and industry supporters. This is an excellent opportunity for industry to engage with students on a more one-to-one level. The atmosphere gives the student a chance to demonstrate their research and area of expertise.

- Resume Exchanges: Held at each CCEFP FPIRC (formerly Annual Meetings) in 2011, 2012, 2013, 2014 and most recently, 2015. A one-on-one session between Center students and representatives of corporate supporters.
- Research Poster Sessions: Held at each CCEFP FPIRC (formerly Annual Meetings) since inception. 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 cash award competition is included.
- The Fluid Power Scholars Program was launched in 2010. It is a sponsorship program for incoming interns to attend a fluid power immersion short-course at MSOE at the outset of the internship experience. To date, 59+ Fluid Power Scholars have been supported through the program. Over 75% of Scholars transition to full-time employees after the internship.

- The CCEFP and NFPA coordinate and sponsor the Parker Chainless Challenge Competition for undergraduate engineering students interested in fluid power.
- The CCEFP supports the NFPA Fluid Power Challenge Competition for 8th grade students, an engineering design competition using fluid power. Competition judges include representatives from local industries who invited students to ask them questions about their careers. CCEFP has hosted the Challenge at the University of Minnesota and Milwaukee School of Engineering in 2009, 2012, 2013, 2014* and 2015* (*at UMN, MSOE, GT and PU). Over 1400 8th grade students engaged through this program and dozens of corporate sponsors participating.
- The Student Leadership Council (SLC) hosts a Research Webinar once a month. Students and faculty from CCEFP institutions participate, along with industry supporters. These webinars are intended to keep everyone in the Center informed about research progress, give and receive suggestions, and generally promote inter-university collaboration as well as cooperation between academia and industry. These webcasts are well attended, with an average of 73 participants per session.
- Student Retreats: As funding allows, 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.

4. Plans, Milestones and Deliverables

- All FPIRC research poster sessions will continue to include a competition, with industry representatives as judges.
- Resume exchange and Industry Kiosks will continue at future CCEFP FPIRC events. Students will have a chance to meet with industry supporters one-on-one and visit corporate kiosks, which are of particular interest.
- Industry sponsorships will be encouraged as a way of getting middle and high school students interested in fluid power.
- The NFPA University Education Committee has been formed between NFPA and CCEFP to design a new mutual workforce development strategic plan.
- The Student Leadership Council will continue, serving as the student voice to the CCEFP.
- Holding retreats at company facilities will provide students the chance to interact with practicing engineers and will facilitate opportunities for knowledge transfer.

5. Member Company Benefits

This broad 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.

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	Student Leadership Council CCEFP Graduate Students NFPA Pascal Society Members
Industrial Partner:	All CCEFP Industry Members

FPIRC14, Laboratory for Systems Integrity and Reliability (LaSIR), Vanderbilt University.

EO Project D.5: CCEFP Webinar Series

1. Project Goals and Description

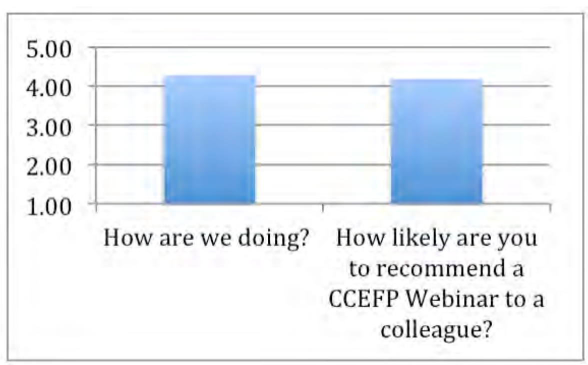
The goal of the Webinar series is to maintain a consistent means of technology transfer throughout the Center—students, faculty and industry supporters. On a regular basis, the CCEFP hosts a Webinar featuring two presentations, each discussing either research projects or other Center-wide programs (e.g., special topics, strategic planning, education and outreach, project evaluation, etc.). These Webinars are open to the public and CCEFP students, faculty, and industry supporters through the NFPA Pascal Society and more broadly. The Webinars 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.

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 Webinar 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. It is one of the primary means for engagement of industry supporters and research dissemination.

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. New in 2015, projects associated or affiliated with the CCEFP were invited to present. In addition, guest presenters from industry are invited to give talks on interested concepts or technology in the field.
- In 2015, guest presentations included researchers from Iowa State University, Georgia Institute of Technology, Vanderbilt University, Evonik and Pall Corporation.
- The Center continues to find ways to improve the efficiency and effectiveness of the Webinars. The webinar has moved to "Go-To-Webinar" platform which allows better technology integration to the presentation. In addition, the Student Leadership Council emcees each Webinar, making for seamless transitions between presenters.
- After transitioning to a new system, the CCEFP can track participant data for readily. The 2015 CCEFP Webinar Series had 145 registered participants. Of those, 84 were industry representatives from 35 companies, the remaining representing academia. Polls show attendees join the webinar in groups, thus, viewership is higher than actual registrations. Polls also show attendees would rather have longer webinars with reduced frequency. The 2016 Webinar Series schedule now occurs once per month, rather than bi-weekly.



- Research presentations usually received a follow-up request from industry members for potential collaboration work.

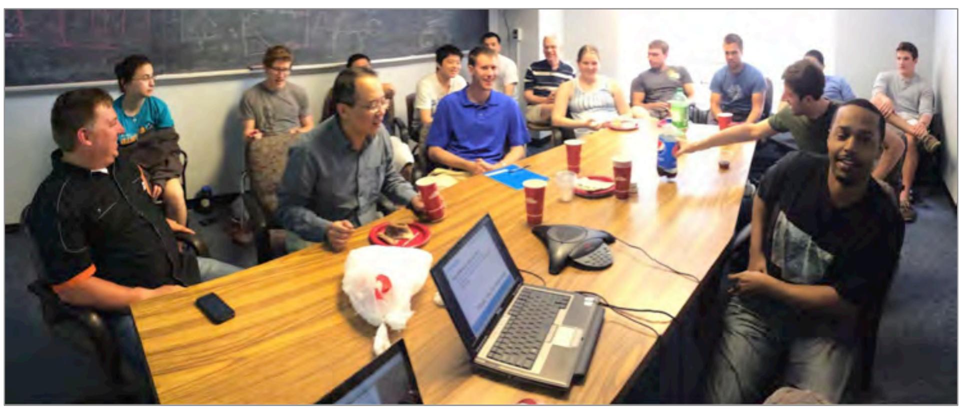
- Presentations are not just project-specific information; they also include information on how each project is aligned with the Center's strategic plan. For research, presentations describe how work is demonstrated on the Center's test beds, how current research aligns with what has been done previously as well as how it is breaking new ground, etc. These inclusions have added important new dimensions to the Webinars 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

4. Plans, Milestones and Deliverables

- The CCEFP Webinar Series will remain a cornerstone of the Center's engagement and workforce development programming as it moves forward into a post-NSF funded ERC. CCEFP will continue to host the Webinars, which are a proven success, popular within the Center network and among its industrial members.
- The National Fluid Power Association (NFPA) has an active promotional campaign surrounding the CCEFP Webinar Series.

5. Member Company Benefits

All Center participants, the public and anyone with an interest have opportunities to get first-hand updates on research, education, and management level activities from project leaders. Webinars also foster a sense of "community" throughout the Center network as all constituents regularly have opportunities to hear and learn from each other.



Screenshot of a webinar presentation

Project Team

Project Leader:	Alyssa A. Burger, Education Outreach Director
Other Personnel:	SLC President and Vice President CCEFP graduate students Invited speakers outside the CCEFP network
Industrial Partners:	All CCEFP Industry Members

Project E.1: External Evaluation of Education and Outreach Program

1. Project Goals

Quality Evaluation Designs (QED) has been the external evaluator of CCEFP Education and Outreach since FY7, 2012-2013. The E&O evaluation has three objectives.

1) Identify objectives that cross-cut all E&O programs, create metrics for assessing them, and report E&O progress on each.
2) Anticipate post-ERC graduation and incorporate the CCEFP organizational and business plan into the evaluation design in order to identify and confirm stakeholder value propositions.
3) In Fiscal Year 10, QED is working closely with the National Fluid Power Association (NFPA) to provide data that strengthens 1) fluid power workforce development and 2) NFPA education and outreach.

2. How Project Supports the EO Program Strategy

Partnership with QED is an application of a key E&O strategy--identifying and working with a strong partner in order to maximize results. Specifically, QED has helped the E&O clarify program objectives, quantify results, and chart a course towards post-ERC graduation sustainability.

3. Achievements

During FY10, QED has pursued the following objectives:

- Continue assessing CCEFP E&O Projects, Activities, and Courses
- Conducting a fluid power Workforce Development Study
- Assessing the effects of NFPA Lab Grants
- Assessing the NFPA Fluid Power Challenge Program

Assessing E&O Projects, Activities, and Courses.

In FY9, QED deployed a survey that assesses each of six objectives that cut across all E&O programs, courses, modules, and activities. The survey is administered online and can be completed in about three minutes. The survey was redeployed in Fall 2015, but in spite of concerted efforts among CCEFP staff and faculty, response rates were very low, ranging from 0% for three programs to 32% for one program. Fluid Power courses and modules excluded, a total of 169 respondents were expected and 41 surveys were completed (24%). Course analytics show that 2,505 students from 131 countries viewed MOOC lectures, and about 200 completed all exercises. Just over 100 surveys from MOOC students were received, which was considered a good response rate. We can't know how many of these were from students who completed most or all assignments, but since surveys were completed at the end of the course, it is likely that most surveys are from those who participated throughout. Among all E&O surveys received, ratings were uniformly high; however, low response rates were concerning.

In early February, QED met with the E&O director, and a new strategy was devised to deploy the E&O survey in a different way. Rather than have students complete the survey at the contact point of a program, course, or activity in which they participated, the survey will be deployed through the CCEFP Project Center, a database of undergraduate and graduate students who have had one or more contacts with CCEFP programs. More students will be reached and higher response rates are anticipated. The E&O survey was moved to the CCEFP survey site in mid-February and then deployed. QED will analyze results in early March.

Conducting a Fluid Power Workforce Development Study

In Fall 2015, QED Principal, Gary Lichtenstein, met with NFPA leadership in Wisconsin to identify ways that QED could pursue E&O objectives now being coordinated between CCEFP and NFPA. One result of that meeting was the Workforce Development Study. The goal of this study is to identify workforce needs across the fluid power industry related to positions that specifically require fluid power knowledge. QED conducted initial interviews with human resource professionals in NFPA member companies, then devised a protocol for interviews among a broader sample. NFPA provided a list of approximately 230 member companies. QED randomly selected one-third of these companies for interviews. Interviews began mid-February and so far, results have been unexpected. Companies are challenged to hire engineers, technicians, and sales people with fluid power experience, but the specific kind of experience they are looking for seems to vary, and may be idiosyncratic to each company. QED will explore this and other findings and report results later this spring. We believe that this study will make a significant contribution to NFPA and the fluid power industry, if we can get sufficient numbers of respondents, which has been a challenge to date. QED will report study results later this spring.

Assessing the Results of NFPA Lab Grants
For the past four years, NFPA has promoted a program whereby the organization awards $25,000 grants to institutions of higher education in order to promote fluid power programs. Beginning 2014, the grant program was limited to two-year and technical institutions. The grants can be used for labs and courses in order to increase the numbers of students exposed to fluid power. *What are the effects of this program at the institutions that receive these grants? Do these grants have lasting effects on fluid power curricula and labs? Are more students exposed to fluid power as a result? Does this exposure result in more students pursuing fluid power jobs and careers?* These are some of the questions that will be addressed in QED's Lab Grant study. In March and April, 2016, QED will conduct site visits and extensive interviews at two institutions that received lab grants in 2014. We will produce case studies that reveal how the lab grants affected the curricula, facilities, faculty, and students at each institution.

Assessing the NFPA Fluid Power Challenge Program
Each year, NFPA sponsors the *Fluid Power Challenge*, an engineering design competition for 8^{th} graders. Middle school students attend a one-day workshop, in which they learn basic fluid power concepts, then receive kits that are used in a competition a few weeks later. NFPA has approximately 2,000 student surveys from the past three years that have not been analyzed. QED received the surveys in mid-February, and has begun entering the data. Results will be reported in March 2016.

4. Summary
Since QED began as the external evaluator E&O at CCEFP, we have tried to strengthen the program, which evolved haphazardly in the early years. The E&O survey has helped program leadership define what is and is not E&O at CCEFP. Survey results indicate that those who have directly participated in E&O programs find great value in their experiences. Now that the E&O survey is on the CCEFP web site, we hope that continued assessment will help provide direction and focus to E&O in the future. QED's activities at NFPA are targeted at workforce development by assessing the needs that companies have related to hiring positions requiring fluid power knowledge, and determining the effectiveness of NFPA programs designed to expose middle school and college students to fluid power.

Project Team

Project Leader:	Quality Evaluation Designs (QED)
Personnel:	Gary Lichtenstein, Principal, Quality Evaluation Designs Jenifer Helms, Senior Research Associate, Quality Evaluation Designs

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Associated Project Abstracts: Research

Thrust 1— Efficiency

Adjustable Linkage Pump
Project Leader: James Van de Ven
Sponsors: -- Cat Pumps
Abstract: This PFI: AIR Technology Translation project focuses on translating a variable displacement adjustable linkage pump to fill the need for a hydraulic pump with high efficiency at low volumetric displacement. The project will result in a functional prototype of a multi-cylinder variable displacement linkage pump. This adjustable linkage pump has the following novel features: 1) it uses low friction pin joints, 2) it can reach true zero displacement, 3) the piston reaches the same top dead center position regardless of the displacement, and 4) it can pump corrosive fluids. These features improve efficiency and allow the pump to be used in a wide range of applications and environments, when compared to market leading variable displacement hydraulic pumps. This project addresses the following technology gaps as it translates from research discovery toward commercial application: constructing a dynamic model of the pump, constructing a framework for multi-domain multi-objective optimization of machines with mechanisms and applying the method to optimize the pump for water pumping applications, and designing and testing a multi-cylinder prototype.

Advanced Hydraulic Systems for Next Generation of Skid Steer Loaders
Project Leader: Monika Ivantysynova
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Aeration and Fluid Efficiency
Project Leader: Paul Michael
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Building a Hardware-in-the-loop Simulation Testbed and a Living Laboratory for Evaluating Connected Vehicle-Highway Systems
Project Leader: Zongxuan Sun
Sponsors: -- FHWA
Abstract: The objective of this project is to build a hardware-in-the-loop simulation (HiLS) testbed to test and assess the performance of connected vehicles applications, such as the cooperative adaptive cruise control (CACC). Recently a number of applications that will take advantage of the connected vehicle-highway systems have been proposed. These applications are intended to use wireless communications among vehicles and between vehicles and the roadway infrastructure to improve mobility and environmental sustainability. An example of such applications is CACC, which is an enhancement of the existing adaptive cruise control (ACC) system. With vehicle-to-vehicle and vehicle-to-infrastructure communication, it is expected that shorter time headways between vehicles and smoother ride can be achieved through the CACC system, resulting in higher traffic capacity and better driver comfort. The proposed HiLS testbed integrates a microscopic traffic model and a wireless communication model (software) with real-time on-road traffic signals and a laboratory powertrain research platform (hardware). This HiLS testbed enables the effective testing and evaluation of the mobility and environmental benefits of CACC or other connected vehicles applications in a safe and economical fashion.

CAREER: Control of Mechatronic Automotive Propulsion Systems
Project Leader: Zongxuan Sun
Sponsors: -- NSF
Abstract: The research objective of this Faculty Early Career Development (CAREER) project is to develop control methodologies to enable the transformation of the automotive propulsion system from a traditional mechanical system into a flexible mechatronic system. The specific goal is to provide design tools to ensure precise motion control of the mechatronic actuators that will replace the mechanical components and eliminate the mechanical links in the automotive propulsion system, and therefore achieve the necessary control means to maximize the energy conversion and power transfer efficiency. To achieve the above objective, studies of new design methods for time-varying internal model based tracking control will be conducted and validated in various automotive mechatronic systems.

Detailed modeling of Gerotor units
Project Leader: Andrea Vacca
Sponsors: -- Thomas Magnete GmbH
Abstract: Unavailable due to confidentiality of project.

Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump
Project Leader: Andrea Vacca
Sponsors: -- Dae Jin Hydraulics - TECPOS
Abstract: Unavailable due to confidentiality of project.

EFRI-RESTOR: Novel Compressed Air Approach for Off-Shore Wind Energy Storage
Project Leader: Perry Li
Sponsors: -- National Science Foundation
Abstract: The goal of this project is to develop an efficient, powerful and cost effective localized energy storage concept for off-shore wind power using high pressure compressed air. The system is to be capable of storing several hours worth of wind energy. Research involves heat transfer improvement, efficient machine element, and system optimization and control.

Energy Efficienct Fluid Field Trial
Project Leader: Paul Michael
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Energy Efficient Fluids
Project Leader: Paul Michael
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Energy Efficient Fluids
Project Leader: Paul Michael
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Energy saving hydraulic system architecture for next generation of combines utilizing displacement control
Project Leader: Monika Ivantysynova
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Evaluation And Design Improvements For A Hydraulic Pump
Project Leader: Monika Ivantysynova
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Evaluation and Design Study of the Piston/Cylinder Interface of a Swash Plate Type Hydraulic Motor
Project Leader: Monika Ivantysynova
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Evaluation of performance of counterbalance valves
Project Leader: Andrea Vacca
Sponsors: -- Oerlikon Fairfield
Abstract: Unavailable due to confidentiality of project.

Investigation of Alternative Cylinder Block Materials using Fluid Structure Interaction Modeling (FSTI)
Project Leader: Monika Ivantysynova
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Modeling of external gear pumps operating with power law fluids and experimental validation
Project Leader: Andrea Vacca
Sponsors: -- Procter & Gamble
Abstract: Unavailable due to confidentiality of project.

Modelling and analysis of swash plate axial piston pump
Project Leader: Monika Ivantysynova
Sponsors: -- Confidental
Abstract: Unavailable due to confidentiality of project.

MRI: Development of a Controlled-Trajectory Rapid Compression and Expansion Machine
Project Leader: Zongxuan Sun
Sponsors: -- NSF
Abstract: Rapid compression machines are instruments that use a single piston or opposed pistons to compress the gas mixture in a cylinder rapidly and create desired temperature and pressure conditions to investigate the fuel ignition, emission formation mechanism, and fluid and chemistry interaction etc. The objective of this project is to develop a rapid compression and expansion machine with the ability to control its piston trajectory in real-time. Unlike conventional rapid compression machines, the proposed instrument can control the trajectory of the piston to track any desired reference signal. This unique capability enables the real-time control of the combustion chamber volume and therefore affects the time history of the temperature, pressure and species concentration. Such functionalities when combined with gas sampling analysis and optical measurement will allow researchers to directly access the combustion processes in a dynamic and controlled fashion. Given its unique capabilities, the proposed instrument will enable novel and exciting research work in fuel, advanced combustion, new engine architectures and control, which could significantly reduce the energy consumption and emissions for transportation, construction, and agriculture. The proposed instrument will advance the shared research infrastructure at the University of Minnesota and promote multi-disciplinary research. Additionally, designing and constructing instrument is a critical skill required for both academia and industry, and the proposed instrument provides an excellent platform of training both graduate and undergraduate students to understand the theories and physical systems as well as gaining hands-on experience.

New Geometries for External Gear Machines towards the reduction of Noise Emissions
Project Leader: Andrea Vacca
Sponsors: -- Casappa S.p.A.
Abstract: Unavailable due to confidentiality of project.

Numerical Modeling of GEROTORs unit
Project Leader: Andrea Vacca
Sponsors: -- Thomas Magnete GmbH
Abstract: Unavailable due to confidentiality of project.

Optimal design of a fuel injection pump
Project Leader: Andrea Vacca
Sponsors: -- Robert Bosch SpA (Italy)
Abstract: This project is aimed at identifying the best design configuration for an internal gear pump for fuel injection.

Thrust 3— Effectiveness

Electrohydraulic Braking System
Project Leader: Andrea Vacca
Sponsors: CNH America, Inc.
Abstract: Unavailable due to confidentiality of project.

High Pressure Compliant Material Development
Project Leader: Kenneth Cunefare
Sponsors: Sauer-Danfoss
Abstract: Develop material(s) with significant compliance throughout 40-400 Bar system pressure range. An existing material has been shown to be effective at removing high frequency pressure ripple between 0 and 40 Bar system pressure where the material bulk modulus is below 500 Bar. We expect the material development will result in the identification of several materials which can be appropriately combined in order to achieve ~500 Bar compliance from 40-400 Bar system pressure.

New Generation Of Green, Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology
Project Leader: Andrea Vacca
Sponsors: -- Confidential
Abstract: The proposed research effort aims to formulate a green, viable, energy-efficient and economical solution to the current dependency of hydraulic powered machines on oil-based lubricants. This goal will be attained by proposing a novel â€“ leakage risk free â€“ hydraulic technology based on the use of water as working fluid. Energetic performance even superior to current state-of-the-art machines will be reached by studying new designs for the most critical component of the hydraulic system - the pump - and by defining novel system architectures, based on the principle of the displacement control actuation, which eliminates power losses due to fluid throttling.

The approach of study will combine a numerical-experimental approach, and will take as reference two representative systems for agricultural machines. The research will not only demonstrate the feasibility of the proposed technology, but it will show a potential of about 50% of fuel consumption reduction with respect to current solutions.

Entirely performed at the biggest academic fluid power lab in the nation, the research will benefits from the investigators' expertise in modeling thermal-elasto-hydrodynamic effects within hydrostatic machines and from their past experience in formulating new system layout concepts. The study will also advance the fundamental knowledge about the behavior of high pressure water-hydraulic lubricating interfaces in positive displacement machines.
3: Effectiveness

Noise measurements and valve plate design to reduce noise and maintain low control effort for tandem pumps.
Project Leader: Monika Ivantysynova
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Phase 3: Low Cost Compressed Natural Gas
Project Leader: Perry Li
Sponsors: -- Confidential
Abstract: Unavailable due to confidentiality of project.

Static Dissipating Hydraulic Filters
Project Leader: Paul Michael
Sponsors: Confidential
Abstract: Unavailable due to confidentiality of project.

Viscosity Measurements of Polymer Solutions at Elevated Temperatures and Pressure
Project Leader: Scott Bair
Sponsors: -- Confidential
Abstract: The limiting-low-shear viscosity of 100 polymer solutions were measured with falling cylinder viscometers using various sinkers which apply shear stress of less than 100 Pa. Three temperatures, 120, 140 and 160Â°C, were investigated for each sample. Viscosity measurements were made at a pressure of 400 psig. For each sample, an empirical formula was be provided to enable the calculation of viscosity at arbitrary temperatures.

Testbed Related

Controllable Hydraulic Ankle Prosthesis
Project Leader: William Durfee
Sponsors: -- Minneapolis VA Medical Center
Abstract: Develop a passive hydraulic ankle prosthesis with joint locking and unlocking enabled with a switching valve. The prosthesis is intended to adapt to variable slope terrain. This project is a joint collaboration between the Minneapolis VA Medical Center and the University of Minnesota. Project P.I. is Dr. Andrew Hanson at the VAMC.

CPS: Synergy: Integrated Modeling, Analysis and Synthesis of Miniature Medical Devices
Project Leader: Pietro Valdastri
Sponsors: -- National Science Foundation
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.

Development of a Forearm Simulator to Recreate Abnormal Muscle Tone Due to Brain Lesions
Project Leader: Elizabeth Hsiao-Wecksler
Sponsors: -- Jump Trading Simulation and Education Center, Bradley University, University of Illinois College of Medicine in Peoria.
Abstract: The goal of this project is to create a forearm medical training simulator that replicates different degrees of abnormal muscle behaviors (spasticity and rigidity) in the elbow. Since these hypertonic

muscle behaviors display increased muscle resistance that are speed or position dependent, we will take a new design approach by using a passive hydraulic device. Through a purely mechanical design that uses viscous Netwonian fluid and adjustable flow channels, the device has the potential to generate a range of speed- or position-dependent resistive feedbacks without need for a computational control scheme. The final simulator will have the potential to improve spasticity and rigidity evaluation of patients by providing more practical training opportunities to young medical professionals.

Passive hydraulic medical training simulator for mimicking joint spasticity and rigidity
Project Leader: Elizabeth Hsiao-Wecksler
Sponsors: -- Jump ARCHES
Abstract: This search project explores the design of a medical training simulator that uses the resistance of fluid flow to mimic spasticity or rigidity at the elbow. Specifically, by changing surrounding channel dimensions and/or orifice sizes of a piston moving through a viscous fluid, different levels of resistance can be generated while flexing an artificial forearm. The forearm is attached to the piston. This design is based purely on mechanical devices to control fluid flow, meaning that no electronics or electromechanical devices or controls are necessary.

Wearable eMbots to Induce Recovery of Function
Project Leader: William Durfee
Sponsors: -- University of Michigan
Abstract: An NIH-funded project collaboration with the University of Michigan (U Mich is the lead) to create and evaluate a new form of stroke recovery wearable robot that uses a hydraulic transmission to couple motion from the good side to motion of the impaired side.

Education & Outreach

REU Site: Research Experience for Undergraduates in Fluid Power
Project Leader: Kim Stelson
Sponsors: -- NSF
Abstract: None
EO Thrust C: College Education

Manufacturing

Fluid Power Advanced Manufacturing Technology Consortium
Project Leader: Kim Stelson
Sponsors: -- Georgia Tech, AMT, NFPA
Abstract: The Fluid Power Advanced Manufacturing Consortium (FPAMC) was founded in June 2015 with a NIST AMTech planning grant to the University of Minnesota. The consortium's objective is to establish a sustaining, interdisciplinary consortium focused on creating, maintaining, expanding and facilitating implementation of an advanced manufacturing roadmap for the U.S. fluid power industry. This group includes members from industry, trade associations, academia and Oak Ridge National Lab. Key facilitators for the FPAMC are the National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power (CCEFP) and the National Fluid Power Association (NFPA). Principal Investigators for the FPAMC are Prof. Kim Stelson of the University of Minnesota and Prof. Tom Kurfess of the Georgia Institute of Technology.

