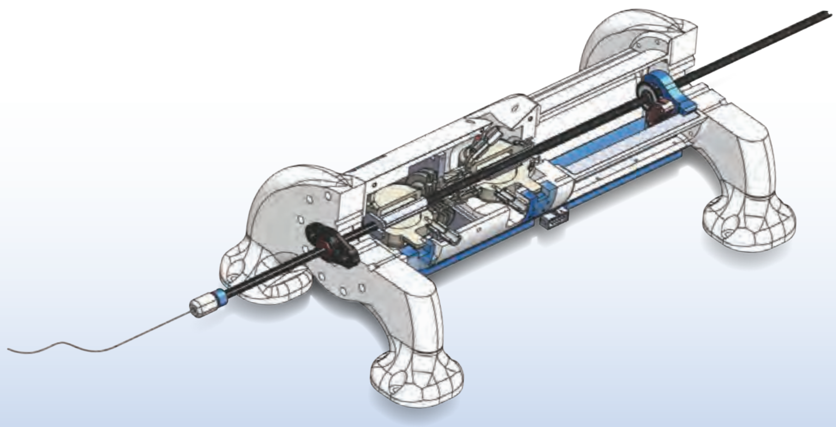
www.ccefp.org

9th ANNUAL REPORT
VOLUME 2

COOPERATIVE AGREEMENT #EEC 0540834 / DUE DATE: MARCH 3, 2015



CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

University of Minnesota

Georgia Institute of Technology

Milwaukee School of Engineering

North Carolina Agricultural & Technical State University

Purdue University

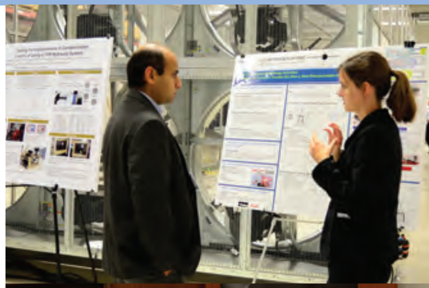
University of Illinois at Urbana-Champaign

Vanderbilt University

Dr. Kim Stelson, Director

Dr. Eric Barth, Co-Deputy Director

Dr. Zongxuan Sun, Co-Deputy Director



Volume II Table of Contents — Page

This page is intentionally left blank

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.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor	Perry Li, University of Minnesota; Thomas Chase, University of Minnesota
1E.3: High Efficiency, High Bandwidth, Actively Controlled Variable Displacement Pump/Motor	John Lumkes, Purdue University; Monika Ivantysynova, Purdue University
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	Perry Li, University of Minnesota; Thomas Chase, University of Minnesota
1E.5: System Configuration & Control Using Hydraulic Transformers	Perry Li, University of Minnesota
1E.6: High Performance Actuation System Enabled by Energy Coupling Mechanism	John Lumkes, Purdue University; Monika Ivantysynova, Purdue University
1F.1: Variable Displacement Gear Machine	Andrea Vacca, Purdue University
1G.1: Energy Efficient Fluids	Paul Michael, Milwaukee School of Engineering
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;
A Characterization of the Pressure-Viscosity and Compressibility Response of Five Oils for a Wide Range of Temperatures	Scott Bair, Georgia Tech *Sponsors:* Deere and Company
Advanced Hydraulic Systems for Next Generation of Skid Steer Loaders	Scott Bair, Monika Ivantysynova *Sponsors:* Confidential
Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump	Andrea Vacca, Purdue University *Sponsors*: Confidential
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	Perry Li, University of Minnesota Terrence Simon, University of Minnesota *Sponsors:* National Science Foundation

Project Name	PI / Institution / Sponsor
Energy Efficient Fluids	Paul Michael, MSOE *Sponsors:* Confidential
Energy Saving Hydraulic System Architecture Utilizing Displacement Control	Monika Ivantysynova, Purdue University *Sponsors*: Confidential
Evaluation and Design Improvements for a Hydraulic Pump	Monika Ivantysynova, Purdue University *Sponsors*: Confidential
Evaluation and Design Study of the Piston/Cylinder Interface of a Swash Plate Type Hydraulic Motor	Monika Ivantysynova, Purdue University *Sponsors*: Confidential
Investigation of Alternative Cylinder Block Materials using Fluid Structure Interaction Modeling (FSTI)	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Modeling and Analysis of Swash Plate Type Piston Motor	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Modeling and Analysis of Swash Plate Axial Piston Motor	Monika Ivantysynova, Purdue University *Sponsors:* Confidential
Modeling of Lubricating Features of External Gear Machines and Development of Quieter Solutions	Andrea Vacca, Purdue University *Sponsors:* Casappa S.p.A.
MRI: Development of a Controlled-Trajectory Rapid Compression and Expansion Machine	Zongxuan Sun, David Kittleson & Kim Stelson, University of Minnesota *Sponsors:* National Science Foundation
New Geometries for Gear Machines towards the Reduction of Noise Emissions	Andrea Vacca, Purdue University *Sponsors:* Casappa S.p.A.
Numerical Modeling of GEROTORs Unit	Andrea Vacca, Purdue University *Sponsors:* Thomas Magnete GmbH

Thrust 2 – Compactness

Project Name	PI / Institution / Sponsor
2B.2 Miniature HCCI Free-Piston Engine Compressor	David Kittelson, University of Minnesota Will Durfee, University of Minnesota
2B.3: Free Piston Engine Hydraulic Pump	Zongxuan Sun, University of Minnesota
2B.4: Controlled Stirling Thermocompressors	Eric Barth, Vanderbilt University
2C.2: Advanced Strain Energy Accumulator	Eric Barth, Vanderbilt University
2C.3: Flywheel Accumulator for Compact Energy Storage	James D. Van de Ven, University of Minnesota
2F: MEMS Proportional Pneumatic Valve	Thomas Chase, University of Minnesota
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
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	Andrea Vacca, Purdue University
3D.1: Leakage/Friction Reduction in Fluid Power Systems	Richard Salant, Georgia Institute of Technology
3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems	Scott Bair, Georgia Institute of Technology
3E.1: Pressure Ripple Energy Harvester	Kenneth Cunefare, Georgia Institute of Technology
High Pressure Compliant Material Development	Kenneth Cunefare, Georgia Tech *Sponsors:* Sauer-Danfoss
Model Predictive Control of Pneumatic Actuators	Wayne Book, Georgia Tech *Sponsors:* National Defense Science and Engineering Graduate Fellowship (NDSEG)
New Generation Of Green, Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology	Monika Ivantysynova, Purdue University *Sponsors*: Confidential

Project Name	PI / Institution / Sponsor
Rheology Modeling for Mechanical Face Seals	Scott Bair, Georgia Tech *Sponsors:* John Crane
Self-powered Leak Detection System for Pipeline Monitoring	Kenneth Cunefare, Georgia Tech *Sponsors:* Veraphotonics, Mistras
Static Dissipating Hydraulic Filters	Paul Michael, MSOE *Sponsors*: 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 *Sponsors:* Minneapolis VA Medical Ctr.
CPS: Synergy: Integrated Modeling, Analysis and Synthesis of Miniature Medical Devices	Pietro Valdastri, Vanderbilt University *Sponsors:* confidential
Modulation of Anticipatory Postural Adjustments in Parkinson's disease Using a Portable Powered Ankle-Foot Orthosis	Elizabeth Hsiao-Wecksler, UIUC *Sponsors:* NSF IGERT Student Fellowship
Wearable eMbots to Induce Recovery of Function	William Durfeee, University of Minnesota *Sponsors:* NIH, University of Michigan

EDUCATION AND OUTREACH PROJECTS

Project Name	PI / Institution / Sponsor
EO A.1 Interactive Fluid Power Exhibits	J. Newlin, Science Museum of Minnesota
EO B.1 Research Experiences for Teachers (RET)	Alyssa Burger, University of Minnesota
EO B.3b Portable Fluid Power Demonstrator	John Lumkes, Purdue University
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.4a Bradley University Capstone Senior Design Project	Elizabeth Hsiao-Wecksler, UIUC
EO C.4b Parker Hannifin Chainless Challenge	Brad Bohlmann, Univ. of Minnesota
EO C.8 Student Leadership Council (SLC)	Alyssa Burger, University 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 Evaluation	James Van de Ven, Univ. of Minnesota
NSF REU Site Award	Kim Stelson, University of Minnesota *Sponsors:* National Science Foundation
NFPA Foundation Grant	Alyssa Burger, University of Minnesota *Sponsors*: NFPA Foundation
NC A&T State University Regional Collaborations for Excellence in STEM	Eui Park, NC A&T Sponsors: EO Thrust A: Public Outreach

This page is intentionally left blank

Project 1B.1: Next Steps towards Digital Prototyping of Pumps and Motors

Research Team

Project Leader: Monika Ivantysynova, Department of Agricultural and Biological Engineering and School of Mechanical Engineering, Purdue University

Graduate Students: Andrew Schenk, PhD student, Daniel Mizell, PhD 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 fluid-structure-thermal simulation models which are capable of predicting the performance of critical lubricating interfaces inside axial piston machines. This research addresses three key areas which must be investigated before these models can be used in practical pump design. They are:

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

2. Project Role in Support of Strategic Plan

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

3. Project/Test Bed Description

A. Description and explanation of research approach

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

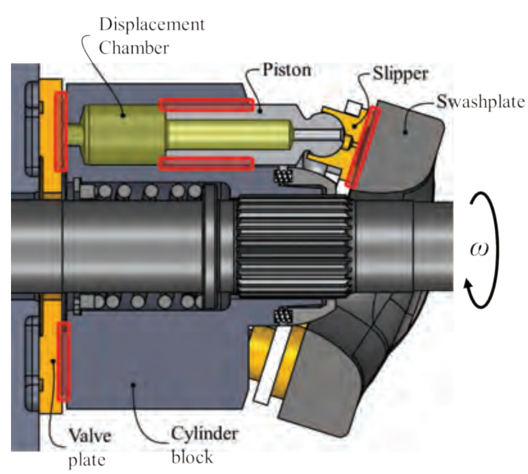


Figure 1: Swashplate axial piston machine cross section and identification of the three lubricating interfaces in red

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

B. Achievements

Achievements prior to the reporting period

Previous work made significant progress in advancing a model predicting the temperatures at the outlet and case port based on the performance and design of a hydraulic pump or motor using the conservation of energy [1]. Given an inlet temperature, the model was able to predict the working temperature of the fluid in the case and outlet volumes as a function of the operating condition (speed, differential pressure, and displacement) within 5°C for the port temperature while correctly predicting the trends of an increasing temperature with an increasing speed and pressure. Steady state measurements were taken on an existing unit to verify the results of the parameterized pump design and the thermal model [2].

Further work was also done to advance the validation of the cylinder block – valve plate interface of the lubrication model. A specially designed valve plate and end case was equipped with various thermal couples in order to measure the temperature distribution on the surface without disrupting the normal fluid film of the interface [3]. Confirming the modeling approach used, the simulation was able to accurately predict the simulated temperature field results both in trend and magnitude to within a few degrees.

Utilizing the validated model for the piston – cylinder interface, previous research investigated the impact that the clearance between the piston and the bore had on the energy dissipation. The diameter of the bore was varied from the nominal design of a commercially manufactured variable displacement swashplate type axial piston machine at a variety of operating conditions. The results demonstrated that by further reducing the bore diameter from the nominal value, the energy dissipation can be further improved. This improvement is limited by the reliability of the machine and the achievable tolerances in the manufacturing process.

Achievements during the reporting period

To further validate the lubrication model of the slipper - swashplate interface along with the impact that not only the deformations have but also the wear incurred on the surfaces during the initial pump run-in process, a pump was specially modified to allow for the insertion of six high-speed eddy current displacement transducers to be mounted inside of the swashplate. As the rotating slippers pass over the stationary sensor face, the specially calibrated sensors measure the dynamic film thickness between the swashplate and slipper allowing for a direct comparison to simulation results [4]. A diagram of pump modifications to incorporate the sensors is shown in Fig. 2.

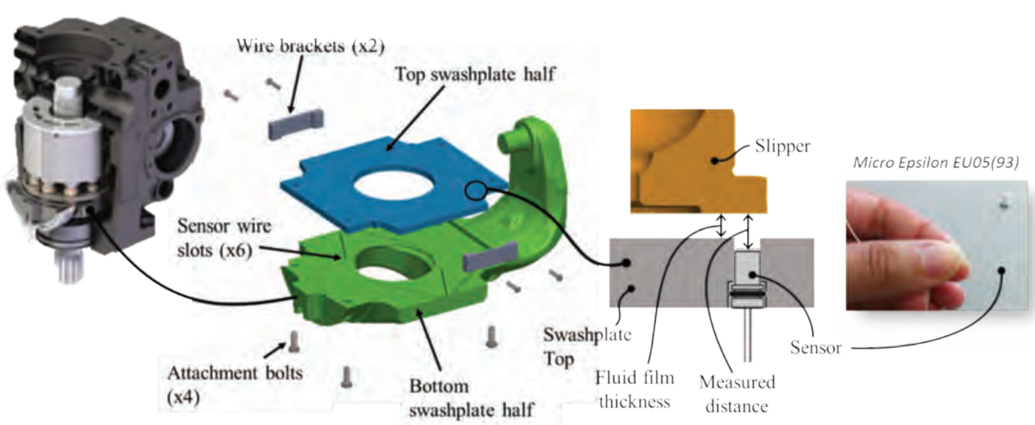


Figure 2: Modified pump incorporating sensors

The slipper test rig was used to investigate the impact of slipper wear on fluid film thickness. Figure 3 (left) shows the measured film thickness at each of the six sensor locations with a diagram of the sensor location number at the bottom. The film thicknesses for each of the nine slippers in the rotating kit during initial operation are plotted with a thin line, and after the run-in wear period, the film thicknesses are plotted with a thick line. It is clear that especially during the high pressure stroke, the slipper wear has a significant impact on changing the lubrication operation. Simulations for the same operating condition both considering the nominal (un-worn) slipper design as well as including the run-in wear profile are presented in Fig. 3 (right). Similar changes in film thickness and tilting behavior between the nominal and worn slipper designs are predicted further validating that the current model is able to predict the behavior of the fluid film while considering both deformations and the influence of the wear profiles of the running surfaces [5, 6].

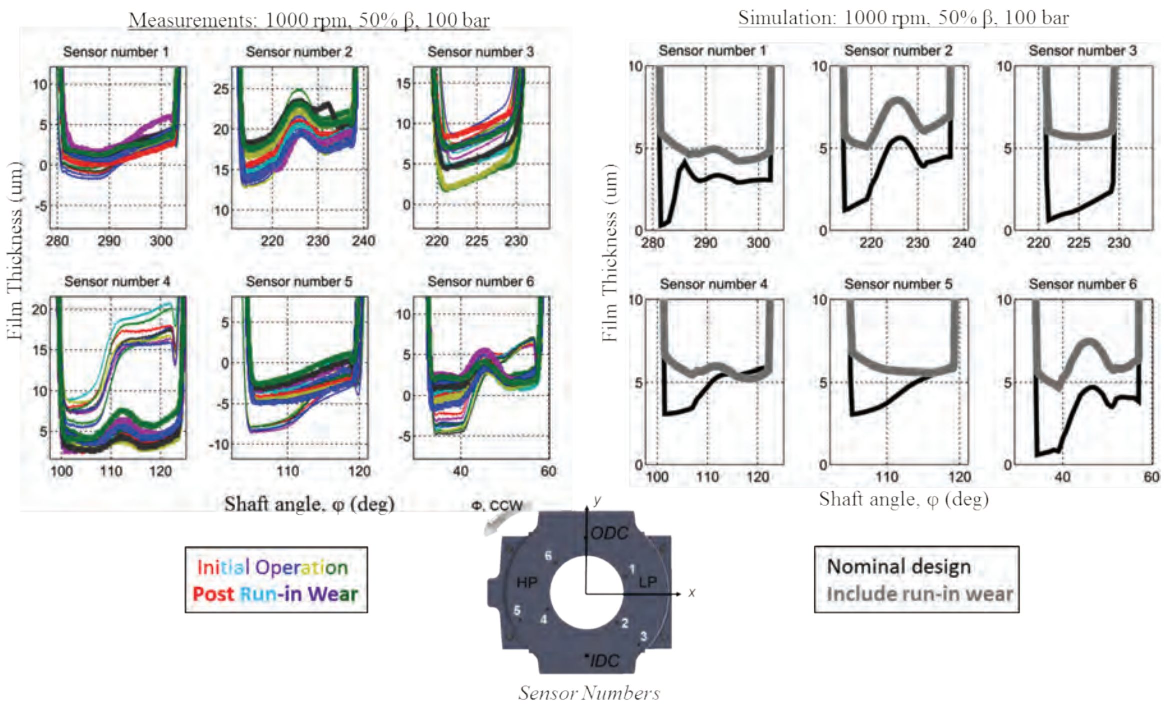


Figure 3: Measured and simulated slipper fluid film thickness

Previous research has shown that the port and case flow temperatures are critical input parameters for the fluid structure and thermal interaction simulation model. The use of the port and case flow prediction model utilizing a simplified heat transfer model of the pump has shown be difficult to obtain realistic value for some different designs. The main reason for that situation is that the heat transfer coefficient as a required input parameter itself is unknown and difficult to be determined accurately. Unfortunately the existing port and case flow temperature prediction model is very sensitive to those coefficient. To improve the accuracy of the port and case temperature prediction, and eliminate the requirement of the inputs that are difficult to be determined accurately, a large number of measured temperature data was studied from different pumps and an empirical port and case flow temperature prediction model was developed.

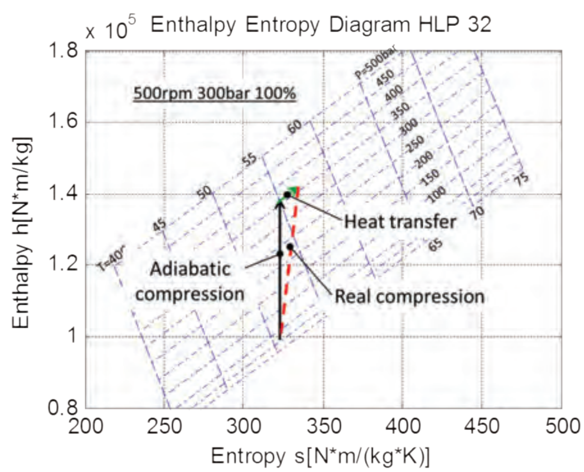


Figure 4: Temperature variation due to pressure change and heat transfer

Since in a real axial piston machine, the fluid pressure changes over a very short time period and the heat transfer occurs under constant pressure mostly, in this empirical model the fluid temperature variation process has been divided into two vectors as shown in Figure 4. The vertical black vector represents an adiabatic compression or expansion and the green vector represents the temperature variation due to the heat transfer at constant pressure. 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. Comparing to the measured temperature, this model predicts the port and case temperature at a reasonable accuracy over different operating conditions on different sized pumps [7].

In order to use the port and case flow temperature prediction model coupled with the fluid structure and thermal interaction model to support design new pumps and motors, the simulation need to start with given pump design, given inlet port temperature, given fluid properties and estimated outlet port and case flow temperatures. In a second step the pump outlet port and case flow temperature prediction model is used to calculate the outlet port temperature and the case flow temperature based on the power loss and the outlet and case flow rate from the fluid structure and thermal interaction model. In a third step the obtained outlet port and case flow temperature will be used to rerun the fluid structure and thermal interaction model to update the power loss and the outlet and case flow rate. The described iteration cycle between the two models will be repeated until the outlet and case flow temperature converge as shown in Figure 5.

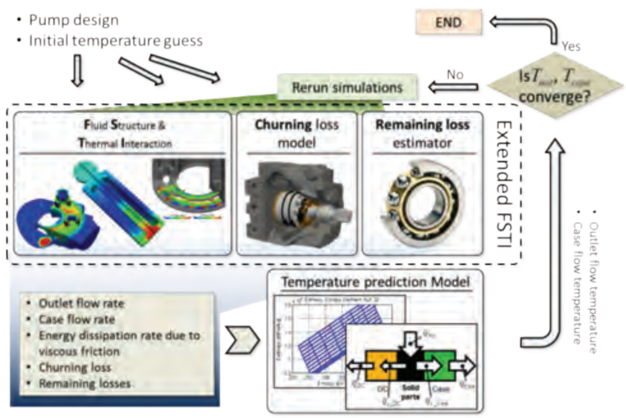


Figure 5: Simulation process of a new pump or motor

The previously experimentally validated piston – cylinder block lubrication model 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 in the gap over various operating conditions. 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 as shown in Fig. 6 [8]. The results of the simulations, as shown in Fig. 7, show potential improvements of overall energy dissipation of up to 30% at full displacement and 45% at partial displacements. Critical fluid film thicknesses and areas of friction are also able to be investigated to better understand what is occurring between the piston and cylinder allowing to even better improve the overall operation of the machine as the hydrodynamic pressure build up in the fluid due to the surface profile is improved [9].

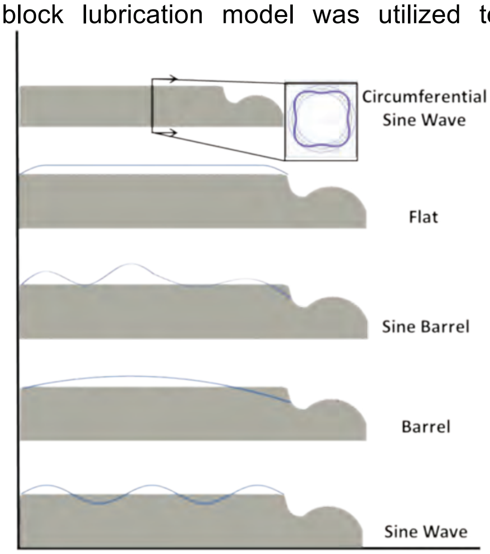


Figure 6: Various micro-surface shapes on the piston surface

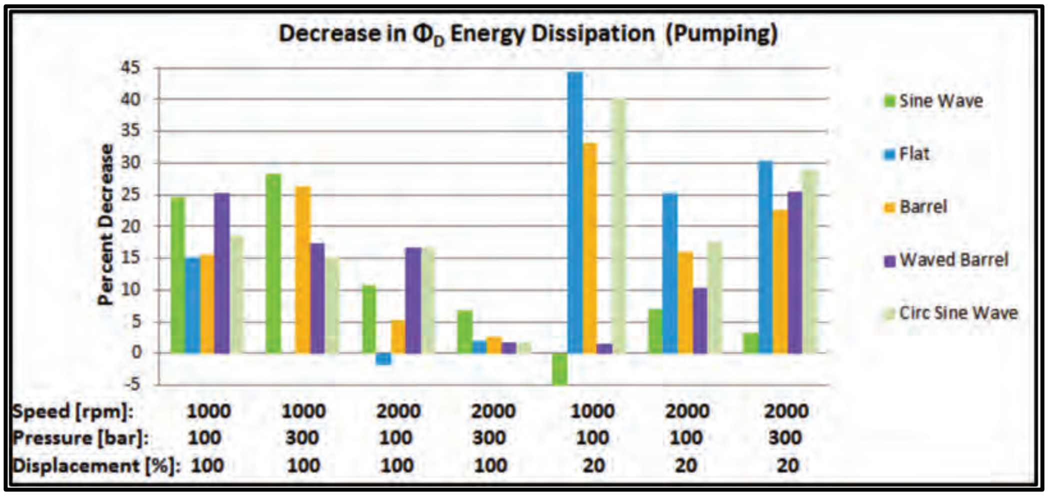


Figure 7: Reduction in energy dissipation due to micro-surface shaping of the piston

C. Member company benefits

- Deeper and more comprehensive understanding of physical phenomena enabling successful operation of axial piston pumps and motors.
- Discovery of the impact of surface shaping and material properties on pump and motor operation.
- Fundamental modeling of complex fluid structure interaction enabling further digital prototyping.
- 10% overall efficiency improvement of an axial piston pump using surface shaping techniques demonstrated with prototype waved valve plate measurements [10].
- Preferential patent licensing options for waved pump lubricating surfaces [11, 12].
- Project 1B.1 research has led to seven associated projects on pump modeling with different member companies with a total investment of ~$1.1 million since 2006.

D. References

1. Zecchi, M., Mehdizadeh, A., Ivantysynova, M. 2013. A novel approach to predict the steady state temperature in ports and case of a swashplate type axial piston machine. *Proceedings of the 13th Scandinavian Int. Conf. on Fluid Power*, Jun. 3-5, Linkoping, Sweden.
2. Schenk, A., Zecchi, M., Ivantysynova, M. 2013. Accurate prediction of axial piston machine performance through a thermo-elasto-hydrodynamic simulation model.
3. Zecchi, M. 2013. A novel fluid structure interaction and thermal model to predict the cylinder block / valve plate interface performance in swash plate type axial piston machines. PhD thesis, Purdue University.
4. Schenk, A. 2014. Predicting lubrication performance between the slipper and swashplate in axial piston hydraulic machines. PhD thesis, Purdue University.
5. Schenk, A. and Ivantysynova, M. 2014. A transient thermoelastohydrodynamic lubrication model for the slipper / swashplate in axial piston machines. ASME Journal of Tribology. TBD (Under Review)
6. Schenk, A. and Ivantysynova, M. 2014. A transient fluid structure interaction model for lubrication between the slipper and swashplate in axial piston machines. Proceedings of the 9th International Fluid Power Conference (9IFK), Mar. 24-26, 2014. Aachen, Germany, Vol 1. pp.398-409.
7. Shang, L., Ivantysynova, M. 2014. Port and case flow temperature prediction for axial piston machines. *International Journal of Fluid Power*. (Under Review)
8. Wondergem, A. 2014. Piston/Cylinder interface of axial piston machines – effect of piston micro-surface shaping. Master's thesis, Purdue University.

9. Wondergem, A. and Ivantysynova, M. 2014. The Impact of the Surface Shape of the Piston on Power Losses. Proc. of the 8th FPNI PhD Symposium, Lappeenranta, Finland.
10. Baker, J and Ivantysynova, M. Power loss in the lubricating gap between cylinders block and valve plate of swash plate type axial piston machines. International Journal of Fluid Power 10(2), pp. 29–43.
11. Zecchi, M. and Ivantysynova, M. 2012. An investigation of the impact of micro surface shaping on the cylinder block/valve plate inter-face performance through a novel thermo-elasto-hydrodynamic model. *Proc. of the 7th FPNI PhD Symposium*, Reggio Emilia, Italy, pp 589 - 610 **-** Recognized paper award.
12. Zecchi, M., Ivantysynova, M. 2013. Spherical valve plate design in axial piston machines – A novel thermo-elasto-hydrodynamic model to predict the lubricating interface problem. *The 8th Int. Conf. on Fluid Power Transmission and Control*, Apr. 9-11, Hangzhou, China, pp. 325-329.

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

Research Team

Project Leader:	Perry Y. Li, University of Minnesota, Mechanical Engineering
Other Faculty:	Thomas R. Chase, University of Minnesota, Mechanical Engineering
Graduate Students:	John Dekarski, Ed Sandberg, Haink Tu, Rachel Wang, and Mike Rannow
Industrial Partners:	Eaton, Parker Hannifin, Sauer-Danfoss, and others

1. Statement of Project Goals

The goal of the project is to demonstrate efficient, high performance control of hydraulic power using on/off valves in a throttle-less manner. This goal will be met through the development of critical enabling technologies such as novel high speed rotary on/off valves that will be integrated with fixed displacement pump/motors (P/M) to create "virtually variable displacement pump/motors (VVDPM)". A prototype VVDPM will then be performance mapped using an existing CCEFP test stand. Due to limitations of the power unit and dynamometer on the test stand, prototype performance is to be mapped up to 20 MPa operating pressure and 3000 RPM shaft speed.

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

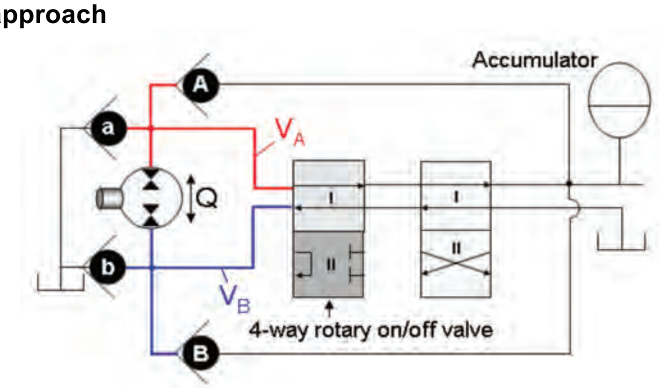


Figure 1: Hydraulic schematic of a VVDPM using a 4-way tandem rotary on/off valve. Check valves a and b prevent cavitation while check valves A and B reduce pressure spikes during transition.

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

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

The approach used in Project 1E.1 is to develop novel on/off valves that use continuous rotary motion to generate on/off switching [10]. These rotary valves do not need to start and stop; therefore, the only power required is that to overcome friction (proportional to frequency squared). Moreover, in applications where the pump or motor shaft speed is fixed (i.e. constant flow rate through the valve), the rotary actuation power can be obtained by scavenging energy in the fluid stream without using an external actuator. The average response time and effective flow area for several commercial on/off valves and a few valves found in the literature [2, 3] are compared to the prototype rotary valve in Figure 2.