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Thrust 1: Efficiency

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Thrust 3: Effectiveness

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Testbeds and General

Heinrich, M., Mattson, C., Ramuta, M., Stock, J., Liang, J., Morris, M., Tippett, S., Hsiao-Wecksler, E. and Henderson, J. “Pneumatic Elbow Simulator of Spasticity and Rigidity for Training of Healthcare Clinicians.” Proceedings of the 2015 Fluid Power Innovation and Research Conference (FPIRC) Chicago, IL., October (2015)

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Zhang, C. and Sun, Z. “A New Approach to Reduce Engine-out Emissions Enabled by Trajectory-based Combustion Control.” ASME 2015 Dynamic Systems and Control Conference Columbus, Ohio, October 28-30 (2015): pp.V001T11A002 DOI: 10.1115/DSCC2015-9838

Data Management Plan

This document presents the plan followed by the CCEFP ERC in the management of data generated by the activities of the award. It specifies the tools used to ensure that all data relevant to reporting are stored in the system. It also details the types of repositories required for dissemination of the data generated by the Center and its partners in the conduct of the program.

Expected Types of data
Research results of every project have a variety of different formats for raw data. There is no general rule to justify raw data formats. These data will be stored locally and every project leader needs to have access to raw data for generating higher level of data that will be stored in the CCEFP Project Center. They are expected to be in the form of spreadsheets, presentations, images and rich-text documents. Final project review presentations representing ERC outcomes are saved on our secure website.

Format and Content Standards
To manage data generated in the CCEFP, we have designed a web-based reporting system for record keeping.

The web-based reporting system at www.ccefp.net is designed to a) track all research and education activities, b) provide a means for project review and c) foster data dissemination among the collaborating scientists, students and affiliated personnel. The system is based on a data schema developed by the ERC Administrative Directors' Data Collection Workshop. This system is built on Drupal, an open-source system that allows a network of ERC centers to easily develop and implement new reporting and management features, and thus make a wide range of data available to stakeholders.

Additional information includes the following:
1. Personal reporting information - (publications, courses, meetings, outreach events, etc. - used in Table 1 of Annual Report)
2. Personnel information (includes faculty, staff, consultants and temporary employees)
3. Students and alumni (includes a history of CCEFP fellowships, stipends, employment and gender/minority/disability status)
4. Industrial memberships (includes a history, level and length of membership along with notes and documentation)
5. Invention disclosures, patents and licenses
6. Donations, technology transfer or translational research support
7. Capital equipment and assets (purchased and donated) - under development
8. Financial records
9. Base award, amendments, supplemental awards, associated awards from other agencies
10. Inventories (e.g., CCEFP computer hardware and software, licensing agreements)
11. Records of research, educational outreach and industrial activities necessary for CCEFP performance evaluation.

Access and Sharing
All research data generated in the course of conducting the projects of the CCEFP will be stored locally by the organization that generates the data. Each organization will be responsible for protecting the data in accordance with the governing university standards and the Center's by-laws. As all universities retain rights to data and other intellectual property generated in the course of its research (in accordance with the Bayh-Dole Act), each participant has the obligation to protect such data and share it with other participants and stakeholders formally and informally during presentations throughout the year, and formally annually via a written report to our sponsors, and in accordance with the center by-laws.

The reporting system has a built-in data repository used for annual reports. Access to data is secured by user name and password. There are four levels of user access: confirmed participant, PI, site content manager, and site technical administrator. Site access is provided to basic users, known as confirmed participants, by the site technical administrator and is limited to administrative tasks (create, delete, and update their own data). PI’s have access to these same administrative tasks and also have limited access to students' profiles. PI's can delete and update data for students who are working on their projects. The site content manager has access to view and edit fields. The site technical administrator is the only level that has access to the full Administration Menu, where changes to the layout of the site itself can be made. Two individuals on the administrative team at CCEFP headquarters have been granted Site Technical Administrator access.

Period of Retention
All data generated by the Center is retained for a period of no less than five years beyond the end date of the award.

Data Storage and Preservation
Each participating institution is responsible for their own data storage and preservation in accordance with their individual university's policies and standards.

The CCEFP Project Center serves as a central repository for the data necessary to be shared among participants for ongoing project activities. The data is maintained in a secure MySQL database provided by CCEFP's web hosting service. The database is backed up to a local archive once a day, and to a second remote server once a week.

CCEFP headquarters houses research project and administrative information throughout the year. This data is housed on a secure server on the University of Minnesota campus, and backups are completed daily. An identical hard drive of data is stored off-site and swapped out for a fresh backup on a regular basis.

Douglas E. Adams
Department of Civil and Environmental Engineering
School of Mechanical Engineering
Vanderbilt University

Professional Preparation

University of Cincinnati	Mechanical Engineering	B.S.	1994
Massachusetts Institute of Technology	Mechanical Engineering	M.S.	1997
University of Cincinnati	Mechanical Engineering	Ph.D.	2000

Appointments

2013-present	Distinguished Professor and Chair, Civil and Environmental Engineering and Professor of Mechanical Engineering, Vanderbilt University
2010-2013	Kenninger Professor, School of Mechanical Engineering, Purdue University
2009-2013	Professor, School of Mechanical Engineering, Purdue University
2005-2009	Associate Professor, School of Mechanical Engineering, Purdue University
2000-2005	Assistant Professor, School of Mechanical Engineering, Purdue University

Closely Related Products

1. Kusnick, J., and Adams, D. E., "Wind Turbine Rotor Imbalance Detection using Nacelle and Blade Measurements", *Wind Energy*, accepted for publication.
2. Meyer, A., and Adams, D. E., "Damage identification of ground vehicle through passive probing of suspension damping", 2013, *Experimental Mechanics*, Vol. 53(4), p. 557.
3. Gupta, L., Brouwer, M., Sadeghi, F., Peroulis, D., and Adams, D., "High Temperature Dynamic Viscosity Sensor for Engine Oil Applications," 2012, *Sensors & Actuators: A. Physical*, Vol. 173(1), pp. 102-107.
4. Mahulkar, V., and Adams, D. E., "Derivative Free Filtering in Hydraulic Systems for Fault Identification", 2011, *Control Engineering Practice*, Vol. 19, Issue 7, pp. 649-657
5. Mahulkar, V. and Adams, D. E., "Minimization of Degradation through Prognosis Based Control for a Damaged Aircraft Actuator," 2009, *Proceedings of the Dynamic Systems and Control Conference*, Hollywood, CA, Paper No. DSCC2009-2787, pp. 669-676.

Significant Products

6. Myrent, J., Kusnick, J., Barrett, N., Adams, D., and Griffith, D., "Structural Health And Prognostics Management For Offshore Wind Turbines: Case Studies Of Rotor Fault And Blade Damage With Initial O&M Cost Modeling," April 2013, Sandia Report SAND2013-2735, unlimited release.
7. Pham, H., Sharp, N., Adams, D. E., and Dietz, J. E., "Lithium-Ion Battery Cell Health Monitoring using Vibration Diagnostic Test," 2013, *Proceedings of the International Mechanical Engineering Congress and Exposition*, San Diego, CA, IMECE-63962.
8. Adams, D. E., "Health Monitoring of Structural Materials and Components," 2007, John Wiley & Sons, Chichester, U.K.
9. Adams, D. E., "Chapter 18: Prognosis Applications and Examples," 2005, John Wiley & Sons, (Editors) Professor Daniel Inman, Dr. Charles Farrar and Dr. Daniel Inman, "Damage Prognosis."
10. Adams, D. E., and Jata, K., "Part 17: Damage Prognosis in Metallic and Composite Structures," *Encyclopedia of Aerospace Engineering*, John Wiley & Sons, 2010.

Synergistic Activities

Recent Patent Activities:
(a) Peroulis, D., Kovacs, A., Koester. D., Sadeghi, F., Scott, S., and Adams, D. E., "Highly-Reliable Micro-Electromechanical System Temperature Sensor," August 2013, US 2013/0202012 A1.
(b) Calhoun, K., Kiser, R., Adams, D., Gul, K., Yoder, N., Bruns, C., and Yutzy, J., "System and Method for Detecting Fault Conditions in a Drivetrain Using Torque Oscillation Data," May 2013, US 2013/0116937 A1.
(c) Adams, D. E., Yutzy, J., and Dana, S., "Load Shape Control of Wind Turbines," December 2012, US 2012/029254.

(d) Bond, R. and Adams, D. E., “Entropy-Based Impact Load Identification,” November 2013, US 2013/0298690 A1.
(e) Adams, D. E., Caruthers, J., Sadeghi, F., Suchomel, M., Sharp, N., and David, A., “Vibratory Analysis of Batteries,” January 2013, US 2012/026351.
(f) Adams, D. E., Di Petta, T., and Koester, D., “Extended Smart Diagnostic Cleat,” January 2013, US 2012/029954.

Dissemination: Delivered over 150 invited seminars and keynote addresses worldwide including keynote lecture at upcoming NSF-sponsored International Conference on Next Generation Wind Energy in Spain (2014), and invited lectures at 2013 Dresden Airport Seminar, 2009 Marie Curie Action on Stability, Identification and Control of Structural Dynamics in Belgium, 2008 National Academy of Engineering Workshop on Material State Awareness, and 2003 NSF-sponsored Pan American Studies Institute on Prognosis in Brazil.

Education initiatives: Launched NSF DUE-supported inquiry-based laboratory course in 2002 in experimental structural dynamics and offered course for seven semesters, sponsored 30 undergraduate research students on special projects, and delivered 30 short courses for continuing education in nonlinear system identification and diagnostics & prognostics to NASA Glenn/Kennedy, Center for Monitoring of Structures (Germany), Air Force Research Laboratory, Palmdale Aerospace Institute, and at other venues.

Managing Editor of Structural Health Monitoring: An International Journal, Sage Publications. Former Associate Editor of ASME Journal of Dynamic Systems, Measurement and Control.

Conference Organization activities: Organized and chaired many sessions on nonlinear system identification and structural health monitoring at ASME IMECE, SEM IMAC, and other meetings. Served on many conference organizing committees such as IEEE International Conf on PHM, USNCTAM, Intl. Conf. on Advances in Experimental Mechanics, etc.

Collaborators & Other Affiliations

Collaborators within the last 48 months (other than students listed):

Daniel Griffith (Sandia National Lab), Charles Farrar (Los Alamos National Lab), Fu-Kuo Chang (Stanford Univ.), R. Byron Pipes, Farshid Sadeghi, CT Sun, James Caruthers, Kartik Ariyur, Edward Delp, Steven Son, Jeffrey Rhoads, Stuart Bolton, Patricia Davies, Anil Bajaj, Alok Chaturvedi, Jan Vitek, and Ananth Grama (Purdue University), Michael Steer and Mohammed Zikry (North Carolina State Univ.), John Scales (Colorado School of Mines), Michael Todd (University of California San Diego), Eric Barth, Florence Sanchez, Sandra Rosenthal, Ronald Schrimpf, Janos Sztipanovits, Caglar Oskay, and Sankaran Mahadevan (Vanderbilt University).

Ph.D. Students Supervised:

Chulho Yang (Oklahoma State), Timothy Johnson (Dow Corning), Muhammad Haroon (University of Braunschweig), Shankar Sundararaman, Hao Jiang (Oakridge National Laboratory), Shawn McKay (RAND Corporation), Kamran Gul (ExxonMobile), Jonathan White (Sandia National Lab), Vishal Mahulkar (Eaton Corp), Nathanael Yoder (ATA), Janette Meyer (Purdue), Nasir Bilal (Purdue), Sara Underwood (General Electric), Janene Silvers (Purdue), and Major Eric Dittman (United States Air Force).

Ph.D. and M.S. Advisors:

Ph.D.: Randall Allemang, Dept. of Mechanical Engineering, University of Cincinnati.
M.S.: Kamal Youcef-Toumi, Dept. of Mechanical Engineering, Massachusetts Institute of Technology

Research Visitors:

Prof. Hoon Sohn, KAIST, Korea; Professor Ioannis Georgiou, National Technical University of Athens, Greece; Dr. Jose Machorro Lopez, Instituto Politecnico NAcional, Mexico; Dr. Darryll Hickey, University of Sheffield.

Andrew Alleyne
Department of Mechanical and Science Engineering
University of Illinois at Urbana-Champaign

Professional Preparation

Ph.D.	Univ of California, Berkeley,	1994
M.S.	Univ of California, Berkeley	1992
B.S.E.	Princeton Univ.	1989

Research Areas

Control of Nonlinear Systems with Applications to Manufacturing, Thermal Systems, Vehicle Systems, Fluid Power.

Appointments

- NRC Research Associate, Wright Pat Air Force Base, 2011-2012
- F.I.R.S.T. Visiting Professor, ECEE Dept, CU Boulder, Jul 210-Aug. 2010.
- Associate Dean for Research, College of Engineering, Illinois, January 2009 – date
- Professor, Department of Mechanical Science and Engineering, UIUC, August 2004 – date
- Visiting Professor of Vehicle Mechatronics, Faculty of Design, Engineering and Production, Delft University of Technology, The Netherlands, January 2003 - July 2003
- Ralph M. and Catherine V. Fisher Professor of Engineering, UIUC, Aug 2002-date
- Associate Professor, Dept. of Mechanical & Industrial Engr, UIUC, Aug. 2000-date.
- Assistant Prof., Dept. of Mechanical & Industrial Engr, UIUC, Aug. 1994-Aug. 2000.

Selected Research Awards	Selected Teaching Awards
• NSF Faculty Early Career Development CAREER Award, 1996 • UIUC College of Engineering Xerox Award for Faculty Research, 2000. • Fulbright Fellowship (Netherlands) 2002-2003 • 2003 SAE Ralph R. Teetor Award • Ralph M. and Catherine V. Fisher Professorship, UIUC College of Engineering, 2002-date. • ASME Dynamic Systems and Control Division Outstanding Young Investigator Award, 2003. • Distinguished Lecturer, IEEE Control Systems Society, 2004 – 2007 • Fellow, ASME, 2005 • 2008 ASME Gustus L. Larson Memorial Award • 2011 NRC Research Award	• UIUC List of Teachers Ranked as Excellent by Their Students, 1995,2004,2006 • UIUC Engineering Council Award for Excellence in Advising, 1998,1999 • UIUC Engineering Accenture Award for Excellence in Advising, 2001, 2003 • UIUC College of Engineering Teaching Excellence Award, 2008 • UIUC Campus Award for Excellence in Undergraduate Teaching, 2008

Closely Related Products

- Deppen, T., A. Alleyne, K. Stelson and J. Meyer, “Model Predictive Control Of An Electro-Hydraulic Powertrain With Energy Storage,” 2011 ASME Dynamic Systems and Control Conference, Arlington, VA, Oct 2011.
- Deppen, T., A. Alleyne, K. Stelson, and J. Meyer, "A Model Predictive Control Approach for a Parallel Hydraulic Hybrid Powertrain," 2011 American Controls Conference, San Francisco, CA, 2713 - 2718, June 2011.
- Meyer, J, K. Stelson, T. Deppen, and A. Alleyne, "Developing an Energy Management Strategy for a Four-Mode Hydraulic Hybrid Passenger Vehicle," 52nd IFPE National Conference on Fluid Power, Las Vegas, NV, March 22-26, 2011.

- Deppen, T., J. Meyer, A. Alleyne, and K. Stelson, "Predictive Energy Management for parallel Hydraulic Hybrid Vehicle," 2010 ASME Dynamic Systems and Control Conference, Boston, MA, October 2010.
- Deppen, T., A. Alleyne, K. Stelson, J. Meyer, "Optimal Energy Use in a Light Weight Hydraulic Hybrid Passenger Vehicle," accepted for ASME Journal of Dynamic Systems, Measurement and Control.

Significant Products

- Zhang, R., A. Alleyne, and E. Prasetiawan, "Modeling and H-2/H-infinity MIMO Control of an Earthmoving Vehicle Powertrain," ASME Journal of Dynamic Systems, Measurement, and Control, 124, 625-636, Dec. 2002.
- Zheng, D. and A. Alleyne, "Modeling and Control of an Electro-hydraulic Injection Molding Machine with Smoothed Fill-to-Pack Transition," ASME Journal of Manufacturing Science and Engineering, 125, 154-163, Feb. 2003.
- Zhang, R., A. G. Alleyne, and E. A. Prasetiawan, "Performance Limitations of a Class of Two-Stage Electro-Hydraulic Flow Valves," Int'l J. of Fluid Power, 3:1, 47-55, April 2002.
- Havlicsek, H. and A. Alleyne, "Nonlinear Control of an Electrohydraulic Injection Molding Machine via Iterative Adaptive Learning," IEEE/ASME Transactions on Mechatronics, 4:3, 312-323, 1999
- Zhang, Y. and A. Alleyne, "A Simple Novel Approach to Active Vibration Isolation with Electrohydraulic Actuation," ASME Journal of Dynamic Systems, Measurement, and Control, 125, 125-128, March 2003.

Selected Editorships	Synergistic Activities
• Associate Editor, ASME J. Dyn Sys Meas & Cntrl, 2000-03 • Editor, Vehicle System Dynamics, 2001-2008 • Associate Editor, IEEE Control Systems, 2003-2009 • Associate Editor, IEEE Trans on Control Syst Tech, 2010-date • Associate Editor, IFAC Control Engr Practice, 2010-date	• DARPA/DSO Defense Science Study Group, 2008-2010 • U.S. Air Force Scientific Advisory Board, 2009-2013 • Wash U, St. Louis, ME Board, 2009-date • Quanser Consulting, (Educational tools for controls) 2000-date

Collaborators within the past 48 Months:

Kim Stelson, Perry Li, Will Durfee (U. of Minnesota); Lucy Pao (Univ of Colorado); Placid Ferreira, John Rogers, Mark Shannon, Paul Kenis, Kent Choquette, Ilesami Adesida, Qin Zhang, Amy Wagoner Johnson, Elizabeth Hsiao-Wecksler, Eric Loth, Bill King, Jennifer Berhnard, William King (UIUC), Jakob Stoustrup (Aalborg), Maarten Steinbuch (TUEindhoven)

Invited Lectures (Last Five Years)

UCLA (2012), UC Irvine (2012), U Cincinnati (2012), Univ Florida (2011), Washington Univ, St. Louis (2010), U. Notre Dame (2010), Illinois Inst of Techn (2010), Northwestern University (2009), Johns Hopkins U, (2009), U. Arkansas (2008), Iowa St (2008), MIT (2008), U. Washington (2008), Aalborg University-Denmark (2007), TU Eindhoven (2007), Washington University in St. Louis (2007), RPI (2007), University of the West Indies (2007), Clemson University (2007).

Scott Bair
The George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology

Professional Preparation

Georgia Institute of Technology	Mechanical Engineering	B.S.	1972
Georgia Institute of Technology	Mechanical Engineering	M.S.	1974
Georgia Institute of Technology	Mechanical Engineering	Ph.D.	1990

Appointments

Regents' Researcher	Georgia Institute of Technology	2010-2012
Principal Research Engineer	Georgia Institute of Technology	1992-2010
Senior Research Engineer	Georgia Institute of Technology	1985-1992
Research Engineer	Georgia Institute of Technology	1974-1985

Closely Related Products

Publications Most Closely Related to Proposal

Bair, S., McCabe, C. and Cummings, P., "Comparison of NEMD with Experimental Measurements in the Non-Linear Shear Thinning Regime," Physical Review Letters, 88, 5, 8302, 2002.

Bair, S., "The High Pressure Rheology of Some Simple Model Hydrocarbons," Proc. I. Mech. E., 216, J, 2002, pp. 139-150.

Bair, S., McCabe, C. and Cummings, P., "Calculation of Viscous EHL Traction for Squalane using Molecular Simulation and Rheometry," Tribology Letters, 13, 4, pp. 251-254, 2002.

Bair, S., "Pressure-Viscosity Behavior of Lubricants to 1.4 GPa and Its Relation to EHD Traction," STLE Tribology Transactions, 43, 1, pp 91-99, 2000.

Bair, S. and Qureshi, F., "The Generalized Newtonian Fluid Model and Elastohydrodynamic Film Thickness," ASME, J. Tribology, 125, 1, pp. 70-75, 2003.

Significant Products

Bair, S., "Normal Stress Difference in Liquid Lubricants Sheared Under High Pressure," Rheologica Acta, 35, 13, pp 13-23, 1996.

Bair, S., Qureshi, F., and Khonsari, M., "Adiabatic Shear Localization in a Liquid Lubricant Under Pressure," Trans. ASME, Journal of Tribology, 116, 4, 1994.

Bair, S. and Winer, W.O., "A New High-Pressure, High Shear Stress Viscometer and Results for Lubricants, "Tribology Transactions, 36, 4, pp. 721-725, 1993.

Bair, S., Qureshi, F., and Winer, W. O., "Observations of Shear Localization in Liquid Lubricants Under Pressure," Trans. ASME, Journal of Tribology, 115, 3, 1993.

Bair, S., Green, I., and Bhushan, B., "Measurements of Asperity Temperatures of a Read/Write Head Slider Bearing in Hard Magnetic Recording Disks," Trans. ASME Journal of Tribology, 113, No. 3, 1991.

Synergistic Activities

Awards

Co-Recipient of the 1983 Best Paper of the Year for the Tribology Division/ASME
Co-Recipient of the 1991 Best Paper of the Year for the Tribology Division/ASME
Jacob Wallenberg Foundation, 1996
Recipient of the 2000 Alfred Hunt Award from STLE for best paper
Fellow of ASME
Fellow of STLE

Co-Recipient of the 2006 Alan Berman Research Publication Award (with Roland and Casalini)
Recipient of the 2007 Alfred Hunt Award from STLE for best paper
Recipient of the 2009 Naval Research Laboratory Chemistry Division Alan Berman Research Publication Award (with Roland, Bogoslovov, Casalini, Ellis, Rzosca, Czuprynski, and Urban)
Recipient of the International Award for 2009, the highest honor given by the Society of Tribologists and Lubrication Engineers.

US Patents

4,349,130	Liquid Metering Pump
4,347,643	Power Assist Drive Upright Vacuum Cleaner and Power Assist Drive System
4,391,018	Vacuum Cleaner with Wheel and Nozzle Height Adjusting Mechanism [with Vermillion and Gromek]
4,998,228	Drinking Water Filter [with Eager]
5,562,692	Fluid Jet Surgical Cutting Tool
5,643,299	Hydrojet Apparatus for Retractive Surgery
5,735,815	Method of Using Fluid Jet Surgical Cutting Tool
5,853,384	Fluid jet Surgical Tool and Aspiration Device
5,865,790	Method and Apparatus for Thermal Phaco-emulsification by Fluid Throttling
6,126,668	Microkeratome
6,527,766	Instrument and Method for Phacoemulsification by Direct Thermal Irradiation

Collaborators And Other Affiliations

Collaborators Over The Last 48 Months:
Ashlie Martini, Purdue University, CCEFP
Ivan Krupka, Brno University, Czech Republic, Elastohydrodynamic film thickness measurements
Riccardo Casilini, George Mason University, Viscosity correlations
Mike Roland, Naval Research Laboratory, Viscosity correlations
Michael Khonsari, Louisiana State University, Elastohydrodynamic numerical simulations
Punit Kumar, National Institute of Technology Kurukshetra, Elastohydrodynamic numerical simulations
Paul Michael, MSOE, CCEFP
Kees Venner, U. of Twente, Netherlands, Elastohydrodynamic numerical simulations
Arno Laesecke, NIST Boulder, Viscosity correlations
Philippe Vergne, INSA de Lyon, Elastohydrodynamic numerical simulations
Wassim Habchi, Lebanese American University, simulations
Hubert Schwarze, Technische Universität Clausthal, high-frequency viscosity measurements under pressure

Eric J. Barth
Department of Mechanical Engineering
Vanderbilt University

Professional Preparation

University of California Berkeley	Engineering Physics	B.S., 1994
Georgia Institute of Technology	Mechanical Engineering	M.S., 1996
Georgia Institute of Technology	Mechanical Engineering	Ph.D., 2000
Vanderbilt University	Mechanical Engineering	Post Doc, 2002

Appointments

2010 – present	Associate Professor of Mechanical Engineering, Vanderbilt University
2002 – 2010	Assistant Professor of Mechanical Engineering, Vanderbilt University
2000 – 2002	Research Assistant Professor of Mechanical Engineering, Vanderbilt University

Closely Related Products

1. D. B. Comber, E. J. Barth, R. J. Webster III. "Design and Control of an Magnetic Resonance Compatible Precision Pneumatic Active Cannula Robot," ASME Journal of Medical Devices. 8(1), 011003 (Dec 06, 2013) (7 pages) doi:10.1115/1.4024832.
2. D. B. Comber, D. Cardona, R. J. Webster III, and E. J. Barth, "Precision Pneumatic Robot for MRI-Guided Neurosurgery," DMD2012-6929, ASME Design of Medical Devices Conference, 2012, Minneapolis, MN. Note: **Winner of the 3-in-5 competition**.
3. J. A. Riofrio and E. J. Barth. "Experimental Assessment of a Free Elastic-Piston Engine Compressor with Separated Combustion Chamber," *Bath/ASME Symposium on Fluid Power and Motion Control (FPMC 2008)*, pp. 233-244, September 10-12, 2008. Bath, U K. NOTE: Winner of the **best paper award** for the entire Symposium.
4. Y. Zhu, E. J. Barth. "An Energetic Control Methodology for Exploiting the Passive Dynamics of Pneumatically Actuated Hopping". *ASME Journal of Dynamic Systems, Measurement and Control*, vol. 130, issue 4, pp.041004-1 – 041004-11, July 2008.
5. N. Gulati, E. J. Barth. "Dynamic Modeling of a Monopropellant-Based Chemofluidic Actuation System". *ASME Journal of Dynamic Systems, Measurement, and Control,* vol. 129, no. 4, pp.435-445, July 2007.

Significant Products

1. Pedchenko, Alexander, E. Pitt, and Eric Barth. "Analytical Tools for Investigating Stability and Power Generation of Electromagnetic Vibration Energy Harvesters." *IEEE/ASME Transactions on Mechatronics*. Year: 2015, Volume: PP, Issue: 99, Pages: 1 - 1, DOI: 10.1109/TMECH.2015.2469638
2. N. Gulati, E. J. Barth. "A Globally Stable, Load Independent Pressure Observer for the Servo Control of Pneumatic Actuators". *IEEE/ASME Transactions on Mechatronics*, vol. 14, issue 3, pp.295 – 306, DOI 10.1109/TMECH.2008.2009222, June 2009.
3. Y. Zhu, E. J. Barth. "Passivity-based Impact and Force Control of a Pneumatic Actuator". *ASME Journal of Dynamic Systems, Measurement and Control*, vol. 130, issue 2, pp.024501-1 – 024501-7, March 2008.
4. N. Gulati, E. J. Barth. "Dynamic Modeling of a Monopropellant-Based Chemofluidic Actuation System". *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 129, no. 4, pp.435-445, July 2007.
5. M. Goldfarb, E. J. Barth, M. A. Gogola, J. A. Wehrmeyer. "Design and Energetic Characterization of a Liquid-Propellant-Powered Actuator for Self-Powered Robots". *IEEE/ASME Transactions on Mechatronics*, vol. 8, no. 2, pp. 254-262, June 2003.

Synergistic Activities

1. General Chair of the 2015 ASME/Bath Symposium on Fluid Power and Motion Control
2. Technical Sessions Chair of the 2015 Fluid Power Innovation & Research Conference
3. Co-Deputy Director of the NSF Center for Compact and Efficient Fluid Power (2014-present)
4. Associate Editor of the International Journal of Fluid Power (2014-present)
5. Local Chair of the 2014 Fluid Power Innovation & Research Conference held at Vanderbilt (LASIR) Oct 13- 15, 2014
6. Associate Editor of ASME Journal of Dynamic Systems, Measurement and Control (2012-2014)
7. Chair of the ASME Fluid Power Systems and Technology (FPST) Division (2010-2012)
8. Management Committee Member, NSF Center for Compact and Efficient Fluid Power (CCEFP)
9. Member of the Faculty Advisory Committee for the Vanderbilt Center for Technology Transfer and Commercialization (CTTC) (2012-current)
10. Member of the ASME Dynamic Systems and Control Division (DSC) Conference Editorial Board (2009-2011)
11. ASME Fluid Power Systems and Technology Division (FPST): Executive Committee Member.
12. ASME Division of Dynamic Systems and Control (DSCD): Member of Mechatronics Technical Committee.
13. ASME Division of Dynamic Systems and Control (DSCD): Member of the Robotics Technical Committee.
14. Member of the National Fluid Power Association (NFPA) by invitation
15. Program Committee Member of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), October 9-14, 2006, Beijing, China.
16. Program Committee Member of the 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2005), July 24-28, 2005, Monterey, California, USA
17. Track Representative of Fluid Power Systems Technology Division (FPST) for IMECE 2005.
18. US Air Force Summer Faculty Fellow, AFRL, Wright-Patterson Air Force Base, 2005.

Collaborators & Other Affiliations

Collaborators: Andrew Alleyne, Ph.D., Department of Mechanical and Industrial Engineering, UIUC, Wayne Book, Ph.D., George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Michael Goldfarb, Ph.D., Department of Mechanical Engineering, Vanderbilt University, Monika Ivantysynova, Ph.D., Department of Mechanical Engineering, Purdue University, Suhada Jayasuriya, Ph.D., Department of Mechanical Engineering Texas A&M University, Perry Y. Li, Ph.D., Department of Mechanical Engineering, University of Minnesota, Nader Sadegh, Ph.D., George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Corey Schumacher, Ph.D, AFRL/VACA, Wright Patterson Air Force Base, Kim A. Stelson, Ph.D., Department of Mechanical Engineering, University of Minnesota, Alvin Strauss, Ph.D., Department of Mechanical Engineering, Vanderbilt University, Roger Quinn, Ph.D., Dept. of Mechanical and Aerospace Engineering, Case Western Reserve University

Advisors: Harry Bingham (deceased), Ph.D., Department of Physics, University of California Berkeley, Ye-Hwa Chen, Ph.D., School of Mechanical Engineering, Georgia Institute of Technology, Aldo Ferri, Ph.D., School of Mechanical Engineering, Georgia Institute of Technology, Michael Goldfarb, Ph. D., Department of Mechanical Engineering, Vanderbilt University, Bonnie Heck, Ph.D., School of Mechanical Engineering, Georgia Institute of Technology, Nader Sadegh, Ph. D., School of Mechanical Engineering, Georgia Institute of Technology, George Vachtsevanos, Ph.D., School of Electrical Engineering, Georgia Institute of Technology, David Nygren, Ph.D., Physics, Lawrence Berkeley National Laboratory

Thesis Advisor to (all in Dept. of Mechanical Engineering, Vanderbilt University): Alexander Pedchenko, Ph.D. (2015), Dave Comber, Ph.D. (2015, Anna Winkelmann, M.S. (2015), Collin Grimes, M.E. (2014), Mark Hofacker, Ph.D. (2013), John Tucker, M.S. (2012), Chao Yong, Ph.D. (2011), Alexander Pedchenko, M.S. (2011), Andy Willhite, Ph.D. (2010), Jose Riofrio, Ph.D. (2008), M.S. (2005), Taib Tariq Mohamad, M.Engineering. (2007), Yong Zhu, Ph.D. (2006), Navneet Gulati, Ph.D. (2005), Mark Adams, M.S. (2004). *Current*: Edward Pitt, Ph.D. Student, Josh Cummins, Ph.D. Student, Tyler Gibson, Ph.D. Student, Yue Chen, Ph.D. Student, Rebecca Neuenschwander, M.S. Student.

Bradley F. Bohlmann
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

University of Minnesota	Mechanical Engineering	B.S., 1985
University of Michigan, Dearborn	Mechanical Engineering	M.S., 1988
University of Saint Thomas	Business	M.B.A., 2000

Academic/Professional Appointments

12/10-5/11 & 10/12-1/13	Acting Industrial Liaison Officer, National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power, University of Minnesota
2012-present	Teaching Specialist, Mechanical Engineering, University of Minnesota
2010	Adjunct Professor, Mechanical Engineering, University of Minnesota
2009-present	Sustainability Director, National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power, University of Minnesota
1997-2009	Business Development Manager, Advanced Technology, Eaton Fluid Power Group
1990-1997	Manager, Technical Services, Cummins Power Generation
1986-1989	Project Engineer, Lead Engine Engineering, Chrysler Motors

Closely Related Products

Rahul Dutta, Feng Wang, Bradley Bohlmann, Kim Stelson, "Analysis of Short-term Energy Storage for Mid-size Hydrostatic Wind Turbine", in Proceeding of the 2012 ASME Dynamic Systems and Control Conference, DSCC-2012-8815, Fort Lauderdale, FL, USA, 2012 (selected as a top 20 outstanding paper).

Synergistic Activities

Teaching Specialist, Mechanical Engineering, University of Minnesota

- Course coordinator for the ME 4054W Capstone Design Projects course in Spring 2010, Spring 2012, Spring 2013, Fall 2013, Spring 2014, Spring 2016. Responsibilities include soliciting and approving project proposals from industry and UMN researchers, giving lectures, grading, etc.

REU Advisor, 2012

Advisor, ME 4054W Capstone Design Projects course, University of Minnesota

- Fall 2011-Spring 2012: Advised a team of 5 undergraduate students working on a fluid power capstone design project. The project focused on a national competition funded by Parker Hannifin called the Chainless Challenge. The competition required that the mechanical link between the pedals and the drive wheel(s) of a bike be replaced with a hydraulic transmission. Twelve universities participated in the competition and the UMN team took second place overall.
- Fall 2012-Spring 2013: Advised a team of 5 undergraduate students working on a fluid power capstone design project focused on improving the previous year's bike in the Chainless Challenge.
- Fall 2013-Spring 2014: Advised a team of 5 undergraduate students working on a fluid power capstone design project focused on an all new hybrid hydraulic drivetrain for the Chainless Challenge. Eleven teams participated in the competition and UMN team took third place overall.

Collaborators And Other Affiliations

Kim Stelson, University of Minnesota, Feng Wang, PostDoc, University of Minnesota

Member, Technical Advisory Group, CALSTART (2005-2011)

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Wayne J. Book
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology

Professional Preparation

Massachusetts Institute of Technology	Mechanical Engineering	PhD.	1974
Massachusetts Institute of Technology	Mechanical Engineering	S.M.	1971
University of Texas, Austin	Mechanical Engineering	B.S.M.E.	1969

Appointments

2011 – present	Professor Emeritus
2001 – 2011	HUSCO/Ramirez Chair in Fluid Power and Motion Control, Georgia Tech
1986 - 2011	Professor, Georgia Institute of Technology
1980 - 1986	Associate Professor, Georgia Institute of Technology
1974 - 1980	Assistant Professor, Georgia Institute of Technology
1987 Summer	Faculty Fellowship, Oak Ridge National Laboratory
1981 – 1982	Visiting Scientist, The Robotics InstituteCarnegie-Mellon U.
1976 Summer	Research Fellow, NASA Johnson Space Center
1974 Summer	Research Associate, M.I.T. Dept. of Mechanical Engineering
1974 – present	Consultant, Numerous Companies

Closely Related Products

1. Munir, Saghir and Wayne Book, "Internet Based Teleoperation using Wave Variables with Prediction," *ASME/IEEE Transactions on Mechatronics*,v7 n2, June 2002, p 124-133.
2. Rhim, Sungsoo and Wayne J. Book, "Adaptive Time-delay Command Shaping Filter for Flexible manipulator Control," *IEEE/ASME Transactions on Mechatronics*, v9, n4, Dec. 2004, pp 619-626.
3. Gao, Dalong and Wayne J. Book, "Steerability for Planar Dissipative Passive Haptic Interfaces," in *IEEE/ASME Transactions on Mechatronics*, v11 n2, April 2006.
4. Ching, Ho and Wayne J. Book, "Internet-Based Bilateral Teleoperation Based on Wave Variable with Adaptive Predictor and Direct Drift Control," *ASME J. Dynamic Systems, Measurement and Control*, v128, n1, 8pp, March 2006.
5. Rhim, S., A. Hu, N. Sadegh, W.J. Book, "Combining a Multirate Repetitive Learning Controller with Command Shaping for Improved Flexible Manipulator Control," *ASME J. of Dynamic Systems, Measurement, and Control*, v123 n 3, September 2001, pp385-390.

Significant Products

6. Love, L.J. and W.J. Book, "Force Reflecting Teleoperation with Adaptive Impedance Control," *IEEE Transactions on Systems, Man, and Cybernetics Part B: Cybernetics*, v34, n1, pp.159-165, Feb. 2004.
7. George, Lynanne, and Wayne J. Book, "Inertial Vibration Damping Control of a Flexible Base Manipulator" *IEEE/ASME Transactions on Mechatronics*, v8 n2, June 2003, pp 268-271.
8. Krauss, Ryan and Wayne Book, "Transfer Matrix Modeling of a Hydraulically Actuated Flexible Robot," *International Journal of Fluid Power*, v8, n1, March 2007, pp 51-58.
9. Kontz, Matthew and Wayne Book, "Electronic Control of Pump Pressure for a Small Haptic Backhoe," *International Journal of Fluid Power,* v8, n2, pp 5-16, Aug. 2007.
10. Kontz, Matthew and Wayne Book, "Flow Control for Coordinated Motion and Haptic Feedback" *International Journal of Fluid Power* v8, n3, Nov. 2007.

Synergistic Activities

Editorial Activities: Senior Technical Editor, ASME J Dynamic Systems, Measurement and Control, 1994-99; Associate Editor 1984-1987. Associate Editor, IEEE Trans Automatic Controls. Also Int J of Fluid Power, 2004-present Management Committee, Joint ASME-IEEE Trans Mechatronics, 1995-2008. Chair, 1999, Ed. Board and Associate Editor, J. of Systems and Control Eng. 2011-present.

Co-Founder of CAMotion, Inc. for commercialization of advanced motion control technology for automating manufacturing and material handling, 1997. Treasurer and consultant 1997 - present.

Conference Organization activities: General Chairman 1993 IEEE International Conference on Robotics and Automation, Atlanta, GA. General Chairman, 1988 ACC of the American Automatic Control Council. Service in various capacities in ASME, IEEE and the American Automatic Control Council.

Founding Director, Computer Integrated Manufacturing Systems (CIMS) Program, 1983-1987. The program won the 1986 University LEAD award for excellence in education in computer integrated manufacturing awarded by the Society of Manufacturing Engineers.

Steering and Advisory Committee service: Steering Committee, Oak Ridge National Laboratory, Center for Engineering Systems Advanced Research, 1983 - 1994. Advisory Committee, New York State Center for Advanced Technology .on Automation and Robotics, Rensselaer Polytechnic Institute, 1989 - 1993. Potomac Institute for Policy Studies NASA Computing And Communications Tech. Advisory Group, 2004.

Collaborators & Other Affiliations

Collaborators within the last 48 months (other than students listed):

Stephen Dickerson, Nader Sadegh, Christopher Paredis, Kenneth Cunefare, Richard Salant, all from the Georgia Institute of Technology. Kim Stelson and Perry Li (U. Minnesota); Michael Goldfarb (Vanderbilt U.); Monika Ivantysynova (Purdue U.); Andrew Alleyne (U. Illinois);

Ph.D. Students Supervised:

Noparat Punyapas, Viboon Sangveraphunsiri, Gordon Hastings, Thomas Alberts, Sabri Cetinkunt, Bau San Yuan, Jeh Won Lee, Dong Soo Kwon, Soo-Han Lee, J.J. Wang, Jae Lew, Jonathan Cameron, David Magee, Lonnie Love, John Hogan, Klaus Obergfell, Sungsoo Rhim, Saghir Munir, Lynnane George, Davin Swanson, Haihong Zhu, Lawrence Tognetti, Dalong Gao, Ho Ching, Amir Shenouda, Ryan Kraus, Benjamin Black, Patrick Op den Bosch, Longke Wang, Aaron Enes, Mark Elton.

Ph.D. and M.S. Advisors:

Ph.D.: Daniel Whitney, Dept. of Mechanical Engineering, MIT.
M.S.: Russel Jones, Dept. of Civil Engineering, Massachusetts Institute of Technology

Research Visitors:
Prof. Dong Soo Kwon, KAIST, Korea

Alyssa A. Burger
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

University of Minnesota	Kinesiology	B.S., 2003
University of Minnesota	Science Education	M.Ed., 2012

Appointments

2006 – present Education Outreach Director
Center for Compact and Efficient Fluid Power
University of Minnesota
Direct, develop and coordinate education and outreach programs

1998 – 2004 Executive Administrative Specialist
Department of Mechanical Engineering
University of Minnesota
Coordinate the administrative functions of a division

Synergistic Activities

- Advisor, University of Minnesota AISES Student Chapter and giiwed'anang Northstar AISES Alliance
- Advisor, CCEFP Student Leadership Council
- Lead Personnel, NSF OEDG Grant: Manoomin
- Lead Personnel, TRIBES-E, Teaching Relevant-Inquiry Based Environmental Science And Engineering Teacher Workshop
- Lead Personnel, Minnesota North Star Louis Stokes Alliance for Minority Participation

Collaborators

Gillian Roehrig, STEM Education Center Director
Tamara Moore, STEL Education Center Co-Director
Diana Dalbotten, Diversity Director, National Center for Earth-surface Dynamics
Holly Pellerin, gidaa Coordinator, NCED and CCEFP
Lowana Greensky, Indian Education Director, St. Louis County Schools

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Thomas R. Chase
Professor, Mechanical Engineering
University of Minnesota

Professional Preparation

Rochester Institute of Technology	Mechanical Eng	B.S., 1977
Rochester Institute of Technology	Mechanical Eng	M.S., 1983
University of Minnesota	Mechanical Eng	Ph.D., 1984

Appointments

2003-present:	Professor of Mechanical Engineering, University of Minnesota
1991-2003:	Associate Professor of Mechanical Engineering, Univ of Minnesota
1985-1991:	Assistant Professor of Mechanical Engineering, Univ of Minnesota
1983-1985:	Assistant Professor of Mechanical Engineering, Univ of Rhode Island

Closely Related Products

1. Tu, H. C., Rannow, M. B., Wang, M., Li, P. Y., Chase, T. R. and Van de Ven, James D., 2012, "Design, Modeling and Validation of a High-Speed Rotary Pulse-Width-Modulation On/Off Hydraulic Valve", *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 134, No. 6, Paper #061002.
2. Li, Perry Y., and Chase, Thomas R., 2012, "Pulse Width Modulated Fluidic Valve", US Patent #8286939 B2.
3. Tu, H., Rannow, M., Wang, M., Li, P., Chase, T., and Cheong, K.L., 2011. "High-Speed 4-way Rotary On/Off Valve for Virtually Variable Displacement Pump/Motor Applications", *Proceedings of the ASME 2011 Dynamic Systems and Control Conference*, Arlington, VA.
4. Cheong, K. L., Li, P.Y., Sedler, S., and Chase, T.R., 2011. "Comparison Between Input Coupled and Output Coupled Power-Split Configurations in Hybrid Vehicles", *Proceedings of the 52nd National Conference on Fluid Power*, Paper No. NCFP_I11-10.2.
5. Fikru, Nebiyu and Chase, Thomas R., 2011. "A Review of MEMS Based Pneumatic Valves", *Proceedings of the 52nd National Conference on Fluid Power*, Paper No. NCFP_I11-11.2.

Significant Products

6. Michael, D. G., et al. (including T. R. Chase), 2008, "The Magnetized Steel and Scintillator Calorimeter of the MINOS Experiment", *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Vol. 596, No. 2, pp. 190-228.
7. Michael, D. G., et al. (including T. R. Chase), 2006, "Observation of Muon Neutrino Disappearance with the MINOS Detectors in the NuMI Neutrino Beam", *Physical Review Letters*, Vol. 97, No 19, article #191801.
8. Adamson, P., et al. (including T. R. Chase), 2006, "First Observations of Separated Atmospheric ν_μ and ν_μ events in the MINOS Detector", *Physical Review D (Particles and Fields)*, Vol. 73, No. 7, article #072002.
9. Chase, Thomas R., 2006, "A Note on the Waldron Construction for Transmission Angle Rectification", *ASME Journal of Mechanical Design*, Vol. 128, No. 2, pp. 509-512.
10. Langlais, T. E., Vogel, J. H., and Chase, T. R., 2003, "Multiaxial Cycle Counting for Critical Plane Methods", *International Journal of Fatigue*, Vol. 25, No. 7, pp. 641-647.

Synergistic Activities

1. Associate Editor, ASME Journal of Mechanical Design, 9/1/04-12/31/12.
2. Level 3 Manager for Scintillator Module Design, NuMI Off-Axis υ_e Appearance (NOν A) Experiment, responsible for the design of approximately $2 million of components for neutrino detector modules (an experiment of the Fermi National Accelerator Laboratory).
3. Director of Undergraduate Studies, Mechanical Engineering Department, 2009-present.
4. Level 3 Manager for Scintillator Module Design, Main Injector Neutrino Oscillation Search (MINOS) Experiment, responsible for the design and purchase of over $1 million of components for neutrino detector modules. The MINOS Collaboration includes approximately 32 institutions internationally.
5. Member, Executive Committee, Design Engineering Division of the American Society of Mechanical Engineers, 1998-2004 (Chair, 2002-03).

Collaborators & Other Affiliations

Collaborators Over The Last 48 Months:
J. Davidson, W. Lipinski & G. Venkatesan (UMN Mechanical Engineering Dept) – Solar Fuels Via Partial Redox Cycles with Heat Recovery
K. Heller, M. Marshak, E. Peterson, R. Poling (Univ of Minnesota Physics Dept) – NOν A Experiment
P. Li (Univ of Minnesota Mechanical Engineering Dept) – CCEFP Projects 1E.1, 1E.4 & TB3
E. Hsiao-Wecksler (UIUC Mechanical Engineering Dept) – CCEFP Project 2F
S. Trolier-McKinstry (PSU Dept of Materials Science & Engineering) – CCEFP Project 2F
H. Conrad & W.-J. Seong (Univ of Minnesota Dental School) – Dental Implant Study
F. Kelso (Univ of Minnesota Mechanical Engineering Department) – Textbook project

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:

1. Gopinath Venkatesan, Post-Doctoral Research Associate, 2013-14
2. Edward Sandberg, MSME, 2013
3. Henry Kohring, MSME (John Deere), 2012
4. Stephen Sedler, MSME, 2012
5. Ross Makulec, MSME, 2011
6. Tyler Kuhlmann, MSME (MTS Systems Inc.), 2010
7. Anne Fundakowski, MSME, 2010
8. David Grandall, MSME (Stefan Maier Organbuilding), 2010
9. John Robelia, MSME, 2009
10. Benjamin Nitti, MSME, 2008

Total Number of Graduate Students advised: 37 (completed)

Graduate and Postdoctoral Advisors
Ph.D. Advisor: Professor Arthur G. Erdman, University of Minnesota
M.S.M.E. Advisor: Professor Richard Budynas, Rochester Institute of Technology

Kenneth A. Cunefare
George W. Woodruff School of Mechanical Engineering
The Georgia Institute of Technology

Professional Preparation

The University of Illinois at Urbana-Champaign	Mechanical Engineering	Bachelor of Science	1982
The University of Houston	Acoustical Engineering	Master of Science	1987
The Pennsylvania State University	Mechanical Engineering	Doctor of Philosophy	1990
The Technical University of Berlin	Structural Acoustics		1990-1991

Appointments

2006-present	Professor, Georgia Institute of Technology
1997-2006	Associate Professor, Georgia Institute of Technology
1990-1997	Assistant Professor, Georgia Institute of Technology
1990-1991	F.V. Hunt Postdoctoral Fellow, The Technical University of Berlin
1988-1990	NASA GSRP Fellow, The Pennsylvania State University
1987-1988	NASA GSRP Fellow, The University of Houston
1986-1987	Senior Engineer, Exxon Company U.S.A., Houston, Texas
1984-1986	Senior Project Engineer, Exxon Company U.S.A., Midland, Texas
1982-1984	Project Engineer, Exxon Gas Systems, Inc., Houston, Texas
1981	Intern, McDonnell Douglas Aircraft Corporation

Closely Related Products

1. Jindou Wang, W. Steve Shepard* Jr., and Kenneth A. Cunefare, “Actuation of a discontinuous structure with piezoelectric actuators,” Journal of Sound and Vibration, **309**(3-5), pp. 677-694, 2008.

2. F. Casadei, M. Ruzzene, L. Dozio, and K. A. Cunefare, "Broadband vibration control through periodic arrays of resonant shunts: experimental investigations on plates," Smart Materials and Structures, **19**, pp.1-13, 2010.

3. Ken Marek, Nick Earnhart, and Kenneth A. Cunefare, “Modeling and validation of an in-line silencer,” Proceedings of the 6th Fluid Power Net International PhD Symposium, Lafayette, IN, June 15-19, 2010. Volume 1, pp. 101-114. CD Proceedings.

4. Benjamin S. Beck* and Kenneth A. Cunefare, "Experimental analysis of a cantilever beam with a shunted piezoelectric periodic array," Journal of Intelligent Material Systems and Structures, **20**(11), pp. 1177-1187, 2011.

5. John P. Arata, Michael J. Leamy, Jerome Meisel, Kenneth Cunefare, David Taylor, “Backward-looking simulation of the Toyota Prius and General Motors two-mode power-split HEV powertrains,” SAE International Journal of Engines, June, 2011, **4**(1), pp 1281-1297.

Significant Products

6. Nicholas E. Earnhart* and Kenneth A. Cunefare, “Compact Helmholtz Resonators for Hydraulic Systems,” accepted for publication, International Journal for Fluid Power, October, 2011

Synergistic Activities

Member, National Committee on Education in Acoustics, Acoustical Society of America. 1998-2011.

Member, National Committee on Noise, Acoustical Society of America, 1998-2013.

Integration of NSF funded (ARI grant) laboratory into ME4055, Senior Experimental Methods class.

Active recruitment of women and minorities into my research program. Eight current or former students are women or under-represented minorities (Noelle Curry, Janeen Jones, Lisa Chang, Anne Marie Albanese, Wayne Johnson, Mawuli Dzirasa, Tina Famighetti, Ellen Skow).

Collaborators and other Affiliations

Collaborators and Co-Editors: Dr. Krishan Ahuja (Georgia Tech), Dr. Mark Allen (Georgia Tech), Dr. Yves Berthelot (Georgia Tech), Scott Crane (General Electric), Brian Dater (Northrup-Grumman), Sergio DeRosa (University of Naples), Dr. Stephen Elliott (ISVR, Southampton, U.K.), Steve Engelstad (Lockheed Martin), Dr. Francesco Franco (Post Doc, University of Naples), Dr. Jerry Ginsberg (Georgia Tech), Dr. Ari Glezer (Georgia Tech), Dr. Marty Johnson (VPI), Dr. Greg Larson (Georgia Tech), Dr. Chris Lynch (UCLA), Keith Oglesby (Ford Motor Co.), Dr. Huang Pham (Newport News Shipyard), Eugene Powell (Lockheed Martin), Dr. Nader Sadegh (Georgia Tech), Dr. Manuel Collet (CNRS), Dr. Chan Il Park (Kangnung National University)

Graduate and Post-Doctoral Advisors: Dr. Ashok Belegundu (Penn State), Dr. Courtney Burroughs (Penn State, retired), Dr. Prof. Manfred Heckl (Post-Doctoral Sponsor, Technical University of Berlin, deceased), Dr. Gary Koopmann (Penn State, retired), Dr. Alan Pierce (University of Boston).

Thesis Advisor and Postgraduate-Scholar Sponsor: Dr. Anne Marie Albanese-Lerner (University of Wisconsin), Scott Crane (General Electric), Dr. Noelle Currey (Currey Acoustics), Brian Dater (Northrup-Grumman), Sergio DeRosa (Post-Doc, University of Naples), Muwali Dzirasa (Johns Hopkins), Jesse Ehnert (Arpeggio Acoustic Consulting), Mark Fowler (SY Technology), Dr.Francesco Franco (Post-Doc, University of Naples), Aaron Graf (General Motors), Dr. Mark Holdhusen (University of Wisconsin Marathon County), Dr. Wayne Johnson (Armstrong State University), Janeen Jones (deceased), Dr. Heungsoeb Kim (post-doc, Hangyang University, Korea), Dr. Nila Montbrun (Post-doc, Universidad Simon Bolivar), David Moon (Ford Motor Company), Keith Oglesby (Ford Motor Company), Dr. Victor Rastelli (Post-doc, Universidad Simon Bolivar), Ryan Rye (Motorala), Dr. William Steven Shepard, Jr. (University of Alabama), Dr. Michael Michaux (University of Southern California), Dr. Manuel Collet (post-doc, CNRS), Dr. Chan Il Park (post-doc, Kangnung National University), Tina Famighetti (Arpeggio Acoustics), Alex Michaud (Cerami & Associates), John Arata, Ken Marek (current PhD student), Nick Earnhart (current PhD student), Ben Beck (current PhD student), Flaviano Tateo (current PhD student), Ellen Skow (current PhD student), Elliott Gruber (Current MS student).