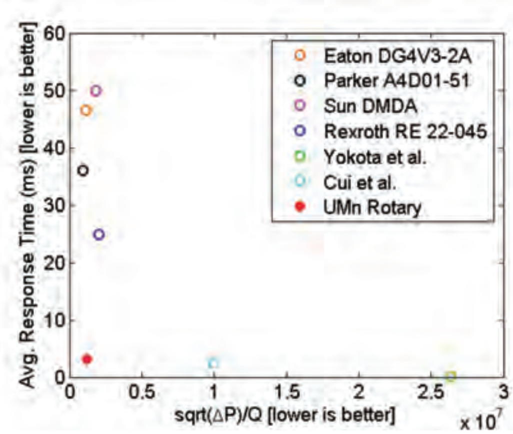


Figure 2: Effective flow area and response times of existing on/off valves

B. Achievements

a) Achievements in previous years

An analysis-driven design of a virtually variable displacement pump/motor based on a rotary valve was completed in Year 6 of the center. No further funding for this project was requested after Year 6. However, a prototype was constructed using carry-forward funding. The prototype is based on the spool valve architecture that has been under development since the inception of the CCEFP [10,17]. This architecture has evolved from a 3-way self-spinning design for the control of fixed displacement pumps to a 4-way tandem design for the control of pump/motors [13,16]. The prototype utilizes a commercially available fixed displacement bent-axis P/M. It was combined with the rotary valve by re-packaging it in a custom case.
After prototype construction, attempts at efficiency testing were plagued with various problems that had to be addressed before the prototype would operate reliably. The major problem of the spool seizing was overcome last year. However, efficiency mapping of the prototype has since been delayed by building construction at the University of Minnesota, which forced two moves of our lab.

b) Achievements in the past year

Achievements over the past year include modifying the base bent axis P/M, fixing various instrumentation issues with the test stand, and mapping the efficiency of the base unit to validate the data coming from the test stand.

It was found that the fixed displacement bent-axis P/M, when tested alone, had poor mechanical efficiency. This problem was traced to a custom end-cap that interfaces with the PWM valve block. The problem was corrected by adding shims to better replicate the stock end-cap. The base fixed-displacement P/M is now performance mapped and volumetric and mechanical efficiencies are appropriate for that device. This has validated that instrumentation issues with the test stand have all been resolved.

The experiment had to be moved twice over the last year because of facility upgrades at the University of Minnesota. The PWM valve block is now re-installed and the VVDPM performance is being mapped. Its performance will then be compared to the fixed displacement base P/M, and standard variable displacement P/M's.

Figure 3 shows the prototype on the test stand. The prototype VVDPM is on the left side of the picture, with the 4-way rotary valve housed in a steel block bolted to a standard bent-axis fixed displacement P/M. The spool is actuated axially via a closed loop position control, and spun with the DC motor seen on top.

The variable displacement P/M seen on the right hand side is used to load the prototype when motoring, and drive the prototype when pumping.

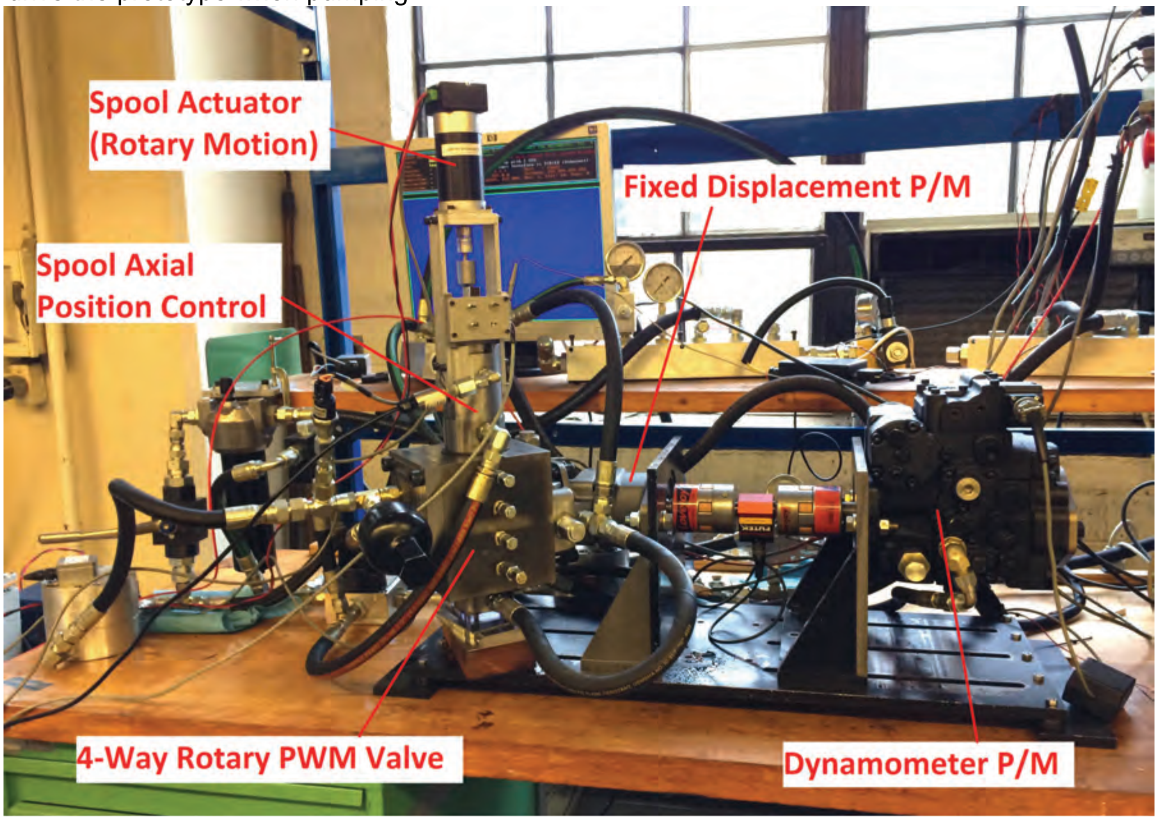


Figure 3: Prototype setup on test stand

a) Plans for the next year

This project is nearing completion. No additional funding is expected through the CCEFP beyond year 9. Now that the VVDPM prototype is operating reliably and the test stand is outputting correct data, its efficiency will be evaluated and a paper prepared to discuss results.

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

b) Expected milestones and deliverables

- Efficiency performance map of the prototype VVDPM generated
- Paper to discuss results of prototype testing

C. Member company benefits

Member companies will benefit from the development of innovative on/off valve architectures, new digital control and estimation algorithms, design insights, high frequency hydraulic sensing techniques, and an expanded knowledge of applications. Also, the practical knowledge gained and challenges to be overcome in turning the concept of a PWM controlled VVDPM into a working prototype will be an asset as high speed on/off hydraulic valve technology evolves.

D. References

[1] Li, P., Li, C., Chase, T., 2005. "Software enabled variable displacement pumps". Proceedings of the ASME IMECE '05 #81376, Orlando, FL.

[2] Yokota, S., and Akutu, K., 1991. "A fast-acting electro-hydraulic digital transducer (a poppet-type on-off valve using a multilayered piezoelectric device)". JSME International Journal.

[3] Cui, P., Burton, R., and Ukrainetz, P., 1991. "Development of a high speed on/off valve". Transactions of the SAE.

[4] Rannow, M., Tu, H., Li, P., and Chase, T., "Software Enabled Variable Displacement Pumps – Experimental Studies," Proceedings of the ASME IMECE '06 #14973, Chicago, IL.

[5] Tu, H., Rannow, M., Van de Ven, J., Wang, M., Li, P., and Chase, T., "High speed rotary pulse width modulated on/off valve", Proceedings of the ASME IMECE '07 #42559, Seattle, WA.

[6] Rannow, M. and Li, P., "On/Off Valve Based Position Control of a Hydraulic Cylinder", Proceedings of the ASME IMECE '07 #42590, Seattle, WA.

[7] Wang, M. and Li, P., "Event Based Kalman Filter Observer For Rotary High Speed On/Off Valve", Proceedings of the 2008 American Control Conference, pp 1546-1551, June, 2008.

[8] Wang, M., and Li, P., "Duty ratio control of a rotary PWM valve with periodic measurement error", Proceedings of the 2009 American Control Conference, St. Louis, MO.

[9] Rannow, M. and Li, P., "Soft switching approach to reducing transition losses in an on/off hydraulic valve", Proceedings of the ASME 2009 DSCC #2617, Hollywood, CA.

[10] Tu, H., Rannow, M., Wang, M., Li, P., and Chase, T., "Modeling & validation of a high speed rotary PWM on/off valve", Proceedings of the ASME 2009 DSCC #2763, Hollywood, CA.

[11] Rannow, M., Li, P., Chase, T., Tu, H., and Wang, M., 2010. "Optimal design of a high-speed on/off valve for a hydraulic hybrid vehicle application". Proceedings of the 7th International Fluid Power Conference, Aachen, Germany.

[12] Wang, M., Tu, H., Rannow, M., Li, P., and Chase, T., "CFD Analysis of a Novel High Speed Rotary On/Off Valve", Proceedings of the 2010 6th FPNI - PhD Symposium, West Lafayette, IN.

[13] Tu, H., Rannow, M., Wang, M., Li, P., and Chase, T., "The Advantages and Feasibility of Externally Actuating a High-speed Rotary On/Off Valve", 2011 International Fluid Power Exhibition (IFPE), Las Vegas, NV.

[14] Wang, M., Li, P., Tu, H., Rannow, M., and Chase, T., "Direct Displacement Control of Hydraulic Actuators Based on a Self-Spinning Rotary On/Off Valve", 2011 International Fluid Power Exhibition (IFPE), Las Vegas, NV.

[15] Li, P. and Wang, M., "Passivity Based Nonlinear Control of Hydraulic Actuators Based On An Euler-Lagrange Formulation", Proceedings of the 2011 ASME DSCC, Arlington, VA.

[16] Tu, H., Rannow, M., Wang, M., Li, P., Chase, T., and Cheong, K.L., "High-speed 4-way rotary on/off valve for virtually variable displacement pump/motor applications", Proceedings of the 2011 ASME DSCC, Arlington, VA.

[17] Tu, H., Rannow, M., Wang, M., Li, P., Chase, T., and Van de Ven, J., "Design, Modeling and Validation of a High-Speed Rotary PWM On/Off Valve for Use in Virtually Variable Displacement Pumps", ASME J. of Dynamic Systems, Measurement and Control 134:6-061002, 2012.

[18] Rannow, M. and Li, P., "Soft Switching Approach to Reducing Transition Losses in an On/Off Hydraulic Valve", ASME J. of Dynamic Systems, Measurement and Control 134:6-064501, 2012.

[19] M. Wang and P. Y. Li, "Displacement Control of Hydraulic Actuators Using a Passivity Based Nonlinear Controller", ASME DSC Conference, [DSCC2012-MOVIC2012-8784], Ft. Lauderdale, 2012

[20] M. Wang and P. Y. Li, "Passivity based adaptive control of a two chamber hydraulic actuator", 2012 American Control Conference, Montreal, Quebec, Canada, June 2012.

[21]M. Wang, CFD Analysis, Sensing and Control of a Rotary Pulse Width Modulating Valve, PhD Dissertation, Department of Mechanical Engineering, University of Minnesota, 2012.

[22]Tu,, H, High Speed Rotary PWM On/O_ Valves for Digital Control of Hydraulic Pumps and Motors, PhD Dissertation, Department of Mechanical Engineering, University of Minnesota, 2013

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 translate the successful fundamental research of pump chamber voiding 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. This requires two outcomes: the development of optimal control strategies that allow the digital pump/motor to switch seamlessly between operating modes (flow limiting/flow diverting) while maintaining optimal efficiency and minimal noise, and the compact integration of valves and embedded controls to enable mobile operation. Full four-quadrant operation has been demonstrated in all proposed operating modes, and efficiency and noise tradeoffs were characterized for each mode. The results have been encouraging and provide motivation for a focused effort to implement a digital pump/motor on a test bed.

2. Project Role in Support of Strategic Plan

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

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

- *Efficient Components and Systems (improve 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 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

a) 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.

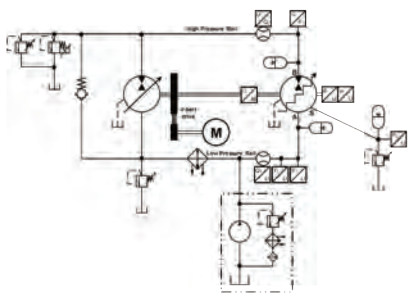


Figure 1: Schematic of test setup

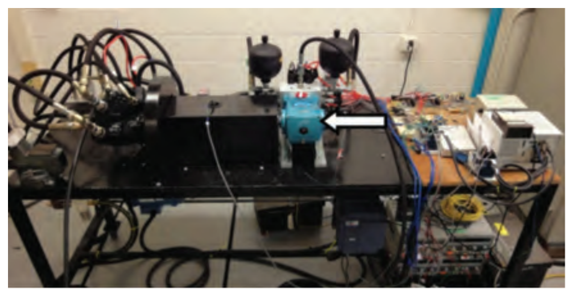


Figure 2: Picture of test setup

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

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

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

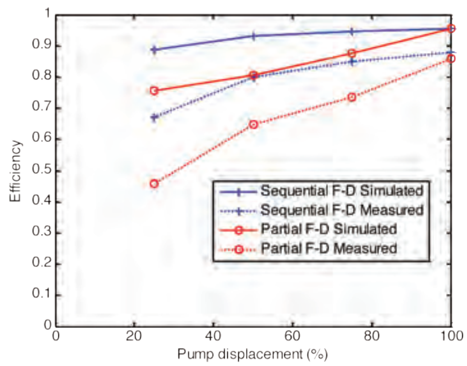


Figure 3: Sequential and partial flow-diverting, measured and simulated

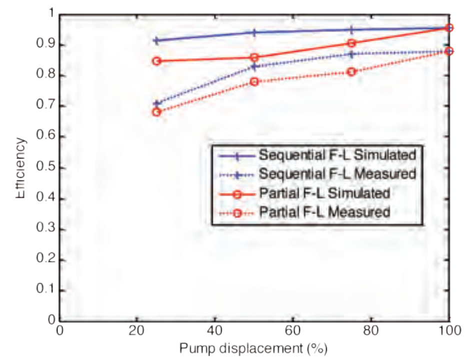


Figure 4: Sequential and partial flow-limited, measured and simulated

Figure 5 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 6. The operating strategy with the best efficiency for the conditions and parameters stated in this work is sequential F-L, followed by sequential F-D, next is partial F-L and the worst efficiency is partial F-D.

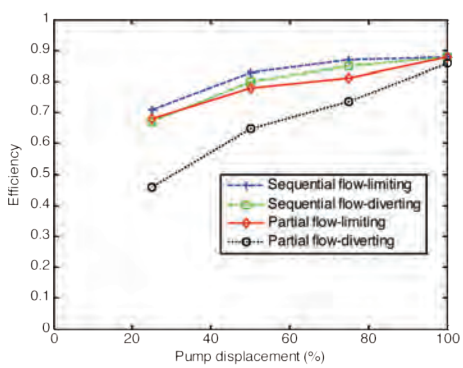


Figure 5: Measured results of 4 operating strategies at 700 rpm and 103 bar

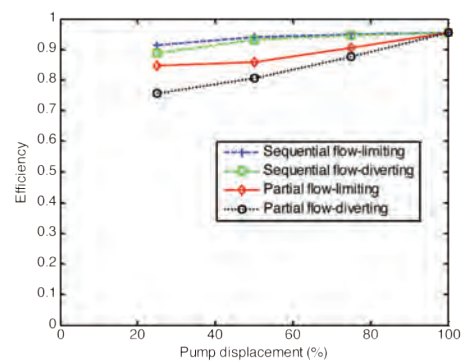


Figure 6: Simulated results of 4 operating strategies at 700 rpm and 103 bar

b) <u>Acheivements in the past year</u>

<u>Valve correction algorithm</u>

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. This is experimentally shown by the red circles in Figure 7. This 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 event do not overlap, this algorithm would 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, so it would measure the valve transition time for the current cycle and send the signal to the next cycle to open the valve in advance. More optimization needs to be done for faster speeds.

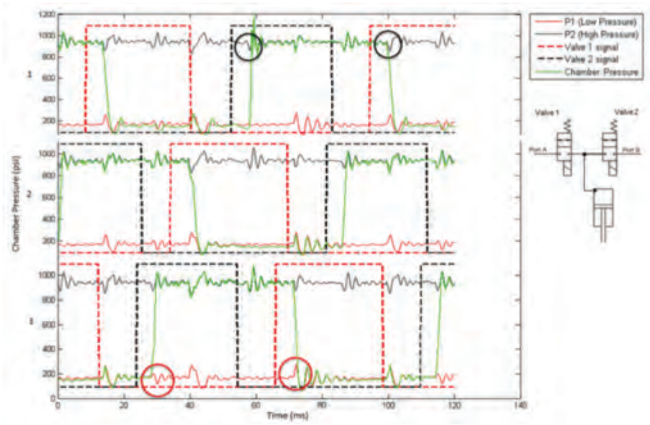


Figure 7: Valve timing algorithm

Experimenting with peak and hold and reverse current driving strategy

To further improve our valve speeds, 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 involves 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 the solenoid to keep the armature in place.

Table 1: Comparison of average total turn-on and turn-of time of modified and original valves DTDA-XCN valves

	Forward (ON)		Reverse (ON)		Forward (OFF)		Reverse (OFF)	
Peak Duration (ms)	Modified (ms)	Original (ms)	Modified (ms)	Original (ms)	Modified (ms)	Original (ms)	Modified (ms)	Original (ms)
0	26.04	31.97	39.44	33.30	162.56	79.10	95.70	-
2	14.70	22.77	27.17	24.83	130.1	50.17	64.50	-
4	7.50	6.50	10.43	7.57	59.03	19.83	24.24	-
6	6.77	6.30	7.57	6.57	29.30	27.37	20.50	11.63
8	6.43	6.50	7.37	6.50	32.30	62.97	21.50	16.17
10	7.10	6.77	7.50	6.63	49.30	83.77	28.96	45.30

As shown in Table 1, 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 8, 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 showed that 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.

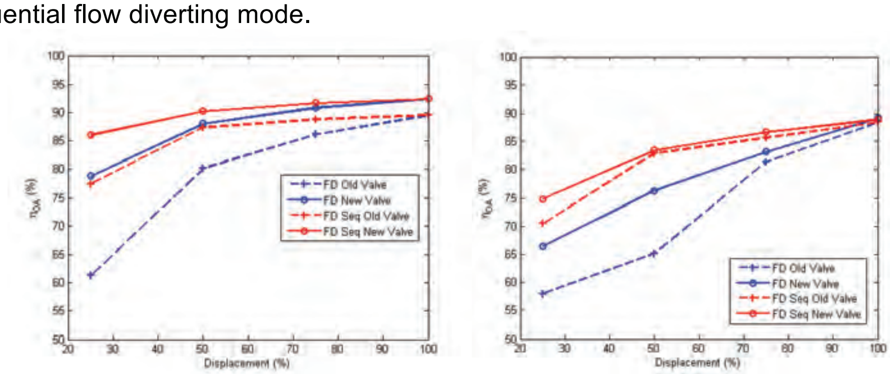


Figure 8: Digital pump/motor simulated (left) and measured (right) efficiency comparison when using the old and new valves for flow diverting and sequential flow diverting strategies

C. Plans

a) Plans for the next year

There are two primary tasks for next year. The first task is to investigate different pump driving strategies. When running at constant displacements, the valve signals become repetitive per cycle, so we are studying different options of controlling the pump/motor which would minimize the effects of valve timing on the efficiency and system behavior. This study is driven by the capabilities and freedom in operating strategies of the current test stand and all the experimental data gathered which allow us to study the feasibility of multiple configurations.

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

b) Expected milestones and deliverables

Project Tasks:

- Task 1: Investigate different pump/motor configurations which are less valve dependent [4 months]
- Task 2: Investigate and develop mode switching algorithm [6 months]
  Real-time switching between operating strategies (partial flow diverting/limiting and sequential)
- Task 3: Investigate the use of project 1E.6 valves [4 months]
  Validate further efficiency improvement by using faster and less non-linear on/off valves
- Task 4: Design and construct a test bed ready digital pump/motor prototype [12 months]
- Task 5: Implementing the portable prototype into an actual machine [4 months]

Milestones:

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

New for Y9/Y10

- Design and simulate a new pump/motor design [May 2015]
- Experimentally validated mode switching algorithm [August 2015]
- Built a new pump/motor prototype [Oct. 2015]
- Design of test bed ready mobile digital pump/motor unit with integrated electronics, sensors, and rotary group [Feb. 2016]
- Construction of test bed ready mobile digital pump/motor unit with integrated electronics, sensors, and rotary group [April 2016]
- Implementation of mobile digital pump/motor prototype on a test bed [June 2016]

D. Member company benefits

This project has and will continue to benefit CCEFP member companies by providing new digital pump/motor design tools, on/off valve designs, and digital pump/motor operating strategies for further development and commercialization by member companies. It indirectly benefits member companies through its role as an enabling technology for other CCEFP test beds. Industry partner involvement will be critical while developing the appropriate performance metrics, benchmarking 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.

E. References

[1] Ehsan, M., Rampen, W. H. S., & Salter, S. H. (1996). Computer simulation of the performance of digital-displacement pump-motors. Fluid Power Systems and Technology: Collected Papers, 3, 19-24. (Proceedings of the 1996 International Mechanical Engineering Congress & Exposition.)

[2] Payne, G. S., Kiprakis, A. E., Rampen, W. H. S., Chick, J. P., & Wallace, A. R. (2007). Efficiency and dynamic performance of Digital DisplacmentTM hydraulic transmission in tidal current energy converters. Proceedings of the Institution for Mechanical Engineers, Part A: Journal of Power and Energy, 221, 207-218.

[3] Rampen, W. (2006). Gearless transmissions for large wind turbines – The history and future of hydraulic drives. http://www.artemisip.com/Pictures/GearlesstransmissionsBremenNov06.pdf

[4] Linjama, M. and Huhtala, K.: "Digital Pump-Motor with Independent Outlets"; Proceedings of the 11th Scandinavian International Conference on Fluid Power, Linkoping, Sweden (2009).

[5] Heikkila, Mikko, Jyrki Tammisto, Mikko Huova, Kalevi Huhtala, and Matti Linjama: "Experimental Evaluation of a Piston-Type Digital Pump-Motor-Transformer with Two Independent Outlets"; Fluid Power and Motion Control, pp 83-97; (2010).

[6] Lumkes, John H. and Andruch, John III: "Hydraulic Circuit for Reconfigurable and Efficient Fluid Power Systems"; Proceedings of the 12th Scandinavian International Conference on Fluid Power, Tampere, Finland; (2011).

[7] Merrill, K., Holland, M., and Lumkes, J., "Analysis of Digital Pump/Motor Operation Strategies", Proceedings of the 52nd National Conference on Fluid Power, March, 2011.

[8] Holland, M., Wilfong, G., Merrill, K., & Lumkes, J. (2011). Experimental Evaluation of Digital Pump/Motor Operating Strategies with a Single-Piston Pump/Motor. Proceedings of the 52nd National Conference on Fluid Power.

[9] Merrill, K., Breidi, F., and Lumkes, J., "Simulation Based Design and Optimization of Digital Pump/Motors", Proceedings of the ASME/BATH 2013 Symposium on Fluid Power & Motion Control, October, 2013.

[10]Nieling, M., Fronczak, F. J., & Beachley, N. H. (2005). Design of a virtually variable displacement pump/motor. Proceedings of the 50th National Conference on Fluid Power, 323-335.

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

Research Team

Project Leader:	Perry Li, Mechanical Engineering, University of Minnesota
Other Faculty:	Thomas Chase, Mechanical Engineering, University of Minnesota
Graduate Students:	Mike Rannow, Chad Larish, John Dekarski
Industrial Partner:	Danfoss Power Solutions

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

Most hydraulic systems contain one or more devices to transform between rotary mechanical power and hydraulic power, such as a pump, motor, or transformer. Two methods are commonly used to vary the flow or speed of these devices: adding a throttling valve in series with one of the hydraulic ports of the device, or building the device such that its displacement can be varied. The variable displacement option is generally more efficient. However, in existing state-of-the-art designs, the efficiency of variable pumps and motors dramatically decreases as the displacement is decreased. This is a significant barrier to the creation of efficient hydraulic systems. The drop off in efficiency is caused by the fact that the dominant power losses, primarily leakage and friction, do not decrease as the output power is decreased. The majority of variable pumps and motors are either bent-axis or swashplate type piston machines where their displacement is varied by changing the stroke length of the pistons. In this approach, high pressure is applied to all pumping pistons, regardless of the displacement. As a result, leakage and friction losses remain constant.

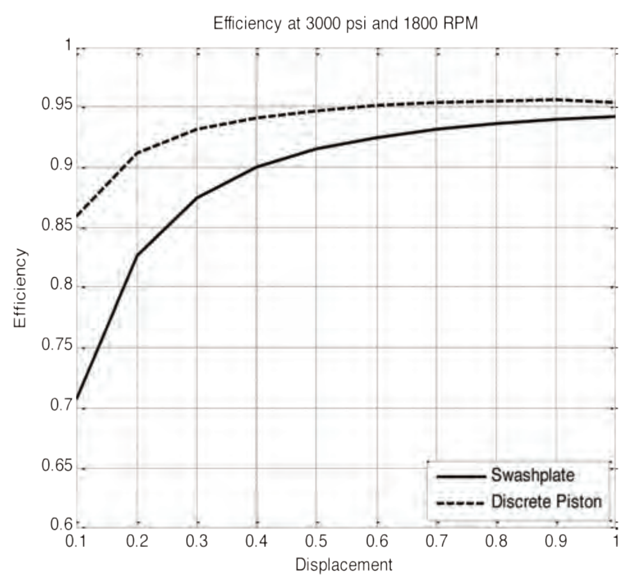


Figure 1: Efficiency comparison of standard swashplate vs. discrete piston control

A new approach to improving the efficiency decrease with displacement is the piston-by-piston variation method. Research that was initiated at the University of Edinburgh, and has continued with the start-up company Artemis Intelligent Power, has produced a method of reducing the displacement of a radial-piston device by disabling individual pistons when not needed [1,2]. This so-called piston-by-piston approach has been demonstrated to significantly improve the efficiency of hydraulic machines at low displacements. This increase in low displacement efficiency can be seen in Fig. 1.

The Artemis design is based on two electronically latched check valves to enable or disable each piston. When a piston is disabled, high pressure fluid is not applied to it, removing the leakage and some of the friction losses associated with that piston. Thus, a portion of the losses will scale down with displacement. With separate valves controlling the fluid in and out of each piston, the constant losses associated with valve plates, as used in many conventional alternatives, are also eliminated.

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

Using a mechanical control method offers many advantages. The simplicity of a single input control of displacement versus more complex electronically controlled valve timing provides reliability and cost benefits. Actuation power is reduced since a rotary valve does not need to be accelerated and decelerated, and it doesn't require constant holding power, as typical solenoid valves do. Having the valve mechanically coupled to the drive shaft ensures repeatable timing, and this strategy can power the spool despite contaminated oil. The mechanical approach does suffer one disadvantage: control flexibility is reduced as a result of replacing flexible electric controls with fixed mechanical controls. However, this is anticipated to have only a slight effect on the overall efficiency.

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

B. Achievements

a) Achievements in previous years

The initial phase of this project was to examine how the losses in variable displacement pumps/motors scale with displacement, in both conventional and piston-by-piston approaches. The goal of this phase was to demonstrate the feasibility of the approach and define the magnitude of the potential energy savings.

The rough design concept has been developed into a detailed prototype design. A number of valving approaches were considered, and the selected on/off valve concept was designed to fit into a custom pump housing for a wobble-plate style pump-motor. The design incorporates elements from a donated pump prototype, along with 25 different custom designed parts. The detailed design of the pump/motor components was an iterative process that included dynamic modeling as well as CFD analysis. A design review was held with industry champion Danfoss Power Solutions, who provided some helpful feedback on the design. The primary design changes resulting from the review centered on material selection and heat treatment options.

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

b) Achievements in the past year

In the past year, the model for the various loss types in the swashplate and discrete piston designs was reviewed with an industry expert. As a result of the review, a number of updates were made to the model.

Fig. 2: Prototype during inspection and assembly

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

The prototype hardware is shown in Fig. 2. Assembly is nearly complete. It will be tested for efficiency and dynamic performance, and if the results are promising, it will be demonstrated on Test Bed 3, the Hydraulic Hybrid Passenger Vehicle. At that point the original project plan will be complete. If the efficiency tests are promising, the next step will be to contact member companies to gauge the interest in further developing the technology. A logical next step for this research is to investigate whether the approach can be extended to a piston-by-piston transformer.