Summary: 11 Ph.D., 22 M.S., 7 Post-Doc

William K. Durfee
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

Harvard University, Cambridge, MA	A.B.	1976	Eng. & Applied Physics
M.I.T., Cambridge, MA	M.S.	1981	Mechanical Eng.
M.I.T., Cambridge, MA	Ph.D.	1985	Mechanical Eng.

Appointments

1976	Laboratory Supervisor, Harvard University.
1976-1978	Project Engineer, Harvard-MIT Rehabilitation Engineering Center.
1978-1985	Research Assistant, Department of Mechanical Engineering, MIT.
1985-1990	Assistant Professor, Department of Mechanical Engineering, MIT.
1986-1988	W. M. Keck Foundation Assistant Professor of Biomedical Eng., Dept. of Mech. Eng., MIT.
1990-1991	Associate Professor, Department of Mechanical Engineering, MIT.
1991-1993	Brit and Alex d'Arbeloff Associate Prof. of Engineering Design, Dept. of Mech. Eng., MIT.
1993-2001	Associate Professor and Director of Design Education, Dept. of Mechanical Eng., University of Minnesota.
2001-present	Professor and Director of Design Education, Dept. of Mechanical Eng., University of Minnesota. Additional appointments to the Graduate Faculty in the Department of Biomedical Engineering, the program in Human Factors and the program in Product Design.
2015-present	Associate Department Head, Department of Mechanical Enginering

Closely Related Products

1. J Xia and WK Durfee, Analysis of small-scale hydraulic actuation systems. *ASME Journal of Mechanical Design*, 135(9):091001-1 - 091101-11, 2013.
2. KA Shorter, J Xia, ET Hsiao-Wecksler, WK Durfee and GF Kogler, Technologies for powered ankle foot orthotic systems: possibilities and challenges. *IEEE Trans Mechatronics*, 18(1):337-347, 2013.
3. KA Shorter, GF Kogler, E Loth, WK Durfee, ET Hsiao-Wecksler, A portable powered ankle-foot orthosis for rehabilitation, *J Rehab Res Dev*, 48(4):459-472, 2011.
4. L Tian, DB Kittelson and WK Durfee, Experimental tests and simulations of a 1.5 cc miniature glow-ignition two-stroke engine, *SAE 2010-32-0018, Proceedings of Small Engine Technology Conference*, Linz, Austria, 2010.
5. W Durfee, J Xia, E Hsiao-Wecksler, Tiny hydraulics for powered orthotics, *IEEE International Conference on Rehabilitation Robotics*, 1-6, 2011.

Significant Products

1. Durfee W, Rivard A, Design and simulation of a pneumatic, stored-energy, hybrid orthosis for gait restoration. *J Biomechanical Eng*, 127(6):1014-1019, 2005.
2. Durfee, W.K. and P.A. Iaizzo. Rehabilitation and muscle testing. In: *Encyclopedia of Medical Devices and Instrumentation, 2nd ed*. J.G. Webster, ed., Vol 6, pp 62-71, Hoboken, John Wiley & Sons, 2006.
3. Durfee WK, Weinstein SA, Bhatt E, Nagpal A, Carey JR, Design and usability of a home telerehabilitation system to train hand recovery following stroke. *Journal of Medical Devices*, 3(4):041003, 2009.
4. Goldfarb, M, K Korkowski, B Harrold, W Durfee, Preliminary evaluation of a controlled-brake orthosis for FES-aided gait. *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* 11(3):241-248, 2003.
5. Durfee WK, Savard L and Weinstein S, Technical feasibility of remote assessments for rehabilitation. *IEEE Trans. Neural Systems and Rehabilitation Engineering*, 15(1):23-29, 2007.

Synergistic Activities

1. Technical Program Chair and co-founder, annual Design of Medical Devices Conference.
2. Former Education Co-Director, Center for Compact and Efficient Fluid Power (CCEFP), an NSF Engineering Research Center
3. Project co-leader for Test Bed 6, Wearable Fluid Power Devices in the 10 to 100 W Range, a project of the CCEFP and Project co-leader for 2B2; HCCI Engine-Compressor, a project of the CCEFP
4. Work on passive and active exoskeletons for rehabilitation
5. Collaborate with companies on product development, projects with 3M, Micro-Medical Devices, Toro, Aetrium, Augustine Medical, Donaldson, Spinal Designs, Honeywell, Select Comfort, Sulzer Medica, Enhanced Mobility Technologies, Medtronics, EnduraTEC, Machine Magic, Scimed, Sulzer Spine Tech, Andersen Windows, Hormel, Introspective, Geodigm, VivaCare, Comedicus, Hearing Components, Newco, Pando, IMI Visions, Tennant, Devicix, Lake Regent Medical , Best Buy, Graco, Nesos, Boston Scientific and others.

Collaborators & Other Affiliations

(i) Collaborators:
A. Erdman (UMN), P. Iaizzo (UMN), K. LaBat (UMN), E. Bye (UMN), K. Stelson (UMN), P. Li (UMN), C. Adams (UMN), B. Hammer (UMN), T. Ebner (UMN), J. Carey (UMN), D. Kittleson (UMN), E. Stern (UMN), E. Davis (Sister Kenny), T. Rosenthal (Systems Technology), J. Wachtel (Veridian Group), Lars Oddson (Sister Kenny) ("UMN" = University of Minnesota)

(ii) Graduate Advisor:
Dr. Michael J. Rosen, University of Vermont

(iii) Thesis and post-doc advisees in past 5 years:
L. Tian, J. Xia, R. D. Celotta, G. Brahmbhatt, S. Ponkshe, M. Steckler, S. Freeman, K. Vedula, P. Johnson, A. Srivasta, B. Koch, N. Carlson, J. Young, A Kangude, B. Burgstahler, R. Dargus, E. Leingang, M. Waddell, B. Krueger, B. Koch, B. Neubauer, S. Hashemi, A. Ries, J. Nath, K. Boughner, D. Johnson, J. Skelton, J. Lind, A. Stech.

Total number of advisees: 15 Ph.D., 71 MS, no post-docs

Randy H. Ewoldt
Department of Mechanical Science & Engineering
University of Illinois at Urbana-Champaign

Professional Preparation

Iowa State University	Mechanical Engineering	B.S., 2004
Massachusetts Institute of Technology	Mechanical Engineering	S.M., 2006
Massachusetts Institute of Technology	Mechanical Engineering	Ph.D., 2009
University of Minnesota – Twin Cities	Institute for Math. and its Apps. & Dept. Chem. Engr. and Matl. Sci.	Post-Doc, 2009-2011

Appointments

Assistant Professor, University of Illinois at Urbana-Champaign	Aug 2011 – Present
Postdoctoral Fellow, University of Minnesota – Twin Cities	Sept. 2009 – Aug. 2011

Products (selected)

[1] Corman, R. C., L. Rao, N. A. Bharadwaj, J. T. Allison, and R.H. Ewoldt, "Setting Material Function Design Targets for Linear Viscoelastic Materials and Structures," *Journal of Mechanical Design*, *in press*

[2] Schuh, J. K. and R.H. Ewoldt, "Surface texture depth profile effects on decreasing friction with Newtonian fluids in full film lubricated contact," *Tribology International*, *in press*

[3] Johnston, M. T., W. P. King, and R.H. Ewoldt, "Shear stress characteristics of microtextured surfaces in gap-controlled hydrodynamic lubrication," *Tribology International*, 82, 123–132 (2015)

[4] Rao, L. G., J.K. Schuh, R.H. Ewoldt, and J. T. Allison, "On Using Adaptive Surrogate Modeling in Design For Efficient Fluid Power," in *ASME 2015 International Design Engineering Technical Conferences*, paper no. DETC2015–46832 (2015)

[5] Ewoldt, R.H., "Extremely soft: Design with rheologically-complex fluids," *Soft Robotics*, 1(1) (2013) (**invited review for inaugural issue**)

[6] Johnston, M.T. and R.H. Ewoldt, "Precision rheometry: Surface tension effects on low-torque measurements in rotational rheometers," *Journal of Rheology*, 57(6), 1515-1532 (2013)

[7] Ewoldt, R.H., "Defining nonlinear rheological material functions for oscillatory shear," *Journal of Rheology*, 57(1) 177–195 (2013)

[8] Felts, J., S. Somnath, R.H. Ewoldt, W.P. King, "Nanometer-scale flow of molten polyethylene from a heated atomic force microscope tip," *Nanotechnology*, 23 (21) 215301 (2012)

[9] Celli, J.P., B.S. Turner, N.H. Afdahl, S. Keates, I. Ghiran, C. Kelly, R.H. Ewoldt, G.H. McKinley, P. So, S. Erramilli, and R. Bansil, "Helicobacter pylori moves through mucus by reducing mucin viscoelasticity," *Proceedings of the National Academy of Sciences*, 106 (34) 14321-14326 (2009)

[10] Ewoldt, R.H., A.E. Hosoi and G.H. McKinley, "New measures for characterizing nonlinear viscoelasticity in large amplitude oscillatory shear," *Journal of Rheology* 52(6), 1427-1458 (2008); **highest number of citations among all articles published in Journal of Rheology 2004-present**

Synergistic Activities

[1] *Industrially-relevant short courses on rheology*: Lecturer for nine rheology short courses for practicing users of rheology (Minneapolis, San Francisco, Boston, Houston, Belgium, Montreal).

[2] *The Rheology Zoo:* Outreach and educational effort to encourage diversity and broad participation of underrepresented groups in engineering (funding from NSF-BRIGE Award #1342408 and NSF-CAREER Award #1351342). The Zoo is a hands-on curated library of rheologically interesting

materials that will serve as a platform for outreach, engagement, and undergraduate research opportunities.

[3] *School of Art+Design Collaborative teaching:* For three semesters, collaborative teaching to use rheology as a disruptive technology in industrial design studio projects, and integrate design and creativity into a graduate-level course on non-Newtonian fluids and rheology.

[4] *Software Development:* **MITlaos**, a fully-documented and free software to calculate rheological properties from data, based on Ewoldt et al. J. Rheol. 2008. Requested by over 185 corporate, government, and academic research groups across the world.

Collaborators & Other Affiliations

1. Collaborators and Co-Editors (last 48 months)

Kyung Hyun Ahn (Seoul National University, Korea), James Allison (UIUC), Jonathan Bailey (UIUC, Carle Hospital), Frank Bates (Minnesota), Rafael Bras (Wrigley), Paul Braun (UIUC), Lucas M. Caretta (MIT), Kwang Soo Cho (Kyungpook National University, Korea), C. Clasen (KU-Leuven), Karin Dahmen (UIUC), C. J. Dimitriou (MIT), C.J. Espinoza Santos (UIUC), J. Felts (Texas A&M), Jonathan B. Freund (UIUC), Douglas Fudge (U. Guelph, Canada), Francisco Galindo-Rosales (University of Porto, Portugal), A. Kate Gurnon (U. Delaware), Sascha Hilgenfeldt (UIUC), Anette "Peko" Hosoi (MIT), Gavin Horn (UIUC), W. Hu (Minnesota), Kyu Hyun (Pusan National University, Korea), Iwona Jasiuk (UIUC), Waltraud M. Kriven (UIUC), William King (UIUC), Seung Jong Lee (Seoul National University, Korea), John H. Long (Vassar), Carlos Lopez-Barron (ExxonMobil), Chris Macosko (Minnesota), Luca Martinetti (Minnesota), Gareth McKinley (MIT), Leslie D. Morgret (Wrigley), Eric Morrison (EarthClean), Florian Nettesheim (DuPont), T.S.K. Ng (MIT), Martin Ostoja-Starzewski (UIUC), Marianne E. Porter (FL Atlantic), Lakshmi Rao (UIUC), F.J. Rubio-Hernandez (University of Málaga, Spain), Kenneth S. Schweizer (UIUC), A. Sevilla (Universidad Carlos III de Madrid, Spain), Cliff (S.S.) Shin (UIUC), H. Craig Silvis (Dow Chemical), S. Somnath (UIUC), J. Song (Dow Chemical), Johannes Soulages (ExxonMobil), James W. Swan (MIT), P. Tourkine (Ecole Normale Superieure), Norman J. Wagner (U. Delaware), Manfred Wilhelm (Karlsruhe Institute of Technology), T. M. Winegard (U. Guelph, Canada), Charles F. Zukoski (U Buffalo)

2. Graduate and Postdoctoral Advisors

Post-Doctoral: Christopher Macosko (Minnesota)

Ph.D. Gareth McKinley and Anette “Peko” Hosoi (MIT);

S.M. Anette “Peko” Hosoi and Gareth McKinley (MIT)

3. Thesis Advisor and Post-Scholar Sponsor (last five years)

N. Ashwin Bharadwaj, Brendan Blackwell, Olivia Carey-De La Torre, Gaurav Chaudhary, Rebecca Corman, Michael Johnston (now Boeing, CA), Jeremy Koch, Mansi Kumar, Arif Nelson, Jonathon Schuh, Piyush Singh (all UIUC)

Total Graduate Students Advised: 11 **Total Postdoctoral Scholars Sponsored: 0**

Vito R. Gervasi
Research and Development
Milwaukee School of Engineering

PROFESSIONAL PREPARATION

Milwaukee School of Engineering	Manufacturing Engineering Technology	B.S, 1996 Milwaukee
School of Engineering	Mechanical Engineering	M.S., 2003

APPOINTMENTS

1993-present Director, Research & Development, Rapid Prototyping Research, Milwaukee School of Engineering
1985-1990 United States Air Force, honorable discharge

Closely Related Products

1. Gervasi, Vito R., Josh Rocholl, Adam J. Schneider, Doug C. Stahl. "Casting Process." U.S. Patent 8,312,913, issued November 20, 2012. (CMP-Hybrid Casting Process, licensed).

2. Gervasi, Vito R. "Three dimensional object." U.S. Patent 6,641,897, issued Nov 4, 2003. (TetraLattice structure).

3. Douglas Cook, Bradley Knier, Vito Gervasi, Douglas Stahl, Ph.D. "Automatic Generation of Strong, Light, Multi-Functional Structures from FEA Output." Proceedings of the 21st Annual International Solid Freeform Fabrication (SFF) Symposium. Austin, Texas (2010).

4. Gervasi, Vito R. "Method of making three dimensional object." U.S. Patent 6,309,581, issued Oct 30, 2001. (Method of producing lattice structure, licensed).

5. Douglas L. Cook, Vito R. Gervasi," High-Performance, Multi-Functional, Fluid-Power Components Using Engineered Materials," International Fluid Power Expo, Las Vegas, NV, March 2011.

Significant Products

6. Gervasi, Vito R., Douglas Cook, "Reduction Of Complex Objects Into Manufacturable Elements Using The Shell-Slice Approach," Solid Freeform Fabrication Symposium Proceedings, Austin, Texas, August 2009.

7. Gervasi, Vito R., Adam Schneider, and Joshua Rocholl. 2005. "Geometry and Procedure for Benchmarking SFF and Hybrid Fabrication Process Resolution." Rapid Prototyping Journal 11(1), 4- (1st place poster for entire symposium)

8. Gervasi, Vito R., Robert S. Crockett, "Process of making three dimensional object." U.S. Patent 6,623,687, issued Sep 23, 2003 (Intertwined three dimensional lattice structure, licensed).

9. Hsiao-wecksler, Elizabeth T., Alex K. Shorter, Vito Gervasi, Douglas L. Cook, Richard Remmers, Geza F. Kogler, and William K. Durfee. "Portable Active Pneumatically Powered Ankle-Foot Orthosis." U.S. Patent 20,120,289,870 A1, published November 15, 2012.

10. Gervasi, Vito R., Douglas Cook, Robert Rizza, Sheku Kamara, Xue Cheng Liu, "Fabrication of Custom Dynamic Pedorthoses for Clubfoot Correction Via Additive-based Technologies," Solid Freeform Fabrication Symposium Proceedings, Austin, Texas, August 2009 (SFF Symposium Outstanding Paper).

SYNERGISTIC ACTIVITIES
MSOE's executive committee representative for the NSF Center for Compact and Efficient Fluid Power, started June 2006. Primarily involved in research related to thrust area II, "compactness." Former 2D Project leader. Now 2G Co-project leader (ranked #1 among Center projects) and member of the CCEFP Executive Committee. Led hosting of several CCEFP events at Milwaukee School of Engineering. Supports center projects related to additive manufacturing.

Through collaborative efforts between industry and MSOE aimed at bringing innovations to market a number of novel processes, designs and methods invented or co-invented by Gervasi (as well as many trade secrets) are commercially available in the form of many products through three companies, including: DSM-Somos (US patents 6,309,581, 6,641,897, 6,623,687), Orbital Technologies Corporation (Orbitec, US patent 8,312,913), 3DMolecular Designs (US patents 6,793,497, US6,471,520). Products include education molecular models, AM-based patterns for investment casting, reduced-mass components, FGM's, harsh environment components and DoD components.

Promotes activities and education of the Rapid Prototyping Consortium (RPC) industrial membership in areas of additive manufacturing. 1) Educated and trained industrial members and MSOE community on RP related topics at consortium meetings as well as at member locations. 2) Suggested and arranged numerous RPC guest speakers for monthly meetings. 3) Conducted applied research with consortium membership on numerous RP related projects

Contributor to the NIST Measurement Science for Metal-Based Additive Manufacturing Roadmap and participant in ASTM F42 (AM Technologies). Partook in evolving SME's Rapid Prototyping Association (RPA) to the current Rapid Technologies and Additive Manufacturing (RTAM) Community, a significant progression for the education and integration of additive technologies toward the "factory of the future." Currently contributing to the "NAMII/SME additive manufacturing body of knowledge project." Currently involved in the RTAM Masters Exam Committee.
Contributes to several sections of Wohler's Additive Manufacturing and 3D Printing State of the Industry Annual Worldwide Progress Report.

COLLABORATORS & OTHER AFFILIATIONS
Thomas Bray, Doug Cook, Shajan John, Sheku Kamara , A. James Mallmann Ph.D., Subha Kumpaty Ph.D. PE, Eric Durant Ph.D., Paul Michael, Matey Kalchev Ph.D., Robert Rizza Ph.D., Douglas Stahl, Tim Herman Ph.D.(3DMD), Josh Rocholl (Orbital Technologies Corporation), Liu Xue-Cheng Ph.D. M.D. (Medical College of Wisconsin), T. Wohler (Wohler's & Associates, Mark Abshire (DSM), Eric Barth Ph.D. (Vanderbilt University), Tom Chase Ph.D. (University of Minnesota), William Durfee Ph.D. (University of Minnesota), Elisabeth Hsiao-Wecksler Ph.D. (University of Illinois Urbana-Champaign), Geza Kogler Ph.D., C.O., L.O. (IL), L.Ped. (IL), B.C.O. (University of Illinois Urbana-Champaign), Richard Remmers (Bucyrus International, Inc./Caterpillar Inc.), Arthur Sauer (Orbital Technologies Corporation), Dan Maas (X-One), Robert Webster Ph.D.(Vanderbilt University), Kim Stelson Ph.D. (University of Minnesota)

GRADUATE ADVISORS

G. Hoffmann (Retired), Matthew Panhans Ph.D. (Milwaukee School of Engineering), William Howard Ph.D. (East Carolina University)

THESIS ADVISOR

Graduate Students: Richard Remmers (Bucyrus International, Inc. /Caterpillar Inc.)

Biographical Sketch for Elizabeth T. Hsiao-Wecksler

PROFESSIONAL PREPARATION

Cornell University	Ithaca, NY	Mechanical Engr.	BS	1987
Rochester Institute of Technology	Rochester, NY	Mechanical Engr.	MS	1994
University of California-Berkeley	Berkeley, CA	Mechanical Engr.	PhD	2000
Harvard Medical School & Boston University	Boston, MA	Rehabilitation Engr.	Postdoc	2000-2002

APPOINTMENTS

University of Illinois at Urbana-Champaign

Associate Head for Undergrad Programs, Dept of Mechanical Science and Engineering, 09/15- present
Professor, Dept of Mechanical Science and Engineering, 08/15 - present
Associate Professor, Dept of Mechanical Science and Engineering, 08/09 – 08/15
Affiliate, Neuroscience Program, 03/11
Affiliate, Department of Industrial and Enterprise Systems Engineering, 10/05
Affiliate, Department of Bioengineering, 07/02

IntelliWheels, Inc., Champaign, Illinois

Co-founder 05/10; Scientific Advisory Board 05/10 – 05/12

Xerox Corporation, Rochester, New York

Senior Project Engineer, Low Volume Printers and Copiers Division, 07/87 - 08/94

PRODUCTS (peer-reviewed from 49 journals and 12 ext conf proc) *work supported by NSF

Select Related Products:

1. *Hsiao-Wecksler, E.T., Farooq, D., Xiao, C., Oo, Y.L., Krishnan, G., Singh, G., Forearm and Wrist Support for Crutch Users. U.S. Non-provisional Patent Application #14/882,292, Oct 13, 2015.
2. *Hsiao-Wecksler, E. T., E. Loth, G. Kogler, K. A. Shorter, J. E. Thomas, and J.N. Gilmer, "Portable Active Pneumatically Powered Ankle-Foot Orthosis", United States Patent Application (Pub. No.: US 2011/0112447 A1).
3. *Shorter, K.A., Hsiao-Wecksler, E.T., Kogler, G.F., Loth, E., and Durfee, W.K., "A Portable-Powered-Ankle-Foot-Orthosis for rehabilitation." J Rehab Res Dev, 48(4): 459-472, 2011. http://www.rehab.research.va.gov/jour/11/484/pdf/shorter484.pdf
4. * Xiao, C., Oo, Y., Farooq, D., Singh, G., Krishnan, G., Hsiao-Wecksler, E.T. "Pneumatic Sleeve Orthosis for Lofstrand Crutches: Application of Soft Pneumatic FREE Actuator", Design of Medical Devices Conference, Minneapolis, MN, April 11-14, 2016.
5. * Islam, M., Hagan, M.T., and Hsiao-Wecksler, E.T. "Gait State Estimation for Powered Ankle Orthosis using Modified Fractional Timing and Artificial Neural Network", Design of Medical Devices Conference, Minneapolis, MN, April 11-14, 2016

Select Significant Products:

1. * Boes, M.K., Klaren, R.E., Kesler, R.M., Islam, M., Learmonth, Y., Petrucci, M.N., Motl, R.W. and Hsiao-Wecksler, E.T. "Spatiotemporal and Metabolic Impacts on Gait of a Powered Ankle Exoskeleton in Persons with Multiple Sclerosis", 39th Annual Meeting of the American Society of Biomechanics, Columbus, OH, August 5-8, 2015.
2. *Petrucci, M.N., MacKinnon, C.D., and Hsiao-Wecksler, E.T., "A Step Towards Reducing Freezing of Gait in Parkinson's Disease: Using a Portable Powered Orthosis", 7th World Congress of Biomechanics, Boston, MA, July 6-11, 2014.
3. *Boes, M.K., M. Islam, Y. D. Li, and E.T. Hsiao-Wecksler. "Fuel Efficiency of a Portable Powered Ankle-Foot Orthosis", IEEE 13th International Conference on Rehabilitation Robotics (ICORR 2013), Seattle, WA, June 24-26, 2013. http://dx.doi.org/10.1109/ICORR.2013.6650445.
4. *Li, D., Becker, A., Shorter, K.A., Bretl, T. and Hsiao-Wecksler, E.T. "Estimating System State During Human Walking with a Powered Ankle-Foot Orthosis", IEEE/ASME Transactions on Mechatronics, 16(5):835-844, 2011. http://dx.doi.org/10.1109/TMECH.2011.2161769
5. *Chin, R., Hsiao-Wecksler, E.T., Loth, E., Kogler, G., Manwaring, S.D., Tyson, S.N., Shorter, K.A., and Gilmer, J.N. "A pneumatic power harvesting ankle-foot orthosis to prevent foot-drop", Journal of NeuroEngineering and Rehabilitation, 6:19 (16 June) 2009. Invited Paper. doi:10.1186/1743-0003-6-19 http://www.jneuroengrehab.com/content/6/1/19

SYNERGISTIC ACTIVITIES

- *NSF ERC experience*: I lead the pneumatic arm of the Human Assist Devices Testbed within the NSF Engineering Research Center for Compact and Efficient Fluid Power (CCEFP, #0540834, 5/06-5/16). To create a technology-pull testbed to address the void in lightweight, compact, untethered, and energy-dense fluid power sources and associated components in the 1-10 W range, I proposed a portable, pneumatically-powered, ankle-foot orthosis for gait assistance of persons with disabilities. With collaborators across the seven ERC universities and multiple industry collaborators, this work produced the world's first full untethered portable powered ankle-foot orthosis.
- *REU sponsorship:* Since 2002, I have actively included over 95 undergraduate and high school student researchers in my group; some have been in my group for 3-4 years. Thirteen have been supported with NSF REU funds via CCEFP or an REU supplement. Sixteen have been co-authors or first authors in journal papers, conference presentations and/or invention disclosures.
- *Development of research tools:* Developed techniques for (a) quantitatively assessing motion patterns in dynamic systems with specific interest in analyzing abnormal gait or wheelchair propulsion biomechanics (NSF#0727083), and (b) assessing postural responses to impulse perturbations.
- *Engineering education:* UIUC College Eng instructional grants revise, integrate and coordinate all design courses in ME dept from freshman through senior year: 2013-2015, co-PI; 2015-2016, PI. *Course development:* Human and Robotic Locomotion Seminar: Interdisciplinary graduate seminar course with faculty and labs from Mechanical Engineering, Electrical Engineering, Kinesiology, Psychology, and Anthropology. This collaborative effort resulted in a NSF award (#0727083).
- *Outreach*: Coach for FIRST Lego League robotics team of 4^{th}-8^{th} grade students 2011-2014 (advanced to State tournament twice). Faculty advisor for national Chainless Challenge fluid powered bicycle design competition 2011-2015 (1^{st} place 2013, 2^{nd} 2015). UIUC College of Engineering Girls' Adventures in Mathematics, Engineering, and Science (GAMES) summer camp for 9^{th}-12^{th} grade girls, and 4H Extension for Advanced Science Siesta weekends for 7^{th} -10^{th} grade girls.
- *Service:* Elected as Program Chair and Program Chair-elect (2010-2012) for American Society of Biomechanics. Session co-chair and reviewer for multiple conferences. Ad-hoc reviewer for NIH, NSF, Veterans Admin. Faculty advisor for: Phi Sigma Rho (sorority for engineering and engineering technology students), ASME UIUC Student Chapter, and iRobotics (student robotics org at UIUC).