Milestones

- Analyze piston disabling strategies (complete)
- Determine how swash plate and piston-by-piston losses scale with displacement (complete)
- Generate and analyze valve architectures (complete)
- Model selected mechanism to predict losses and dynamic performance (complete)
- Complete mechanical design of the pump/motor (complete)
- Analyze flow paths using Computational Fluid Dynamics (complete)
- Hold design review with Saur-Danfoss (complete)
- Finish prototype construction (2/15)

- Test efficiency of the pump/motor (5/15)

C. Member company benefits

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

D. References

1. Ehsan, M., Rampen, W., Salter, S., “Modeling and Dynamic Performance of Digital Displacement Pump-Motors and Their Application as Hydraulic Drives for Nonuniform Loads,” ASME Journal of Dynamic Systems Measurement and Control, 2000, Vol. 122, pp. 210-215.
2. Artemis Intelligent Power Website: http://www.artemisip.com/
3. Lumkes, J., Batdorff, M., and Mahrenholz, J. (2009). Characterization of losses in virtually variable displacement pumps. International Journal of Fluid Power, 10(3) pp. 17-27.
4. Merrill, K., Holland, M. and Lumkes, J. (2010). Efficiency Analysis of a Digital Pump Motor as Compared to a Valve Plate Design. Proceedings of the 7th International Fluid Power Conference (7.IFK), Aachen, Germany, March 22-24.
5. Tu, H. et al, “High speed rotary pulse width modulated on/off valve,” Proceedings of the 2007 ASME-IMECE, Vol. 4, pp. 89–102. IMECE2007-42559.
6. Tu, H. et al, “Modeling and Experimental Validation of a High Speed Rotary On/off Valve,” Proceedings of the 2009 ASME-IMECE.
7. Wang, M., Tu, H., Rannow, M., Li, P., and Chase, T., “CFD Analysis of a Novel High Speed Rotary On/Off Valve”, Proceedings of the 2010 6th FPNI - PhD Symposium, West Lafayette, IN.
8. Tu, H., Rannow, M., Wang, M., Li, P., and Chase, T., "The Advantages and Feasibility of Externally Actuating a High-speed Rotary On/Off Valve", 2011 International Fluid Power Exhibition (IFPE), Las Vegas, NV.
9. Tu, H., Rannow, M., Wang, M., Li, P., Chase, T., and Van de Ven, J., “Design, Modeling and Validation of a High-Speed Rotary PWM On/Off Valve for Use in Virtually Variable Displacement Pumps”, *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 134, No. 6, Paper #061002
10. Tu, H., Rannow, M., Wang, M., Li, P., and Chase, T., "Modeling & validation of a high speed rotary PWM on/off valve", Proceedings of the ASME 2009 DSCC #2763, Hollywood, CA.
11. Rannow, M., Li, P., Chase, T., Tu, H., and Wang, M., 2010. “Optimal design of a high-speed on/off valve for a hydraulic hybrid vehicle application”. Proceedings of the 7th International Fluid Power Conference, Aachen, Germany.
12. Pelosi, M. and Ivantysynova, M. 2010. A Fully Coupled Thermo-Elastic Model for the Rotating Kit of Axial Piston Machines. Bath ASME Symposium on Fluid Power and Motion Control (FPMC2010), Bath, UK.

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 or Test Bed 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 or Test Bed 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/Test Bed Description

A. Description and explanation of research approach

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

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

One aim of this project 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 [1-10]. 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 will 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. While most hydraulic control concepts are based on flow control (e.g. via control of valves and pump displacement) [11-14], transformers are in contrast pressure control devices. Therefore, control strategies and methods for analysis can be quite different from the more conventional hydraulic systems.

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

B. Achievements

Achievements in previous years

Comparison of transformer configurations: 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 with respect to size (as measured by overall displacement), flow/pressure ripples and efficiencies. For each configuration, average and piston-by-piston dynamic models have been created. 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 [16-18].

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. Such 'port switching' could be achieved by the addition of two 3-way valves.

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 models of a 19cc IHT with 9 pistons and a 25cc PM transformer with 10 pistons (5 in each unit) configured in 3 different manners (Figs. 1-3) have been developed and used to generate efficiency maps at the input pressure of 200MPa. IHT is predicted to be 3~5% more efficient than the 3 PM transformer configurations. Moreover, each of the 3 PM transformer configurations is found to have its own best efficiency region – 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. This suggests that by allowing switching between PM configurations, a system that is efficient over the whole range of operating transformation ratios can be achieved.

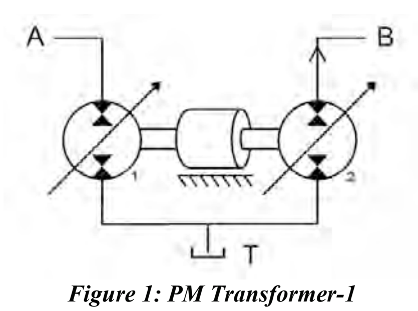


Figure 1: PM Transformer-1 Tank port Shared

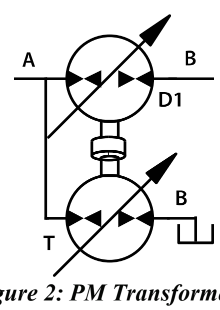


Figure 2: PM Transformer-2 Output Port Shared

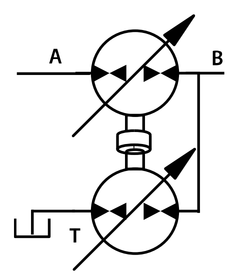


Figure 3: PM Transformer-3 Input Port Shared

Prototype acquisition: It was decided to further study PM transformers with port switching capability because of the sizing and efficiency advantages. To this end, a donation of a manually controlled pump/motor hydraulic transformer prototype (Fig. 6) was obtained from Takako Industries. This device consists of two variable displacement 3.15 cc/rev micropiston P/M units in the traditional pump/motor configuration. Design work was done to modify the prototype to allow for computer control.

Achievements in the past year

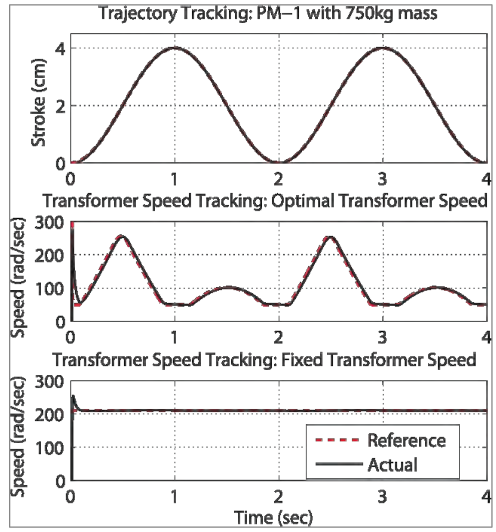


Figure 4: (Top) Cylinder trajectory tracking results (Middle, Bottom) Transformer speed regulation

Trajectory Tracking Control In the past year, a trajectory tracking controller has been developed for a transformer controlled hydraulic actuator. In addition to controlling the actuator trajectory, this controller also regulate the transformer speed at target value. Initially, a backstepping control approach based on quadratic Lyapunov function was taken to meet the flow demand for the actuator pressure dynamics and to regulate the transformer speed at the predetermined value [20]. The controller was later modified to use a passivity based backstepping approach based on a Lyapunov function that is based on natural stored compressible energy [21]. A supervisory control for specifying the transformer speed for the given load condition and minimizes losses has also been developed. Simulated results in Fig. 4 show that the controller is able to achieve trajectory tracking and regulation of the transformer speed. Experimental implementation and testing is currently underway.

Prototype Modification and Efficiency Characterization: The prototype transformer obtained from Takako Industries last year was modified to allow for computerized control of its displacements (Fig. 6). A test bench was constructed and implemented, with solenoid valves configured as shown in Fig. 7-8, to enable switching between the various pump/motor configurations. An operator can also switch between a cylinder, motor, or an orifice load depending on the requirements of the experiment. Baseline efficient maps have also been generated for each transformer configuration of the prototype operating off of a 10.5MPa (1500psi) distribution rail, as shown in figure 5.

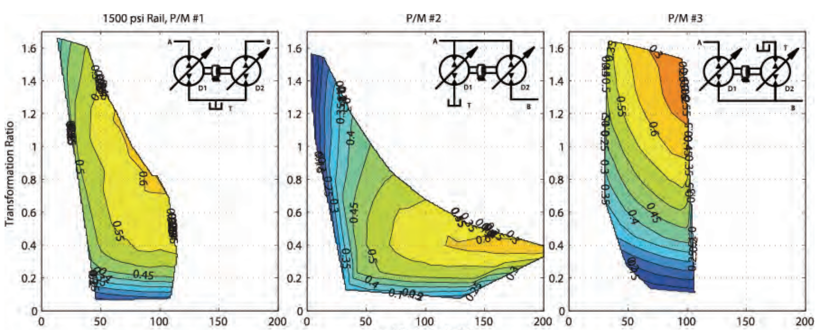


Figure 5: Experimental Efficiency Maps for Prototype

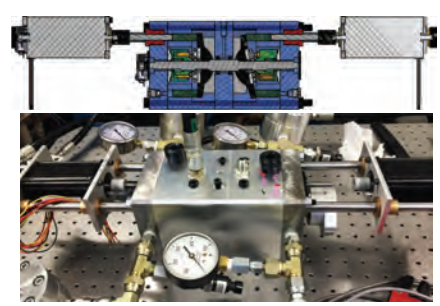


Figure 6: Automated prototype

Fig. 9 shows an open loop test of the prototype transformer switching configurations during operation. It can be observed that switching configurations can rapidly change the output pressure of the transformer, even as the unit's swashplates are held fixed.

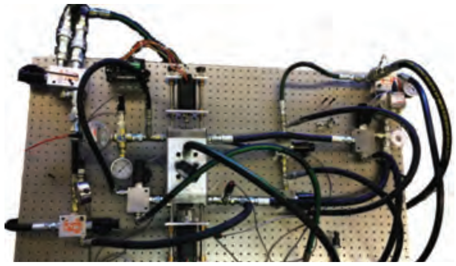


Figure 7: Experiment setup

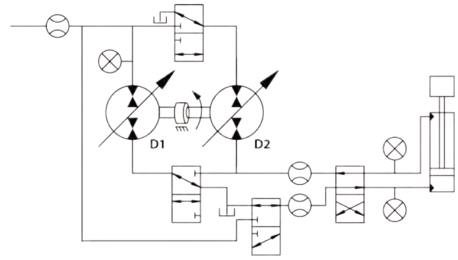


Figure 8: Schematic of experiment setup

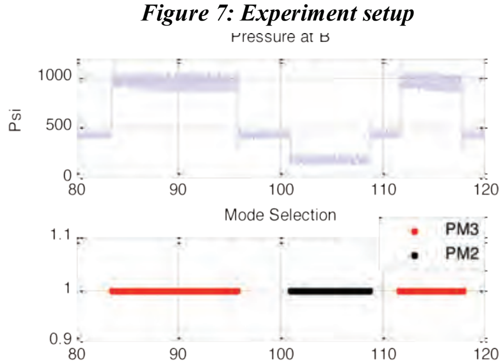


Figure 9: Mode switch in operation

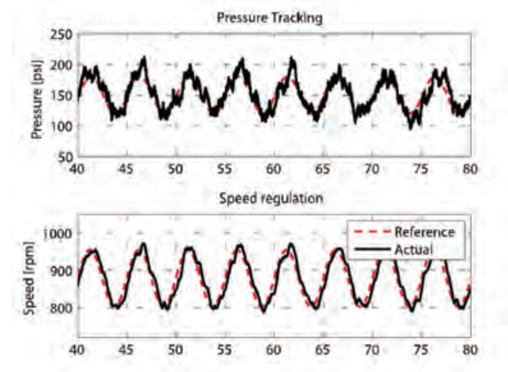


Figure 10: Implementation with orifice

Implementation of the Controller: Initial experimental testing of the trajectory tracking controller has also been performed in the PM-1 configuration (Fig.1). Fig. 10 shows that transformer was able to provide arbitrary output pressure while regulating its speed at arbitrary speed when connected to an orifice load, and Fig. 11 shows cylinder trajectory tracking performance. Implementation with other transformer configurations is underway.

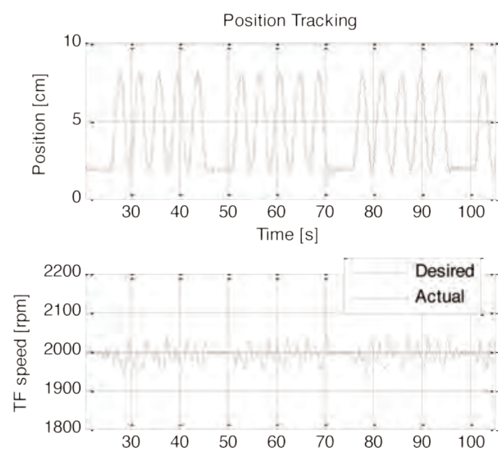


Figure 11: Implementation with Cylinder

C. Plans

Plans for the next year.

Control for Efficiency: Control algorithms will be developed for efficiency of the system in addition to trajectory tracking. One approach is to regulate the transformer operating speed to reduce energy loss in the transformer as with the supervisory control shown earlier. Another approach is to regenerative energy during braking motion (Fig. 12). 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

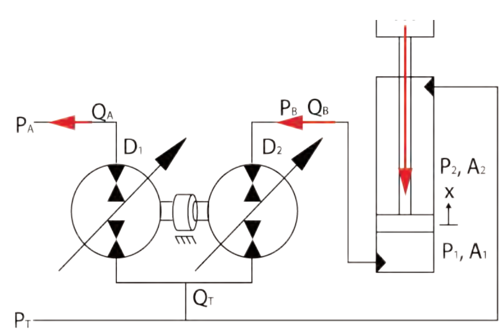


Figure 12: Energy recovery with transformer

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.

Demonstration of Transformer Controlled System: Controllers being developed will be implemented on a human power amplifier device in University of Minnesota (Fig. 13). Initial evaluation of the controller's precision, accuracy, stability, and energy efficiency will be done in this environment. Ultimately, performance of the controller will be demonstrated on TB 4, a patient transfer device at Georgia Tech (Fig. 14).

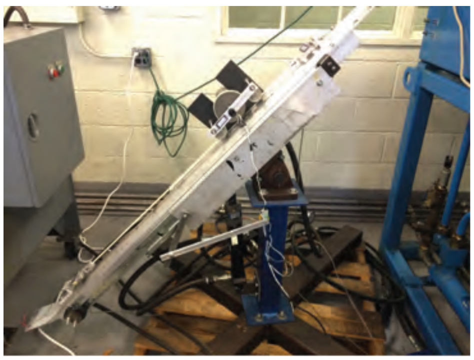


Figure 13: Human Power Amplifier

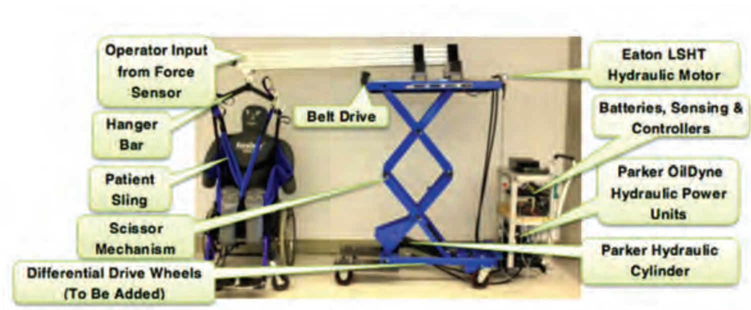


Figure 14: Patient Transfer Device

Expected milestones and deliverables

Results from the exhaustive quantitative comparison study for IHT and PM transformer designs will be published. Control methodologies that ensures not only precision but also efficiency of the system will be developed and implemented on the test setup in University of Minnesota and will be integrated into TB 4 at Georgia Tech.

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.

[1] P. J. Achten, "Pressure Transformer", US Patent #6166139, Sept, 2000.

[2] R. Schaeffer, Hydraulic Transformer, US Patent #6887045, May, 2005.

[3] E. Bishop, Digital Hydraulic Transformer, US Patent Application: 2009/0178399---A1

[4] F.T. Brown, S.C. Tentarelli, and S. Ramachandran, "A hydraulic rotary switched-inertance servo transformer", ASME J. of Dynamic Systems Measurement and Control, 110(2):144-150, 1988.

[5] L. Gu, M.Qiu, B. Jin, and J. Cao, "New hydraulic systems made up of hydraulic power bus and switched mode hydraulic power supplies," Chinese Journal of Mechanical Engineering, vol. 39, no.1, pp.84-88, 2003

[6] M. Jien, X. OuYang and H. Yang. "The CFD Simulation Research on Hydraulic Transformer," Proceedings of the 6th JFPS International Symposium on Fluid Power, Tsukuba, 2005

[7] R. Werndin, J-O Palmberg. "Controller Design for a Hydraulic Transformer" Fluid Power Transmission and Control; Proceedings of the 5th Int. Conference on Fluid Power Transmission and Control, 2001

[8] R. Werndin and J.-O. Palmberg, “Hydraulic Transformers - Comparison of Different Designs,” Proceedings of the 6th Int. Conference on Fluid Power Transmission and Control, 2003

[9] J. Jiang, and C. Liu, "Modeling and Simulation for Pressure Character of the Plate-Inclined Axial Piston Type Hydraulic Transformer," Proceedings of the 2010 IEEE International Conference on Information and Automation. Harbin, China. June, 2010.

[10] Xiaoping Ouyang, “Hydraulic Transformer Research”, PhD Dissertation, Mechatronics and Control Engineering, Zhejiang University, Hangzhou, China, 2005.

[11] P. Y. Li and M. Wang, “Passivity Based Nonlinear Control of Hydraulics Actuators Based On an Euler---Lagrange Formulation”, 2011 ASME Dynamic Systems and Control Conference / Bath Fluid Power and Motion Control Symposium, Washington D.C., 2011.

[12] L. Wang, “Adaptive Control of Variable Displacement Pumps”, PhD dissertation, Mechanical Engineering, Georgia Tech, 2011.

[13] Kugi, A., Nonlinear control based on physical models. No. 260 in Lecture Notes in Control and Information Sciences. Springer, 2000.

[14] Yao, B., Bu, F., Reddy, J., and Chiu, G.,“Adaptive robust motion control of single---rod hydraulic actuators: Theory and experiments”. IEEE/ASME Transactions on Mechatronics, 5(1), March, pp. 79–91, 2000.

[15] P. J. Achten, G. Vael and B. Innas, “Transforming future hydraulics: a new design of a hydraulic transformer.,” *SICFP*, pp. 1–24, 1997.

[16] Noah D. Manring, "The Discharge Flow Ripple of an Axial-Piston Swash-Plate Type Hydrostatic Pump," Transactions of the ASME Vol. 122, June 2000

[17] Jun, Z., and Yi, W., ‘‘Research for pressure and flow pulsating characteristic of swash plate axial piston pump with even pistons,’’ ICFP Symposium, Hangzhou, China, pp. 325 – 327. 1985

[18] J. Bergada, J. Watton and S. Kumar, “Pressure, flow, force and torque between the barrel and port plate in a an axial piston pump”, ASME J. of Dynamic Systems and Control, Vol. 130:1/011011-1, 2008.

[19] David A. Winter, Biomechanics and Motor Control of Human Movement, Fourth Edition. John Wiley & Sons, Inc 2009. ISBN: 978-0-470-39818-0

[20] S. Lee and P. Y. Li, “Transformer control of hydraulic actuator using a backstepping nonlinear controller”, Submitted the 2014 International Symposium on Flexible Automation (ISFA), June 2014.

[21] Li, P. Y., and Wang, M., 2014. “Natural storage function for passivity-based trajectory control of hydraulic actuators”. IEEE/ASME Transactions on Mechatronics, 19(3), July, pp. 1057–1068.

Project 1E.6: High Performance Valve Actuation Systems

Research Team

Project Leader:	John Lumkes, Agricultural & Biological Engineering, Purdue
Other Faculty:	Monika Ivantysynova, ABE/ME, Purdue
	Andrea Vacca, ABE/ME, Purdue
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.

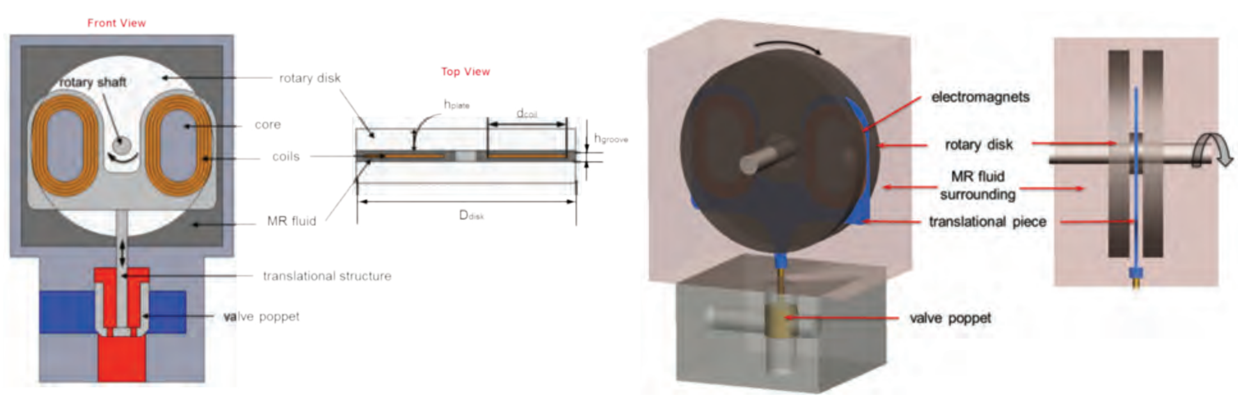
2. Project Role in Support of Strategic Plan

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 concept of a valve actuation mechanism, 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 (Lord, 2011). 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: MR fluid energy coupler actuator valve

The ECAV design has the following advantages:

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

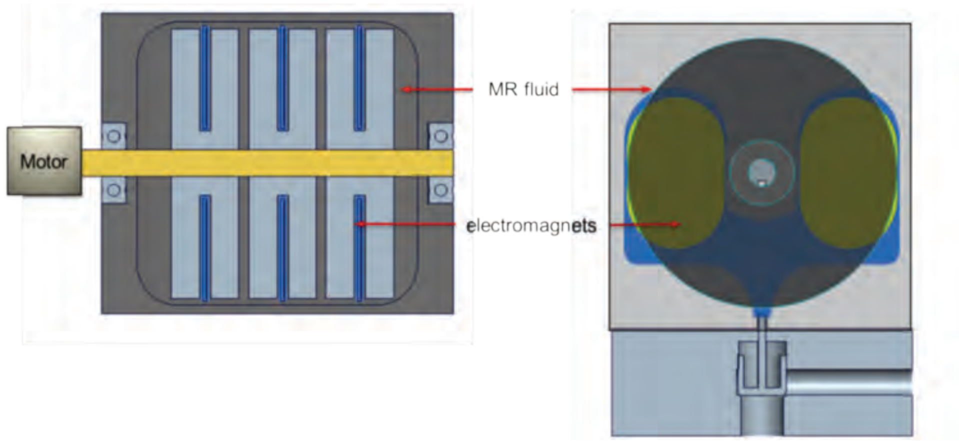


Figure 2: ECAV stack valves configuration

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 implementation of the computer solved models, prototyping and experimentation of the design began to compare 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. Bidirectional capabilities of opening and closing the ECAV were proven successful. Figure 3 shows the achievement of bidirectional capability in the ECAV.

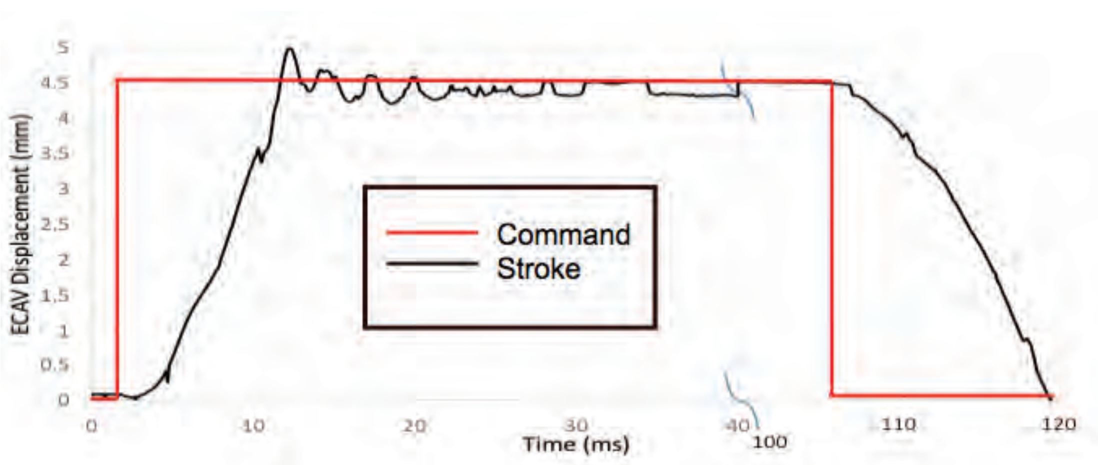


Figure 3: The switch-on, hold, switch-off cycle for the MR fluid ECA

b) Achievements in the Past Year

Tests were conducted to determine the dynamic performance of a prototype MR fluid ECAV. The third generation prototype proved the most successful in experimental testing. This prototype is built upon and utilizes the successful parts off of the previous designs. This translational piece has its coil windings around a 3D printed spool with a steel core to focus the magnetic field in the assembly.

Figure 4 shows a comparison of the measured displacement profile with what was modeled across three different supply voltages of 48V, 72V, and 96V respectively. Simulated results matched the experimental results quite well.

The ECAV response time for 1.5mm stroke (100L/min nominal flow) was predicted to be 2.8ms and the resulting electric energy consumption was evaluated as 1.2J electric power per switch. Also, large displacements up to 7mm can be achieved in 7ms. This demonstrates the significant potential for large stroke high bandwidth actuators.

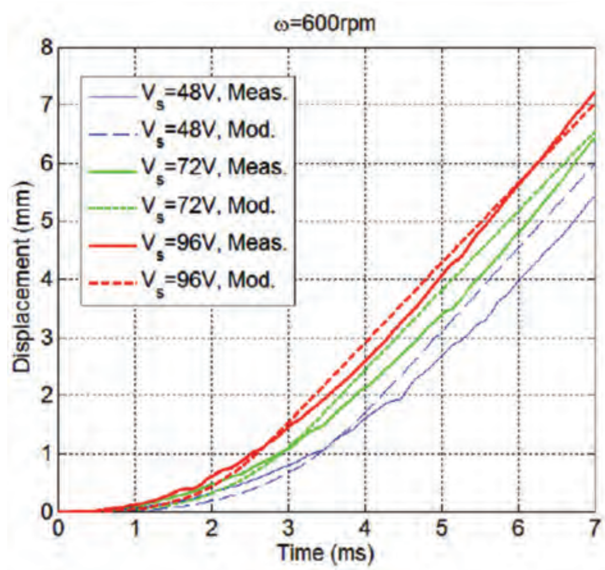


Figure 4: Dynamic Displacement Profile

C. Plans

a) Plans for the Next Year

The proposed work over the next year includes task 1) to develop the bidirectional proportional control algorithms for the Energy Coupler Actuated Valve (ECAV), and task 2) integrate the ECAV with both a poppet and a spool valve body and investigate experimentally the pressure-flow-time performance. These two tasks will be completed concurrently in the first year of the project. The third 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.

b) Expected Milestones and Deliverables

Tasks 1 & 2 will be completed concurrently in the first year of the project. The control algorithms will initially be developed on the existing actuator prototype while the valve poppet and spool, and associated housings, are developed. Task 3 (figure 5) is to develop and test integrated valve units with embedded

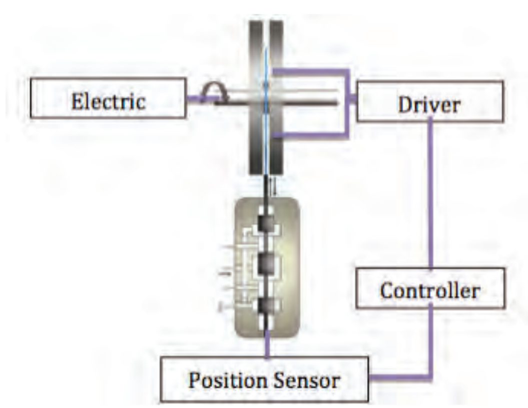


Figure 5: Valve Assembly with embedded sensors

electronics, working towards the goal of incorporating high performance valves into test bed supporting projects like digital pump/motors, control of swash plate displacement, and for enabling new energy storage configurations (Linjama & Huhtala, 2010). Another outcome of task 3 and possible application is the integration of the ECAV on the digital pump/motor test stand, as shown in Figure 6. This would provide a great multi-valve testing platform while improving the overall efficiency, controllability, and operating envelope of the digital pump/motor.