COLLABORATORS & OTHER AFFILIATIONS (at UIUC unless otherwise noted)

Collaborators and Co-Editors in 48 mon: MJ Angelini, CL Beck, MK Boes, FF Bradley, S Daigle, H Dankowicz, G Deetjen, LA DiBerardino, S Downing, WK Durfee (UMN), J Elrod, I Ensari, P Ferreira, B Harton, CJ Hass (UFL), J Henderson (BradleyU), GP Horn, MK Hsu (unemployed), P Hur (Texas A&M), M Islam, C Jayaraman, RM Kesler, RE Klaren, GF Kogler (GaTech), G Krishnan, Y Li (Western Digital), CD MacKinnon (UMN), Y Moon, RM Motl, B Neubeuer, Y Oo, K Park (Trine U), MN Petrucci, IM Rice, R Roemmich, KS Rosengren (Wisconsin), G Singh, KA Shorter (UMichigan), B Slavens (U Wisc-Milwaukee), DL Smith (Skidmore College), JJ Sosnoff, S Tawfick, SR Tippett (BradleyU), Z Wang, C Xiao

Graduate Advisors and Postdoctoral Sponsors: (Total Graduate Advisor: 1, Total Postdoctoral Sponsor: 3)

Stephen N. Robinovitch, Simon Frasier (Grad)	James J. Collins, Boston University
Lewis A. Lipsitz, Harvard Medical School	D. Casey Kerrigan, University of Virginia

*Thesis Advisor and Postgraduate-Scholar Sponsor (*at UIUC unless noted)*:* Grad students advised: 25 (total; 6 PhD, 2 MS/PhD, 14 MS), Postdoc sponsored: 1 (none in past 5 years). MJ Angelini (unknown), MK Boes (UIUC), R Chin (Unknown), SC Daigle (IntelliWheels), LA DiBerardino (Ohio Northern U), RJ Doyle (Unknown), BA Duiser (Rolls-Royce), D Farooq (Caterpillar), P Hur (Texas A&M), J Jang (UIUC), RM Kesler (UIUC), Y Li (Western Digital), EA Morris (Caterpillar), MJ Major (Northwestern U), KM McHugh (Unknown), K Park (Trine U), C Imbs Ragetly (Paris, France), A Ramachandran (Boeing), R Riemer (Ben Gurion U), KA Shorter (UMichigan), MJ Socie (Rehab Inst Chicago), MJ Wineman (Watlow)

Dr.h.c. Monika Ivantysynova, Ph.D
MAHA Professor Fluid Power Systems
School of Mechanical Engineering & Agricultural and Biological Engineering
Purdue University

Professional Preparation

Slovak Technical University of Bratislava, CZ	Mechanical Engineering	M.S.E.	1979
Slovak Technical University of Bratislava, CZ	Mechanical Engineering	Ph.D.	1983

Appointments

August 2004 – present	Maha Professor Fluid Power Systems, Director Maha Fluid Power Research Center, School of Mechanical Engineering and Agricultural and Biological Engineering, Purdue University
1999 – 2004	Professor Mechatronic Systems, Institute for Aircraft Systems Engineering, Technical University of Hamburg-Harburg, Germany
1996 – 99	Professor Fluid Power and Control, Department of Mechanical Engineering, Duisburg University, Germany
1992 -1996	Senior Researcher and Managing Director of the Institute for Aircraft Systems Engineering at Technical University of Hamburg-Harburg, Germany
1990 -1992	Senior Researcher and Project Manager at the Institute for Machine Design at Technical University of Hamburg-Harburg, Germany
1989 -1990	Project Manager for Mobile Hydraulics, Commercial Hydraulics, Hamburg, Germany
1988– 1990	Assistant Professor, Institute of Robotics, Technical University Bratislava, Czechoslovakia,
1984 – 1988	R & D Project Engineer for design and development of pumps, motors and hydraulic drive systems at ZTS VUHYM in Dubnica, Czechoslovakia
1983 - 1984	Product Development Engineer, Head of Department of Automation Systems at VEB Elektronik Gera, Germany

Closely Related Products

1. Pelosi, M. and Ivantysynova, M. 2012. A Geometric Multigrid Solver for the Piston-Cylinder Interface of Axial Piston Machines. Tribology Transactions, Vol. 55, Issue. 2, pp. 163 - 174.
2. Pelosi, M. and Ivantysynova, M. 2012. Heat Transfer and Thermal Elastic Deformation Analysis on the Piston/Cylinder Interface of Axial Piston Machines"; ASME Journal of Tribology. Vol. 134, October 2012, pp. 1- 15.
3. Zecchi, M. and Ivantysynova, M. 2012. A novel approach to predict the cylinder block / valve plate interface performance in swash plate type axial piston machines. ASME/Bath Symposium on Fluid Power and Motion Control (FPMC 2012), Bath, UK, pp. 13-28.
4. Pelosi, M. and Ivantysynova, M. 2011. Surface Deformation Enables High Pressure Operation of Axial Piston Pumps. ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VI, USA. **Best paper award**
5. Schenk, A. and Ivantysynova, M. 2011. An Investigation of the Impact of Elastohydrodynamic Deformation on Power Loss in the Slipper Swashplate Interface. 8th JFPS International Symposium on Fluid Power, Okinawa, Japan.- **Best paper award.**

Significant Products

1. Sprengel, M. and Ivantysynova, M. 2012. Coupling Displacement Controlled Actuation with Power Split Transmissions in Hydraulic Hybrid Systems for Off-Highway Vehicles. ASME/Bath Symposium on Fluid Power and Motion Control (FPMC 2012), Bath, UK, pp. 505-517.
2. Hippalgaonkar, R., Zimmerman, J. and Ivantysynova, M. 2011. Investigation Of Power Management Strategies For A Multi-Actuator Hydraulic Hybrid Machine System. SAE 2011 Commercial Vehicle Engineering Congress, , Sep 13-14 2011, Rosemont, IL, USA. SAE Technical Paper 2011-01-2273

3. Hughes, E.C., Williamson, C.A., Zimmerman, J.D. Ivantysynova, M.M. 2012. Displacement – controlled hydraulic system for multi-function machines. US Patent No: US 8,191,290 B2 issue June 5, 2012.
4. Ivantysynova, M. and Baker, J. 2009. Power Loss in the Lubricating Gap Between Cylinder Block and Valve Plate of Swash Plate Type Axial Piston Machines. International Journal of Fluid Power, Vol. 10, No. 2, pp. 29 - 43.
5. Ivantysyn, J. and Ivantysynova, M. 2000. Hydrostatic Pumps and Motors, Principles, Designs, Performance, Modelling, Analysis, Control and Testing. New Delhi. Academia Books International., 512 pages, ISBN 81-85522-16-2.

Synergistic Activities

- Co-founder and member of scientific board of Fluid Power Net International http://fluid.power.net 1999 – present
- Member of European Fluid Power Research Centre FPCE, http://www.fpce.net 2002 - 2005
- Executive Committee Member, Thrust and Test Bed Leader, Engineering Research Center for Compact and Efficient Fluid Power (CCEFP), 2006 – present
- Founder and Editor-in-Chief of the International Journal of Fluid Power since 2000
- Developed and taught two new graduate courses in the field of Fluid Power 2005 – present

Collaborators and Other Affiliations

(a) Collaborators in last four years:
All PI's of the CCEFP (Kim Stelson, Perry Li and Will Durfee, University of Minnesota, Wayne Book and Richard Salan, Gerogia Tech, Mike Goldfarb and Eric Barth, University of Vanderbuilt, Andrew Alleyne and Eric Loth, University of Illinois, John Lumkes Steve Frankel and Ashlie Martini, Purdue University)), Wayne John Book (Georgia Institute of Technology), Richard Burton (University of Saskatchewan), Peter John Chapple (NTNU Norwegian University of Science and Technology), Richard Kimbel (Parker Hannifin), Joe Kovach (Parker-Hannifin), Noah Manring (University of Missouri), Jean-Charles Mare (INSA Toulouse), Massimo Milani (University of Modena), Takao Nishiumi (National Defense Academy, Japan), Petr Noskievic (Technical University of Ostrava), Roberto Paoluzzi (IMAMOTER - C.N.R), Robert Rahmfeld (Sauer-Danfoss), Jari Rinkinen (Tampere University of Technology), Rudolf Scheidl (University of Linz), Scott Schuh (Bobcat), J. Weber (TU Dresden), Andrzej Sobzyk (Krakow University), Matti Vilenius (Tampere University of Technology), Howard Zhang (Parker-Hannifin).

(b) Thesis and Dissertation Advisor for Prof. Ivantysynova:
Prof. Paciga (TU Bratislava)

(c) Thesis or Dissertation Advisor in last five years:
Jonathan Baker, Shekhar Degaonkar, Reece Garret, Andrew Fredrickson, Najoua Jouini, Richard Klop, Kyle Williams, Christopher Wiliamson, Matteo Pelosi, Ganesh Seeniraj, Josh Zimmermann, Rajneesh Kumar, Shinok Lee, Rohit Kumar, Matteo Pelosi, Micheal Cross, Brent Warr, Jess Rose, Matt Kronlage, Domgjune Albert Kim

Total number of graduate students supervised: 87 Postdoctoral scholars: 6 Undergraduate Research Students: 25

Steven X. Jiang
Department of Industrial and Systems Engineering
North Carolina A&T State University

Professional Preparation

East China Institute of Technology	Mechanical Engineering	BS, 1992
Nanjing University of Science & Technology	Manufacturing Engineering	MS, 1998
Clemson University	Industrial Engineering	Ph.D. 2001

Appointments
Associate professor, Department of Industrial and Systems Engineering, North Carolina A&T State University, 2008-Present
Assistant Professor, Department of Industrial and Systems Engineering, North Carolina A&T State University, 2002-2008

Closely Related Products
Publications Most Closely Related to Proposal:
Hughes, K., Jiang, X. (2010), "Using Discrete Event Simulation to Model Excavator Operator Performance", International Journal of Human Factors and Ergonomics in Manufacturing and Service Industries, 20(5), 408-423.

Chung, C.,Jiang, X., Jiang, Z., Udoka, S. (2010), "Using Digital Human Modeling to Predict Operator Performance of a Compact Rescue Crawler", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Lee, A., Jiang, S. (2010), "Assessing Operator Workload for a Fluid Powered Rescue crawler", The journal of Management and Engineering Integration, 3(2), 48-53.

Hughes, K., Jiang, S., Jiang, Z., Park, E., and Mountjoy, D. (2011), "Assessment of Excavator Operator Performance Using an Integrated Human Performance Model", The journal of Management and Engineering Integration, 4(1), 88-98.

Franklin, C., Jiang, Z., Jiang, X. (2011), "Learning Curve Analysis of a Haptic Controller", The journal of Management and Engineering Integration, 4(1), 63-70.

Synergistic Activities
Hughes, K., Jiang, X., Jiang, Z., Mountjoy, D., Park, E. (2010), "A Preliminary Study of an Integrated Human Performance Model", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Delpish, R., Jiang, X., Park, E. , Udoka, S., Jiang, Z., (2010), "Development of a User-Centered Framework for Rescue Robot Interface Design", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Jenkins, Q., Jiang, X. (2010), "Measuring Trust and Application of Eye Tracking in Human Robotic Interaction", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Liu, Y., Jiang, X., Jiang, Z., Park, E. (2010), "Predicting Backhoe Excavator Operator Performance Using Digital Human Modeling", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Osafo-Yeboah, B., Elton, M., Jiang, X., Book, W., Park, E. (2010), "Usability Evaluation of a Coordinated Excavator Controller with Haptic Feedback", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Synergistic Activities

- Co-chair of Human Factors and Ergonomics Track, 2007 Industrial Engineering Research Conference (IERC)
- Co-chair of Human Factors and Ergonomics Track, 2008 Industrial Engineering Research Conference (IERC)
- Editorial Board, International Journal of Industrial Ergonomics
- Editorial Board, Journal of Management and Engineering Integration

Collaborators And Other Affiliations

Collaborators Over The Last 48 Months:
Drs. Zongliang Jiang, Eui Park, Udoka Silvanus, NCA&T, CCEFP
Dr. Wayne Book, Georgia Institute of Technology, CCEFP
Drs. Lauren Davis and Salil Desai, NCA&T
Dr. Kevin Taaffe, Clemson University

Graduate and Postdoctoral Advisors:
Dr. Anand Granmopadhye, Clemson University

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
Khaliah Hughes (SAS), Gerald Watson (US Navy), Edem Tetteh (Paine College), Paul Nuschke (Electronic Ink), Porsche Williamson (GE), Ritson Delpish (NCA&T), Yang Liu (NC A&T), Benjamin Osafo-Yeboah (NCA&T), Quaneisha Jenkins (NCA&T), Charlie Chung (Virginia Tech), Antonio Lee (NCA&T)

Total Number of Graduate Students advised: 20

David B. Kittelson
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

University of Minnesota	Mechanical Engineering	B.S.	1964
University of Minnesota	Mechanical Engineering	M.S.	1966
University of Cambridge, England	Chemical Engineering	Ph.D	1972

Appointments

2003-2004	Overseas Fellow, Engineering Department, Cambridge University
2003-present	Frank B. Rowley Professorship in Mechanical Engineering
1996-present	Director, Center for Diesel Research.
1987-2005	Director, Power and Propulsion Division
1985-1986	Overseas Fellow, Engineering Department, Cambridge University
1980-present	Professor, Department of Mechanical Engineering
1976-80	Associate Professor, Department of Mechanical Engineering
1970-76	Assistant Professor, Department of Mechanical Engineering

Closely Related Products

1. Tian, Lei, David B. Kittelson, William K. Durfee, 2009. Miniature HCCI Free-Piston Engine Compressor for Orthosis Application, JSAE paper number 20097176.
2. Aichlmayr, H. T. Kittelson, D. B. and Zachariah, M. R., 2003 "Micro-HCCI Combustion: Experimental Characterization and Development of a Detailed Chemical Kinetic Model with Coupled Piston Motion" Combustion and Flame Vol. 135, No. 3, pp. 227-248, 2003.
3. Aichlmayr, H. T., D. B. Kittelson, and M. R. Zachariah, "Miniature Free-Piston Homogeneous Charge Compression Ignition Engine-Compressor Concept-Part I: Performance Estimation and Design Considerations Unique to Small Dimensions," Chemical Engineering Science Vol. 57 No 19, pp. 4161-4171, 2002.
4. Aichlmayr, H. T., D. B. Kittelson, and M. R. Zachariah, "Miniature Free-Piston Homogeneous Charge Compression Ignition Engine-Compressor Concept-Part II: Modeling HCCI Combustion in Small-Scales with Detailed Homogeneous Gas Phase Chemical Kinetics," Chemical Engineering Science Vol. 57 No. 19 pp. 4173-4186, 2002.
5. Franklin, Luke M.; Anil S. Bika; Winthrop F. Watts; and David B. Kittelson, 2010. Comparison of Water and Butanol Based CPCs for Examining Diesel Combustion Aerosols, Aerosol Science and Technology, 44:629–638.

Significant Products

6. Gidney, J.T.; N. Sutton; M.V. Twigg; and D.B. Kittelson; 2010, Exhaust inorganic nanoparticle emissions from internal combustion engines, Internal Combustion Engines: Performance, Fuel Economy and Emissions, Chandos Publishing, Oxford, pp 133 – 146.
7. Gidney, Jeremy T., Martyn V. Twigg, and David B. Kittelson, 2010. Effect of Organometallic Fuel Additives on Nanoparticle Emissions from a Gasoline Passenger Car, Environmental Science and Technology, v 44, n 7, p 2562-2569.
8. Swanson, Jacob and David Kittelson, 2010. Evaluation of thermal denuder and catalytic stripper methods for solid particle measurements, Journal of Aerosol Science, Volume 41, Issue 12, Pages 1113-1122.
9. Swanson, Jacob; Kittelson, David B.; Pui, David Y. H.; Watts, Winthrop, 2010. Alternatives to the gravimetric method for quantification of diesel particulate matter near the lower level of detection, Journal of the Air and Waste Management Association, v 60, n 10, p 1177-1191.
10. Watts, Winthrop F., David D. Gladis, Matthew F, Schumacher, Adam C. Ragatz, and David B. Kittelson, 2010. Evaluation of a Portable Photometer for Estimating Diesel Particulate Matter Concentrations in an Underground Limestone Mine, Ann Occup Hyg 54(5): 566-574.

Synergistic Activities
We maintain and active research program on engine combustion and emissions.

Collaborators and Other Affiliations
Collaborators and Co-Editors: Aichlmayr, H. T., Sandia National Labs; Baltensperger, U., Paul Scherrer Institute; Bischof, Oliver F., TSI, Inc.; Bukowiecki, N., Paul Scherrer Institute; Burtscher, H., Paul Scherrer Institute; Caldow, Robert, TSI, Inc.; Cao, Feng, University of Minnesota; Carter, J., University of Rochester; Collings, Nick, Cambridge University; Couderc, J. Univ. of Rochester; Cox, C., Univ. of Rochester; Dallas, Andrew, Donaldson; Docherty, Kenneth S., UC Riverside; Driscoll, K., University of Rochester; Eberly, S., Univ. of Rochester Elder, A. C., University of Rochester; Finkelstein, J., University of Rochester; Frampton, M., University of Rochester; Gelein, R., University of Rochester; Goersmann, C., Johnson-Matthey; Goodier, S. P., British Petroleum; Grose, M., TSI, Inc.; Hands, Tim, Cambustion, Ltd.; Higgins, K.J., University of Minnesota; Hopke, P. K., Clarkson College; Ische, E. E., University of Minnesota; Jacobson, M. Z., Stanford; Jeong, C-H., University of Rochester; Johnson, J. P., University of Minnesota; Johnson, Tim, TSI, Inc. Jung, Heejung, UC Riverside; Kasper, A., Paul Scherrer Institute; Kim, E., University of Rochester; Kuehn, T.H., University of Minnesota; Kumarathasan, P., University of Rochester; Lawson, D. R., NREL; Lee, D., University of Minnesota; Liu, W., University of Rochester; Liu, Z. Gerald, Fleetguard; Ma, Hongbin ,Cummins; McMurry, P. H., University of Minnesota; Miller, Arthur, NIOSH ; Mirme, Aadu, TSI, Inc. ; Morgan, C. G., Johnson-Matthey. Plc.; Murray, I. P., Johnson-Matthey. Plc.; Ng, Iam Pou, Cummins; Nickolaus, Chris, Cambustion, Ltd.; Niemelä, Ville, Dekati; Oberdörster, G., University of Rochester; Ortiz, M., Corning; Park, Kihong, University of Minnesota; Paul, Schaberg, Sasol; Payne, M. J., British Petroleum; Phipps, R., University of Rochester; Pöcher, Arndt, TSI, Inc.; Premkumari K., University of Rochester; Preston, H., British Petroleum; Ramachandran, G. J., University of Minnesota; Remerowki, M. L., University of Minnesota; Roberts, J.T., University of Minnesota; Rowntree, C. J., British Petroleum; Sakurai, Hiromu, University of Minnesota; Savstrom, J. C., Donaldson Company; Schauer, J., University of Wisconsin; Sem, Gilmore J., TSI, Inc.; Stolzenburg, M. R., Univ. of Minnesota; Swanson, Jacob, Univ. of Minnesota; Swor, Thaddeus, Fleetguard; Tobias, Herbert J., UC Riverside; Twigg, Martyn, Johnson-Matthey, plc.; Utell, M., University of Rochester; Vasys, Victoria N., Fleetguard; Vincent R., University of Rochester; Walker, A. P., Johnson-Matthey; Warrens, C. P., British Petroleum; Watts, W., Univ. of Minnesota; Weingartner, E., Paul Scherrer Institute; Xia, X., Univ. of Rochester; Yang, C.H., University of Minnesota; Zachariah, Michael R.. University of Maryland; Zareba W., Univ. of Rochester; Zarling, Darrick D., University of Minnesota; Zhao, W., University of Rochester; Zhuo, L..University of Rochester; Ziemann, Paul J., UC; Riverside; Zink, U., Corning.

Graduate and Post Doctoral Advisors: M.S. – Edward Fletcher, University of Minnesota
Ph.D. – Alan Hayhurst, Cambridge University

Thesis Advisor and Postgraduate-Scholar Sponsor: (last 5 years) Jason Johnson, TSI Inc.; Jeffrey Campbell, US State Department; Jacob Swanson, UofM; Andy Tan, Cummins; David Hall, Phillips Temro; Brad Dana, MTS; John Dixon, Cummins; Suwandi Iskak, M.S., University of Minnesota; Jason Johnson, M.S. Donaldson; Hamed Kebriaei, M.S. Cummins; Junghwan Kim, M.S., University of Wisconsin; Bamidele Fayemi, M.S., Nigeria; Arthur Miller, Ph.D., NIOSH; Hongbin Ma, Post-doc., Cummins; Jake Savstrom, M.S., Donaldson Co.; Heejung Jung, Ph.D., UC Riverside; Matt Cambio, M.S., ThermoKing; John Debauche, M.S., ; Thomas Robert, M.S., Thermo-King; Iam Pou Ng, M.S., Cummins; Qiang Wei, Ph.D., Horiba; Hans T. Aichlmayr, Ph.D., Sandia National Labs

Thomas R. Kurfess, P.E.
HUSCO Ramirez Distinguished Chair in Fluid Power and Motion Control
and
Professor
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia USA

Professional Preparation:

M.I.T., Cambridge, MA	Mechanical Engineering	**S.B.** (1986)
M.I.T., Cambridge, MA	Mechanical Engineering	**S.M.** (1987)
M.I.T., Cambridge, MA	Electrical Engineering and Computer Science	**S.M.** (1988)
M.I.T., Cambridge, MA	Mechanical Engineering	**Ph.D.** (1989)

Appointments:

2012-Present, HUSCO Ramirez Distinguished Chair in Fluid Power and Motion Control and Professor, Woodruff School of Mechanical Engineering, GA Tech, Atlanta, GA.
2012-2013, Assistant Director for Advanced Manufacturing, Office of Science and Technology Policy, Executive Office of the President of the United States of America, Washington, DC.
2005-2012, Professor and BMW Chair of Manufacturing Integration, Department of Mechanical Engineering, Clemson University, Clemson, SC.
2000-2005, Professor, Woodruff School of Mechanical Engineering, GA Tech, Atlanta, GA.
1993-2000, Associate Professor, Woodruff School of Mechanical Eng., GA Tech, Atlanta, GA.
1993, Associate Professor of Mech. Eng. and Engineering and Public Policy, Carnegie Mellon University (CMU), Pittsburgh, PA.
1989-93, Assistant Professor of Mech. Eng. and Engineering and Public Policy, CMU, Pittsburgh, PA.
1992-present, participating guest in the Precision Engineering Program at the Lawrence Livermore National Laboratory (LLNL), Livermore, CA.
1992-93, Summer Faculty LLNL, in the Precision Engineering Program, Livermore, CA.

Products

1. Carter J. A., Tucker, T. M., Kurfess, T. R., “3-Axis CNC Path Planning Using Depth Buffer and Fragment Shader,” Computer-Aided Design & Applications, Vol. 5, No. 5, pp. 612-621, 2008.
2. Panyam, M., Tucker, T. M., Kurfess, T. R., “Least-Squares Fitting of Analytic Primitives on a GPU,” Journal of Manufacturing Systems, Vol. 27, No. 3, pp. 130-135, July 2008.
3. Tarbutton, J. A., Kurfess, T. R., Tucker, T. M., “Graphics Based Path Planning for Multi-Axis Machine Tools,” Computer-Aided Design & Applications, Vol. 7, No. 6, pp. 612-621, 2010.
4. Tarbutton, J. A., Kurfess, T. R., Tucker, T. M., “Machining by Ray-Casting into Voxel Models, Proceedings of 2010 International Symposium on Flexible Automation,” Tokyo, Japan, July 12-14, 2010 UPL-2503.

Products (other)

1. Kurfess, T. R., “CMMs Are Key to Auto Quality” Manufacturing Engineering, Vol. 137, No. 3, pp. 131-140, September 2006.
2. Roth, J.T., Mears, L., Djurdjanovic, D., Yang, X. and Kurfess, T. R., “Quality and Inspection of Machining Operations: CMM Integration to the Machine Tool,” ASME Journal of Manufacturing Science and Engineering, Vol. 131, No. 5, October 2009.
3. Kurfess, T. R. (Editor), Robotics and Automation Handbook, 2005, CRC Press, Inc., Boca Raton, FL.
4. A. J. Henderson, C. Bunget, and T. R. Kurfess, "On-machine monitoring of tool wear with touch probes," *Proceedings of NAMRI/SME,* vol. 39, p. 8, 2011.
5. M. Estrems, H. T. Sanchez, T. R. Kurfess, C. Bunget, A. J. Henderson, and B. J. Richardson, “Influence of size effect and radial runouts on the end milling of a nickel-based superalloy," *Proceedings of NAMRI/SME,* vol. 39, p. 8, 2011.

Synergistic Activities

1. Board of Director MT Connect Institute.
2. Co-Chair National Network for Manufacturing Innovation Working Group, Advanced Manufacturing Partnership 2.0.
3. Board of Directors, Society of Manufacturing Engineers.
4. Board of Directors, National Center for Manufacturing Sciences.
5. Board of Directors, National Center for Defense Manufacturing and Machining.
6. Board of Editors, International Journal of Engineering Education.
7. Member National Academies Panel on Manufacturing Engineering.

Collaborators & Other Affiliations

Collaborators and Co-Editors:

Douglass Chinn (Sandia National Laboratories), R. Cowan* (Georgia Tech), Steven Danyluk (Georgia Tech), Levent Degertekin (Georgia Tech), Craig Henderson (Sandia National Laboratories), Steven Liang* (Georgia Tech), Shreyes Melkote* (Georgia Tech), Mark L. Nagurka* (Marquette University)

Graduate Advisors:

C. L. Searle (M.I.T.), D.E. Whitney (M.I.T)

Thesis Advisor:

M.S: R. Anderson, K. Aravalli, P. Aussaguel, S. Billington, S. Bittle, V. Bobba, J. Bradon, Z. Brooks*, S. Burns, A. Caccialupi, J. Ceremuga, A. Chen, W. Choi, I. Chuckpaiwong, A. Claudet, R. Coulter, R. Cowan, M. Crudele, M. Cummings, T. Dawson, C. Gallagher, S. Gamble, M. Greene, O. Karhade, B. Kim, H. Kohli, K. Laughlin, M. Leclerc, T. Lloyd, D. Longanbach, R. Lopez, J. Miller, C. Moore, J. Morrisette, J. Nichols, P. Padmanabhan, M. Panyam, J. Rayner, J. Reyer, B.J. Richardson, U. Sadiq, M. Schmittdiel, M. Shilling, M. Shilling, J. Shiroishi, J. Sills, W. Stone, J. Stuhlfire, J. Tarbutton, G. Toledo, T. Tucker*, J. Tucker, B. Ulmer, J. Whidby, T. Williams, A. Wilson, M. Yang, S. Yim.

Ph.D.: M. Aminzadeh*, P. Amy, M. Arant, M. Bowler*, Aoyu Chen*, Austin Chen, W. Choi, I. Chuckpaiwong, A. Claudet, T. Dawson, D. Delorenzis, A. Henderson, Hodge Jenkins, O. Karhade, B. Kim, D. Konobrytskyi, K. Kreuger, J. Limroth, D. Longanbach, L. Mears, P. Murray, J. Nichols, H. Razavi, M. Shilling, W. Stone, J. Tarbutton, T. Tucker*, H. Vasseur, S. K. Wang

Post-Graduate Scholars: A. Bryan, C. Bunget, G. Bunget, S. De Rosa (University of Naples "Federico II"), Manuel Estrems (Universidad Politécnica de Cartagena, Spain), P. Gutheil (Fachhochschule Trier, Germany), Y. Jung (Pusan National University, Korea), J. Karandikar* (Georgia Tech), D. Kim (Kumoh National University of Technology), P. Kerstiens (Fachhochschule Gelsenkirchen, Bocholt, Germany), J. Marquez (ETSII. Polytechnic University of Madrid), H. Razavi (Georgia Tech)

Number of MS students: 55, Number of Ph.D. students: 25, Post-doctoral scholars sponsored: 11
* Indicates current

Michael J. Leamy
G. W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology

PROFESSIONAL PREPARATION

Clarkson University, Potsdam, NY	Mechanical Engineering	B.S. 1993
University of Michigan, Ann Arbor, MI	Mechanical Engineering	M.S. 1995
University of Michigan, Ann Arbor, MI	Mechanical Engineering	Ph.D. 1998
Technion, Haifa, Israel	Nonlinear Mechanics	1998-1999
NASA Langley Research Center	Computational Mechanics	1999-2000

APPOINTMENTS

Jul. 2012 – Present	Georgia Institute of Technology, Associate Professor
Aug. 2007 – Jul. 2012	Georgia Institute of Technology, Assistant Professor
Sep. 2004 – Aug. 2007	MITRE Corporation, Research Scientist
Sep. 2003 – Aug. 2004	University of Maine, Assistant Professor
Jun. 2000 – Aug. 2003	United States Military Academy, West Point, Assistant Professor

CLOSELY RELATED PROJECTS

1. Leamy, M.J., 2012, "Exact Wave-Based Bloch Analysis Procedure for Investigating Wave Propagation in Two-Dimensional Periodic Lattices," *Journal of Sound and Vibration*, **331**: 1580-1596.
2. Narisetti, R.K., Ruzzene, M., Leamy, M.J., 2011, "A Perturbation Approach for Analyzing Dispersion and Group Velocities in Two-Dimensional Nonlinear Periodic Lattices," *Journal of Vibration and Acoustics*, **133** (6): 061020, pp. 1-12.
3. Farzbod, F., Leamy, M.J., 2011, "Analysis of Bloch's Method in Structures with Energy Dissipation," *Journal of Vibration and Acoustics*, **133** (5): 051010, pp. 1-8.
4. Manktelow, K., Leamy, M., Ruzzene, M., 2011, "Multiple Scales Analysis of Wave-Wave Interactions in a Cubically Nonlinear Monoatomic Chain," *Journal of Nonlinear Dynamics,* **63**: 193-203.
5. Narisetti, R.K., Leamy, M.J., Ruzzene, M., 2010, "A Perturbation Approach for Predicting Wave Propagation in One-Dimensional Nonlinear Periodic Structures," *Journal of Vibration and Acoustics*, **132** (3): 031001, pp. 1-11.

SIGNIFICANT PRODUCTS

1. Kulpe, J.A., Lee, C.-Y., Leamy, M.J., 2011, "Computation of Acoustic Absorption in Media Composed of Packed Microtubes," *Journal of the Acoustical Society of America*, **130** (2): 826-834.
2. Lee, C.-Y., Leamy, M.J., Nadler, J.H., 2010, "Frequency Band Structure and Absorption Predictions for Multi-Periodic Acoustic Composites," *Journal of Sound and Vibration*, **329**: 1809-1822.
3. Farzbod, F., Leamy, M.J., 2009, "The Treatment of Forces in Bloch Analysis," *Journal of Sound and Vibration*, **325**: 545-551.
4. Leamy, M.J., DiCarlo, A., 2009, "Phonon Spectra Prediction in Carbon Nanotubes Using a Manifold-Based Continuum Finite Element Approach," *Computer Methods in Applied Mechanics and Engineering*, **198** (17-20): 1572-1584.
5. Leamy, M.J., Lee, C.-Y., 2009, "Dynamic Response of Intrinsic Continua for Use in Biological and Molecular Modeling: Explicit Finite Element Formulation," *International Journal for Numerical Methods in Engineering*, **80** (9): 1171-1195.

SYNERGISTICS ACTIVITIES
Associate Editor, *Journal of Vibration and Acoustics* (2012-Present)
Elected Member of the Technical Committee on Vibration and Sound, ASME (2011-present)
Member of ASME, SAE

SESSION/SYMPOSIA ORGANIZER (MOST RECENT)

- Technical Track Co-Chair, 'Multiscale Mechanics of Materials,' *49th Annual Society of Engineering (SES) Technical Meeting*, 2012, Atlanta, GA.
- Symposium Co-Organizer, 'Emerging Applications in Dynamic Systems,' *24th Conference on Vibration and Noise*, 2012 ASME IDETC Conference, Chicago, IL.
- Member of Scientific Advisory Board, *Phononics 2011 – International Conference on Phononic Crystals, Metamaterials & Optomechanics*, 2011, Santa Fe, NM.
- Topic Chair, 'Structural Dynamics,' *ASME IDETC Conference*, 2011, Washington, DC.
- Minisymposium Organizer, 'Computational Mechanics of Phononic Metamaterials and Phononic Crystals,' *11th U.S. National Congress on Computational Mechanics*, 2011, Minneapolis, MN.

COLLABORATORS & OTHER AFFILIATIONS
Collaborators: Prof. Thomas Bradley, Dr. Gary Caille (Colorado State University), Prof. Ken Cunefare, Prof. Aldo Ferri, Prof. Peter Hesketh, Prof. David Hu, Prof. Massimo Ruzzene, Prof. Karim Sabra, Prof. David Taylor (Georgia Institute of Technology), Dr. Mahmoud Hussein (University of Colorado), Prof. Mario Encinosa, Prof. Mark Jack (Florida A&M University), Prof. Chiara Daraio (Cal Tech).

Post Graduate Advisors: Prof. Ahmed Noor (NASA Langley Research Center, University of Virginia), Prof. Oded Gottlieb (The Technion, Israel).

Thesis Advisor and Postgraduate-Scholar Sponsor (Previous 5 Years)
Graduate Students (11): Dr. Farhad Farzbod, 01/2008 – 11/2010, Dr. Raj Narisetti, 06/2008 – 11/2010, Mr. John Arata, 01/2010 – 11/2011, Mr. Kevin Manktelow, 08/2009 – Present
Mr. Kyle Karlson, 08/2009 – Present, Mr. Jason Kulpe, 08/2010 – Present, Mr. Kamil Kocak, 08/2011 – Present, Mr. Dekun Pei, 08/2011 – 12/2012, Mr. Ryan Hopman, 01/2008 – 08/2009, Ms. Dooroo Kim, 09/2007 – 08/2009, Mr. Thibaut Autrusson, 09/2007 – 05/2009
Postdoctoral Scholars (1): Dr. Chang-Yong Lee (01/2008-01/2010).

Perry Y. Li
Professor, Department of Mechanical Engineering
University of Minnesota

Professional Preparation:
Cambridge University, England, Electrical and Information Sci., B.A./M.A (Hons.), Jun 1987
Boston University, Boston, Biomedical Engineering, M.S., Jan 1990
University of California, Berkeley, Mechanical Engineering, PhD, May 1995
Major: Control systems; Minors: Signal processing and bioengineering

Appointments:
University of Minnesota, Minneapolis MN
2008 - present, Professor of Mechanical Engineering
2006 - 2013, Deputy Director, NSF-ERC for Compact and Efficient Fluid Power (CCEFP).
2003 - 2008, Associate Professor of Mechanical Engineering
1999 - present, Graduate faculty in Control and Dynamic Systems (CDyS) Program
1997 - 2003, Nelson Assistant Professor of Mechanical Engineering
Xerox Corporation, Webster, NY
1995 - 97, Research Staff II, Xerox Wilson Center for Research & Technology

Honors:
-Chinese Government High Level Expert in Mechatronics (Visiting Professorship), Institute of Mechatronics Engineering, Zhejiang University (2011-present)
-Visiting Faculty, Department of Mechanical Engineering, University of Bath (Spring 2001)
-Young Investigator Award, Japan/USA Symposium on Flexible Automation (2000-2002)
-Special Recognition Award, Corporate Research & Technology, Xerox Corp. 1997
-Achievement Award, Corporate Research & Technology, Xerox Corp. 1996

Five Relevant Publications: *Available at http://www.me.umn.edu/~lixxx099/publications.html*
1. P. Y. Li and M. Wang, "Natural Storage Function for Passivity-Based Trajectory Control of Hydraulic Actuators", ASME/IEEE Trans. on Mechatronics, Vol. 19, pp.1057-1068, 2014.
2. H. Tu, M. B. Rannow, M. Wang, P. Y. Li, and T. R. Chase, "Design, Modeling and Validation of a High-Speed Rotary PWM On/Off Valve for Use in Virtually Variable Displacement Pumps", ASME J. of Dyn. Sys, Meas. & Control, Vol. 134:6, #061002, 2012. See also "Pulse Width Modulated Fluidic Valve," (with T.R. Chase), U.S. Patent #8,286,939, June 2006/October 16, 2012.
3. P. Y. Li and V. Durbha, "Passive control of fluid powered human power amplifiers", Proc. of the 7th JFPS International Symposium on Fluid Power, Toyama, Japan, September, 2008
4. D. J. Lee and P. Y. Li, Passive bilateral control and Tool Dynamics Rendering for Nonlinear Mechanical Teleoperators. IEEE Trans. on Robotics, Vol. 21:5, pp. 936—951, Oct. 2005.
5. P. Y. Li and R. Horowitz, Passive Velocity Field Control, Part 1: Geometry and Robustness IEEE Transaction on Automatic Control. Vol. 46, No. 9, pp.1346-1359, Sept. 2001.

Other Five Publications:
1. M. Saadat and P. Y. Li, "Modeling & Control of an Open Accumulator Compressed Air Energy Storage (CAES) System for Wind Turbine", Applied Energy137:1, pp.603-616, 2015.
2. K. L. Cheong, Z. Du, P. Y. Li and T. R. Chase, "Hierarchical Control Strategy for a Hybrid Hydro-mechanical Transmission (HMT) Power-Train", 2014 American Control Conference, Portland OR, June 2014
3. Z. Du, K. L. Cheong, P. Y. Li and T. R. Chase, "Fuel Economy Comparisons of Series, Parallel and HMT Hydraulic Hybrid Architectures", 2013 American Control Conference, Washington D.C., June 2013.
4. T. P. Sim and P. Y. Li, "Lattice based n-point Time-Sequential Sampling and Two-Stage Process Control for Maintaining Tone Consistency of Xerographic Processes", IEEE Transactions on Control Systems Technology, Vol. 21, Issue 6, pp. 2024-2037, 2013

5. D. Berg and P. Y. Li, “Achieving Dexterous Manipulation for Minimally Invasive Surgical Robots through the use of Hydraulics”, ASME Dynamic Systems and Control Conference, [paper number DSC-8685], Fort Lauderdale, FL, 2012

Synergistic Activities:

- Novel efficient hydraulic components such as digital displacement pump/motors, hydraulic transformers, hydraulic hybrid vehicles
- Passivity based control of interactive hydraulic and pneumatic robots
- Compressed air energy storage for off-shore wind turbines.
- Teaches u/g senior level lab course on fluid power and fluid power control

Collaborators:
T. Chase, W. Durfee, T. Simon, J. Van de Ven (Minnesota), E. Loth (U. of Virginia)

Graduate advisors: R. Horowitz (PhD, Berkeley), Z. Ladin (MS, Boston)

Post-doctoral advisor to: Dr. J. Van de Ven (U. Minnesota), Dr. T. P. Sim (E-Ink), Dr. Farzad Shirazi (Tehran U., Iran)

PhD Thesis advisor to: (all at U. of Minnesota):

- S. Saimek (King Munkut U, Thailand), D. J. Lee (Seoul National U.), K. Krishnaswamy (Honeywell Labs), Q. Yuan (Eaton Corp), Z. Liu (United Technologies), T. P. Sim (EInk), Rachel Wang (Eaton), D. Berg (U. Wisconsin – Stout), H. Tu (Boston Dynamics), V. Durbha (Whirlpool)

John H Lumkes Jr.
Associate Director, Global Engineering Program
Associate Professor, Agricultural and Biological Engineering
Purdue University

Professional Preparation

Calvin College	Engineering	B.S.E, 1990
University of Michigan—Ann Arbor	Mechanical Engineering	M.S.E., 1992
University of Wisconsin—Madison	Mechanical Engineering	Ph.D., 1997

Appointments

2012-present	Associate Director, Global Engineering Program, Purdue University
2010-present	Associate Professor, Agricultural and Biological Engineering Department Purdue University, West Lafayette, Indiana
2004-2010	Assistant Professor, Agricultural and Biological Engineering Department Purdue University, West Lafayette, Indiana
2001-2004	Associate Professor, Mechanical Engineering Department Milwaukee School of Engineering, Milwaukee, Wisconsin
1997-2001	Assistant Professor, Mechanical Engineering Department Milwaukee School of Engineering, Milwaukee, Wisconsin

Products

(i) Five significant products related to the project

1. Lumkes, J., Hallett, S., and Vallade, L. (2012). Hearing versus experiencing: The impact of a short-term study abroad experience in China on students perceptions regarding globalization and cultural awareness. International Journal of Intercultural Relations, 36(1), 151-159 http://dx.doi.org/10.1016/j.ijintrel.2011.12.004
2. Lumkes. J. (2010). Survey of Three Different Methods of Delivering Engineering Content in Lectures. J. Educational Technology Systems, 38(3):349-366
3. Lumkes, J. 2012. Design of a Sustainable, Locally Manufacturable, Agricultural Utility Vehicle for Developing Countries. International Conference Of Agricultural Engineering, Cigr- Ageng 2012, Valencia 8-12 July 2012, Book Proceeding ISBN 978-84-615-9928-8
4. *Andruch, J. and Lumkes, J. (2008). A hydraulic system topography with integrated energy recovery and reconfigurable flow paths using high speed valves. Proceedings of the 51st National Conference on Fluid Power (NCFP I08-24.1), p 649-657
5. Dare, A., Mohtar, R., Lumkes, J., Imbrie, P., and Ciftci, A. (2011) Assessment of Global Competencies within Purdue University's College of Engineering. Written for presentation at the 2011 ASABE Annual International Meeting, Louisville, KY., August 7-10. Paper no. 1111597.

(ii) Five other significant products

1. Lumkes, J., Control Strategies for Dynamic Systems, Design and Implementation, Marcel-Dekker Inc., 616 pages, ISBN: 0—8247—0661—7, 2002
2. Lumkes, J., *Wilson, D., and Dare, A. (2011) Undergraduate Students Solving Transportation and Energy Problems through Service Learning Projects in Cameroon. Written for presentation at the 2011 ASABE Annual International Meeting, Louisville, KY., August 7-10. Paper no. 1111498.
3. *Andruch, III, John and Lumkes, JR., John H. Regenerative Hydraulic Systems and Methods of Use. U.S. Patent Application 20120233997 Filed on September 29, 2010. Published on September 20, 2012
4. *Mishler, L, Garcia, J., and Lumkes, J. (2011) Engaging Pre-College Students in Engineering Using Hands-on Micro-Processor Controlled Portable Fluid Power Demonstrators. Written for presentation at the 2011 ASABE Annual International Meeting, Louisville, KY., August 7-10. Paper no. 1111500.
5. Batdorff, M., and Lumkes, J. (2009) High fidelity magnetic equivalent circuit in an axisymmetric electromagnetic actuator. IEEE Transactions on Magnetics, 45(8):3064-3072

Synergistic Activities

- Faculty Advisor/Mentor, Purdue Summer Undergraduate Research Fellowship Program (SURF), CCEFP Research Experience for Undergraduates (REU), and Research Experience for Teachers (RET).
- Faculty Advisor, Purdue ASABE Chapter, American Society of Agricultural and Biological Engineers. Advisor for the ¼ Scale Student Design team. (2004-present).
- Faculty Advisor, Purdue Global Design Teams for the African Centre for Renewable Energy & Sustainable Technology (Bangang, Cameroon). Advise and travel with students working on basic utility vehicles, hydroelectric power, and wind energy applications for developing countries (2008-present).
- East Africa Transdisciplinary Development Leader, working with multiple programs within Purdue to develop transdisciplinary activities and partnerships with universities and community-based organizations in East Africa. Focus areas include energy, food, water, environment, education, and income generation.
- SAE International Professional Society Activities: Chair of the SAE Fluid Power Committee (2006-present), SAE Aero Design Competition Rules Committee (2003-present), Board of Directors, Position of Vice Chair of Student Activities, Milwaukee Section of SAE (2003-2004), SAE Aero Design and Formula Design faculty advisor (1998-2004), SAE Chapter Faculty Advisor (1998-2004).

Collaborators & Other Affiliations

(i) Collaborators Agaba. M., Nelson Mandela African Institute of Science and Technology; Alter,K., Purdue; Bechar, A., Purdue; Benedicto, E., Purdue; Blatchley, E., Purdue; Bohlman, B., U of Minnesota; Bralts, V., Purdue; Buckmaster, D., Purdue; Bugusu, B., Purdue; Ciftci, A., Purdue; Denton, N., Purdue; Dian,T., South China University of Technology; Durfee, W., U of Minnesota; Gates, R., Univ. of Illinois; Hallett, S., Purdue; Hamaker, B., Purdue; Ileleji, K., Purdue; Imbertson, P., U of Minnesota; Ivantysynova, M., Purdue; Jun, L., South China University of Technology; Kitio, V., African Centre for Renewable Energy and Sustainable Technologies, Cameroon, & UN Habitat, Nairobi, Kenya; Krutz, G., Purdue; Li, P., U of Minnesota; Martini, A., U of California Merced; Maro, E., Nelson Mandela African Institute of Science and Technology; Meckl, P., Purdue; Mohtar, R., Purdue; Motevalli, V., Purdue; Niba, M., Catholic University of Cameroon, Bamenda; Nielsen, S., Purdue; Njau, K., Nelson Mandela African Institute of Science and Technology; Seay, J., U of Kentucky; Simionescu, P. Texas A&M, Corpus Christi; Stelson, K., U of Minnesota; Steward, B., Iowa State U; Vacca, A, Purdue; Wachs, J., Purdue; Yajun, L., South China University of Technology; Yilaka, A., Catholic University of Cameroon, Bamenda.

(ii) Graduate and Postdoctoral Advisors Ph.D. Advisor, Fronczak, F., U of Wisconsin—Madison

(iii) *Thesis Advisor:* Andruch, J., (MSE, Caterpillar); Batdorff, M., (MSE, Caterpillar); Batdorff, M., (PhD, Caterpillar); Desai, P., (MSE, Cummins); Donaldson, J., (MSE, Kingston Technology); Evans, R., (MSE); Garcia, J., (PhD, Illinois Institute of Technology); Hadj-Kaceem, N., (MSE, TOTAL, France); Hanks, T., (MSE); Haugstad, H., (MSE, Rockwell Automation); Holland, M., (PhD, John Deere); Long, G., (MSE, John Deere); Mahrenholz, J., (MSE, John Deere); McKinley, C., (MSE, Caterpillar); Merrill, K., (PhD, Parker Hannifin); Sun, L., (MSE, Cummins); VanDoorn, B., (MSE, Honda Research), Wilfong, G., (MSE, Fairfield Mfg.)

Current Graduate Students: Breidl, F., (PhD), Helmus, T. (PhD), Limiac, C., (MSE), Robison, J. (MSE), Sheehan, M., (MSE), Skelton, D., (MSE), Wilson, D. (MSE), Xiong, S., (PhD)

Graduated: 14 Master Degree students, 4 PhD students; Current: 5 Master Degree students, 3 PhD students

Paul Michael
Research Chemist
Milwaukee School of Engineering
Fluid Power Institute

Professional Preparation

University of Wisconsin, Milwaukee	Chemistry	BS, 1987
Keller Graduate School	Business	MBA, 2001

Academic/Professional Appointments

2005-present	Research Chemist, MSOE Fluid Power Institute, Milwaukee, WI
1987-present	Part-time Faculty, MSOE Fluid Power Institute, Milwaukee, WI
1993-2005	Technical Director, Benz Oil, Milwaukee, WI
1978-1993	Applications Chemist, Benz Oil, Milwaukee, WI

Closely Related Products

Garcia, JM. Johnson, J. and Michael P., "Toward the Development of a Pump Energy Rating System based upon Performance Indexes," Proceedings of the Fluid Power Innovation Research Conference, Chicago, IL (2015)

Miller, MK. Khalid, H. Michael, P. Guevremont, JM. Garelick, KJ. Pollard, GW. Whitworth, AJ. and Devlin, MT., "An Investigation of Hydraulic Motor Efficiency and Tribological Surface Properties," TLT, 71:6 (2015) editor's choice award

Mettakadapa, S. Bair, S. Aoki, S. Kobessho, M. Carter, L. Kamimura, H. and Michael, P., "A Fluid Property Model for Piston Pump Case Drain and Pressure Compensator Flow Losses," Proceedings of the AMSE/BATH 2015 Symposium on Fluid Power and Motion Control, Paper FPMC2015-9515, Chicago, IL (2015)

Michael, P. Mettakadapa, S. and Shahahmadi, S., "An Adsorption Model for Hydraulic Motor Lubrication," J Tribol, 137:4 (2015)

Krause, Meghan M. and Michael, Paul W., "Relative Humidity Sensors and the Solubility of Water in Lubricants," Environmentally Considerate Lubricants, STP 1575, In-Sik Rhee, Ed., pp. 131–146, ASTM International, West Conshohocken, PA (2014)

Bramer, J. Puzzuoli, A. Michael, P. and Wanke, T. "Hydraulic Fluid Efficiency Effects in External Gear Pumps," Proceedings of the 53rd National Conference on Fluid Power – National Fluid Power Association, Paper NCFP I14-13.3, Las Vegas, NV (2014)

Michael, P. Garcia, JM. Bair, S. Devlin, MT. Martini, A. "Lubricant Chemistry and Rheology Effects on Hydraulic Motor Starting Efficiency," Tribology Transactions, 55: 549-557 (2012)

Michael, P. and Wanke, T. "Hydraulic Fluid and System Standards," Handbook of Hydraulic Fluid Technology, 2nd Edition, GE. Totten and VJ. De Negri Ed., CRC Press, Boca Raton (2012)

Michael, P. Blazel, B. Reuchel, R. and Harville, X. "Hydraulic Fluid Compatibility and Filterability," Proceedings of the 52nd National Conference on Fluid Power – National Fluid Power Association, Paper NCFP I11-35.2, Las Vegas, NV (2011)

Synergistic Activities

Co-Chair, Hydraulic Fluid Thermal Stability Compatibility Section D02.N0.15, ASTM International
Technical Board, National Fluid Power Association
REU Advisor in 2015, 2014, 2013, 2012, 2011, 2010, 2009, 2008 & 2007
RET Advisor in 2009 & 2008
Member Society of Tribologists and Lubrication Engineers

Collaborators and Other Affiliations

Alan Meissner, Engendren – Machine Failure Analysis
Ashlie Martini, UC Merced – Hydraulic Fluid Rheology
Bill Grunze, Price Engineering – Machine Failure Analysis
Don Smolenski, Evonik – Hydraulic Fluid Research
Eric Bretey, Danfoss – Hydraulic Motor Research
Flint Grahl, Mercury Marine – Contamination Analysis
Gilles LeMaire, Poclain Hydraulics – Hydraulic Motor Research
Jack Johnson, IDAS Electrohydraulics – Pump Modeling
Jill Bramer, US Army – Hydraulic Fluid Research
Jonathon Schuh, University of Illinois, Champaign, Urbana – Hydraulic Fluid Rheology
Jose Garcia, Purdue University – Hydraulic Duty Cycle Modeling
Julie Hardwick, Petrocan Lubricants – Hydraulic Fluid Research
Mark Devlin, Afton Chemical – Hydraulic Fluid Research
Mark McAllister, Carrier Vibrating Equipment – Machine Failure Analysis
Matt Simon, Parker Hannifin – Geroler Motor Research
Paul Schlaefer, NewPage Paper – Machine Failure Analysis
Patrick Henning, Spectro Inc – Oil Analysis Instrumentation
Scott Bair, Georgia Tech – High Pressure Rheology
Sravani Gullapalli, Shell Oil – Hydraulic Fluid Research
Tom McCartney, ThermoKing – Common Rail Fuel System Contamination Analysis
Rajeev Kumar, Exxon-Mobil – Hydraulic Fluid Research

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
Graduate Students:

Kelly Burgess, General Dynamics
Hassan Khalid, Pentair
Aaron Kimball, Cobham Mission Systems
Shreya Mettakadapa
Meghan Miller, ExxonMobil
Corey Reynolds, Poclain Hydraulics
Shima Shahahmadi, Oklahoma State University

Research Assistants that have advanced to graduate school:

Chelsey Ericson, University of Wisconsin
Dan Schick, University of Wisconsin
Kelsey Whittaker, University of California, Riverside
Michael McCambridge, Arizona State University
Ricardo Rivera Lopez, University of Pittsburgh
Shima Shahahmadi, Oklahoma State University

Eui H. Park
Department of Industrial and Systems Engineering
North Carolina Agriculture and Technical State University

Professional Preparation

Yonsei University, Korea	Physics	B.S. 1972
Mississippi State University	Industrial Engineering	M.S. 1978
City University	Business Administration	M.B.A. 1980
Mississippi State University	Industrial Engineering	Ph.D. 1983

Appointments

1983 – present	Assistant/Associate/Full Professor, Department of Industrial and Systems Engineering, North Carolina A&T State University
1990 – 2005	Chairperson, Department of Industrial and Systems Engineering, North Carolina A&T State University
1978 – 1982	Senior Engineer, Division of Engineering Computing Systems, Boeing Commercial Airplane Company, Seattle, Washington
1985	Summer Faculty, Information Productions Division, IBM - Charlotte, NC
1983 – present	Consulted with ConVatec, Kaplan, Panel Concepts, Brayton International, Longwood, Guilford County Public Health, Korean Institute of Metals and Machinery, Hyundai, and Korean Management Association.