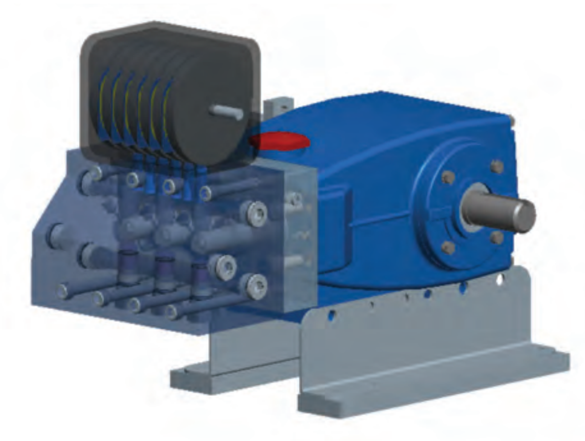


Figure 6: ECAV Digital Pump/Motor Concept

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

E. References

Linjama, M., and Huhtala, K. 2010. “Digital Hydraulic Power Management System – Toward Lossless Hydraulics”. The Third Workshop on Digital Fluid Power, October 13-14, 2010, Tampere, Finland.

LORD Corporation 2011. MRF-132DG Magneto-Rheological Fluid

Project 1F.1: Variable Displacement Gear Machine

Research Team
Project Leader: Andrea Vacca, Department of Agricultural & Biological Engineering and School of Mechanical Engineering, Purdue University
Graduate Student: Ram Sudarsan Devendran (PhD Student)
Undergraduate Student: Marlon Baez

1. Statement of Project Goals

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

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

2. Project's Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

The well-known advantages of external gear machines (EGMs) such as low cost, compactness, reasonable operating efficiency and good reliability make them as one of the prominently used components in fluid power. Despite these advantages, EGMs are fixed displacement and they cannot be used as primary energy conversion units in modern energy efficient layout configurations based on variable flow supplies, such as in load sensing systems, hydrostatic transmissions or in displacement controlled systems [1, 2].

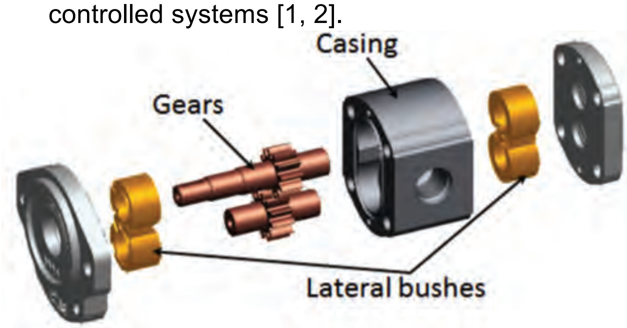


Figure 1: Parts of an external gear machine

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

The proposed solution for VD-EGM

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.

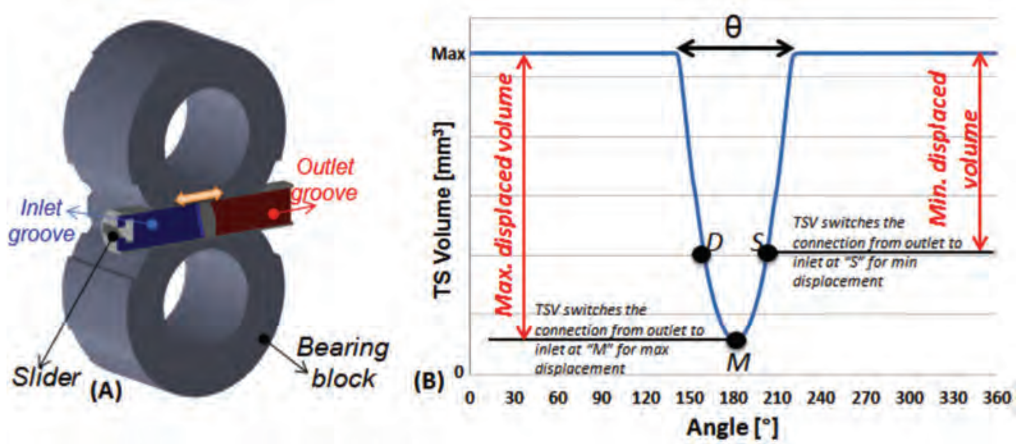


Figure 2: (A) Slider placed within the bearing block of the VD-EGM (B) The progression of TSV as a function of shaft angle. The meshing process realized the displacing action in the angular interval θ, for a portion of the meshing process (between D-S), the volume is trapped between points of contacts.

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.

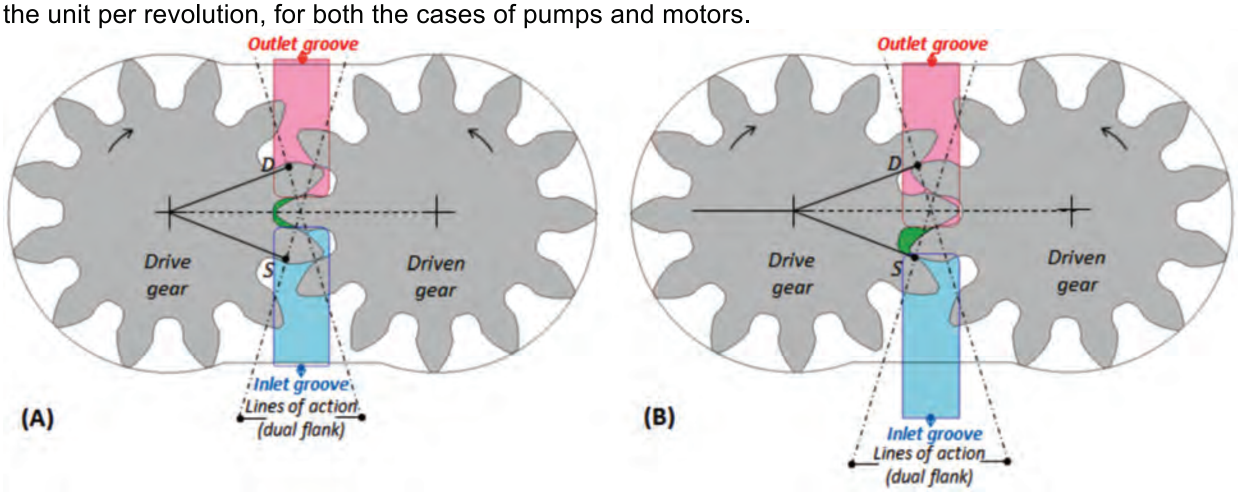


Figure 1: (A) Position of the slier to achieve maximum displacement
(B) Position of the slider to achieve minimum displacement

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.

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. The Omni-comprehensive tool called 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.
2. A state of the gear generator capable of designing asymmetric gears was developed along with a lateral bushings generator [13]. These models were successfully integrated into HYGESIM-Geometrical model to calculate the different features necessary for the simulation of the VD-EGM.
3. A multi-level-multi-objective genetic algorithm based optimization workflow was generated for the simultaneous optimization of the design of asymmetric gears and grooves in the slider. The workflow used HYGESIM at its crux to evaluate the performance of the machine based of several different objective functions such as: 1) Maximize the reduction in displacement 2) Minimize pressure pulsations, 3) Minimize internal pressure peaks and localized cavitation effects and 4) Maximize volumetric efficiency. 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. Preliminary proof of concept tests for the VD-EGM was performed by prototyping the gears using wire electric discharge machining. For the proof of concept, the grooves for max and min displacement were directly machined on two different pairs of lateral bushing. Tests were performed first of the configuration of the optimal gears with the corresponding lateral bushings for max displacement. Followed by switching the lateral bushings for max displacement with those for min displacement. 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].

Achievements during the reporting period:

Started from summer 2013, the research has made significant progress in addressing the research objectives (O1 and O2).

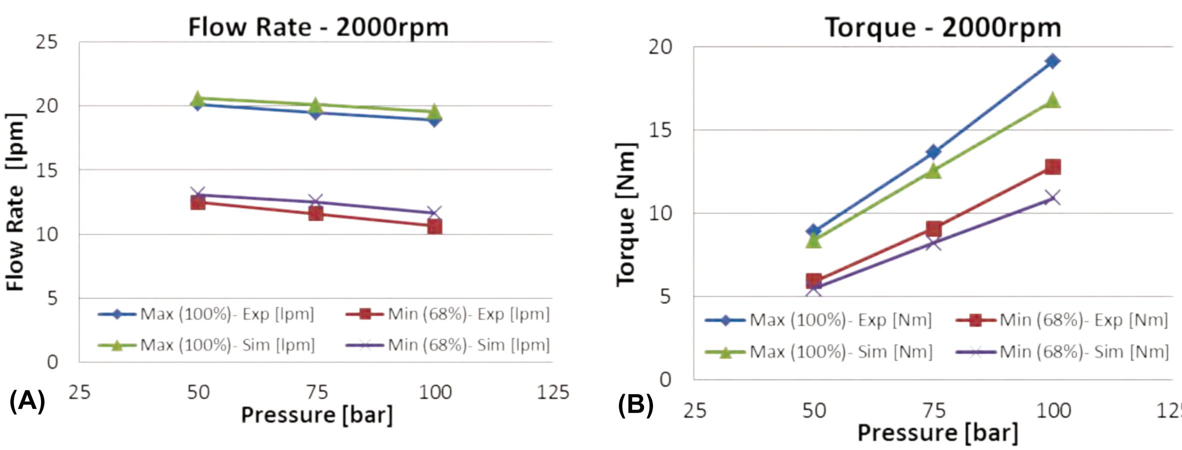


Figure 4: (A) Validation of delivered flow rate for VD-EGM with proof of concept
(B) Validation of input shaft torque for VD-EGM with proof of concept

1. *Validation of HYGESIM model with proof of concept tests*: The results of the simulation tool HYGESIM for VD-EGM was successfully validated with respect to the proof of concept tests.

It can be seen from Figure 4(A) that the flow rate proportionally (68%) reduces at min displacement as compared to those at full or max. displacement. A good agreement between simulated data and measurements can be observed from the figure. Figure 4(B) represents the input shaft torque validation. It can be seen that the input shaft reduces proportionally at min displacement. It can be seen that the input shaft reduces proportionally at min displacement. Approximately 32% reduction in torque is obtained at all the operating conditions tested for min displacement. The lower input shaft torque required reflects on the lower energy consumption at min. displacement, thus supporting the viability of a VD-EGM.

The validations for volumetric efficiency are reported in Figure 5(A). It can be noticed that the volumetric performance at max displacement, as shown by the orange curve matches very closely to that of the reference design. It can also be seen that the vol. efficiency at min displacement is lower than that at max displacement. This can be explained to due to the fact that the internal leakages are greatly dependent on the delivery pressure and hence they have a larger influence on efficiency at lower displacement. The trends of simulated volumetric efficiency at min. displacement matches pretty closely to that of the measured values, thereby purporting the capabilities of HYGESim to predict the performance of the VD-EGM at varying levels of displacement. The validation for delivery pressure ripple is shown in Figure 5(B). It can be seen that in all the conditions, the ripple at max displacement is much lower than that of the reference. Also for min displacement, the ripple is comparable to that of the reference. Hence it is expected that at max displacement, the VD-EGM will perform with very low noise emissions, however at min displacement, the VD-EGM will perform at a higher ripple/noise as compared to max displacement but still within acceptable limits as offered by the reference commercial design.

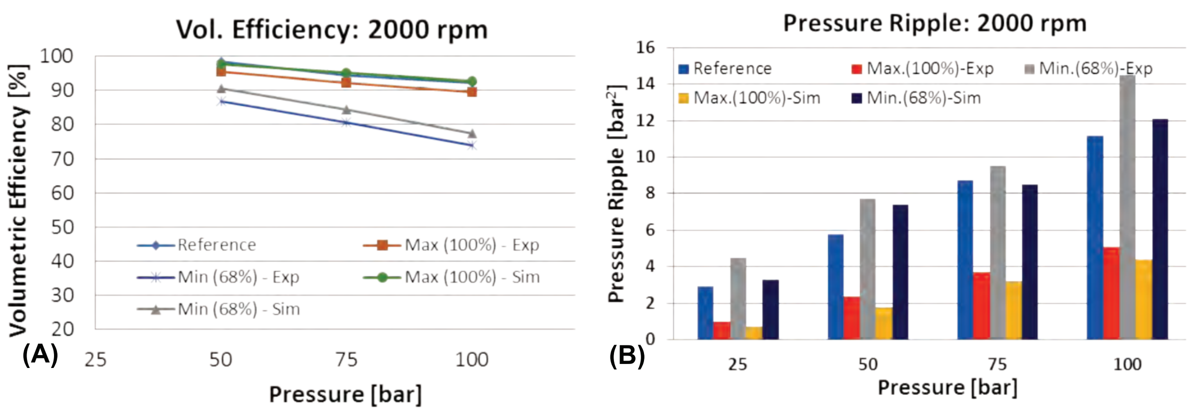


Figure 5: (A) Validation of vol. efficiency for VD-EGM with proof of concept
(B) Validation of delivery pressure ripple for VD-EGM with proof of concept

2. *Prototype Design:* The working idea for idea for the pressure compensated design for VD-EGM can be explained using Figure 6(A). The asymmetric gears are placed inside the casing which has inlet and the outlet ports on the rear flange of the pump. The particular kind of design with ports on the flange allows more room for the placement of additional parts of the actuation system. The high pressure and low pressure regions are represented by HP and LP. The grooves are machined on a movable slider as shown and it is connected with the help of a connecting rod to the spring. The preset pressure in the spring can be adjusted by the bolt which is seen outside the casing.

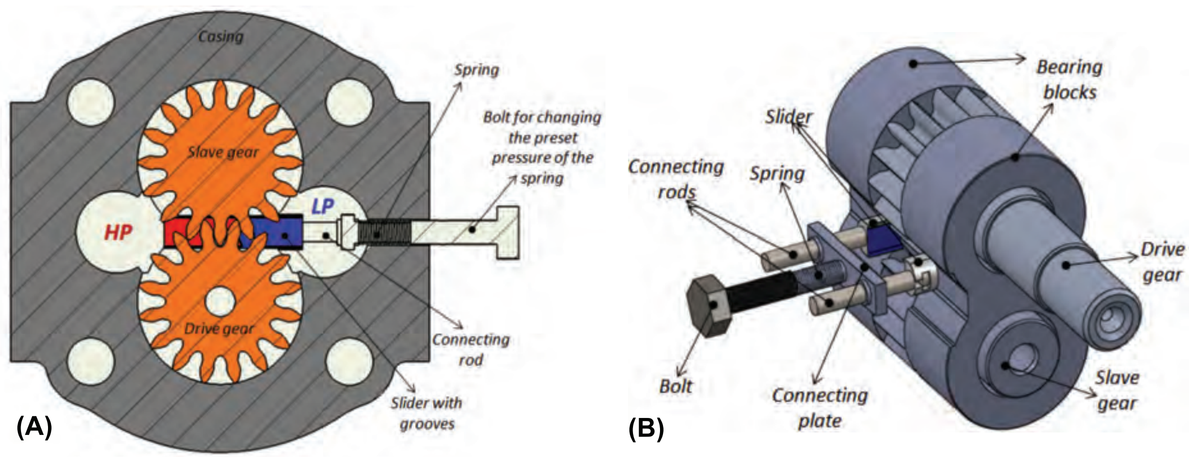


Figure 6: (A) Principle of pressure compensated design for VD-EGM (B) Internal parts of the pressure compensated design

The fluid at HP acts on the left of the slider and on the right the spring force corresponding to its compressed length on the right. Since the slider is movable a balance of forces is achieved on the slider and an equilibrium position of the slider is obtained according to the pressure at the HP and the pre-set spring force. In this way an automatic variation of the displacement can be achieved. The final assembly of the pressure compensated VD-EGM is shown in Figure 6(B).

Planned achievements following the report period

- Deliverables:
  - Prototyping of the actuation system (manual and pressure compensated) for changing the displacement in the proposed VD-EGM design. (May 2015)
  - Testing of VD-EGM prototype and model validation (July 2015)
  - Possible integration in TB.1 - fan drive system (August 2015)
  - Extension of the research to parametric unconventional multi involute profiles (August 2015)
  - Drawings and simulation model for the optimal solution with unconventional multi involute profiles (October 2015)
  - Simulation results purporting the benefits of unconventional designs over standard designs (December 2015)

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

D. References

[1] P. Krus, 1988, *On Load Sensing Systems with Special Reference to Dynamic Properties and Control Aspects*. Linköping Studies in Science and Technology. Dissertations. No. 198

[2] M. Ivantysynova, 1998. *Pump Controlled Actuator - a Realistic Alternative for Heavy Duty Manipulators and Robots*. International Scientific Forum in Fluid Power Control of Machinery and Manipulators, Cracow, Fluid Power Net Publication (2000), chapter 5, pp. 101 – 123.

[3] Tomlinson, S. P., Burrows, C. R., 1992, *Achieving a Variable Flow Supply by Controlled Unloading of a Fixed- Displacement Pump*, ASME Journal of Dynamic Systems Measurement and Control, vol. 114, no. 1, pp. 166-171.

[4] Yang D., Zhong D., 1987, *Radial-Movable Variable Displacement Gear Pump (Motor)*, CN85109203.

[5] Reiners W., Wiggermann G., 1960, *Variable Delivery Gear Pumps*, The Patent Office London, GB968998.

[6] Winmill L.F., 2001, *Adjustable-Displacement Gear Pump*, Patent Application Publication, US2001024618.

[7] Bussi E., 1992, *Variable Delivery Gear Pump*, European Patent Application, EP0478514.

[8] Hoji T., Nagao S., Shinozaki K., 2008, *Gear Pump*, Patent Application Publication, US2008044308.

[9] Clarke J.M., 2002, *Hydraulic transformer using a pair of variable displacement gear pumps*, Patent Application Publication, US2002104313.

[10] Ikeda J., 2002, *Variable Displacement Gear Pump*, JP2002106479.

[11] Svenson E.J., 1930, *Adjustable Displacement Gear Pump*, United States Patent Office, US1912737.

[12] Vacca A., Guidetti M., 2011, *Modelling and experimental validation of external spur gear machines for fluid power applications*. Simulation and Modeling Practice and Theory, 19, 2011.

[13] Devendran, R.S., Vacca, A., 2014, *A Novel Design Concept for Variable Delivery Flow External Gear Pumps and Motors*, International Journal of Fluid Power, 15:3, pg. 121-137

Project 1G.1: Energy Efficient Fluids

Research Team
Project Leader: Paul Michael, Milwaukee School of Engineering (MSOE)
Graduate Students: Shreya Mettakadapa, Shima Shahahmadi, MSOE
Undergraduate Student: Bobby Draeger, MSOE
University Partners: Scott Bair, Georgia Institute of Technology
Tom Chase, University of Minnesota
Industrial Partners: Afton Chemical, Danfoss, Evonik, Idemitsu Lubricants, Gates, Lubrizol, Parker Hannifin, Poclain Hydraulics

1. Statement of Project Goals

The goal of this project is to bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power systems. This goal is being pursued by characterizing hydraulic fluids in benchtop instruments, analyzing fluid efficiency effects in a hydraulic dynamometer, and modeling fluid-component interactions. Improvements in the bulk modulus, boundary friction, and shear stability properties of fluids 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 realized, gaps remain with respect to understanding the relationship between efficiency and the properties of the hydraulic fluids.

2. Project Role in Support of Strategic Plan

This project will increase system efficiency by advancing hydraulic fluid technology. The CCEFP has identified system efficiency as a major technical barrier that must be overcome to achieve the test bed performance objectives. Increased system efficiency also makes possible the use of smaller, more compact valves, pumps, and motors. This project, which incorporates the high-pressure research in project 3D.2, was used to guide the formulation of a hydraulic fluid that improved the low-speed mechanical efficiency properties of the test fluid for the hydraulic hybrid vehicle test bed (TB3).

3. Project Description

A. Description and Explanation of Research Approach

This project seeks to improve the efficiency of hydraulic systems by studying how fluid properties impact hydraulic component performance. In hydraulic pumps, viscosity modifiers (VM) have been found to reduce leakage flow losses. [1] Resistance to permanent viscosity loss due to shear has been identified as a key requirement. [2] However the impact of non-Newtonian viscosity behavior on system efficiency is not well understood. In this project, a hydraulic dynamometer and fundamental fluid property characterizations will be used to develop models for the rational design 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. [3, 4] 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. [5] Models for the relationship between hydraulic motor efficiency and Stribeck number were developed that are of the Michaelis-Menten chemical kinetics form. [6] 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

Fluid Property Evaluations

The high-pressure viscosity, shear stability, traction and bulk modulus properties of the following fluids were evaluated:

- HM46 straight-grade mineral oil
- HV46 high VI mineral oil
- HEES46 synthetic ester
- HBMO46 high bulk modulus fluid

The bulk modulus was determined by Professor Bair of Georgia Tech using a metal bellows pressure vessel. The change in relative volume was measured at 20^0, 50^0, 80^0C and pressures up to 3,000 bar (43,500 psi). These measurements were used to determine pressure and temperature rate of change parameters for use in the Tait equation of state. As shown in Figure 1, the bulk moduli of the HM46, HV46 and HEES46 fluids were approximately 25% lower than that of the HBMO46.

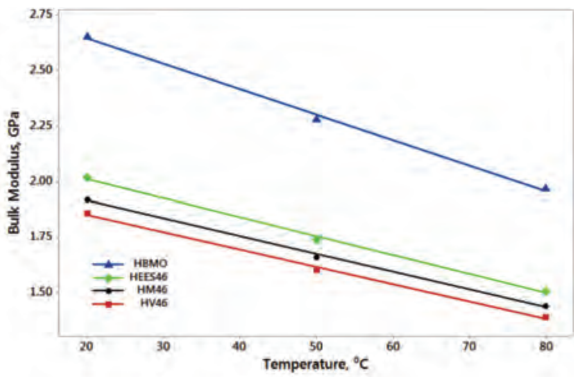


***Figure 1:** Bulk modulus at 250 Bar and 20, 50 and 80^0C. Bulk modulus showed a strong correlation with pump leakage flow rates.*

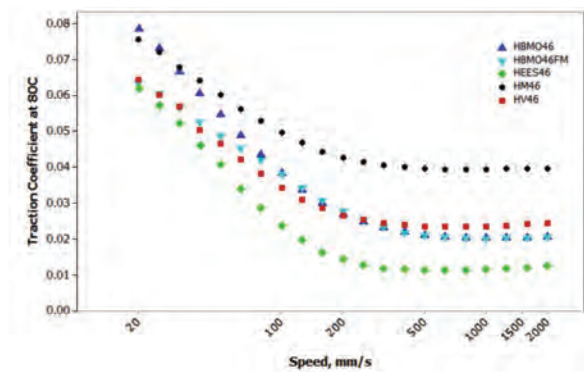


***Figure 2:** Traction coefficient measurements at 50N, 80^0C and 20% SRR. Traction coefficient showed a strong correlation with the low speed mechanical efficiency of hydraulic motors.*

Traction curves were generated using a ball-on-disk tribometer at 50^0, 80^0, 125^0 C with an applied load of 50 N and a 20% slide-to-roll ratio. The test specimens were ANSI 52100 steel and the contact pressure was approximately 1 GPa. As shown in Figure 2, the traction coefficients of HEES46, HBMO46FM and HV46 were approximately 20% lower than that of HM46 and HBMO46.

Efficiency Testing

Pump leakage flow and motor mechanical efficiency measurements were collected in a hydraulic dynamometer at the MSOE Fluid Power Institute. The circuit incorporated a Danfoss Series 45 open-loop variable-displacement axial piston pump. The pump inlet temperature was maintained at 50 and 80^0C ($\pm 1^0$). Pump displacement was controlled by a remote proportional electrohydraulic valve. The combined case drain and compensator flow rates are shown in Figure 3. The HBMO46 and HBMO46FM fluids reduced parasitic pump flow losses by approximately 20%. These findings are significant because reducing flow losses in pumps can improve system efficiency by mitigating the heat load.

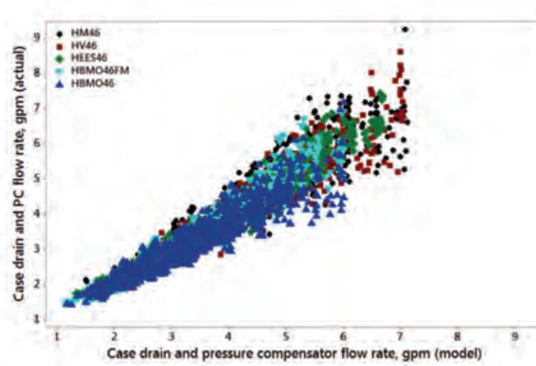


***Figure 5:** Comparison of actual and modelled case drain and pressure compensator flow losses. Modelling results indicate that pump flow losses are affected by the bulk modulus, density, and pressure-viscosity. Model error 0.335 gpm, 5790 data points.*

Torque losses for the radial piston motor are shown in Figure 4. At low speeds (<12 rpm), the losses for the HM46, HV46 and HBMO46 were relatively high while the losses for the HEES46 and HBMO46FM were relatively low. At higher speeds (>12 rpm) torque losses were similar for all of the fluids. Reducing low speed torque losses in motors can improve system efficiency by increasing the power available to engage the payload.

Modeling

Experimentally validated models for pump leakage flow and motor torque losses based upon hydraulic system operating conditions and fluid properties have been developed. The model for relating pump flow losses to fluid properties was developed through an extension of earlier work by Jeong. [7] The leakage flow model incorporated terms for laminar, turbulent, and compressibility flow losses. Step-wise regression was used to maximize model accuracy and minimize the number of variables. It was found that the low shear rate dynamic pressure viscosity was a better predictor of laminar flow losses than the ASTM D5621 test method for sonic shear stability of hydraulic fluid. Further work is required to determine if this is due to the high viscosity stability of the prototype fluids. A comparison of experimental and modeling results is shown in Figure 5.

A model that relates radial piston motor efficiency to fluid properties was developed by Reynolds. [8] The model incorporates a geometric and kinematic analysis of the cam, roller, and piston interfaces. The friction losses shown in Figure 6 were estimated from traction measurements shown in figure 2. While this approach generated a larger mean standard error than the Michaelis-Menten based efficiency equations, this model permits a direct estimate of friction losses based upon traction curve measurements.

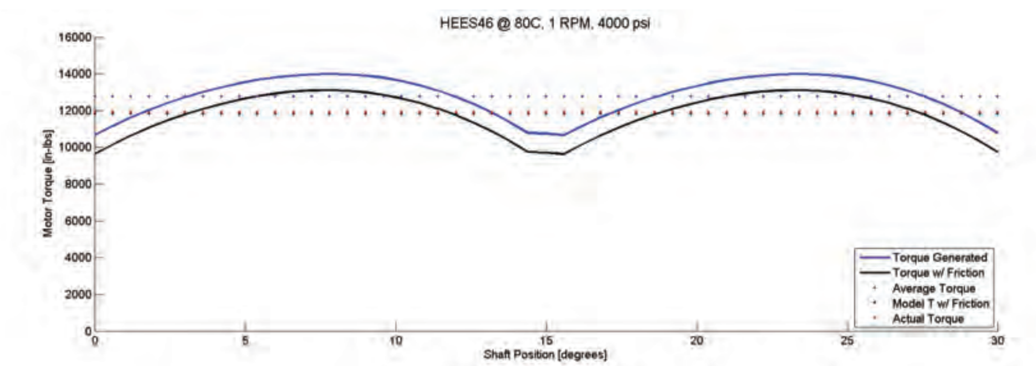


Figure 6: Torque ripple in radial piston motor over 30-degrees of rotation due to cam, roller and piston interactions.

Plans

The near-term objective of project 1G.1 is to investigate the relationship between the shear-dependent viscosity characteristics of fluids and hydraulic component efficiency. Prior investigations have focused on boundary lubrication, friction modifiers, synthetic base stocks and highly shear-stable fluids. In the coming year, extended testing of mineral oil based fluids formulated with low and high shear-stability is planned. Viscosity properties will be characterized through a wide range of shear rates to determine the appropriate conditions for modeling the efficiency of multi-grade hydraulic oils with assistance of Professor Bair.

Plans for the next year

- Task 1: Formulate high and low shear stability multi-grade hydraulic fluids.
- Task 2: Evaluate the shear rate dependence of viscosity using several methods (Sonic, KRL, HTHS)

- Task 3: Evaluated the efficiency of the above hydraulic fluids via dynamometer testing
- Task 4: Expand and combine fluid-effects model for pump and motor.

Expected milestones and deliverables.

- Complete fluid formulations [Q1 2015]
- Complete shear dependent viscosity studies [Q3 2015]
- Complete efficiency testing [Q1 2016]
- Complete modeling effort [Q2 2016]

C. Member Company Benefits

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

D. References

[1] Herzog, S. Zink, M. and Michael, P. "Hydraulic Fluid Viscosity Selection for Improved Fuel Economy," SAE Journal of Commercial Vehicles, 2(2): 61-65 (2009)

[2] Schober, B. and Schiferl, E., "How Shear Testing Relates to the Shear of Hydraulic Fluids in Actual Use," 68th Annual Meeting of the Society of Tribologists and Lubrication Engineers, Detroit, (2013)

[3] Michael, P. Wanke, T. Devlin, M. et.al. "An Investigation of Hydraulic Fluid Properties and Low-Speed Motor Efficiency," Proceedings of the 7th International Fluid Power Conference, Aachen, Germany, Vol. 3, pp. 341-353 (2010)

[4] Michael, P. Garcia, J.M., Bair, S., Devlin, M.T. Martini, A. "Lubricant Chemistry and Rheology Effects on Hydraulic Motor Starting Efficiency," Tribology Transactions, 55: 549-557 (2012)

[5] Miller, M.K. Khalid, H. Michael, P. Guevremont, J.M. Garelick, K.J. Pollard, G.W. Whitworth, A.J., and Devlin, M.T. "An Investigation of Hydraulic Motor Efficiency and Tribological Surface Properties," Tribology Transactions, 57: 622-630 (2014)

[6] Khalid, H., "An Investigation of Hydraulic Motor Efficiency through Stribeck Analysis," TLT, 70:1, 20-23, (2014)

[7] Jeong, H-S., "A Novel Performance Model Given by the Physical Dimensions of Hydraulic Axial Piston Motors: Model Derivation," Journal of Mechanical Science and Technology, 21:1, 83-97, (2007)

[8] Reynolds, C.L., "An Investigation of the Low Speed Operation and Efficiency Effects of Oil within a Radial Piston Hydraulic Motor," Report submitted to the faculty of Milwaukee School of Engineering in partial fulfilment of the requirements for the degree of Masters of Science in Engineering, (2014)

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

Research Team

Project Leader:	Randy Ewoldt, Mechanical Science and Engineering, UIUC
Other Faculty:	James Allison, Industrial and Enterprise Systems Engineering, UIUC
	William King, Mechanical Science and Engineering, UIUC
Graduate Students:	Jonathon Schuh, Mechanical Science and Engineering, UIUC
	Lakshmi Rao, Industrial and Enterprise Systems Engineering, UIUC

1. 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 test beds.

2. 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 test beds.

3. Project Description

A. 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 [2-5]. 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 α 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.

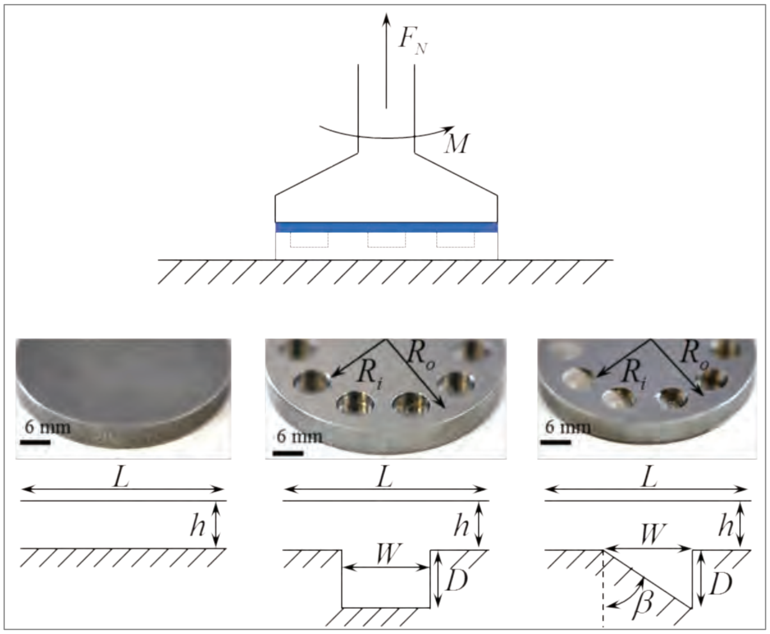


Figure 1: Schematic of experimental setup (modified rotational rheometer) and the three types of textures tested (flat, symmetric, and asymmetric). F_N is the measured normal force and M is the measured torque. The top plate rotates in both directions in order to determine directional-dependent effects.

B. Achievements

Achievements in previous years

This is the first year of this project. However, it builds off of work performed in a previously funded CCEFP project, Project 1D. That work previously developed a novel gap controlled tribo-rheometer, which was fundamental in developing our current experimental setup. It also showed experimentally and numerically that using symmetric surface textures can decrease viscous friction with Newtonian fluids compared to a flat plate reference.

Achievements in the past year

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.

In the past year, we experimentally measured the viscous friction reduction and normal force production for a flat plate, a symmetric texture, and two asymmetric textures with Newtonian and non-Newtonian fluids. Our observations with asymmetric textures, and with non-Newtonian fluids, are both new to the field. We have confirmed, with well-controlled texture profiles, that surface textures can decrease viscous friction from the flat plate reference. We observed enhanced reduction with deeper (larger volume) textures. We have also shown that symmetric textures with Newtonian fluids produce forces that are barely above the experimental resolution for our experimental setup. In contrast, asymmetric textures produce forces that are much larger. The sign of the normal forces are direction dependent for the asymmetric textures, and the magnitude of the force depends on the asymmetry angle β in a non-monotonic way. This suggests that there is an optimal asymmetry angle β for producing normal forces with textures and Newtonian fluids. We have also achieved measurements with non-Newtonian viscoelastic fluids (dilute polymer solutions) with both symmetric and asymmetric textures. The largest normal forces are observed with the combination of viscoelastic (normal stress) effects and asymmetric textures.

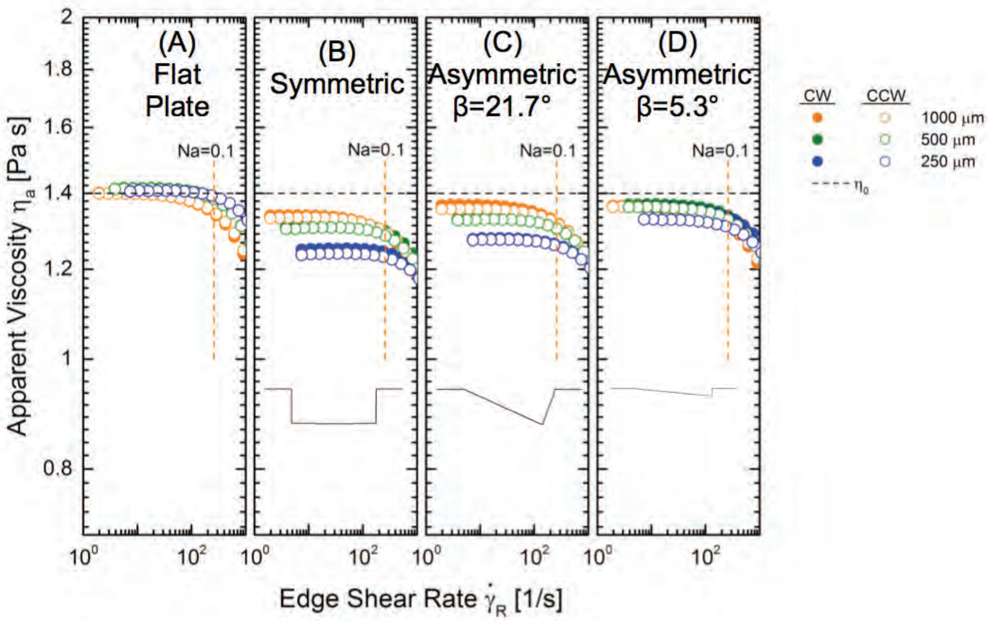


Figure 2: Experimental torque measurement of high viscosity oil standard S600. (A) flat plate; (B) symmetric texture; (C) asymmetric texture with β=21.7°; (D) asymmetric texture with β=5.3°. CW denotes clockwise spin of the upper flat plate (c.f. Figure 1), and gives step contraction for the asymmetric textures. CCW denotes counter clockwise spin, and gives step expansion for linear slope depth. Viscous heating is seen at the highest shear rates when the dimensionless group (the Nahme number) is approximately

$$Na = \frac{U^2}{\kappa}\frac{\partial \eta}{\partial T} > 0.1.$$

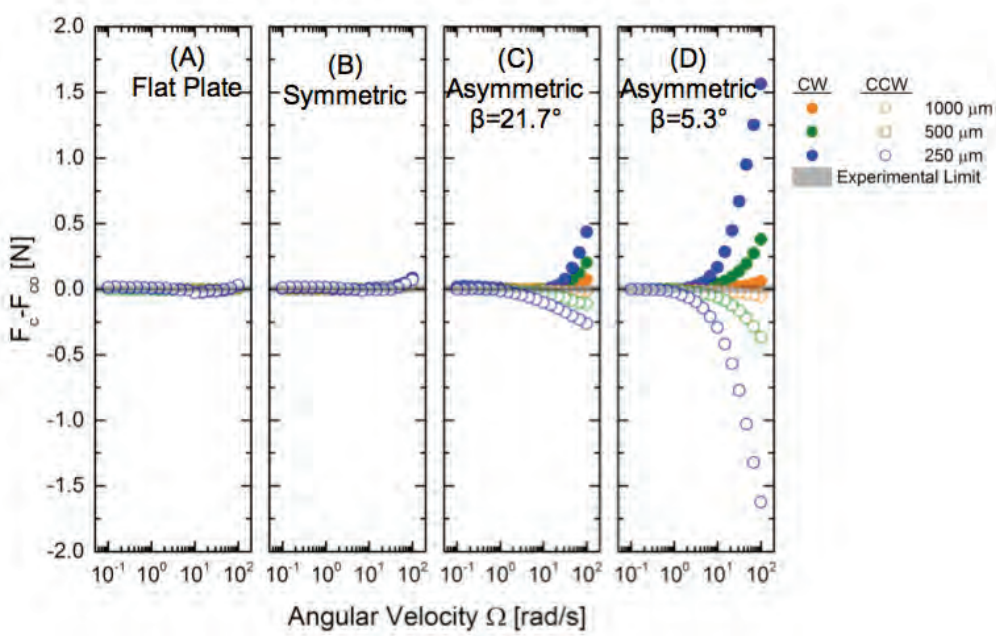


Figure 3: Experimental normal forces measured using high viscosity standard S600. The forces have been corrected for inertia and surface tension effects. Non-parallelism was minimized in the experimental set up. (A) flat plate; (B) symmetric texture; (C) asymmetric texture with β=21.7°; (D) asymmetric texture with β=5.3°. CW denotes clockwise spin, and gives step contraction for the asymmetric textures. CCW denotes counter clockwise spin, and gives step expansion for the asymmetric textures.

C. Plans

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

Since we have shown that an optimal value of β exists for producing normal forces with asymmetric textures, the next step will be to manufacture more asymmetric textures with varying asymmetry angle β values and experimentally testing them with Newtonian fluids. From this experimental data, the optimal value of β can be determined. Numerical work will also be performed and compared to the experimental work in order validate the numerical method and numerically determine the optimal β value, and we will pursue design optimization routines for identifying optimal texture profiles and fluid properties. Finally, experimental work will be performed with Non-Newtonian fluids in order to determine how the combined effects of surface textures and Non-Newtonian fluids compare to the base results of surface textures and Newtonian fluids.

<u>Expected milestones and deliverables</u>

In the next year, we will deliver the optimal value of β for the asymmetric textures. We will also deliver experimental results with viscoelastic Non-Newtonian fluids and surface textures to show the interactions between surface textures and Non-Newtonian fluids, and how these interactions can decrease friction for fluid power systems.

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.

E. References

[1] R. H. Ewoldt, "Extremely Soft: Design with Rheologically Complex Fluids," *Soft Robotics*, vol. 1, pp. 12-20, 2013.

[2] P. Andersson et al., "Microlubrication effect by laser-textured steel surfaces," *Wear*, vol. 262, no. 3-4, pp. 369-379, 2007.

[3] H.L. Costa and I.M. Hutchings, "Hydrodynamic lubrication of textured steel surfaces under reciprocating sliding conditions," *Tribology International*, vol. 40, no. 8, pp. 1227-1238, 2007.

[4] U. Pettersson and S. Jacobsen, "Influence of surface texture on boundary lubricated sliding contacts," *Tribology International*, vol. 36, no. 11, pp. 857-864, 2003.

[5] U. Pettersson and S. Jacobsen, "Textured surfaces for improved lubrication at high pressure and low sliding speed of roller/piston in hydraulic motors," *Tribology International*, vol. 40, no. 2, pp. 355-359, 2007.

[6] S.J. Hupp and D.P. Hart, "Quantifying the effect of lubricant elasticity on micro textured surfaces," *Proceedings of the World Tribology Congress III*, pp. WTC2005-64047, 2005.

[7] S. Kango, R.K. Sharma, and R.K. Pandey, "Thermal analysis of microtextured journal bearing using Non-Newtonian rheology of lubricant and JFO boundary conditions," *Tribology International*, vol. 69, pp. 19-29, 2014.

Project 1J.1: Hydraulic Transmissions for Wind Power

Research Team

Project Leader:	Kim Stelson, Department of Mechanical Engineering, University of Minnesota
Other Researchers:	Mike Gust, University of Minnesota
	Brad Bohlmann, University of Minnesota
Post Doc:	Feng Wang, University of Minnesota
Graduate Students:	Biswaranjan Mohanty, University of Minnesota
	Rahul Dutta, University of Minnesota
Undergraduate Students:	Becca Trietch, Yale University
Industrial Partners:	Bosch Rexroth, Sauer-Danfoss, Linde, Eaton, Clipper Windpower

1. Statement of Project Goals

Wind power is a plentiful, renewable source of energy, able to produce emission-free power in the kilowatt to megawatt range. The US Department of Energy has a goal of having 20% of the nation's energy come from wind by 2030. Land-based or off-shore wind farms can provide wind energy to the grid. However, 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. 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.

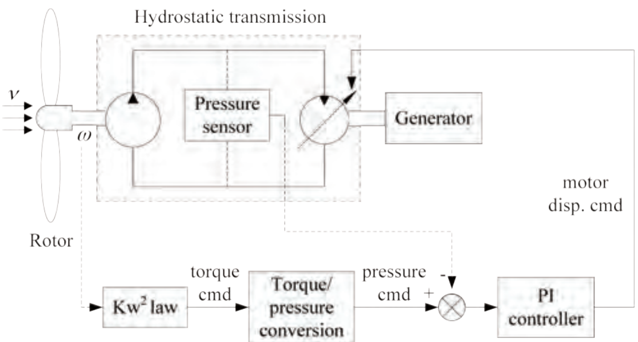
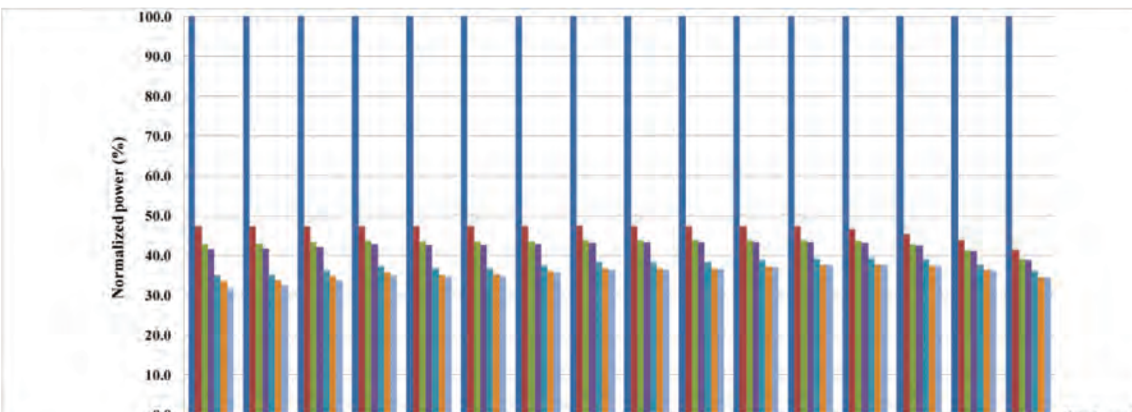


Figure 1: Control schematic of a hydrostatic wind turbine

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. 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.

Short-term energy storage for mid-size hydrostatic wind turbine

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). The working region of the short-term energy storage is the transition region between region 2 and 3.

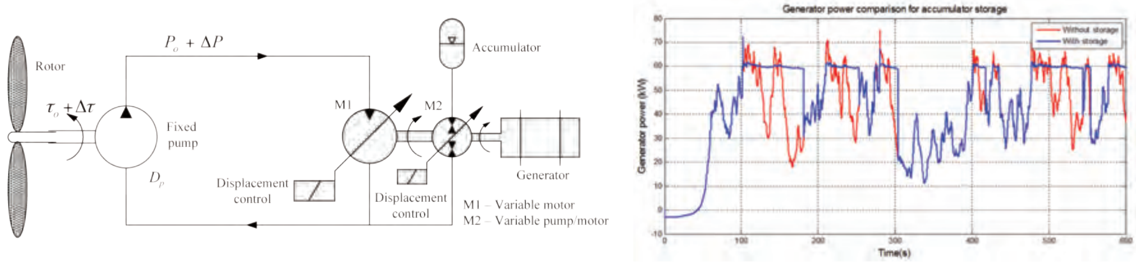


Figure 3: Short-term energy storage for hydrostatic wind turbine

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%.

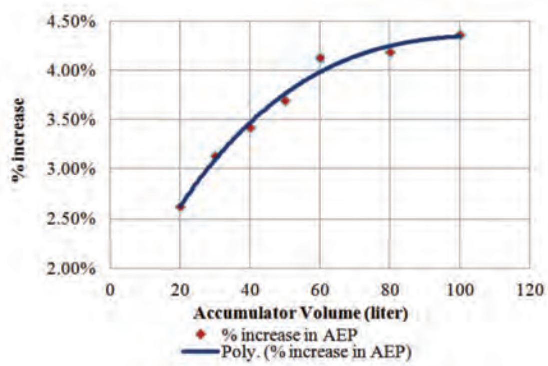


Figure 4: Sensitivity study of accumulator size on turbine AEP

<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. 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.

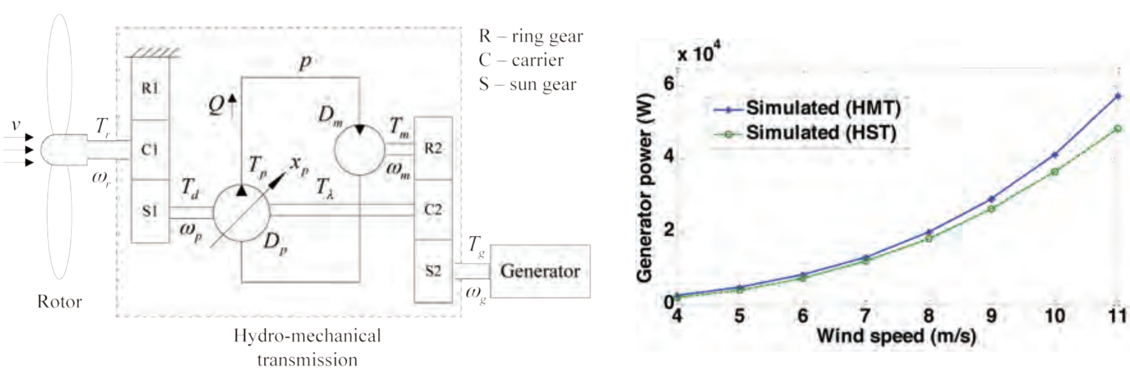


Figure 5: Hydro-mechanical transmission for mid-size wind turbine

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>Hardware-in-the-loop (HIL) power regenerative test 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. 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 wind power simulated by the HSD is virtual and the HST under test is real. It is a hardware-in-the-loop wind platform.

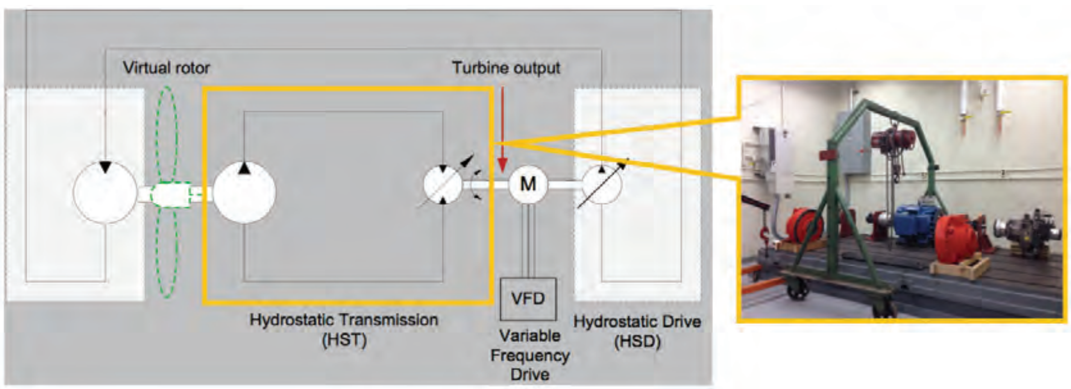


Figure 6: Hardware-in-the-loop power regenerative wind test platform

Instead of dissipating the turbine output power, it combines a VFD electric motor to power the hydrostatic drive. With the power regeneration, the electric motor only needs to make up for the losses in the system, making it possible to simulate large turbine output power with small electric motor. Simulation results show that the test platform can simulate the maximum turbine output power of 110 kW with a 60 kW VFD electric motor.

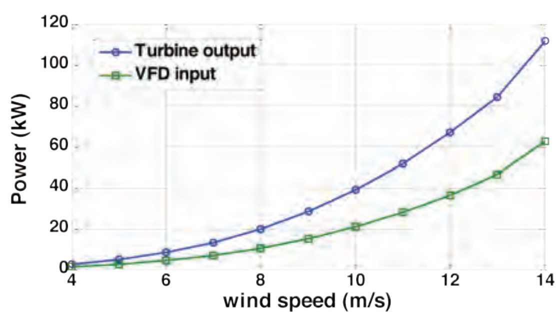


Figure 7: Power regeneration of the HIL wind test platform

One big difference between the HIL wind test 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 HIL wind test platform. Simulation results show that it can simulate the real world rotor shaft dynamics very closely.

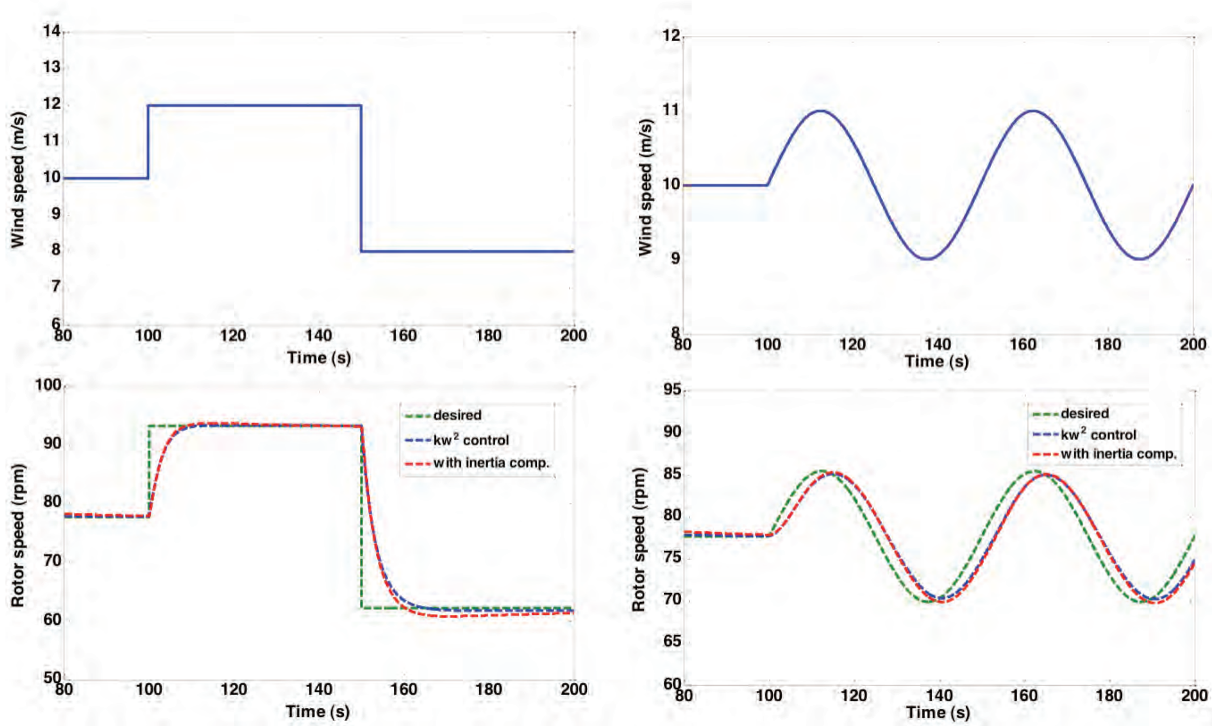


Figure 8: Rotor/blade shaft inertia compensation

Accomplishments:

1. Conducted the system parameters design for HIL wind test platform;
2. Developed a dynamic simulation model of the HIL wind test platform;
3. Developed a control algorithm to simulate the wind power input;
4. Evaluated the power regeneration of the test platform through simulation;
5. Evaluated the proposed rotor/blade shaft inertia compensation strategy through simulation.

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 HIL wind test platform;
- Developed a dynamic simulation model of the HIL wind test platform;
- Developed a control algorithm to simulate the wind power input;
- Evaluated the power regeneration of the test platform through simulation;
- Evaluated the proposed rotor/blade shaft inertia compensation strategy through simulation.

Planned future work:

- Complete the infrastructure of the HIL wind test platform;
- Simulate the different wind power inputs using the platform;
- Validate the proposed control strategy for HST turbine (region 2);
- Test the transmission efficiency at different wind speeds;
- Investigate dynamic behaviors of the HST turbine during wind turbulence;
- Implement different research ideas through the HIL 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.

D. References.

[1] Michael Wilkinson, Ben Hendriks, "Report on wind turbine reliability profiles, work package WP1 – Field data reliability analysis", Reliawind Project Deliverable D.1.3, March 2011.

[2] Rahul Dutta, Feng Wang, Bradley Bohlmann, Kim A. Stelson, "Analysis of short-term energy storage for mid-size hydrostatic wind turbine", ASME Journal of Dynamic Systems, Measurement, and Control, vol.136, no.1, 2013.

[3] Rahul Dutta, Feng Wang, Bradley Bohlmann, Kim A. Stelson, "Analysis of short-term energy storage for mid-size hydrostatic wind turbine", in Proceedings of the ASME Dynamic Systems and Control Conference, Fort Lauderdale, FL, USA, 2012 (selected as the top 20 outstanding finalist paper).

[4] Feng Wang, Becca Trietch and Kim A. Stelson, "Mid-sized wind turbine with hydro-mechanical transmission demonstrates improved energy production", in Proceedings of the 8th International Conference on Fluid Power Transmission and Control, Hangzhou, China, 2013.

[5] Feng Wang and Kim A. Stelson, "Midsize wind turbines with hydraulic transmissions", in Proceedings of the 53rd National Conference on Fluid Power, Las Vegas, NV, USA, 2014.

[6] Feng Wang and Kim A. Stelson, "Model predictive control for power optimization in a hydrostatic wind turbine", in Proceedings of the 13th Scandinavian International Conference on Fluid Power, Linköping, Sweden, 2013.

[7] Brennen Thul, Rahul Dutta, Kim A. Stelson, "Hydrostatic transmission for mid-size wind turbines", in Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV, USA, 2011.

Project 1J.2: A Novel Pressure Controlled Hydro-mechanical Transmission

Research Team

Project Leader:	Kim Stelson, Department of Mechanical Engineering, University of Minnesota
Other Researchers:	Brad Bohlmann, University of Minnesota
	Mike Gust, University of Minnesota
Post Doc:	Feng Wang, University of Minnesota
Graduate Students:	Biswaranjan Mohanty, University of Minnesota
	Emma Frosina, University of Naples Federico II
Industrial Partner:	Mathers Hydraulics

1. Statement of Project Goals

The growing demand of fuel efficient vehicles, low carbon footprint technologies and drivability requires more efficient vehicle drives. This creates opportunities to integrate new technologies to achieve better performance with energy efficiency. The automatic transmission is a widely acceptable solution. 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 wheel 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 world first series hydraulic hybrid delivery vehicle has 60-70% better fuel economy and 40% or more reduction in CO2 emissions [1]. Altair's series hydraulic hybrid city bus delivers 30% or more fuel efficiency than other diesel-electric buses available today [2].

The objective of the project is to develop a compact and efficient pressure-controlled hydro-mechanical transmission suitable for vehicles and mid-size wind turbines. The new transmission is expected to be as efficient as conventional HMT with planetary gears but is more compact and cost-effective. A prototype will be built in partnership with Mathers Hydraulics. The full characteristics of the transmission will be developed and validated through tests. Simulation studies will be conducted to investigate the potential of the transmission in both on-road and off-road vehicles and mid-size wind turbines.

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) or the wind power test bed (TB β).

3. Project Description

A. Description and explanation of research approach

The hydraulic transmission uses a double-acting vane pump as the base module since it has a more balanced design, longer lifetime and quieter operation compared to gear pumps or piston pumps. The structure of the Vane pump Power Split Unit (VPSU) and its hydraulic symbol are shown in Figure 1. The rotor, with the vanes inside, is coupled to the input shaft. The floating ring is coupled to the output shaft. The hydraulic symbol on the right is newly proposed to reflect the fact that it has a floating ring.