Closely Related Products

1. X. Jiang, B. Osafo-Yeboah, and E. Park, "Using the Callsign Acquisition Test (CAT) to Investigate the Impact of Background Noise, Gender, and Bone vibrator Location on the Intelligibility of Bone-Conducted Speech," International Journal of Industrial Ergonomics, International Journal of Industrial Ergonomics 39, pp. 246-254, (2009).

2. Park, E., J. Park, Celestine Ntuen, Daebum Kim, and Jendall Johnson, "Forecast Driven Simulation Model for Service Quality Improvement of the Emergency Department in the Moses H. Cone Memorial Hospital," The Asian Journal on Quality, Vol 9, No 3.

3. Kim, D. E. Park, Celestine Ntuen, and Younho Seong, "An AGV Dispatching Algorithm with Look-ahead Procedure for a Tandem Multiple-load AGV System," The Journal of Management and Engineering Integration, Winter 2009.

4. Seong, Y., E. Park and H. Lee, "Sensemaking and Human Judgment Under Dynamic Environment," Journal of the Ergonomics Society of Korea, Vol. 25, No.3, pp. 1-12, August 2006.

Significant Products

5. Park, E. & C. Ntuen," A Model for Predicting Human Reliability under Workload and Skill Performance," 2006 INFORMS International Conference, Hong Kong, China, June 2006.

6. Ntuen, C. & E. Park, "Human Performance in Monitoring Linear Automation Behavior," Proceedings of 15th Triennial Congress of the International Ergonomics Association, Seoul, Korea, August 2003.

7. Ntuen, C. & E. Park "Supporting Courses of Action Planning with Intelligent Management of Battle Assets,", Proceedings of Command & Control Symposium, National Defense University, July 2003.

8. Ntuen, C., S. Eastman & E. Park, "CAAD: The Commander's Battle Plan Assistance, Handbook of Human-Computer Interface for Military Application (M. Vassillious & T. Huang), Computer Society Press , Chapter 21, pp.237-257, 2001.

9. Park, E., Q. Jenkins, and X. Jiang, " Measuring Trust of Human Operators in New Generation Rescue Robots," Proceedings of 2008 JFPC International Symposium on Fluid Power, Toyama, Japan, September 2008.

10. Ntuen, C. and E. Park, " Predicting Human Reliability under Workload and Skill," Proceedings of the 10th IFAC Symposium on Information Control Problems in Manufacturing, Seoul, Korea, Aug. 2007

Synergistic Activities
Fellow, Institute of Industrial Engineers, since 2000, Board of Directors, Member, Piedmont Triad Center for Advanced Manufacturing, 1997 – 2005, Director, Manufacturing Initiatives, North Carolina A&T State University, 1989 – 1995, Co-Program Chair, Symposium on Human Interactions with Complex Systems, five times since 1991., Principle Investigator in 22 awarded funded research projects totaling over $7 million in the past eleven years.

Collaborators
Dr. Earl Barnes – School of Industrial & Systems Engineering, Georgia Institute of Technology, Dr. Wayne Book – School of Mechanical Engineering, Georgia Institute of Technology, Dr. Daebuem Kim and Young Park – Kangnam University, Korea, Dr. Xiaochun Jinag, Dr. Celestine Ntuen, Dr. Bala Ram, Dr. Sanjiv Sarin, and Dr. Younho Seong – Industrial & Systems Engineering, North Carolina A&T State University, Dr. Gary Rubloff – Institute of Systems Research, University of Maryland

Graduate Advisors: Drs. Larry Brown and Fazli Rabbi (Mississippi State University); Dr. Joe Tanchoco (Purdue University)

Richard F. Salant
Georgia Institute of Technology

Professional Preparation

M.I.T	Mechanical Engineering	BS 1963
M.I.T.	Mechanical Engineering	MS 1963
M.I.T.	Mechanical Engineering	ScD 1967

Appointments

Georgia Power Distinguished Professor	Georgia Institute of Technology	2001- Present
Professor	Georgia Institute of Technology	1987 - 2001
Manager - Fluid Mechanics & Heat Transfer Dept.	Borg Warner Research Center	1972 - 1987
Associate Professor	M.I.T.	1972
Assistant Professor	M.I.T.	1968 - 1972
Assistant Professor	University of California/Berkeley	1966 - 1968

Closely Related Products

1. Yang, B. and Salant, R. F., "Soft EHL Simulations of U-cup and Step Hydraulic Rod Seals," Journal of Tribology, Vol. 131, pp. 021501 -1 – 021501-7, 2009.

2. Salant, R. F., Yang, B. and Thatte, A., "Simulation of Hydraulic Seals," Journal of Engineering Tribology, Vol. 224, pp. 865-876, 2010.

3. Thatte, A. and Salant, R. F. "Visco-Elastohydrodynamic Model of a Hydraulic Rod Seal during Transient Operation," Journal of Tribology, Vol. 132, pp. 041501-1 – 041501-13, 2010.

4. Yang, B. and Salant, R. F., "EHL Simulation of O-ring and U-cup Hydraulic Seals," Journal of Engineering Tribology, Vol. 225, pp. 603-610, 2011.

5. Thatte, A. and Salant, R. F., "Effects of Multi-Scale Viscoelasticity of Polymers on High Pressure, High Frequency Sealing Dynamics," Tribology International, Vol. 52, pp. 75-86, 2012.

Significant Products

6. Salant, R. F., Maser, N. and Yang, B., "Numerical Model of a Reciprocating Hydraulic Rod Seal," Journal of Tribology, Vol. 129, pp. 91-97, 2007 and STLE/ASME Tribology Conference, San Antonio, pp. Trib-06-1052, 2006.

7. Yang, B. and Salant, R. F., "Numerical Model of a Reciprocating Rod Seal with a Secondary Lip," Tribology Transactions," Vol. 51, pp. 119-127, 2008 and 62nd Annual Meeting, STLE, 2007.

8. Shen, D. and Salant, R. F., "A Transient Mixed Lubrication Model of a Rotary Lip Seal with a Rough Shaft," Tribology Transactions, vol. 49, pp. 621-634, 2006 and 61st Annual Meeting, STLE, 2006.

9. Thatte, A. and Salant, R. F., "Transient EHL Analysis of an Elastomeric Hydraulic Seal," Tribology International, Vol. 42, pp. 1424-1432, 2009.

10. Thatte, A. and Salant, R. F., "Elastohydrodynamic Analysis of an Elastomeric Hydraulic Seal during Fully Transient Operation," Journal of Tribology, Vol. 131, pp. 031501-1 - 031501-11, 2009.

Synergistic Activities
Associate Editor, Journal of Tribology (1993-1999)

Associate Editor, Tribology Transactions (2010-present)

Member of Editorial Board: J. of Engineering Tribology, 2006-present; Sealing Technology, Elsevier, 1993-present; Mechanika (Lithuania), 2006-present

ASME – Fellow (1990), Henry R. Worthington Medal (1996), Machine Design Award (2003), Mayo D. Hersey Award (2009).

STLE – Fellow (1997), Edmond E. Bisson Award (2000), Frank P. Bussick Award (2002, 2005, 2007).

Collaborators & Other Affiliations in Last 48 Months
Jia, X. (Tsinghua U.), Wang, Y. (Tsinghua U.), Jung, S. (U. of Stuttgart), Haas, W. (U. of Stuttgart), Flitney, R. (BHR Group), Castleman, L. (Trelleborg).

Graduate Advisor
Tau-Yi Toong, MIT (retired)

Thesis Advisees Over the Last 5 Years*
Shen, D. (Parker); Maser, N. (Pratt and Whitney), Wang, L (Apogee Interactive), Yang, B. (GM), Thatte, A. (GE), Scope, K. (Bettis Nuclear Laboratory), Huang, Y.

Total number of advisees: 22

***** If no affiliation is given, the affiliation is Georgia Tech.

Kim A. Stelson
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

Stanford University	Mechanical Engineering	B.S., 1974
Massachusetts Institute of Technology	Mechanical Engineering	S.M., 1977
Massachusetts Institute of Technology	Mechanical Engineering	Sc.D., 1982

Appointments

2006-present	Director, NSF Engineering Research Center for Compact and Efficient Fluid Power
1994-2006	Director, Design and Manufacturing Division, Department of Mechanical Engineering, Univ. of Minnesota
2015-present	College of Science and Engineering Distinguished Professor, Univ. of Minnesota
1994-2015	Professor, Dept. of Mechanical Engineering, Univ. of Minnesota
2001-2002	Visiting Professor, Univ. of Bath, United Kingdom
1996	Visiting Associate Professor, Univ. of Auckland, New Zealand
1987-1994	Associate Professor, Dept. of Mechanical Engineering, Univ. of Minnesota
1992-1993	Visiting Senior Lecturer, Hong Kong Univ. of Science and Technology
1981-1987	Assistant Professor, Department of Mechanical Engineering, Univ. of Minnesota

Publications

Frosina, E., A. Senatore, D. Buono, and K. A. Stelson, "A Mathematical Model to Analyze the Torque Caused by Fluid-Solid Interaction on a Hydraulic Valve," to be published in *Transactions of A.S.M.E., Journal of Fluids Engineering.*

Ramdan, M. I. and K. A. Stelson, "Optimal Design of a Hydro-Mechanical Transmission Power-Split Hybrid Hydraulic Bus," to be published in *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering.*

Wang, F. and K. A. Stelson, "An Efficient Fan Drive System Based on a Novel Hydraulic Transmission," *IEEE/ASME Transactions on Mechatronics*, Vol. 20, No. 3. Oct. 2015, pp. 2234-2241.

Deppen, T. O., A. G. Alleyne, J. J. Meyer and K. A. Stelson, "Comparative Study of Energy Management Strategies for Hydraulic Hybrids," *Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control*, Vol. 137, no. 4, April 2015.

Dutta, R., F. Wang, B. F. Bohlmann and K. A. Stelson, "Analysis of Short-Term Energy Storage for Mid-Sized Hydrostatic Wind Turbine," *Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control*, Vol. 136, No. 1, Jan. 2014.

Whitten, M. and K. A. Stelson, "Determining Water Content at Saturation for Three Common Wind Turbine Gearbox Oils: Mobilgear SHC XMP 320, AMSOIL EP Gear Lube ISO-320 and Castrol Optigear A320," *ASME/BATH 2013 Symposium on Fluid Power and Motion Control (FPMC 2013),* 6-9 October 2013, Sarasota, FL.

Wang, F. and K. A. Stelson, "Model Predictive Control for Power Optimization in a Hydrostatic Wind Turbine," *The 13th Scandinavian International Conference on Fluid Power, SICFP2013,* 3-5 June 2013, Linköping, Sweden, pp. 155-160.

Deppen, T. O., A. G. Alleyne, J. J. Meyer and K. A. Stelson, "Optimal Energy Use in a Light Weight Hydraulic Hybrid Passenger Vehicle," Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control, Vol. 134, no. 4, July 2012.

Wang, Y., Z. X. Sun and K. A. Stelson, *"Modeling, Control and Experimental Validation of a Transient Hydrostatic Dynamometer," I.E.E.E. Transactions on Control Systems Technology,* Vol. 19, no. 6, Nov. 2011, pp. 1578-1586.

Wang, F. and K. A. Stelson, "Minimizing the Power Dissipation in the Piston-Cylinder Gap Using a Barrel-Shaped Piston," *Bath/ASME Symposium on Fluid Power & Motion Control (FPMC 2012),* 12-14 September 2012, Bath, UK, pp. 123-133.

Synergistic Activities

Director, NSF ERC for Compact and Efficient Fluid Power, 2006-present

Director of Graduate Studies, M.S. in Manufacturing Systems, 1997-2001. A master's degree program for full-time employees in industry.

Director, STEPS Summer Camp for Girls, 2000-2002. A program for high school girls that motivates an interest in engineering by building and launching a rocket.

Associate Technical Editor, *ASME Journal of Manufacturing Science and Engineering*, 1995-2001; *SME Journal of Manufacturing Processes*, 1999-present; and *ASME Journal of Dynamic Systems, Measurement and Control,* 2003-present.

Editorial Board, *Transaction on Control, Automation and Systems Engineering,* 2000-present; and *IMechE Journal of Engineering Manufacture,* 2000-present. Scientific Committee, *Transactions of the North American Manufacturing Research Institute of SME,* 1999-present.

Zongxuan Sun
Department of Mechanical Engineering
University of Minnesota, Twin Cities Campus

Professional Preparation

Southeast University, China	Automatic Control	B.S. 1995
University of Illinois at Urbana-Champaign	Mechanical Engineering	M.S. 1998
University of Illinois at Urbana-Champaign	Mechanical Engineering	Ph.D. 2000

Appointments

1/2014 – present	Co-Deputy Director, NSF Engineering Center for Compact and Efficient Fluid Power
8/2012 - present	Associate Professor, Department of Mechanical Engineering, University of Minnesota
8/2007 - 8/2012	Assistant Professor, Department of Mechanical Engineering, University of Minnesota
11/2006 – 8/2007	Staff Researcher, Research and Development Center, General Motors Corp.
9/2000-10/2006	Senior Researcher, Research and Development Center, General Motors Corp.
7/1999 – 9/2000	Senior Engineer, Western Digital Corp.
8/1996-5/2000	Research Assistant, University of Illinois at Urbana-Champaign

Products

1. Zhang, C., Li, K. and Sun, Z., "Modeling of Piston Trajectory-Based HCCI Combustion Enabled by a Free Piston Engine", Applied Energy, Vol. 139, pp.313-326, 2015.
2. Li, K., Zhang, C. and Sun, Z., "Precise Piston Trajectory Control for a Free Piston Engine", Control Engineering Practice, Vol. 34, pp.30-38, 2015.
3. Li, K., Sadighi, A. and Sun, Z., "Active Motion Control of a Hydraulic Free Piston Engine", IEEE/ASME Transactions on Mechatronics, Vol. 19, No. 4, pp.1148-1159, August, 2014.
4. Li, K. and Sun, Z., "Stability Analysis of a Hydraulic Free Piston Engine with HCCI Combustion", Proceedings of the 2011 Dynamic Systems and Control Conference, Arlington, VA, DSCC2011-5983, Nov., 2011.
5. Sadighi, A., Li, K. and Sun, Z., "A Comparative Study of Permanent Magnet Linear Alternator and Hydraulic Free Piston Engines", Proceedings of the 2011 Dynamic Systems and Control Conference, Arlington, VA, DSCC2011-6041, Nov., 2011.
6. Zhang Z. and Sun, Z., "A Novel Internal Model-Based Tracking Control for a Class of Linear Time-Varying Systems", ASME Transactions on Journal of Dynamic Systems, Measurement and Control, Vol. 132, 011004, January, 2010.
7. Sun, Z. and Kuo, T., "Transient Control of Electro-Hydraulic Fully Flexible Engine Valve Actuation System", IEEE Transactions on Control Systems Technology, Vol. 18, No. 3, pp.613-621, May, 2010.
8. He, X., Durret, R. and Sun, Z., "Late Intake Valve Closing as an Emission Control Strategy at Tie 2 Bin 5 Engine-Out NO_x Level", SAE International Journal of Engines, 1(1), pp.427-443, 2008.
9. Kuo, T., Sun, Z., Kang, J., Eng, J., Chang, C., Brown, B., Najt P. and Chang, M., "Method for Transition Between Control Auto-Ignition and Spark Ignition Mode in Direct Fuel Injection Engines", US patent 7,370,616, 2008.
10. Kuo, T., Sun, Z., Eng, J., Brown, B., Najt, P., Kang, J., Chang, C. and Chang, M., "Methods of HCCI and SI Combustion Control for a Direct Injection Internal Combustion Engine", US patent 7,275,514, 2007.

Synergistic Activities

- Organizer and panelist, Panel discussion "Engine and Combustion Modeling for Model-Based Control," The 2013 SAE World Congress, Detroit, MI.
- Guest editor, "Active Automotive Safety Systems", IEEE Control System Magazine, 2010.
- Session co-organizer, "HCCI Control", The 2010 SAE World Congress.
- Session co-organizer, "Engine Control", The 2009 SAE Powertrain and Fluid Systems Conference.
- Mentor, for minority summer students, GM Research and Development Center, 2002, 2003.

Collaborators & Other Affiliations

Collaborators and Co-Editors: Shih-Ken Chen, Burak Gecim, Kumar Hebbale, Chi-Kuan Kao, Hsu-Chiang Miao (GM), T.-C. Tsao (UCLA), G. Zhu (MSU), David Kittelson, Kim Stelson, Will Northrop, Michael Manser, Juergen Konczak, Henry Liu, David Du (UMN), Sonja Glavaski, Qinghui Yuan, Ben Morris (Eaton), John Brevick (Ford), Arnie Johnson (L3 CPS)

Graduate Advisors and Postgraduate Sponsors: T.-C. Tsao (UCLA)

Thesis Advisor or Postgraduate-Scholar Sponsor: Dr. X. Song (TAMU), Dr. Z. Zhang (Tsinghua University, China), Dr. A. Sadighi (Apple), Dr. P. Gillella (Parker), Dr. Y. Wang (Seagate), Dr. K Li (Cummins), Dr. Y. Yoon (Cummins), V. Gupta (Cummins), A. Heinzen (GM), M. McCuen (Chrysler), V. Mallela (GM), C. Wu (Sunrise America), Brad Guertin (Boston Scientific), M. Yang (Horton), A. Zulkefli, , C. Zhang, Y. Wang, A. Tripathi, Y. Shao, K. Liu, P. Mukherjee (UMN)

Jun Ueda
School of Mechanical Engineering
Georgia Institute of Technology

Professional Preparation

Kyoto University, Japan	Mechanical Engineering	B.S.,	1994
Kyoto University, Japan	Mechanical Engineering	M.S.,	1996
Kyoto University, Japan	Mechanical Engineering	Ph.D.,	2002

Appointments

2008-Present Assistant Professor, Mechanical Engineering, Georgia Institute of Technology
2010-Present Adjunct Faculty, Applied Physiology, Georgia Institute of Technology
2006 Lecturer, Mechanical Engineering, Massachusetts Institute of Technology
2005-2008 Visiting Scholar, Mechanical Engineering, Massachusetts Institute of Technology
2002-2008 Assistant Professor, Information Science, Nara Institute of Science and Technology, Japan
1996-2000 Senior Research Scientist, Advanced Technology R&D Center, Mitsubishi Electric Corporation

Closely Related Products

1. Schultz, J. and Ueda, J., "Analysis of antagonist stiffness for nested compliant mechanisms in agonist-antagonist arrangements," *the 2011 ASME Dynamic Systems and Control Conference* (DSCC'11).
2. MacNair, D. and Ueda, J. David MacNair and Jun Ueda, "A Fingerprint Method for Variability and Robustness Analysis of Stochastically Controlled Cellular Actuator Arrays," *The International Journal of Robotics Research*, Volume 30, Issue 5, pp. 536 - 555, April 2011.
3. Ueda, J.; Ming, D.; Krishnamoorthy, V.; Shinohara, M.; Ogasawara, T. "Individual Muscle Control Using an Exoskeleton Robot for Muscle Function Testing," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol.18, no.4, pp.339-350, Aug. 2010.
4. Ueda, J.,Secord,T., Asada,H. "Large Effective Strain Piezoelectric Actuators Using Nested Cellular Architecture with Exponential Strain Amplification Mechanisms", *IEEE/ASME Transactions on Mechatronics,* Vol. 15, No. 5, pp. 770-782, 2010.
5. Ueda, J., Yoshikawa, T., "Force Reflecting Bilateral Teleoperation with Time Delay By Signal Filtering," *IEEE Transactions on Robotics and Automation*, Vol. 20, No. 3, pp.613- 619, June, 2004.

Significant Products

1. Schultz J.and Ueda, J. "Experimental Verification of Discrete Switching Vibration Suppression," *IEEE/ASME Transactions on Mechatronics*, *in Press*.
2. Ueda, J., Kondo, M., Ogasawara, T " The Multifingered NAIST-Hand System for Robot In-hand Manipulation," *Mechanism and Machine Theory*, Volume 45, Issue 2, Pages 224-238, February 2010.
3. Ueda, J., Odhner, Asada, L., H. Harry, "Broadcast Feedback of Stochastic Cellular Actuators Inspired by Biological Muscle Control," *The International Journal of Robotics Research*, Volume 26, Issue 11-12, pp. 1251--1265, November-December 2007.
4. Ueda, J.,, Ikeda, A., Ogasawara, T., "Grip-force Control of an Elastic Object by Vision-based Slip Margin Feedback during the Incipient Slip", *IEEE Transactions on Robotics*, Vol.21, Issue 6, pp.1139- 1147, December, 2005.
5. Ueda, J., Yoshikawa, T., "Mode Shape Compensator for Improving Robustness of Manipulator Mounted on Flexible Base", *IEEE Transactions on Robotics and Automation*, Vol. 20, No. 2, pp. 256- 268, April, 2004.

Synergistic Activities

1. Early Academic Career Award in Robotics and Automation from IEEE Robotics and Automation Society, for fundamental contributions to robust control of robot dynamics including time-delayed telerobotics, flexible robots, cellular actuator devices, and rehabilitation robots May 2009
2. Associate Editor for *IEEE/ASME Transactions on Mechatronics* April 2008 –Present
3. Associate Editor and Committee Member for *2011 IEEE International Conference on Robotics and Automation* (ICRA 2011), *the 2010 IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics* (BioRob 2010), *2010 Robotics Science and Systems Conference* (RSS 2010), *2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics* (AIM 2009), and *ASME Dynamic Systems and Control Conference* (DSCC 2009, 2010, 2011, 2012).
   a. Organized a panel discussion session on Mechatronics for Biosystems and Healthcare at AIM 2009
   b. Organized a workshop on Biologically Inspired Actuation with Dr. Stefanini at ICRA 2011
   c. Organizes a workshop on Biosystems and Healthcare at DSCC 2011
   d. Serves as Students and Young Members Chair for DSCC 2012
4. Best Automation Paper Finalist *at the 2008 IEEE International Conference on Robotics and Automation* (ICRA 2008) May 2008
5. Training Faculty, National Institute of Child Health & Human Development, "Training Movement Scientists: Focus on Prosthetics and Orthotics" (1T32 HD055180-01A1) at the School of Applied Physiology, Georgia Institute of Technology Feb 2010-Present

Collaborators & Other Affiliations

(i) Collaborators and Co-Editors

Shinohara, M., (Applied Physiology, Georgia Institute of Technology), Kogler, G.(Applied Physiology, Georgia Institute of Technology), Stilman, M (Interactive Computing, Georgia Institute of Technology), Christensen, H. (Interactive Computing, Georgia Institute of Technology), Book, W. (Mechanical Engineering, Georgia Institute of Technology), Krishnamoorthy, V.(Emory University), Webster, R.(Vanderbilt University), Barth, E. (Vanderbilt University), Asada, H. (Massachusetts Institute of Technology), Ogasawara, T. (Nara Institute of Science and Technology, Japan), Takemura, H.(Tokyo University of Science, Japan), Kurita, Y.(Hiroshima University, Japan), Haga, N. (University of Tokyo Hospital, Japan), Burdet, E. (Imperial College, London, UK); Gennisson, J. (ESPCI ParisTech, France); Kaneko M (Osaka University, Japan); Mihailidis, A. (University of Toronto), Gao, D. (General Motors), Stefanini , C. (Biomedical Engineering, Scuola Superiore Sant'Anna, Italy).