The new transmission combines pumping and motoring functions in one unit by floating the ring, making it function as a conventional hydrostatic transmission consisting of a pump and a motor. The pumping unit, consisting of input shaft, rotor/vane assembly and the rotating ring, is no different from a conventional vane pump except for the rotating ring. The motoring unit consists of the rotating ring and the output shaft coupled to it.

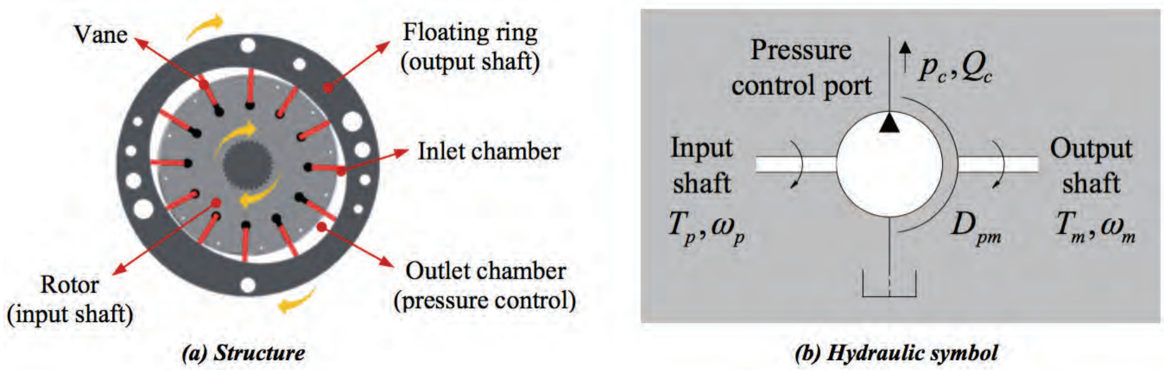


Figure 1: Vane pump Power Split Unit based on double-acting vane pump

Component Study of Vane pump Power Split Unit:

To understand the characteristics of the VPSU, a computational model was developed. The pump geometry is shown in Figure 2. The fluid volume and three dimensional mesh are shown in Figure 3. For ease of understanding the unit is simulated under constant pressure and constant input shaft speed (2400 rpm). The output torque was evaluated at different output shaft speed is shown in figure 4.

Figure 2: Pump Geometry

Figure 3: Fluid volume and its 3D mesh

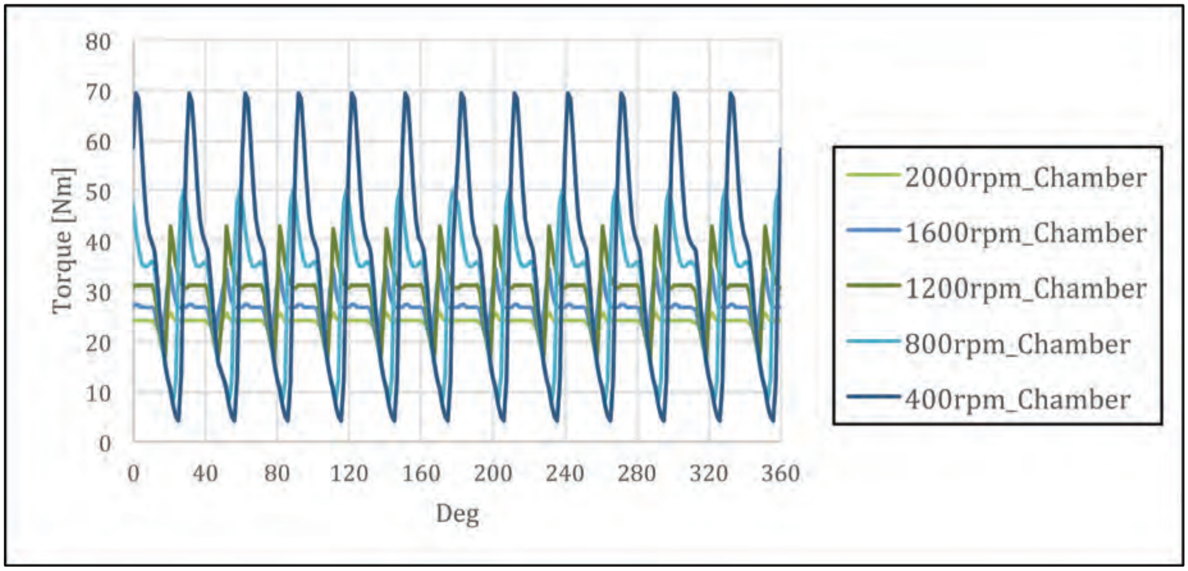


Figure 4: Output torque at 500 PSI at different output shaft speed

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.

Sizing of components of Vane Pump Power Split Transmission (VPPST):

The key component in this design is VPSU which splits power into a hydraulic path to run a variable displacement motor and a mechanical path to rotate the output shaft of the VPSU. The power sharing between mechanical path and hydraulic path is controlled by the hydraulic motor displacement. The hydraulic power is then added to the drive shaft to amplify the torque. The schematic of power split transmission and CAD model is shown in Figure 5.

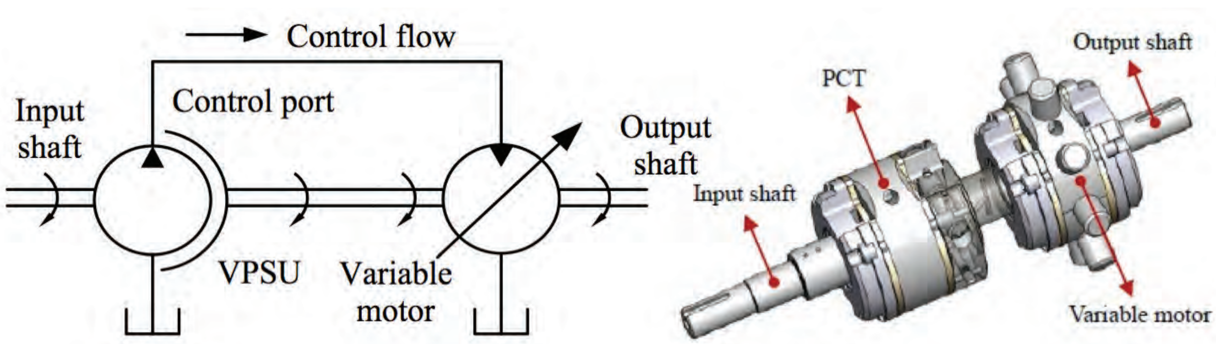
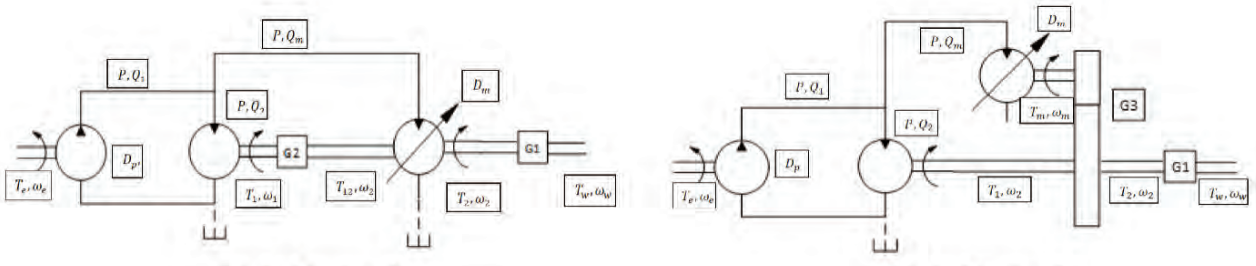


Figure 5: Schematic of VPPSU and its 3D CAD model

The sizing of VPPST is done for class 1 pick-up truck. Two different architectures were studied and shown in Figure 6. The size of the VPSU for 222.5 Kw engine at different operating pressures is shown in Figure 7. The size of motor and intermediate gear ratio at different operating pressures for architecture one and architecture two are shown in Figures 8 and 9.



(a) Architecture 1 *(b) Architecture 2*

Figure 6: Schematic of architectures

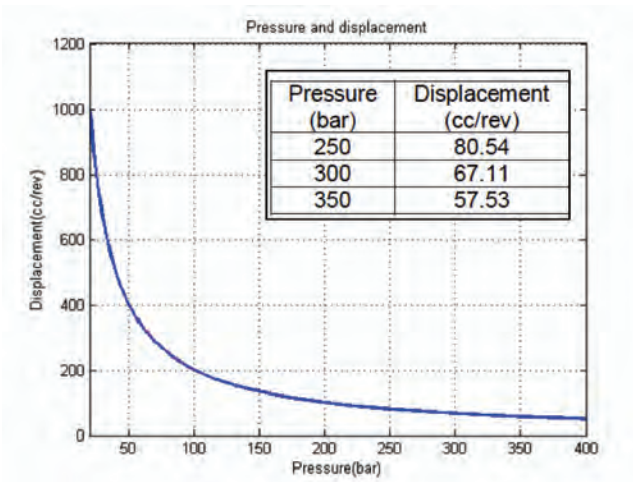


Figure 7: VPSU Displacement at different pressures

Accomplishments:

1. Proposed two different architectures for vane pump power split transmission.
2. Evaluated the size of VPSU, variable displacement motor and intermediate gear at static conditions.
3. Evaluated power required by class 1 pick-up truck at different operating conditions.

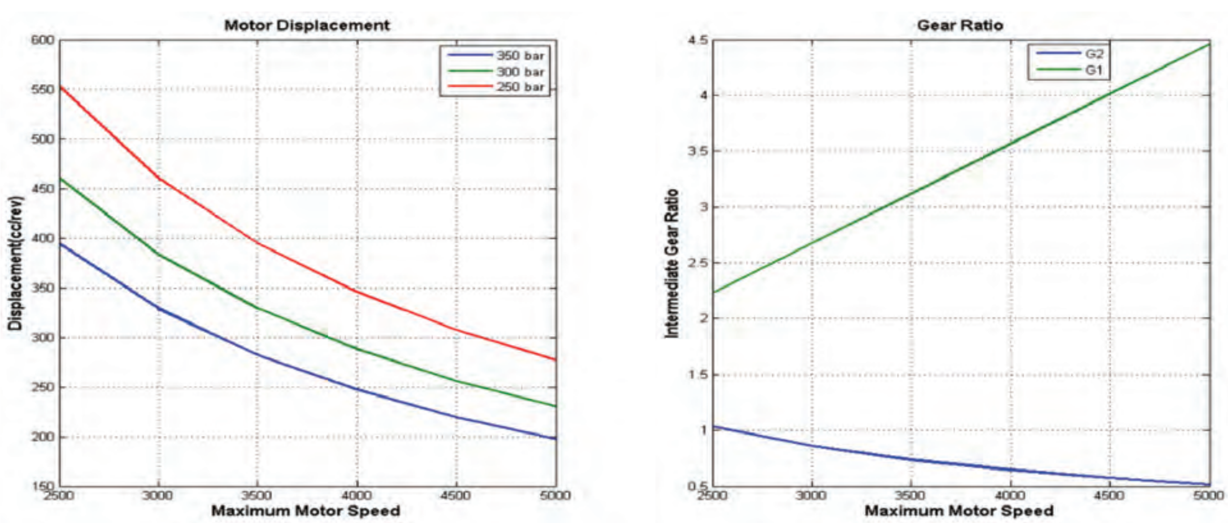


Figure 8: Size of motor and intermediate gear for architecture 1

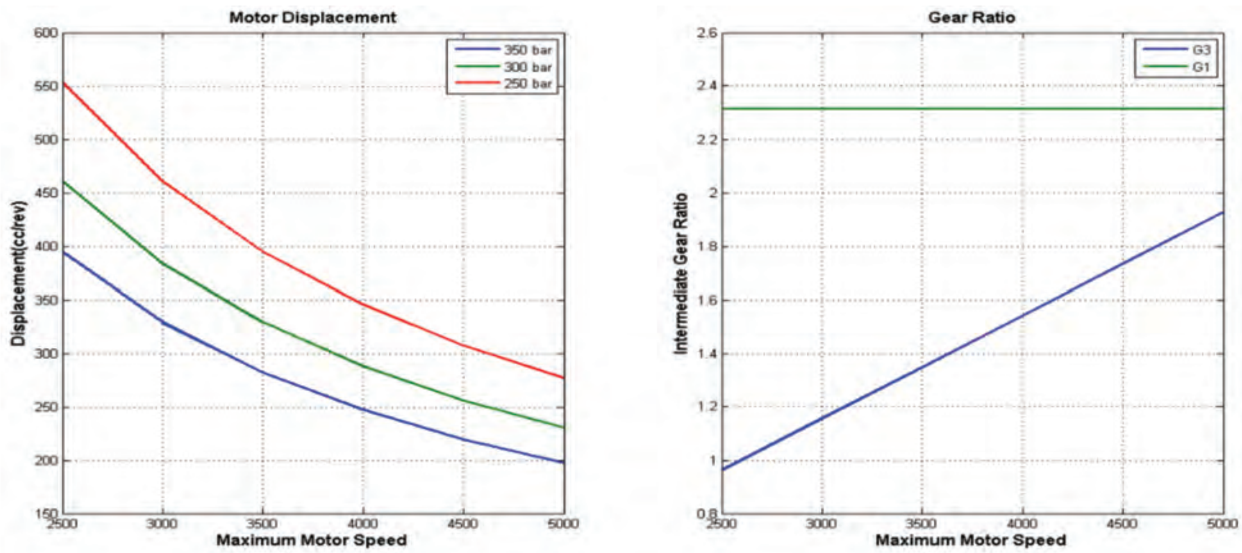


Figure 9: Size of motor and intermediate gear for architecture 2

B. Plans

Planned future work:

- Complete the 3D CFD analysis of VPSU at different operating pressures.
- Investigate the drag effect of hydraulic oil and vane tip on floating ring.
- Validate the CFD result through component testing.
- Simulate the VPPST architecture under dynamic conditions.
- Investigate the engine performance at different drive cycles.
- Implement the control strategy to control swash plate angle.

C. Member company benefits

The vane pump power split transmission represents a large new potential market for fluid power. The current automatic drivetrain solution is a widely acceptable solution. However, it is unable to maintain optimal efficiency over the entire engine operating range. The VPPST is an infinitely variable transmission allows for optimum engine operation by decoupling the engine speed from the drive speed. The transmission also has an integral clutch that allows de-clutching the engine from the drive train by retracting the vanes of the VPSU. The compact unit is quite and cost-effective too. It is going to create a new business for the member of companies.

D. References.

[1] http://www.epa.gov/

[2] http://www.altairbusolutions.com/

[3] Wang, F., Stelson, K. A.," A Novel Pressure Controlled Hydro-mechanical Transmission," Proceedings of the ASME/BATH 2014 Symposium on Fluid Power & Motion Control 2014".

[4] Meisel, J.,"An Analytic Foundation for the Toyota Prius THS-II Powertrain with a Comparison to a Strong Parallel Hybrid-Electric Power Train," SAE Technical Paper 2006-01-0666, Advanced Hybrid Vehicle Powertrains 2006.

[5] HYDROSTATIC TORQUE CONVERTER AND TORQUE AMPLIFIER; Filed: Nov 19, 2010; status: Patent Pending.

[6] HYDROSTATIC TORQUE CONVERTER AND TORQUE AMPLIFIER; Filed: Dec 5, 2012; status: Patent Pending.

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

Research Team

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

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

B. Achievements

<u>Achievements in previous years</u>

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

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

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

The piston and cylinder liner from an AP Hornet .09 model aircraft engine are used in the current generation II prototype, both in the engine and compressor. Piston material is hyper-eutectic aluminum alloy with high silicon content in the alloy for lubricity. The cylinder liner is brass, with a thin layer of chrome plating. At room temperature, the stock cylinder liner is tapered so that it has negative clearance at top dead center (TDC). This causes the aircraft engine to be difficult to turn when cold, but it evens out and creates a good seal when warm. Extra force is required to turn a cold engine, but the crankshaft momentum accomplishes this until it warms up. In a free-piston configuration the rebound spring does not provide enough force to overcome the tight fit. Therefore, the engine cylinder liner was reamed from 12.48 mm at TDC to 12.51 mm and the compressor cylinder liner was reamed to 12.55 mm. With an increased diameter cylinder, thermal expansion causes extra clearance in a warm engine leading to more blow-by leakage. Scuffing and increased wear are also an issue limiting maximum runtime to only a few minutes.

In order to gauge the effectiveness of improvements made to the engine-compressor, thorough testing was done with the current prototype. The prototype was run with glow-plug ignition using methanol-based model airplane fuel. While starting and running, the in-cylinder pressure and piston position were continuously monitored and recorded along with the output from the compressor.

During a typical 20 sec. run, the free-piston engine compressor pressurized a 530 mL air reservoir from atmospheric pressure to approximately 3.4 bar (50 psig). The compressor produced an average of 10 W of cool compressed air power. It was determined that runtime was limited to about 20 sec. because heat transfer and thermal expansion caused increased clearance and excessive leakage. After cooling for a short time, the engine could be restarted.

Since this device is intended to be used in close proximity to people, its noise level, vibration, and heat output need to be considered. While running the engine compressor, the sound level was measured to be approximately 100 dB at a distance of one foot. Temperature measurements have not been taken because the engine does not heat up to its steady state operating temperature during the current short run times.

Achievements in the past year

Work on this project during Year 9 (Feb. 1, 2014 - Jan. 31, 2015) has focused on two areas: First, continuing to improve prototype runtime through materials and component design, and second, obtaining detailed measurements of the compressor performance and developing a model of the compressor.

In order to reduce friction and wear in the prototype engine, a commercially available dry lubricant coating was applied to the sides of the stock piston. This was intended to reduce energy lost to friction and increase the life of the piston and cylinder liner. The coating is 30 μm thick, so the cylinder liner was reamed further to a diameter of 12.56 mm, cutting through almost all of the chrome plating. With the reamed cylinder and the coated piston installed in the engine side of the prototype, continuous running could not be achieved. Detailed roundness and cylindricity measurements of piston and cylinder liner were done professionally. Measurements were also taken of the cylinder liner stock piston previously run in the prototype. The previous parts were much truer than the modified parts. The lack of precision in the piston coating and further reamed liner created inconsistent clearance in the engine. Cylinder liners and pistons will be custom made with greater precision. The parts will be made with brass and aluminum and will have a nickel plating or a low friction nickel-teflon coating. In upcoming tests, various combinations will be tried to determine which gives the longest runtime.

Due to the poor reliability of the free-piston engine compressor prototype, performance data of the compressor side could not be obtained. In order to test the prototype compressor, a test stand was built to run the compressor independently of the free-piston engine. The valves, piston, and cylinder liner from the prototype compressor were transferred into an engine block with a crankshaft to move the piston up and down. The crankshaft is powered by a variable speed electric motor so the compressor can be run continuously at any speed up to 12,000 rpm. The output air from the compressor is sent to a reservoir which can be held at constant pressure with a back-pressure regulator. At steady state operation, the measured mass outflow from the regulator is assumed to equal the mass airflow produced by the compressor. Data from the compressor testing over a range pressures and at various speeds are shown in Figure 1. It was also found that blow-by leakage between the piston and cylinder is significantly reduced when oil is present.

A thermodynamic model of the compressor was created. To begin, the compressor cycle was divided into four ideal processes: adiabatic compression, air delivery, adiabatic expansion, and intake. Pressure, temperature, volume, and mass were calculated through each process to complete a cycle. In order to better match real conditions, losses were included. Leakage was accounted for as well as pressure drop across the intake and output valves. These were based on a simple linear orifice model where mass flow is proportional to pressure difference. With the geometry of the actual compressor included, the model was run under conditions similar to the compressor testing. The loss parameters were adjusted until the data produced by the simulation closely matched that of the test. The simulated airflow data can be seen in Figure 1 overlaid with the test data. The overall efficiency and the volumetric efficiency are predicted by the model. These are shown in Figure 2. The air exiting

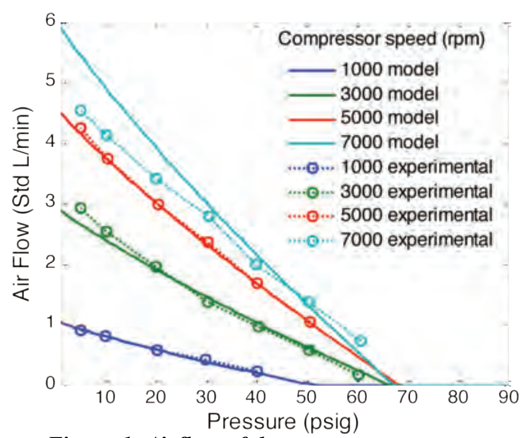


Figure 1. Airflow of the prototype compressor

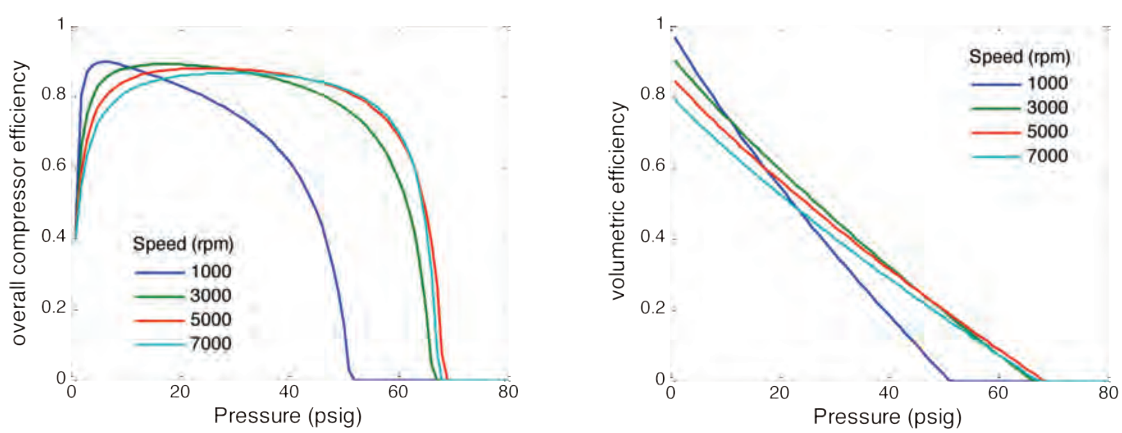


Figure 2. Compressor efficiency as predicted by the model. (Left) Efficiency from work input to compressed air output; this does not include cooling of the air. (Right) Volumetric efficiency.

the compressor is heated above ambient, but the goal of this project is to produce 20 W of cool compressed air power. Losses are incurred when the air cools in the reservoir, which reduces efficiency by almost one half.

A second version of the compressor model has been begun that uses conservation of energy to model the thermodynamics throughout the compressor cycle in small increments. In this model, calculations are based on cylinder volume from slider crank motion to match the crankshaft rotation of the test stand.

C. Plans

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

In the upcoming year, more details will be added to increase the realism of the new air compressor model. Heat transfer in the compressor will be modelled and the orifice flow model of leakage will be improved.

Work will continue on hardware improvements in the engine side of the current prototype. A number of new pistons and cylinder liners are currently being fabricated. These high-precision parts will be tested in the engine to determine what combination of materials and coatings have the best thermal properties to allow the longest run time. Materials to be tested are brass and aluminum coated with either nickel plating or a low-friction nickel-teflon.

When reliable engine operation has been established, the air compressor can be tested as part of the free piston prototype instead of in a separate test stand. These results are expected to be similar to those found from the test stand. The air compressor model can easily be updated to reflect the free-piston motion instead of the crankshaft. Moving forward, hardware improvements can then be made in the prototype compressor. Since it does not experience high combustion temperatures, a material like PTFE could be used to reduce friction. A better seal could be achieved with o-rings. The thin stainless-steel check valves in the compressor may need to be improved, as well. Valve stops can be put in place to prevent exaggerated motion. The current valves deteriorate from fatigue, which is worsened by oil flowing through.

<u>Expected milestones and deliverables</u>

Task 1: Improve engine-compressor performance

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

Task 2: Implement HCCI

- Pure homogeneous charge compression ignition (HCCI) will greatly improve cycle efficiency due to much faster combustion than glow plug ignition. HCCI requires a higher compression ratio, so piston-cylinder leakage must be minimized and design considerations made to achieve adequate compression. Cylinder heating may be needed to assist starting of a cold engine.
- Appropriate fuels that work well for HCCI should be used. One of these is dimethyl-ether (DME), which is clean and renewable. DME exists as a gas under ambient conditions but is stored as a liquid in pressurized cartridges. Due to the low lubricity of DME, some other form of lubrication will need to be added to the engine. It is not easy to mix oil with a gaseous fuel such as DME.
- A better fuel delivery system will be required for the engine. The use of fuel from a pressurized cartridge could provide more consistent fuel flow metering than the current carbureted system.

D. Member company benefits

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

Project 2B.3: Free Piston Engine Hydraulic Pump

Research Team

Project Leader: Zongxuan Sun, Mechanical Engineering, University of Minnesota
Graduate Students: Chen Zhang, Ke Li
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 machines.

3. Project Description

A. Description and explanation of research approach

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

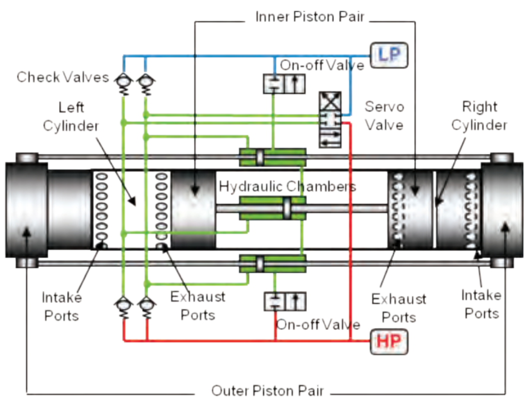


Figure 1: Schematic of the Free Piston Engine Driven Hydraulic Pump

A major technical barrier for the wide spread of the FPE technology is the lack of robust and precise control of piston motion, which is determined by the complex dynamic interactions between the combustion and the load in real time [1-10]. Unlike a conventional ICE with the crankshaft to maintain its piston trajectory, a FPE without such a mechanism is exposed to large cycle-to-cycle variation, especially during transient operation. To address the above challenge, 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

a. Achievements in previous years – precise piston motion control

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, and therefore regulates the piston motion. Additionally, a transient controller was also developed and implemented on the HFPE to deal with the transient period when the engine switched from motoring to firing [16]. Figure 2 and Figure 3 show the related experimental results, which demonstrates the effectiveness of the virtual crankshaft mechanism and the transient controller.

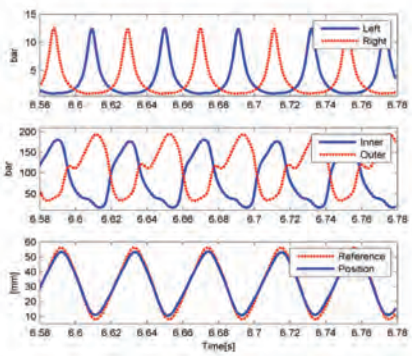


Figure 2(a). Tracking performance from motoring experiment

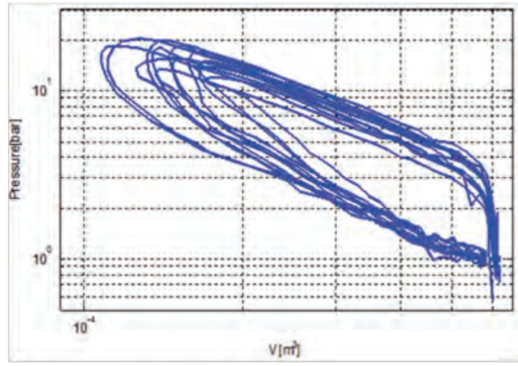


Figure 2(b). Combustion tests with the regulation of the virtual crankshaft

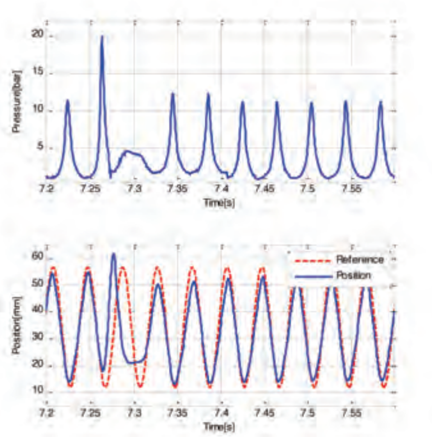


Figure 3(a). Transient period when engine switch from motoring to firing

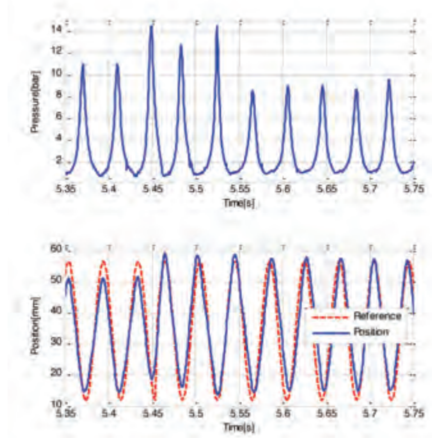


Figure 3(b). System behaviour after applying the transient control

b. Achievements in the past year

In the past year, a high pressure fuel injection system has been designed and integrated with the HFPE, which provides the fuel injection pressure as high as 1000 psi. Such a high injection pressure not only reduces the fuel injection duration, but also improves the air fuel mixing inside the combustion chamber and benefits the combustion afterwards.

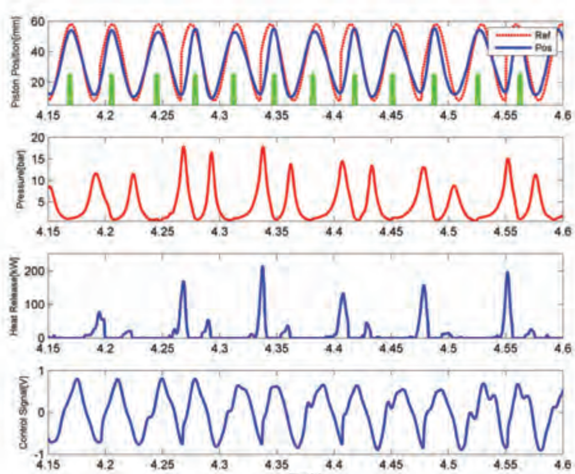


Figure 4. Continuous HFPE combustion operation

Additionally, feedforward controllers are investigated as well to complement the existing virtual crankshaft mechanism and further improve the piston tracking performance. The experimental results demonstrate the effectiveness of the feedforward controllers [17].

Attributed to the improvement on control and the hardware enhancement, we have achieved continuous combustion in the HFPE last year. Figure 4 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 FPE operation with opposed-piston-opposed-cylinder (OPOC) architecture. Note the results also show the cycle-to-cycle variation of the combustion, which is mainly due to insufficient intake manifold pressure. Construction of a custom supercharging system is currently ongoing.

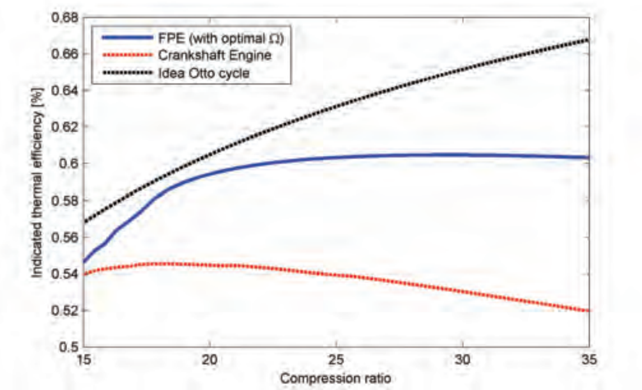


Figure 5. Efficiency gain of the HFPE

Besides the progress on the HFPE opeation, an novel combusiton control method was also proposed to further enhance the engine performance using the ultimate flexibilty of the piston motion in the HFPE. By changing the piston trajectory, we can adjust the volume of the combustion chamber, affect the pressure, temperature and species concentrations of the in-cylinder gases and therefore tailor the combustion process for better engine performance. The corresponding simulation proves this idea (Figure. 5) and shows that higher indicated thermal efficiency can be achieved in the HFPE compared to conventional ICEs [18].

C. Plans

a. Plans for the Next Years

1) *Trajectory-based Combustion Control Development*
Besides the engine efficiency, different piston trajectories also affect the emissions production by varying the temperature profiles inside the combustion chamber. To investigate this hypothesis, the trajectory effect on the emissions performance has to be conducted at first. Afterwards, an optimal trajectory can be provided in terms of the highest efficiency and the minimum emission performance.

2) *Enhancement of HFPE System Capability*
To further improve the system performance and quantify the engine efficiency, new subsystems will be integrated as well. Specifically, a supercharge system will be installed and necessary sensors will be implemented in the loading system in order to measure the effective work output of the HFPE.

3) *Optimization of HFPE for mobile applications*
Since the HFPE does not connect to the load mechanically, accumulators and hydraulic motors are required to mobilize the vehicles, which is similar to the series hybrid vehicles. However, due to the high modularity of the HFPE, the system architecture can be drastically different from the conventional ones. Therefore, a novel system level optimization strategy that ensures smooth operation, optimal efficiency and reduced emissions, needs to be developed.

The optimization strategies will be implemented in a hardware-in-the-loop platform. As in the case of a hydraulic hybrid vehicle, the vehicle dynamics as well as the drivetrain dynamics will be modeled [19-20], and this virtual system is run in real time parallel to the actual HFPE to emulate the numerous loading conditions of the HFPE. Therefore, extensive experiments can be conducted for various applications with different architectures under different drive cycles.

b. Expected milestones and deliverables

- Task 1: Trajectory-based combustion control development [12 months]
    - Investigation on the trajectory effect on the engine emission [4/30/2015]
    - Optimization of the HFPE piston trajectory [1/31/2016]
- Task 2: Enhancement of HFPE system capability [16 months]
    - Installation and testing of the supercharge system [9/30/2015]
    - Installation of the necessary sensor to quantify the engine efficiency [5/31/2016]

- Task 3: Optimization of HFPE for mobile applications [36 months]
    - Optimization of HFPE for mobile applications [3/31/2017]
    - Implementation using a hardware-in-the-loop system [1/31/2018]

Milestones:

- Trajectory-based combustion control development [month 12]
- Enhancement of HFPE system capability [month 16]
- Optimization of HFPE for mobile applications [month 36]

D. Member company benefits

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

E. References

1. Mikalsen, R. and Roskilly, A.P., “A Review of Free-piston Engine History and Applications”, Applied Thermal Engineering, *Vol. 27, Issue 14-15*, pp. 2339-2352, Oct 2007.
2. Golovitchev, V., Montorsi, L. and Denbratt, I. “Towards a New Type of Hybrid Engine: the Two-stroke Free-piston Compression Ignited Engine”, *Proceedings of the 2006 FISITA congress, Yokohama, Japan, Oct., 2006.*
3. Achten, Peter A.J., Oever, Johan P.J. van den, Potma, Jeroen and Vael, Georges E.M., “Horsepower with Brains: The Design of the CHIRON Free Piston Engine”, *SAE Technical Paper Series, 2000-01-2545*, 2000.
4. Somhorst, Joop H.E. and Achten, Peter A.J., “The Combustion Process in a DI Diesel Hydraulic Free Piston Engine”, *SAE Trans., Vol. 105*, 1996.
5. Hibi, A. and Ito, T., “Fundamental Test Results of a Hydraulic Free Piston Internal Combustion Engine”, *Proc. Inst. Mech. Eng., Vol.218, pp.1149-1157*, 2004.
6. Tikkanen, S., Lammila, M. and Vilenius, M., “First Cycles of the Dual Hydraulic Free Piston Engine”, *SAE Technical Paper Series, 2000-01-2546*, 2000.
7. Tikkanen, S. and Vilenius, M., “Control of Dual Hydraulic Free Piston Engine”, *International journal of vehicle autonomous systems, Vol. 4, Issue 1, pp 3-23*, 2006.
8. Mikalsen, R., Jones, E. and Roskilly, A.P., “Predictive Piston Motion Control in a Free-Piston Internal Combustion Engine”, Applied Energy, *Vol.87, pp.1722-1728*, 2010.
9. Mikalsen, R. and Roskilly, A.P., “The Control of a Free-piston Engine Generator. Part 1: Fundamental Analyses”, Applied Energy, *Vol.87, pp.1273-1280*, 2010.
10. Mikalsen, R. and Roskilly, A.P., “The Control of a Free-piston Engine Generator. Part 2: Engine Dynamics and Piston Motion Control”, Applied Energy, *Vol.87, pp.1281-1287,* 2010.
11. Li, K., Sadighi, A. and Sun, Z, “Active Motion Control of a Hydraulic Free Piston Engine,” *IEEE/ASME Trans., Mechatronics*, Vol. 19, Issue. 4, pp. 1148-1159, Aug. 2014.
12. Li, K. and Sun, Z., “Modeling and Control of a Hydraulic Free Piston Engine with HCCI Combustion”, *Proceedings of the 52nd National Conference on Fluid Power, 2011.*
13. Li, K., Sun, Z., “Stability Analysis of a Hydraulic Free Piston Engine with HCCI Combustion”, *Proceeding of 2011 Dynamic Systems Control Conference, Arlington VA, 2011.*
14. Sadighi, A., Li, K., Sun, Z., “A Comparative Study of Permanent Magnet Linear Alternator and Hydraulic Free-piston Engines”, *Proceeding of 2011 Dynamic Systems Control Conference, Arlington VA, 2011.*

15. Li, K., Sadighi, A., Sun, Z., "Motion Control of a Hydraulic Free Piston Engine", *Proceeding of 2012 American Control Conference, Montreal, Canada, 2012.*

16. Li, K., Zhang, C., Sun, Z., "Transient Control of a Hydraulic Free Piston Engine" *Proceeding of 2013 Dynamic Systems Control Conference, Palo Alto, CA, 2011.*

17. Li, K., Zhang, C. and Sun, Z., "Precise Piston Trajectory Control for a Free Piston Engine," *Control Engineering Practice, Volume 34, pp. 30-38, Jan, 2015.*

18. Zhang, C., Li, K. and Sun, Z., "Modeling of Piston Trajectory-based HCCI Combustion Enabled by a Free Piston Engine," *Applied Energy, Volume, 139, pp. 313-326, Feb, 2015.*

19. Wang, Y., Sun, Z. and Stelson, K., "Modeling, Control and Experimental Validation of a Transient Hydrostatic Dynamometer", IEEE Transactions on Control Systems Technology, 2011.

20. Wang, Y. and Sun, Z., "Hybrid Powertrain Control with a Rapid Prototyping Research Platform", *Proceedings of the 2011 American Control Conference, San Francisco, CA, pp.997-1002, June, 2011*.

Project 2B.4: Controlled Stirling Themocompressors

Research Team

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

Stirling machines have long held the promise of being an efficient, clean, reliable, and nearly maintenance-free source of power. However, after a century of research, the design of the Stirling engine in general stagnated in the late nineteenth century. Electric motors and internal combustion engines gradually took over the role of the Stirling engine. The primary reason for this development was the low power density. The early Stirling engines embodied heavy devices which produced only small amounts of power particularly in the sub 10kW scale. In the twentieth century the Stirling engine moved away from its purely kinematic arrangement where the motion of the displacer and power piston are kinematically constrained, towards a purely dynamic arrangement; namely the free-piston Stirling Engine. The free-piston engine replaced the bulky, complicated kinematic linkages with small, lightweight dynamic elements; therefore making the device more compact and more power dense. Primary advantages of a free-piston arrangement 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]. William Beale invented the first dynamic Stirling engine in the 1960's. Although the free-piston Stirling engine showed promise in increasing the power density, they need to maintain self-oscillation. Since free-piston engines must achieve the correct phase dynamically, they are very sensitive to their parametric properties (which are difficult to design), and to the load (which is difficult to hold within acceptable bounds). Despite these difficulties, 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]. The selection of the parameters and the sensitivity of their parameters are generally not well understood. In order to overcome this difficulty, the Stirling engine for this research will control the displacer piston directly. By doing this, the movement of the displacer piston is decoupled from the pressure dynamics in the engine. This allows more design degrees of freedom and ensures that the device is insensitive to load or internal dynamics variations. It also allows the potential to better control and shape the thermodynamic cycle and represents an opportunity to enhance efficiency, power or any weighted combination in real-time.

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.

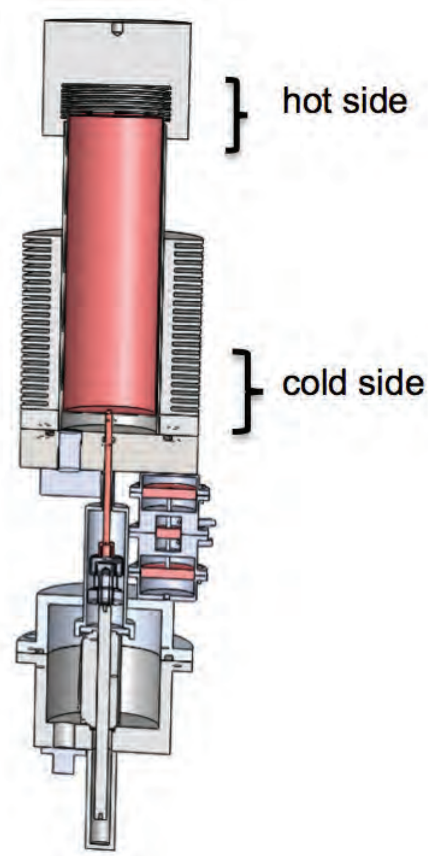


Figure 1. Cross-section of the second generation device

Achievements in the past year

From the experimental results of the first generation device it was clear that the architecture of the device needed some changes. A second generation Stirling device was designed and modeled (see Figure 1). This device has a separate, sealed engine section that is pre-pressurized and uses helium as its working fluid for maximum efficiency and power. The engine section can be paired with many power output stages, such as a compressor, a hydraulic pump, a linear electric generator or a water filtration and desalination system. Here the focus is directed towards the hydraulic pump instead of the pneumatic compressor. This has several reasons. First, in hydraulics the pressure potential energy cannot be lost in the form of heat and will result in higher power deliver efficiencies than a compressor. Secondly, since hydraulic fluid is nearly incompressible, any motion will assure pumping.

A separate pump uses the differential pressure swing inside the engine section to pump hydraulic fluid at a desired output pressure. The pump section is composed of three chambers; the driving chamber, the pumping chamber, and the return chamber (see Figure 2). The driving chamber will be connected to the cold side of the engine section such that they are always at the same pressure. The bottom chamber represents a self-balancing return chamber. This is achieved by staying at an average pressure via a flow restriction induced by simple needle valve. As the displacer piston moves down inside the engine section, the pump stage uses this differential pressure swing to pump hydraulic fluid. When the engine pressure is higher than the average pressure, the piston-rod assembly in the pump section moves down, compressing the hydraulic fluid in the lower pumping chamber. When the desired output pressure is reached, hydraulic fluid is pumped out of the lower pumping section. At the same time, hydraulic fluid is decompressed in the upper pumping chamber such that hydraulic fluid will be pumped in from the low pressure side of the hydraulic system.

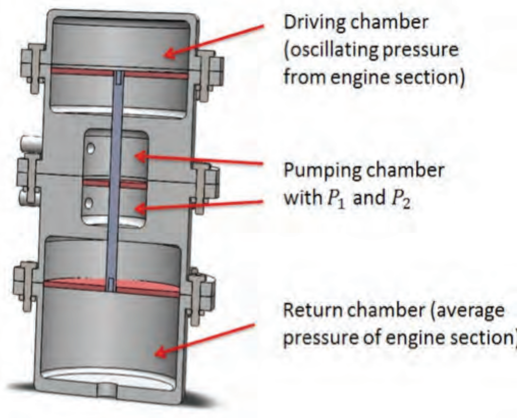


Figure 2. Cross-section of the pumping section

Conversely, when the average pressure is higher than the engine pressure, the piston-rod assembly is moved up, compressing hydraulic fluid in the upper pumping chamber. Once the desired output pressure is reached, pressurized hydraulic fluid is pumped out. Simultaneously, low pressure hydraulic fluid is sucked into the lower pumping chamber through check valves.

More complexity has been added to the dynamic model of the device over the first generation's model. A regenerative effect and shuttle heat transfer losses due to the movement of the displacer piston have been incorporated into the model. The gap in between the outside surface of the displacer piston and the inner surface of the cylinder was modelled to have a regenerative effect. This regenerative channel assumes that the walls of the displacer piston and cylinder store some heat when the displacer piston moves up and transfers heat to the gas when the displacer piston is moving down. Shuttle heat transfer losses occur due to the movement of the displacer piston between the hot and the cold side. As the displacer piston moves up and down, the displacer absorbs heat that it transfers to the cold side when moving down. Similarly the displacer piston cools the hot side when the displacer piston moves from the cold side to the hot side. This effect cannot be avoided but is less severe the longer the length of the displacer. Heat transfer rate into and out of the engine section in the model was limited to the rated output power of the heaters on the hot side and the effectiveness and thermal resistance of the cooling fins on the cold side.

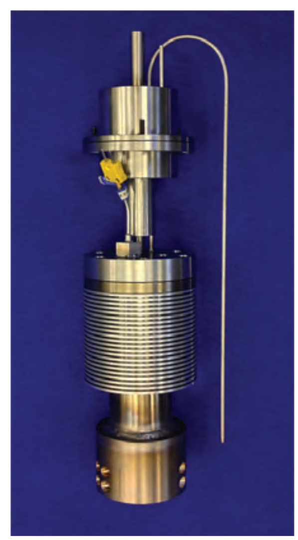


Figure 3. Photograph of the engine section of the second generation device.

The engine section for this prototype has been build and tested (see Figure 3). In order to get a better knowledge about the dynamics inside the engine section, the engine section was tested without having a pump attached. Results look promising but further analysis has to be done this year.

Plans for next year

Experimental results will have to be evaluated and will have to be compared to the performance predicted by the model. With the knowledge of dynamics of the engine section, pump dimensions and parameters will have to be carefully selected. A hydraulic pump will need to be built and attached to the engine section. With the engine and pump section combined, the entire model has to be tested for validation; experimental results have to be evaluated and compared with the dynamic model. For the future, a cooperation with Oak Ridge National Laboratory is highly sought. This would allow 3-D metal printing with their Manufacturing Demonstration Facility (MDF). 3-D printing would open up new designs for heat transfer and material mixing that conventional machining would never be able to do.

Completed and Expected Milestones and Deliverables

- *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 [in progress]
- *Milestone 6*: Power out stage experimentally characterized and dynamic model validated [04/2015]
- *Milestone 7*: First full controlled Stirling power unit modeled and validated [06/2015]
- *Milestone 8*: Design and fabricate the hydrocarbon fueled heater [01/2016]
- *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

[1] G. Walker, “Large Free-Piston Stirling Engines,” Lecture Notes in Engineering, Springer-Verlag, pp.216-221, 1985.

[2] G. Walker, Stirling Engines, Oxford University Press, 1980.

[3] G. Walker and J. R. Senft, Lecture Notes in Engineering: Free Piston Stirling Engines, Springer-Verlag, New York, 1985.

[4] E. H. Cooke-Yarborough, E. Franklin, T. Gesow, R. Howlett, C. D. West, “Thermomechanical generator – an Efficient Means of Converting Heat to Electricity at Low Power Levels,” Proceedings of the IEE, no. 121, p. 749-751.

[5] C. D. West, Principles and Applications of Stirling Engines, Van Nostrand Reinhold Company, New York, 1986.

[6] C. D. West, Liquid Piston Stirling Engines, Van Nostrand Reinhold Company, New York, 1983.

[7] G. T. Reader and M. A. Clarke, “Liquid Piston Stirling Air Engines,” 2nd International Conference on Stirling Engines, 14p, 1984.

Project 2C.2: Carbon Nanotube Advanced Strain Energy Accumulator

Research Team

Project Leader:	Eric Barth, Mechanical Engineering, Vanderbilt University
Graduate Students:	Josh Cummins
Undergraduate Students:	Chris Maurice, Andrew Voss, Daniel Awogbemlia
Industrial Partner(s):	Enfield Technologies, Case New Holland, Lord Corporation, US Army Aberdeen Proving Ground

1. Statement of Project Goals

The goals of this project are to achieve accurate material characterization, address manufacturability issues, improve energy density and strength properties, and achieve distributed strain sensing by incorporating carbon nanotubes into the advanced strain energy accumulator. In year one, selection of an appropriate rubber compound for the accumulator will be completed and manufacturability issues will be addressed. In year two, carbon nanotubes (CNTs) will be incorporated into the new rubber material, the resulting material properties will be measured and compared with the baseline accumulator and distributed strain sensing using the embedded carbon nanotubes will be attempted. If successful, the carbon nanotube strain measurements will be compared with existing measurement methods. The improved rubber material can be applied to both pneumatic and hydraulic accumulators.

2. Project Role in Support of Strategic Plan

First, with the recent interest of Lord Corporation, Enfield Technologies, General Nano, and the Department of Defense, the project has the potential to attract new industrial partners and supporting government agencies thus supporting the sustainability portion of the Center's strategic plan. Next, the project aims to accurately characterize material properties and address manufacturability issues increasing the likelihood of successful transition to production. Additionally, with the incorporation of carbon nanotubes into the elastomeric accumulator, improvements in material properties and energy density can be realized resulting in more efficient and compact energy storage. Furthermore, the addition of carbon nanotubes has the added potential to provide a distributed sensing capability and with it, the ability to monitor the structural integrity of the component, making it safer and easier to use.

3. Project Description

A. Description and explanation of research approach

Material Characterization and Manufacturability

The motivation for the current research has been the development of the advanced strain energy accumulator. Due to the hyperelastic nature of the material, adequately characterizing the strength properties and energy density has been a challenge. Prior to involvement with Lord Corporation, accurately measuring strain and subsequently estimating strain/energy density has previously only been performed on material samples and not on a full prototype. In addition, manufacturing an accumulator for the hydraulic hybrid has had a number of manufacturing challenges that have prevented implementation to date. Lord Corporaton, as a leader in elastomeric materials, offers invaluable knowledge and experience in characterizing and manufacturing elastomeric and non-linear systems. In partnership with Lord Corporation, it is firmly believed that identifying an ideal rubber compound for this particular application, characterizing the selected rubber's material properties and addressing the manufacturability issues is a low hanging fruit with low risk that will be accomplished in the course of this work.

Carbon Nanotube Reinforced Rubber – Strength and Energy Density Improvement

Once the rubber has been accurately characterized and the manufacturing issues have been addressed, more advanced materials can be instituted. Elastomers have large energy densities but lower fatigue strengths. One method that has been investigated to improve the strength properties of rubber is the addition of CNTs into the rubber material. [1, 2] The improvement in the material properties of rubber with CNTs was demonstrated by Kim et al. [1] and was seen to increase as a function of weight percent for both the axial and transverse directions.

Carbon Nanotube Reinforced Rubber – Carbon Nanotube Distributed Strain Sensing

In previous work done on CNT reinforced rubber, the primary goal of the research was either a general investigation of the improvement of material properties or general impact on electrical properties of rubber. [1,2] Kang, Schulz, et al. [3] investigated the ability of CNTs to be used in sensing applications. There is no evidence that CNTs have been incorporated into rubber materials in an effort to improve material properties, utilize the electrical properties and harvest energy in a single device. In addition for the CNTs to be used in a distributed strain sensing capacity, Kim et al. [1] have also shown the ability of CNT reinforced rubber to provide large shielding capability which would be an ideal material property in certain applications including aerospace and defense.

The potential for elastomers with improved strength properties and distributed strain sensing capabilities is great. In the helicopter industry, as far back as 1975, bearings were identified as the number one cost driver of a helicopters transmission system [4] and remain so today. In conversations with a major aircraft Original Equipment Manufacturer (OEM), it was stated that hydraulic repair issues are one of the top warranty drivers in new aircraft. All of these hydraulic components use rubber gaskets and seals, which with improved material properties and strain sensing capability, have the potential to save these industries millions of dollars annually in both material and maintenance costs [5] resulting in a high risk high reward application.

B. Achievements

Achievements in Previous Years

In previous years a low pressure strain energy accumulator prototype demonstrated nearly constant pressure behavior that was measured upon charging, also known as “ballooning,” and discharging the bladder. The thinner the accumulator wall thickness, the more evenly the strain was distributed in the material. A thinner wall however, results in a lower allowable pressure in the bladder. The lower allowable bladder pressure necessitates a change in bladder geometry from the original thick wall shape in order to utilize the full material energy density while maintaining high pressure. The geometry must uniformly strain the material to its maximum thin wall limit in order to maximize material energy density and enable high pressures. Ideal configurations allow pressures that are higher than the elastomeric accumulator material maximum allowable stress.

This initial body of work revealed that the “balloon” concept exhibits a nearly flat P-V curve after the initial radial expansion. While this is desirable, further investigation revealed limitations of the balloon strain energy accumulator design. The distributed piston accumulator design was developed to overcome the limitations of the balloon accumulator design. 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 energy 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. [6] 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 and that the DPEA is not limited by maximum elongation considerations.

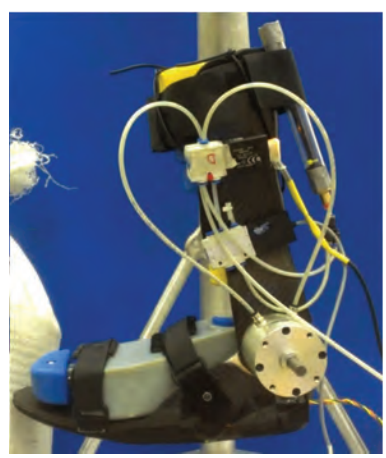


Figure 1: Pneumatic strain energy accumulator implemented on TB6.

In addition to the hydraulic version, the strain energy accumulator was applied to a pneumatic device – the Ankle-Foot Orthosis (AFO) test bed (TB6). A balloon-in-shroud version of the strain energy accumulator was designed and constructed to recycle the exhaust air of the pneumatic rotary actuator of the AFO test bed. It was experimentally demonstrated to have an energy savings in excess of 25% relative to operating with no accumulator. The strain energy accumulator used was dropped in place leaving room for fine tuning of the accumulator to maximize the device efficiency thus fully realizing the energy savings potential of the strain energy accumulator. The pneumatic accumulator used in the AFO test bed is shown above in Figure 1, fully integrated into the test bed.

Achievements in Past Year

Early on in the past year, tasks one, two and five were accomplished in quick order:

- Task 1: Identify rubber type best suited for pneumatic and hydraulic applications in collaboration with Lord Corporation
- Task 2: Work with Lord Corporation to address and overcome manufacturing issues and manufacture samples with specified geometry
- Task 5: Identify carbon nanotube type and carbon nanotube supplier and order carbon nanotubes to be used in research

It was determined that natural rubber was the best material to maximize strain energy recovery due to its minimal losses from hysteresis and the Mullins effect. Switching to natural rubber would also necessitate switching from traditional hydraulic fluids and is being taken into consideration moving forward in evaluating natural rubber for the strain energy accumulator. In addition to identifying natural rubber as the ideal rubber type, Chemlok was identified as the adhesive material that would address a majority of our manufacturing issues. Chemlok offers a metal to rubber bond that is stronger than the rubber itself. This allows for direct interface between the metal and rubber, eliminating for unnecessary connection components that often lead to stress concentrations and points of failure. Finally, the University of Cincinnati and their NanoWorld laboratory offer unique capabilities in growing carbon nanotubes with multiple techniques as well as equipment to fabricate various samples and test specimens.

With the ideal rubber type known, Chemlok identified as the adhesive agent that will solve many manufacturing issues, and carbon nanotubes sourced, task three was under taken:

- Task 3: Conduct material property tests on newly fabricated strain energy accumulator rubber specimens

Various rubber samples in both sheet and tube form were ordered for testing. Simultaneously a material was identified that incorporated gold nanoparticles into rubber that was electrically conductive.

While the material does not have the same material properties or durability required here, it is the closest semi-commercially available material. The test specimens of the gold nanoparticle rubber are shown in Figures 2 and 3 that were used for cyclic loading and damage testing respectively. 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. [8]

Concurrently testing of the rubber test specimens was conducted on a standard MTS load frame. Stress/strain measurements were taken with both the load frame and with the Digital Image Correlation (DIC) system, shown in Figure 4. Both systems were able to obtain stress/strain data, observe hysteresis in the loading and unloading of the dog bone specimen, and observe localized stress/strain data with the DIC system. More information can be found in Cummins et al. [10]

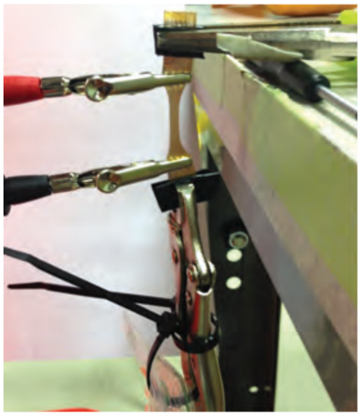


Figure 2: ***Metal Rubber dogbone specimen used for cyclic load testing***

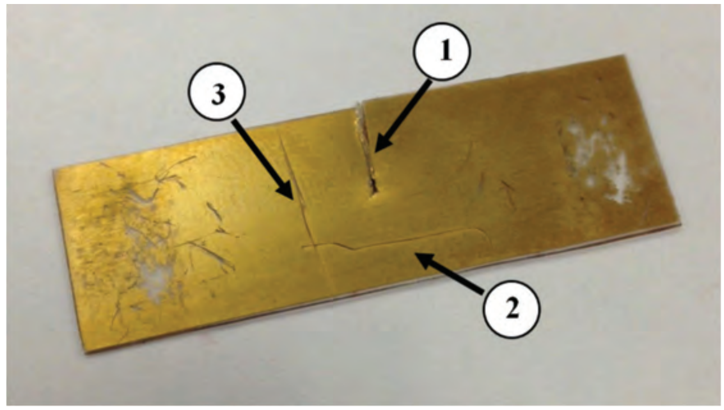


Figure 3: ***Metal Rubber rectangular test specimen used in damage testing 1.) Vertical snip 2.) Horizontal scratch 3.)Vertical scratch***

The next task to be addressed was that of task four:

- Task 4: Conduct testing of new accumulator on test beds

A concerted effort was made to quickly advance the Technology Readiness Level (TRL) of the strain

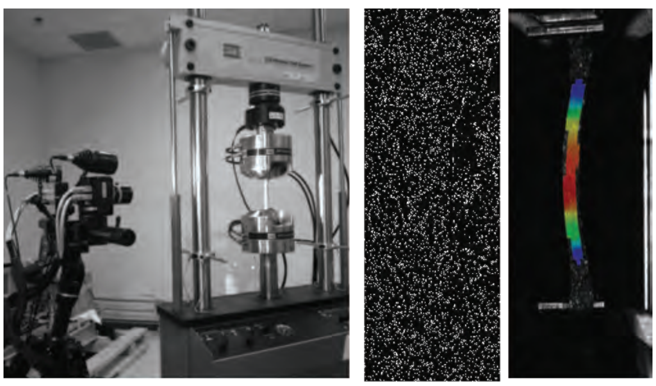


Figure 4: *Load frame and DIC stress/strain testing of rubber tensile test dog bone specimen*

Figure 5: *Pneumatic strain energy accumulator implemented on interactive*

energy accumulator from the previous level of a three to a five. Building off the momentum from the previous year where the strain energy accumulator was integrated as a component in the AFO test bed, thus raising the TRL to a level four, we continued with a breadboard demonstrator. The breadboard demonstrator shown in Figure 5 is a manually operated demonstrator that acts similar to how the hardware would operate within a system, raising the TRL level to that of a level five.