(ii) Graduate and Postdoctoral Advisors

Graduate advisor: Yoshikawa, T., Ritsumeikan University, Japan (formally Kyoto University)
Postdoctoral Advisor: Asada, H. Mechanical Engineering, Massachusetts Institute of Technology

(iii) Thesis Advisor and Postgraduate-Scholar Sponsor

Graduate thesis advisor:
Joshua Schultz, Ph.D. Candidate, Mechanical Engineering, Georgia Institute of Technology
David MacNair, Ph.D. Candidate, Robotics Ph.D. Program, Georgia Institute of Technology
Billy Gallagher, Ph.D. Candidate, Robotics Ph.D. Program, Georgia Institute of Technology
Melih Turkseven, Ph.D. Student, Mechanical Engineering, Georgia Institute of Technology
Gregory Henderson, M.S. Student, Mechanical Engineering, Georgia Institute of Technology
Timothy McPherson, M.S. Student, Mechanical Engineering, Georgia Institute of Technology
Ellenor Brown, Ph.D. Student, Applied Physiology, Georgia Institute of Technology

Postdoctoral scholar:

Dr. Yuichi Kurita, Assistant Professor of Nara Institute of Science and Technology, Japan
Dr. Ding Ming, Postdoctoral Fellow, the Science University of Tokyo, Japan

Andrea Vacca
Associate Professor
Maha Fluid Power Research Center
School of Mechanical Engineering/Dept. of Agricultural and Biological Engineering
Purdue University

Professional Preparation

Univ. of Parma, Italy	Mechanical Engineering	Master Degree (with honors)	1999
Univ. of Florence, Italy	Energetics (Energy Systems)	Ph.D.	2005

Appointments

8/2014 – Present	Associate Professor, ABE/ME, Purdue University
3/2010 – 8/2014	Assistant Professor, ABE/ME, Purdue University
9/2005 – 3/2010	Assistant Professor (with Tenure), Industrial Engineering Dept., Univ. of Parma, Italy
9/2002 – 9/2005	Assistant Professor, Industrial Engineering Dept., Univ. of Parma, Italy

Closely Related Products

1. Cristofori D., Vacca A., 2015, *Modeling Hydraulic Actuator Mechanical Dynamics from Pressure Measured at Control Valve Ports*, J. of Systems and Control Engineering, July 2015, vol 229 n. 6.
2. Opperwall T., Vacca A., 2014, *A combined FEM/BEM model and experimental investigation into the effects of fluid-borne noise sources on the air-borne noise generated by hydraulic pumps and motors*, IMechE Proceedings of the Institution of Mechanical Engineers, Part C, Journal of Mechanical Engineering Science February 2014 vol. 228 no. 3, pp. 457-471.
3. Ritelli, G.F., Vacca, A., 2013, *Energy Saving Potentials of a Novel Electro-Hydraulic Method to Reduce Oscillations in Fluid Power Machines: the Case of a Hydraulic Crane*, SAE International Journal of Commercial Vehicles, Vol. 6 Issue 2 (October), 12 pages.
4. Ritelli G.F., Vacca A., 2013, *Energetic and Dynamic Impact of Counterbalance Valves in Fluid Power Machines*, Energy Conversion and Management, 76 (2013) pp. 701-711.
5. Cristofori, D., Vacca, A., 2012, *A Novel Pressure-Feedback Based Adaptive Control Method to Damp Instabilities in Hydraulic Machines*, SAE Int. J. Commer. Veh. 5(2):2012.

Significant Products

6. Dhar S., Vacca A., 2015, *A novel FSI–thermal coupled TEHD model and experimental validation through indirect film thickness measurements for the lubricating interface in external gear machines*, Tribology International, Vol. 82, Part A, February 2015, pp. 162-175.
7. Zhou, J., Vacca, A., Casoli, P., 2014, *A Novel Approach for Predicting the Operation of External Gear Pumps under Cavitating Conditions*, Simulation Modeling Practice and Theory, Vol. 45, pp. 35-49.
8. Devendran, R.S., Vacca, A., 2013, *Optimal Design of Gear Pumps for Exhaust Gas Aftertreatment Applications*, Simulation Modelling Practice and Theory, vol. 38, pp. 1-19
9. Cristofori D., Vacca A., 2012, *The Modeling of Electro-Hydraulic Proportional Valves,* ASME Journal of Dynamic Systems, Measurement and Control, Vol.134, Issue 2, 021008 (13 pages).
10. Vacca, A., Guidetti, M., 2011, *Modelling and Experimental Validation of External Spur Gear Machines for Fluid Power Applications*, Simulation Modelling Practice and Theory, 19 (2011) 2007–2031.

Synergistic Activities

- Co-author of the book: Berta, G.L., Vacca, A., 2004, Sperimentazione sui Motori a Combustione Interna (in italian), Monte Università Parma Editore – Collana Saperi.

- Leading Scientist for the Fluid Power Research Center (to be established in 2015) of Samara State Aerospace University, Russian Federation, and Member of the International Advisory Council of the same university, 2013-present.
- Developed a Fluid Power Lab at the University of Parma, Italy (2005 - 2009).
- Conference Organization activities: Editorial co-Chair for ASME/Bath Fluid Power and Motion Control Conference 2013,2015; Session organizer for SAE COMVEC 2010,2011,2012,2013 and 2014, Scientific board member and Session organizer for FPNI (Fluid Power Net International) – PhD Symposium 2010,2012,2014; Session organizer for 8th Int. Fluid Power Conference, 2012.
- Chair of SAE – Fluid Power & Hydraulic division (2011-present) and Executive Committee member of ASME – Fluid Power System Division (2012-present).

Collaborators & Other Affiliations

Collaborators and Co-Editors

All co-PI's of the ERC – CCEFP (Center for Compact and Efficient Fluid Power) (D. Adams (Vanderbilt), A. Alleyne (U Illinois) S. Bair (Giorgia Tech), E. Barth (Vanderbilt), W. Book (Giorgia Tech), T. Chase (U Minnesota), W. Durfee (U Minnesota), R. Ewoldt (U Illinois), V. Gervasi (Milwaukee School of Eng), E. Hsiao-Wecksler (U Illinois), M. Ivantysynova (Purdue), M. Khalil (Milwaukee School of Eng), W. King (U Illinois), K. Kunefare (Giorgia Tech), P. Li (U Minnesota), J. Lumkes (Purdue), P. Michael (Milwaukee School of Eng.), E. Park (North Carolina A&T), R. Salan (Giorgia Tech), K. Stelson (U Minnesota), Z. Sun (U Minnesota), S. Udoka (North Carolina A&T), P. Valdastri (Vanderbilt); J. Van De Ven (U Minnesota), R. Webster (Vanderbilt)

Other collabotators and co-Editors: K. Ariyur (Purdue), P. Casoli (U Parma, Italy), B. Manhartsgruber (University of Linz, Austria)

Collaborators from industry: R. Carra (Turolla-Danfoss), A. Fornaciari (Walvoil), G. Franzoni (Parker Hannifin), M. Guidetti (Casappa), N. Gulati (CNH), G. Kassen (CNH), J. Kovach (Komotion Tech.), Y. Lamirand (MGI Coutier), N.J. Nagel (Triumph Aerospace), D. Quast (Parker Hannifin), B. Pizzo (Concentric), M. Zecchi (Turolla-Danfoss)

Graduate Advisors and PostDoctoral Sponsors: P. Berta (U Parma, Italy), B. Facchini (U Firenze, Italy), F. Martelli (U of Firenze, Italy)

Thesis Advisor and PostGraduate Scholar Sponsor: G. Altare (Parker Hannifin), D. Cristofori (CNH), R.S. Devendran (Ford), S. Dhar (Simerics), M. Greco (ZEC, Italy), S. Gulati (Siemens)

Total number of graduate students supervised: 29 (4 PhD)   Undergraduate Research Students: 25

Pietro Valdastri
Department of Mechanical Engineering
Vanderbilt University

Professional Preparation

University of Pisa	Laurea in Electrical Eng	2002
Scuola Superiore Sant'Anna	Ph.D. in Biomedical Eng	2006

Appointments

Vanderbilt University	Assistant Professor in Gastroenterology	2012 – Present
Vanderbilt University	Assistant Professor in Mechanical Eng	2011 – Present
Scuola Superiore Sant'Anna	Assistant Professor in Biomedical Eng	2008 – 2011

Closely Related Products

[1] M. Simi, R. Pickens, A. Menciassi, S. D. Herrell, and P. Valdastri. Fine tilt tuning of a laparoscopic camera by local magnetic actuation: Two-port nephrectomy experience on human cadavers. *Surgical Innovation*, 2012. In press, available on-line.

[2] C. Di Natali and P. Valdastri. Remote active magnetic actuation for a single-access surgical robotic manipulator. *International Journal of Computer Assisted Radiology and Surgery*, 7:S169–S171, 2012. Recipient of the OLYMPUS ISCAS Best Paper Award 2012.

[3] C. Di Natali, T. Ranzani, M. Simi, A. Menciassi, and P. Valdastri. Trans-abdominal active magnetic linkage for robotic surgery: Concept definition and model assessment. In *Robotics and Automation (ICRA), IEEE International Conference on*, pages 695–700, 2012.

[4] M. Simi, N. Tolou, P. Valdastri, J.L. Herder, A. Menciassi, and P. Dario. Modeling of a compliant joint in a magnetic levitation system for an endoscopic camera. *Mechanical Sciences*, 3:5–14, 2012.

[5] T. Ranzani, C. Di Natali, M. Simi, A. Menciassi, P. Dario, and P. Valdastri. A novel surgical robotic platform minimizing access trauma. In *Proc. of 4th Hamlyn Symposium on Medical Robotics*, pages 15–16, London, UK, 2011. Recipient of the Best Oral Presentation Award 2011.

Significant Products

[6] M. Simi, M. Silvestri, C. Cavallotti, M. Vatteroni, P. Valdastri, A. Menciassi, and P. Dario. Magnetically activated stereoscopic vision system for laparoendoscopic sin- gle site surgery. *IEEE/ASME Transactions on Mechatronics*, 2012. In press, available on-line.

[7] P. Valdastri, M. Simi, and R. J. Webster III. Advanced technologies for gastrointestinal endoscopy. *Annual Review of Biomedical Engineering*, 14:397–429, 2012.

[8] P. Valdastri, E. Sinibaldi, S. Caccavaro, G. Tortora, A. Menciassi, and P. Dario. A novel magnetic actuation system for miniature swimming robots. *IEEE Transactions on Robotics*, 27(4):769–779, 2011.

[9] M. Piccigallo, U. Scarfogliero, C. Quaglia, G. Petroni, P. Valdastri, A. Menciassi, and P. Dario. Design of a novel bimanual robotic system for single-port laparoscopy. *IEEE/ASME Transactions on Mechatronics*, 15(6):871–878, 2010.

[10] P. Valdastri, C. Quaglia, E. Buselli, A. Arezzo, N. Di Lorenzo, M. Morino, A. Menciassi, and P. Dario. A magnetic internal mechanism for precise orientation of the camera in wireless endoluminal applications. *Endoscopy*, 42(6):481, 2010.

Synergistic Activities

Olympus ISCAS Best Paper Award, 16th Annual Conference of the International Soci- ety for Computer Aided Surgery (ISCAS) 2012; Best Oral Presentation Award, ASME Design of Medical Devices Conference 2012; Best Oral Presentation, Hamlyn Sym- posium on Medical Robotics 2011; Best Technology Presentation, 19th International Congress of the European Association of Endoscopic Surgery 2011; Best Paper Award, Eurosensors 2008. IEEE RAS, IEEE EMBS, EAES, ASEE member.

Contributing Associate Editors-in-Chief of World Journal of Gastroenterology, Baishi- deng Publishing Group Co., Limited. Associate Editor for IEEE ICRA 2013. Reviewer for IEEE Transactions on Robotics, IEEE/ASME Transactions on Mechatronics, IEEE Transactions on Biomedical Engineering, IEEE Transactions on Magnetics. Developed a new course *Miniaturized Wireless Mechatronic Systems* at Vanderbilt University. The class is a combination of lectures, literature readings, hands-on lab programming of wireless microcontrollers, modeling interactions between the mecha- tronic system and the surrounding environment, and a significant research project. Recent seminars given at: University of Illinois-UC, Tennessee State University, Univer- sity of Colorado - Boulder, Imperial College of London, EPFL, and Tianjin University.

Collaborators & Other Affiliations

Recent Collaborators. Akos Ledeczi (Vanderbilt University), Mark Rentschler (Uni- versity of Colorado - Boulder), Peter Volgyesi (Vanderbilt University).
Graduate Advisor. Paolo Dario (Scuola Superiore Sant'Anna).
Advisees – Ph.D. Primary Adviser (4): Trevor L. Bruns and Charreau S. Bell (Vanderbilt University, expected 2016), Christian Di Natali and Marco Beccani (Van- derbilt University, expected 2015).
Advisees – Ph.D. Co-Adviser (1): Massimiliano Simi (Scuola Superiore Sant'Anna, expected 2013).

James D. Van de Ven
Mechanical Engineering Department
University of Minnesota

Professional Preparation

South Dakota School of Mines and Technology	Mech. Engr.	B.S. 2001
University of Minnesota-Twin Cities	Mech. Engr.	Ph.D. 2006
ERC for Compact and Efficient Fluid Power, Univ. of MN	Mech. Engr.	Postdoctoral 2006-2007

Appointments

Assistant Professor, August 2011 – present, Mechanical Engineering Department, University of Minnesota-Twin Cities, Minneapolis, MN

Assistant Professor, August 2007 – July 2011, Mechanical Engineering Department, Worcester Polytechnic Institute, Worcester, MA.

Postdoctoral Research Associate, July 2006 – July 2007, ERC for Compact and Efficient Fluid Power, University of Minnesota, Minneapolis, MN.

Closely Related Products

1. Van de Ven, J., 2012, “Fluidic Variable Inertia Flywheel and Flywheel Accumulator System,” U.S. Patent Application, Pub. No.: US2012/0011960 A1.
2. Van de Ven, J., 2009, “Increasing Hydraulic Energy Storage Capacity: Flywheel-Accumulator,” International Journal of Fluid Power, v. 10, n. 3, p. 41-50.
3. Van de Ven, J., and McInnis, J., 2011, “Design and Experimental Results of a Bench Top Flywheel-Accumulator for Compact Energy Storage,” National Conference on Fluid Power, International Fluid Power Exposition, Las Vegas, NV, March 23-25, 2011.
4. Strohmaier, K., Cronk, P., Knutson, A., and Van de Ven, J., 2014, “Experimental Studies of Viscous Loss in a Hydraulic Flywheel Accumulator,” National Conference on Fluid Power, International Fluid Power Exposition, Las Vegas, NV, March 4-8, 2014, 0369-000017.
5. Strohmaier, K., and Van de Ven, J., 2013, “Constrained Multi-Objective Optimization of a Hydraulic Flywheel Accumulator,” ASME/BATH 2013 Symposium on Fluid Power & Motion Control, Sarasota, FL, Oct. 6-9, 2013, FPMC2013-4425.

Other Significant Products

1. Wilhelm, S., and Van de Ven, J., 2013, “Design and Testing of an Adjustable Linkage for a Variable Displacement Pump,” Journal of Mechanisms and Robotics, v. 5, n. 4, 041008.
2. Van de Ven, J., 2013, “On Bulk Modulus in Switch-Mode Hydraulic Circuits - Part I: Modeling and Analysis,” Journal of Dynamic Systems, Measurement, and Control, v. 135, n. 2, 021012.
3. Van de Ven, J., 2013, “On Bulk Modulus in Switch-Mode Hydraulic Circuits - Part II: Experimental Results,” Journal of Dynamic Systems, Measurement, and Control, v. 135, n. 2, 021014.
4. Van de Ven, J., and Katz, A., 2011, “Phase-Shift High-Speed Valve for Switch-Mode Control,” Journal of Dynamic Systems, Measurement, and Control, v. 133, n. 1.
5. Van de Ven, J., and Erdman, A., 2007, "Laser Transmission Welding of Thermoplastics: Part I: Temperature and Pressure Modeling," Journal of Manufacturing Science and Engineering, v. 129, n. 5, p. 849-858.

Synergistic Activities

Developments in Research

During the past seven years, Dr. Van de Ven has been involved of nine projects resulting in provisional patents in the field of energy conversion and storage including a flywheel-accumulator, a high energy density open accumulator, a hydro-mechanical hybrid drive train with independent wheel torque control, two unique high-speed on-off hydraulic valves, constant pressure accumulator, locking soft switch, and an adjustable linkage pump. Through these and other projects, the PI mentored over 30 graduate and undergraduate research assistants. In the past eight years, Dr. Van de Ven has published over 60 journal and conference papers and given over 40 technical presentations.

Innovations in Teaching

The PI's innovations in teaching are in three main areas: 1) Development of the Fundamentals of Fluid Power MOOC hosted by Coursera. First offered Fall of 2014 with over 8000 students. 2) The use of active learning in the engineering classroom as a way to engage students and promote student centered learning. 3) Promoting and developing collegiate level fluid power content as the Education Director of the Center for Compact and Efficient Fluid Power. In this role Van de Ven is generating content for the Fluid Power OpenCourseWare site, including video capturing lectures and developing minibooks on fluid power topics. Dr. Van de Ven was selected as Mechanical Engineering Teacher of the Year in 2011 and Advisor of the Year in 2010 at WPI.

Professional Service

Dr. Van de Ven has served the professional community in numerous ways including: Education Director of the Center for Compact and Efficient Fluid Power, Co-Chair of ASME Fluid Power Systems & Technology Division, Educational Program co-chair for 2014 International Fluid Power Exposition, Technical Committee member for 2011 International Fluid Power Exposition, session chair at numerous conferences, reviewer for numerous journals and conferences, and organizer of the 2009 New England Manipulation Symposium.

Collaborators and Other Affiliations

Collaborators and Co-Editors

Allard, Adam (US Hydraulics)
Chase, Thomas (University of Minnesota)
Crane, Stephen (LightSail Energy)
Demetriou, Michael (WPI)
Erdman, Arthur (University of Minnesota)
Fischer, Gregory (Worcester Polytechnic Institute)
Gennert, Michael (Worcester Polytechnic Institute)
Hynes, Tod (XL Hybrids)
Lados, Dianna (Worcester Polytechnic Institute)
Li, Perry (University of Minnesota)
Loth, Eric (University of Virginia)
Michalson, William (WPI)
Olinger, David (Worcester Polytechnic Institute)
Padir, Taskin (Worcester Polytechnic Institute)
Rufo, Mike (Boston Engineering)
Simon, Terrence (University of Minnesota)
Smith, Brian (KaZaK Composites)
Stelson, Kim (University of Minnesota)
Tary, Imre (KaZaK Composites)
Tryggvason, Gretar (University of Notre Dame)
Weagle, David (dw-link Incorporated)

Graduate Advisors and Postdoctoral Sponsors

Erdman, Arthur – Professor – University of Minnesota – Ph.D. Advisor
Li, Perry – Associate Professor – University of Minnesota – Postdoctoral Sponsor
Stelson, Kim – Professor – University of Minnesota – Postdoctoral Sponsor

Graduate Students Advisees: Total Graduated: 13

Bacon, Brandon (WPI)
Banwat, Prasanna (WPI)
Beckstrand, Brandon (WPI)
Corby, Sebastian (UMN)
Cronk, Paul (UMN)
Cusack, Jessy (WPI)
Forbes, Tyler (WPI)
Gaffuri, Paul (WPI)
Jorgenson, Richard (WPI/UMN)
Judge, Andrew (WPI)
Katz, Allan A. (WPI)
Knutson, Anthony (UMN)
McInnis, Jennifer (WPI)
Mies, Ben J. (WPI)
Samant, Rohan (WPI)
Savage, Cleveland (UMN)
Strohmaier, Kyle (UMN)
Sullivan, Thomas (UMN)
Tian, Hao (UMN)
Triana, Dominic (UMN)
Wang, Lak Kin (WPI)
Wu, Jeslin (WPI)
Wilhelm, Shawn (WPI/UMN)
Wong, Lak Kin (WPI)
Yudell, Alexander (UMN)

Feng Wang
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

Zhejiang University	Mechanical Engineering	PhD.	2009
Zhejiang University	Mechanical Engineering	B.S.M.E.	2003

Appointments

2010 – present	Postdoctoral associate in Dept. of Mechanical Engineering, University of Minnesota
2003 – 2009	Research associate in Dept. of Mechanical Engineering, Zhejiang University

Closely Related Products

1. R. Dutta, F. Wang, B. Bohlmann, K. Stelson, 'Analysis of Short-term Energy Storage for Mid-size Hydrostatic Wind Turbine', accepted, under revision, submitted to ASME Journal of Dynamic Systems, Measurement, and Control, 2012.
2. F. Wang, B. Trietch and K. A. Stelson, 'Mid-sized wind turbine with hydro-mechanical transmission demonstrates improved energy production', to be appear in Proc. 8th International Conference on Fluid Power Transmission and Control (ICFP 2013), Hangzhou, China, 2013.
3. R. Dutta, F. Wang, B. Bohlmann and K. A. Stelson, "Analysis of short-term energy storage for mid-size hydrostatic wind turbine," in Proc. ASME Dynamic Systems and Control Conference, Fort Lauderdale, FL, USA, 2012, selected as top 20 outstanding finalist papers.

Significant Products

4. K. A. Stelson and F. Wang, "Minimizing the power dissipation in the piston-cylinder gap using a barrel-shaped piston," in Proc. Bath/ASME Symp. Fluid Power Motion Control, Bath, U.K, 2012.
5. F. Wang, M. Ramdan, and K. A. Stelson, "Comparison between hydraulic hybrid and electric hybrid in passenger vehicles using ADVISOR 2004," in Proc. 52nd National Conf. Fluid Power, Las Vegas, USA, 2011, NCFP I11-2.2.
6. K. A. Stelson and F. Wang, "A simplified model to optimize positive-displacement hydraulic pump and motor efficiency," in Proc. Bath/ASME Symp. Fluid Power Motion Control, Bath, UK, 2010, pp417-429.

Synergistic Activities

Technical advisory work to the REU (Research Experience for Undergraduate) student, 2012;
Technical advisory work to the senior design of the REU student, 2012-2013;

Collaborators & Other Affiliations

Collaborators within the last 48 months (other than students listed):

Kim Stelson, Brad Bohlmann, Mike Gust, Zongxuan Sun, all from University of Minnesota;

Ph.D. Students Supervised:

None

Ph.D. and M.S. Advisors:
None

Research Visitors:
None

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Robert J. Webster III
Department of Mechanical Engineering
Vanderbilt University

Professional Preparation

Clemson University	Electrical Engineering	B.S., 2002
John Hopkins University	Mechanical Engineering	M.S., 2004
John Hopkins University	Mechanical Engineering	Ph.D., 2007

Appointments

2008 – Present Assistant Professor in Mechanical Engineering, Vanderbilt University

Closely Related Products

1. E. M. Boctor, M. A. Choti, E. C. Burdette, and R. J. Webster III. Three-dimensional ultrasound-guided robotic needle placement: An experimental evaluation. International Journal of Medical Robotics and Computer Assisted Surgery, 4(2):180–191, 2008.

2. R. J. Webster III, J. M. Romano, and N. J. Cowan. Mechanics of precurved-tube continuum robots. IEEE Transactions on Robotics, 25(1):67–78, 2009.

3. R. J. Webster III, T. E. Murphy, L. N. Verner, and A. M. Okamura. A novel twodimensional tactile slip display: Design, kinematics and perceptual experiments. ACM Transactions on Applied Perception, 2(2):150–165, 2005.

4. R. J. Webster III. Object capture with a camera-mobile robot system: An introductory robotics project. IEEE Robotics and Automation Magazine, 13(1):85–88, March 2006.

5. R. J. Webster III, N. J. Cowan, G. S. Chirikjian, and A. M. Okamura. Nonholonomic modeling of needle steering. International Journal of Robotics Research, 25(5/6):509–526, May/June 2006.

Significant Products

6. R. A. Lathrop, T. T. Cheng, and R. J. Webster III. Laparoscopic image guidance via conoscopic holography. ASME Journal of Medical Devices, 57(6), 1497-1506, 2010.

7. D. C. Rucker and R. J. Webster III. Parsimonious evaluation of concentric-tube continuum robot equilibrium conformation. IEEE Transactions on Biomedical Engineering Letters, 56(9), 2308-2311, 2009.

8. P. Valdastri, R. J. Webster III, C. Quaglia, M. Quirini, A. Menciassi, and P. Dario. A new mechanism for meso-scale legged locomotion in compliant tubular environments. IEEE Transactions on Robotics, 25(5), 1047-1057, 2009.

9. D. C. Rucker, B. A. Jones, and R. J. Webster III. A Geometrically Exact Model for Externally Loaded Concentric Tube Continuum Robots. IEEE Transactions on Robotics, 26(5), 769-780, 2010.

10. E. M. Boctor, R. J. Webster III, H. Mathieu, A. M. Okamura, and G. Fichtinger. Virtual remote center of motion control for needle placement robots. Journal of Computer Assisted Surgery, 9(5):175–183, 2004.

Synergistic Activities
ASME Dynamic Systems and Controls Division, Robotics Technical Committee, SPIE Medical Imaging Program Committee.

Reviewer for Journals: IEEE Transactions on Robotics, IEEE/ASME Transactions on Mechatronics, IEEE Sensors, Robotica, Applied Bionics and Biomechanics, The International Journal of Robotics Research.

Reviewer for Conferences: IEEE International Conference on Robotics and Automation, IEEE/RSJ International Conference on Intelligent Robots and Systems, Medical Image Computing and Computer Assisted Intervention,

Best Poster, ASME Design of Medical Devices Conference 2009, Best Paper Finalist at IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, 2006.

Recent seminars at given at: Duke University, Carnegie Mellon University, University of Georgia, Scuola Superiore Sant'Anna, and Johns Hopkins University.

Collaborators and Other Affiliations
Recent Collaborators – Michael Goldfarb (Vanderbilt University), Gabor Fichtinger (Queens University), Pietro Valdastri (Vanderbilt University), Brian Jones (Mississippi State University), Emad Boctor (Johns Hopkins University), Robert Labadie (Vanderbilt University), J. Michael Fitzpatrick (Vanderbilt University), Robert Galloway (Vanderbilt University), Ron Alterovitz (University of North Carolina), Clif Burdette (Acoustic MedSystems, Inc.).

Graduate Advisors – Allison Okamura and Noah Cowan (Co-Advisors, Johns Hopkins University).

Advisees – Ph.D. Primary Adviser (7): D. Caleb Rucker (2011), Ray Lathrop (expected 2013), Jenna Gorlewicz (expected 2013), Louis Kratchman (expected 2014), Philip Swaney (expected 2015), Hunter Gilbert (expected 2015), Neal Dillon (expected 2015), Richard Hendrick (expected 2016).

Advisees – Ph.D. Co-Adviser (3): Jadav Das (2010), David Comber (expected 2014), Trevor Bruns (expected 2016),

Advisees – M.S. Primary Adviser (4): Diana Cardona (2012), Byron Smith (expected 2012), Christopher Marince (expected 2014), Peter York (expected 2014).