Figure 6 shows the strain energy accumulator breadboard demonstrator that was developed in conjunction with CCEFP member company Enfield Technologies. This automated breadboard demonstrates how the accumulator would behave in an automated system, further supporting a TRL classification of level five. These demonstrators are being brought to trade shows where they are being displayed as interactive displays to attract new member companies to the CCEFP.

Figure 6: *Pneumatic strain energy accumulator implemented on industry partner automated*

Additionally, it is believed that taking the breadboards to manufacturing trade shows will help attract new CCEFP member companies and provide new opportunities to transition the strain energy accumulator into preproduction environments such as manufacturing equipment that relies on pneumatic components. Through utilizing existing relationships with current Center member companies, forging new relationships with potential new member companies and other Engineering Research Centers (ERC's), and receiving additional award money for exhaust gas recirculation it is anticipated that the pneumatic strain energy accumulator will reach a TRL level of six or possibly even seven in the coming year on its way to successful commercialization in the final year of National Science Foundation funding as the Center looks to become self-sustaining.

C. Plans

Plans for the next year

In the coming year various elements of tasks one through five will continue to be addressed as the accumulator continues its development on the way to commercialization. Additionally, heavy emphasis will be placed on tasks six through eight:

- Task 6: Manufacture CNT reinforced elastomer samples
- Task 7: Conduct strength and distributed strain sensing tests to determine material properties and materials ability to measure and monitor strain with CNT reinforced rubber
- Task 8: Apply material to test beds, identify new applications and conduct necessary and/or additional testing such as energy saving studies or EMI shielding tests.

Specific plans for tasks one through five already started include continuing to study natural rubber and compare to other rubbers, study Chemlok at attachment points, quantify energy savings, look for parameters to optimize and use digital image correlation system to measure stress/strain of strain energy accumulator in situ.

Expected milestones and deliverables

- Quantification of energy savings of strain energy accumulator
- Complete fabrication of carbon nanotube embedded elastomer
- Test material properties of CNT elastomer up to 300% strain
- Demonstrate distributed strain sensing capability
- Test carbon nanotube elastomer material on test beds
- Identify new applications and conduct additional testing possibly to include EMI shielding ability

D. Member company benefits

The carbon nanotube advanced 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 understanding and application of carbon nanotube elastomers. 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. Advancements and advantages such as those aforementioned will help inspire and motivate member companies in innovation as was mentioned in the panel discussion at the inaugural Fluid Power Innovation and Research Conference (FPIRC). 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 with General Nano which have led to discussions with the University of Cincinnati and their NSF Engineering Research Center and possible future joint efforts between the ERC's. 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.

E. References

1. Kim YA, Hayashi T, Endo M, Gotoh Y, et al. “Fabrication of aligned carbon nanotube-filled rubber composite.” Scripta Materialia 54 (2006): 31-35.

2. Bokobza L. “Multiwall carbon nanotube elastomeric composites: A review.” Polymer 48 (2007): 4907-4920.

3. Kang I, Schulz MJ, Kim JH, Shanov V, et al. “A carbon nanotube strain sensor for structural health monitoring.” Smart Materials and Structures 15 (2006): 737-748.

4. Reddick HK Jr. “Army Helicopter Cost Drivers.” Army Air Mobility Research and Development Laboratory, Fort Eustis, VA. Aug 1975.

5. Bond R, Underwood S, Adams DE, Cummins JJ. “Structural Health Monitoring-Based Methodologies for Managing Uncertainty in Aircraft Structural Life Assessment.” Proceedings of the 9th International Workshop on Structural Health Monitoring. Sep, 10th-12th, 2013.

6. Tucker JM and Barth EJ. “Design, Fabrication, and Evaluation of a Distributed Piston Strain-Energy Accumulator,” International Journal of Fluid Power 14:1 (2013): 47-56.

7. Stelson K. Center Overview & Infrastructure Presentation, NSF Site Visit, Minnesota, MN, February 20, 2008.

8. Cummins JJ, Maurice C, Song Y, Sanchez F, Barth EJ, Adams DE. “Elastomeric Evolution: A New Look at Carbon Nanotube Reinforced Elastomers.” Proceedings of the 40th European Rotorcraft Forum 2014. September 2nd-5th, 2014.

9. Cummins JJ, Pedchenko A, Barth EJ, Adams DE. “Advanced Strain Energy Accumulator: Materials, Modeling and Manufacturing.” Proceedings of the 2014 Bath/ASME Symposium on Fluid Power and Motion Control. September 10th-12th, 2014.

10. Cummins JJ, Barth EJ, Adams DE. “Project 2C.2 Carbon Nanotube Advanced Strain Energy Accumulator.” Proceedings of the 2014 Fluid Power Innovation and Research Conference. October 13th-15th, 2014.

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

Research Team

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

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

The hydraulic flywheel accumulator can theoretically increase the energy density of hydraulic energy storage by over an order of magnitude while maintaining, good round-trip (storage-regeneration) efficiency. Overcoming the energy density barrier is key to implementing a hydraulic hybrid power train in a passenger vehicle. The proposed work will demonstrate the hydraulic flywheel accumulator at an energy density of three times that of an advanced conventional accumulator, while generating the modeling, simulation, and optimization tools necessary to further increase the energy density in follow-on work.

3. Project Description

A. Description and explanation of research approach

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

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

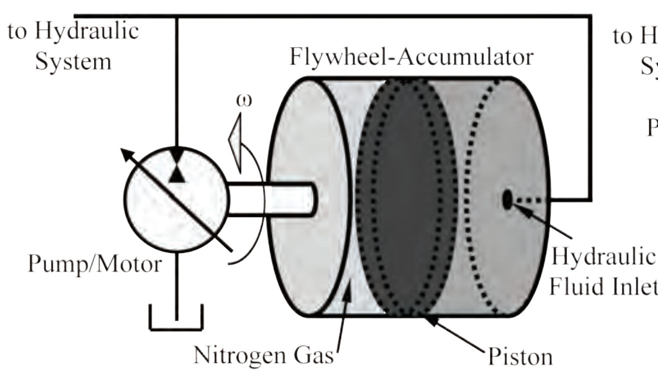


Figure 1. Diagram of the hydraulic flywheel accumulator. The pump/motor is coupled to the flywheel-accumulator directly or through a geared connection. The hydraulic inlet is at the center of the opposite end.

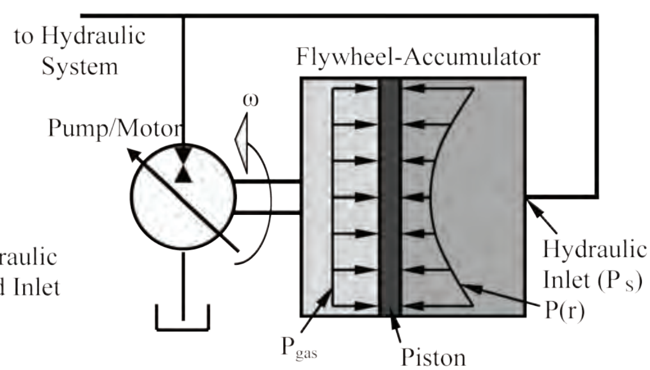


Figure 2. Pressure distributions of the gas and hydraulic fluid in the device. Due to the centripetal acceleration and density of the hydraulic fluid, a parabolic pressure distribution is formed.

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

There are two important reasons that the HFA is superior to using a fixed inertia flywheel coupled to a hydraulic system through a pump/motor, as has been done in prior works [21, 22]. First, high power transients can be absorbed in the hydro-pneumatic domain, allowing use of a small displacement pump/motor. A small pump motor, assuming it is variable displacement, will operate at a higher average displacement, and thus be more efficient than a larger pump/motor operating at a lower average displacement. The smaller pump/motor also improves compactness and reduces weight. Second, due to the energy conversion losses in a pump/motor, storing energy in the hydro-pneumatic domain is more efficient. By setting up the control strategy to allow the system pressure to vary slightly (say 10%), small energy charge and discharge events can be achieved purely pneumatically with less energy loss, while maintaining large energy storage capacity through the rotating kinetic domain.

B. Achievements in the past year

During the past year of CCEFP funding, an energy loss model has been constructed, the geometry of a high energy density prototype has been optimized, and the detail design of the prototype has been completed. A cross-sectional view of the HFA, designed for easy prototyping, is presented in Figure 3. The housing consists of a composite cylinder and metallic liner, which acts both as a flywheel rotor, storing the majority of the kinetic energy in the HFA, and as a mechanism to contain fluid pressure in the radial direction. Most of the strength of the housing is provided by the composite, while the liner facilitates sealing to the piston and end caps. Two end caps fit inside of the housing, concentrically on an axle, and sealing against the liner. The end cap and axle system acts to contain fluid pressure in the axial direction. Split retaining rings, nested in counter bores in the end caps and grooves in the axle, prevent outward axial movement of the end caps and, on the gas side, transmit torque between the end cap and the axle. The gas side of the axle is coupled to the storage PM. The gas-side end cap is constrained to the housing with radial pins which prevent motion in the axial and tangential directions. The axle has internal ports of diameter on the oil side of the HFA to allow for addition and extraction of oil. The oil-side end cap is constrained to the housing only concentrically, such that the internal pressure of the HFA does not impose any axial stress on the housing via the end caps. Besides the compressive interaction that might arise during HFA operation, there is no radial constraint between the end caps and the housing. The piston, which separates the oil from the gas, has axially-sliding seals at both the axle and the housing.

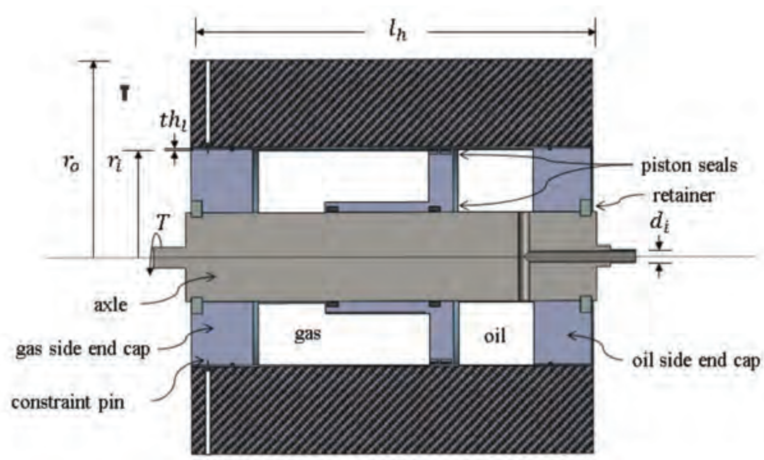


Figure 3. Cross-sectional view of the energy dense HFA using a center tie-rod.

An elitist genetic optimization, specifically the NSGA II, was used to optimize the HFA design for application in a hybrid vehicle. The optimization had two objectives, minimizing system mass and minimizing drive cycle losses over a drive cycle. The optimization was subject to two constraints. The first requires that an HFA design solution must exhibit a material safety factor of 3. The second requires an HFA design solution to allow the vehicle to complete one cycle of the Urban Dynamometer Driving Schedule. Given the axial piston pump-motors that appear to be suitable for the HFA, the upper bound on maximum angular velocity is set to 1,885 rad/s (18,000 RPM). To avoid solutions with impractically-low energy density, the lower bound on ω_{max} is chosen to be 2,865 rad/s (3,000 RPM). Further bounds were applied to the geometry of the HFA for packaging purposes. The Pareto optimal front for the solution candidates is shown in Figure 4. The solutions between the dotted vertical lines were further evaluated as candidates for the laboratory prototype.

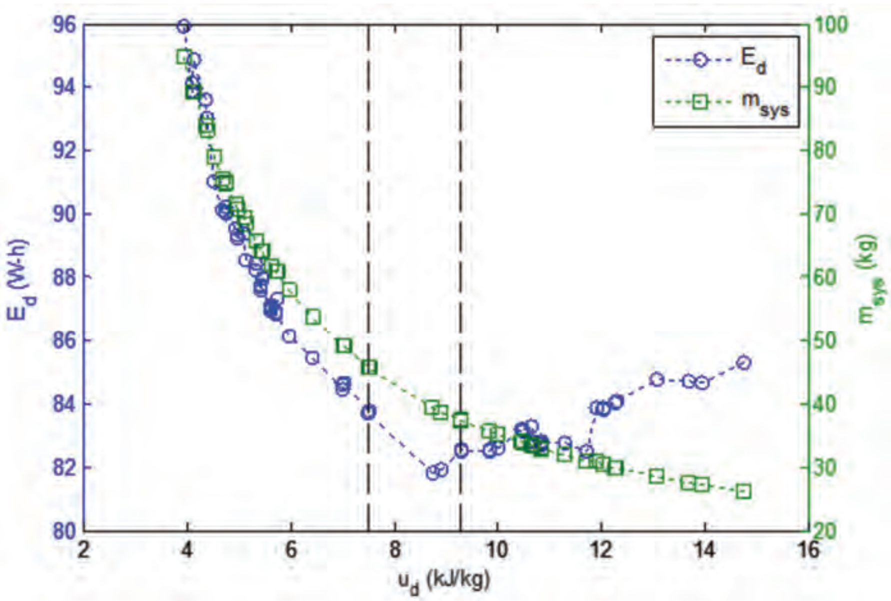


Figure 4. Energy Capacity and System Mass vs. Energy Density for the Laboratory-scale Pareto-optimal Set

Figure 4 illustrates important trends in the Pareto optimal results. Beginning with the most accumulator-like solutions (the far-left of this plot), increasing energy density of the HFA allows the design energy capacity to decrease. This is primarily due to the fact that a vehicle with a lower-mass energy storage system incurs less rolling resistance. However, at a certain point (near 9 kJ/kg), increases in energy density cease to pay off, at least from the perspective of design energy capacity, E_d. The higher operating speeds required by the most energy-dense solutions lead to large drive cycle losses. To compensate, these solutions must actually have a higher energy capacity, even though the road loads continue to decrease with mass. In light of this phenomenon, the logical choice for the laboratory prototype is the solution with the minimum design energy capacity.

Based on geometry determined through the optimization, a laboratory prototype was designed. Through detailed design, the seals, bearings, tolerances, and off-the-shelf components were selected. An isometric and cross-sectional view of the prototype is shown in Figure 5. The parts for this prototype are currently being fabricated.

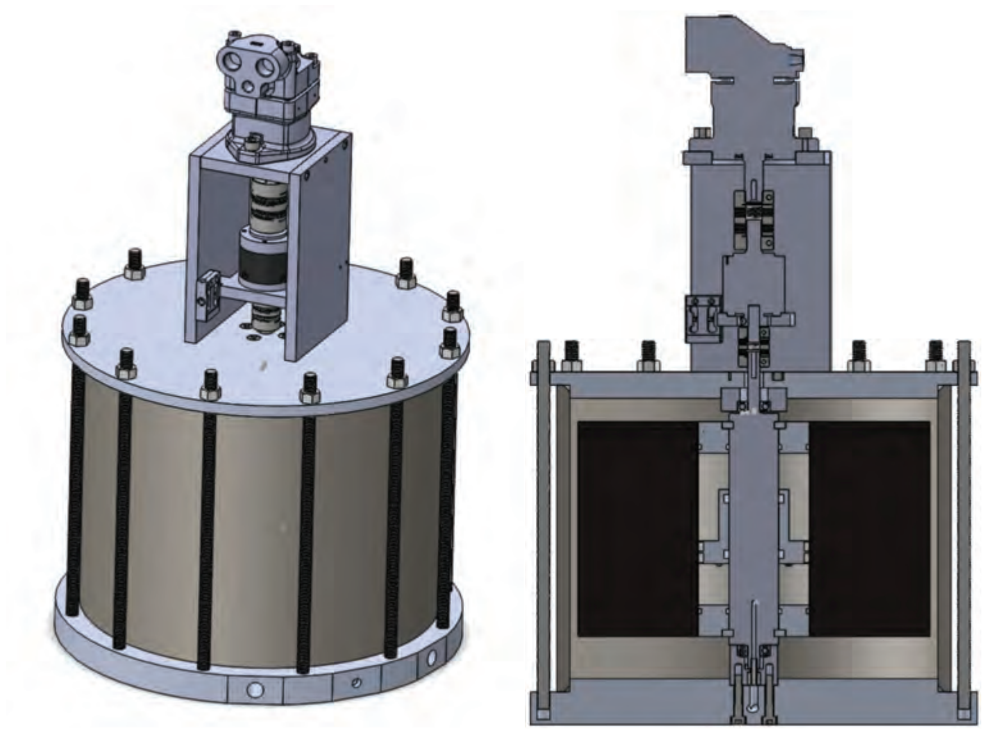


Figure 5. Cross-sectional view of the flywheel accumulator prototype system.

C. Plans

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

- Task 1: Conduct viscous dissipation experiments.
- Task 2: Drive train simulation and optimization of the HFA parameters.
- Task 3: Perform a detailed design of prototype HFA.
- Task 4: Fabricate the HFA prototype
- Task 5: Perform designed experiments with the HFA prototype.

Milestones:

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

D. Member company benefits

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

E. References

[1] Pourmovahed, A., 1993, "Sizing Energy Storage Units for Hydraulic Hybrid Vehicle Applications," American Society of Mechanical Engineers, Dynamic Systems and Control Division, New Orleans, LA, 52, pp. 231-246.

[2] Van de Ven, J. D., 2009, "Increasing Hydraulic Energy Storage Capacity: Flywheel-Accumulator," International Journal of Fluid Power, 10(3), pp. 41-50.

[3] Bitterly, J. G., 1998, "Flywheel Technology: Past, Present, and 21st Century Projections," Aerospace and Electronic Systems Magazine, 13(8), pp. 13-16.

[4] Van de Ven, J. D., 2013, "Fluidic Variable Inertia Flywheel and Flywheel Accumulator System," Worcester Polytechnic Institute, US Patent 8,590,420.

[5] Van de Ven, J. D., and McInnis, J., 2011, "Design and Experimental Results of a Bench Top Flywheel-Accumulator for Compact Energy Storage," International Fluid Power Exposition, National Conference on Fluid Power, Las Vegas, NV.

[6] Strohmaier, K., and Van de Ven, J. D., 2013, "Constrained Multi-Objective Optimization of a Hydraulic Flywheel Accumulator," ASME/BATH 2013 Symposium on Fluid Power & Motion Control, Sarasota, FL (FPMC2013-4425).

[7] Greenspan, H. P., and Howard, L. N., 1963, "On a time-dependent motion of a rotating fluid," Journal of Fluid Mechanics, 17(3), pp. 385-404.

[8] Strohmaier, K. G., Cronk, P. M., Knutson, A. L., and Van de Ven, J. D., 2014, "Experimental Studies of Viscous Loss in a Hydraulic Flywheel Accumulator," International Fluid Power Exposition: National Conference on Fluid Power, Las Vegas, NV(0369-000017).

Project 2F: MEMS Proportional Pneumatic Valve

Research Team

Project Leader: Prof. Thomas Chase, Mechanical Engineering
Graduate Student: Nebiyu Fikru and Erik Hemstad
Industrial Partner(s): Enfield Technologies & Parker Hannifin

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 position sensing strategies for the MEMS scale devices.

2. Project Role in Support of Strategic Plan

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

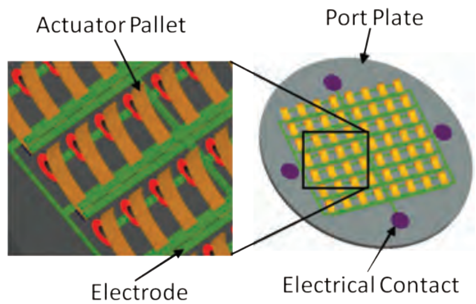
3. Project Description

A. Description and explanation of research approach

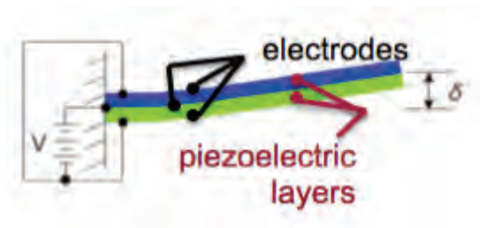
Microvalves have been under development over the past 30 years. However, previous valves can only deliver flow rates on the scale of milliliters per minute [1]. The basic concept underlying our novel valve design is illustrated in Fig. 1(a). We have overcome the flow limitation by ganging together an 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 large orifice having equivalent area. Therefore, the concept of parallelizing the flow using multiple miniature orifices and actuators is sound. Also, 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 valve manufacturing when taken to the commercial production scale.

Our valves will utilize a "bimorph" piezoelectric architecture, illustrated in Fig. 1(b). Two layers of piezoelectric material are sandwiched between platinum electrodes. The two layers have the same polarity, but they are subjected to reverse voltages. As a result, the bottom layer expands as the top layer contracts, causing the actuator to deflect as a cantilever beam subjected to pure bending. Alternatively, one active layer can be deposited on a passive layer, which is described as a "unimorph" actuator.

Since the actuators in Fig. 1(a) are connected in parallel, common electrical contact points are used to supply electric current to all actuators simultaneously. As the supply current is increased, deflection of the actuator pallets increases, thereby increasing the flow rate. Proportional control could also be achieved through a digital wiring scheme which fully opened sub-groups of actuators in binary combinations.



(a) Basic device architecture.



(b) Structure of a "bimorph" 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, first to Year 7-8 and then again to Year 9-10. Accomplishments during the first four years include: performing a literature review on pneumatic MEMS valves [1], constructing an ISO 6358 compatible [6] test stand, demonstrating the valve concept on a "meso-scale" version of the MEMS valve, integrating a capacitive displacement sensor on the meso-scale valve, developing a compressible flow model with improved ability to model valve flow at low displacements, and fabricating and testing early prototype MEMS scale port plates. The "meso scale" valve utilizes a commercially available 35 mm X 12.7 mm X 2 mm piezobender. It served to demonstrate the remarkably low power consumed by piezoelectric actuators, both at the macro- and micro-scale.

The most notable previous achievement was fabricating a functional MEMS unimorph actuator array in year 8. Unimorphs are simpler to fabricate than bimorphs, but they suffer from lower force or deflection for the same applied voltage. They were fabricated as a stepping stone toward bimorph fabrication in Year 9. Our actuator arrays utilize PZT as the piezoelectric material due to its outstanding piezoelectric coefficient, a measure of tip deflection per unit voltage applied. A related notable achievement was establishing a relationship with the only facility in the United States that can fabricate thin film PZT for MEMS on a contract basis: the Nanofabrication Lab of Pennsylvania State University (PSU) [7,8]. All of our MEMS actuator arrays are fabricated at that facility.

Achievements in the past year

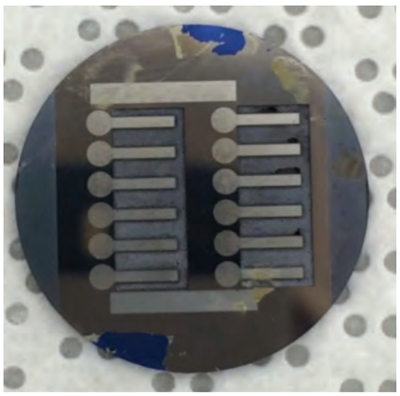
Achievements in the time period between February 1, 2014 and January 31, 2015 include:

- The first successful bimorph MEMS actuators were fabricated in May 2014 (see Fig. 2). The actuators demonstrated substantially larger deflection than unimorph actuators fabricated in 2013 (480 μm vs. 84 μm)[1] at a lower actuation voltage (12 V vs. 40 V).
- Three wafers of bimorph actuators, each containing 14 devices, were fabricated between August and December 2014[2] (see Fig. 3(a)). These are our first wafers to contain multiple types of devices. The

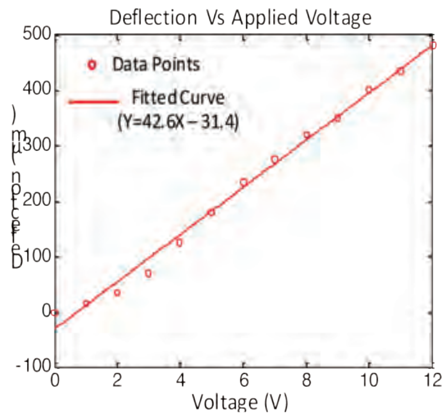
[1] A portion of the improvement in deflection is attributable to better control of the etch depth of the silicon base wafer, as described in the last achievement bullet.

[2] The four month development time was due to a series of unanticipated fabrication problems arising at the PSU Nanofabrication Lab. The most serious was delaminating of the device layers, which was apparently caused by high environmental humidity at the time the PZT layers were deposited on the wafers.

multiple devices enable us to experiment with different actuator geometries efficiently. A key indicating the different device types is provided in the Figure. Actuators on "pre-wired" devices are connected to device-wide electrode busses upon fabrication. Actuators on "wire bonded" devices are not. The latter style provides for leaving individual actuators disconnected from the main device bus in the case that shorting occurs between the electrodes of any actuators. This problem has occasionally occurred on previous actuator arrays, thereby disabling the entire array. However, connecting every actuator individually is labor intensive, so the pre-wired style is preferred in the case that the devices are free of shorting.



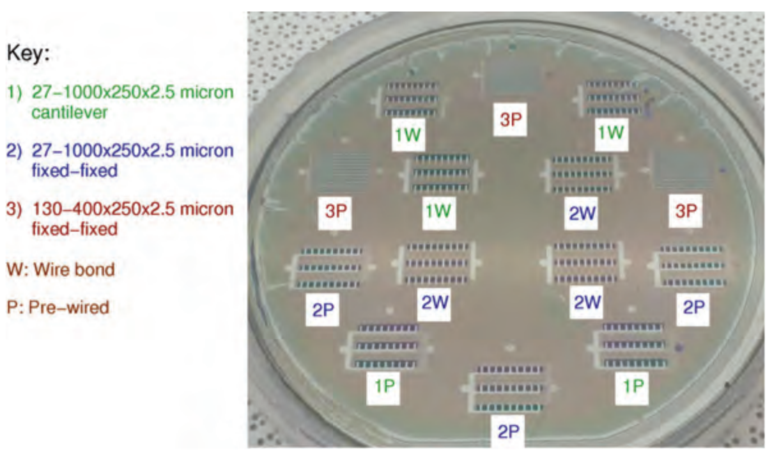
(a) View of top of device.



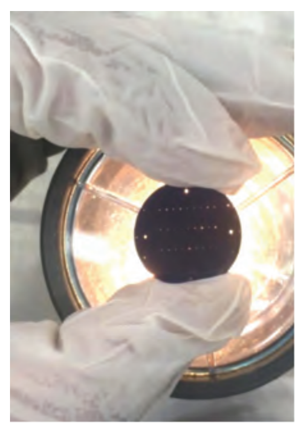
(b) Deflection vs. actuation voltage.

Figure 2. First working bimorph actuator array (May 2014).

- Three different styles of port plates were designed to match the actuator geometries listed in Fig. 3(a) (see an example in Fig. 3(b)). The first style contains 27-80 μm orifices, the second contains 27-29 μm orifices and the third contains 130-29 μm orifices. They are designed for modular combination with actuator arrays where possible; for example, any of actuator styles 1P, 1W, 2A or 2W (see Fig. 3(a)) can be combined with either style of port plate containing 27 orifices. This provides a wide variety of potential valve geometries with different pressure and flow capacities. A total of 27 port plates were then fabricated.



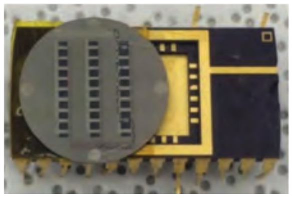
Wafer including 14 devices of 5 different types



(a) Sample port plate: 27-Φ80 μm orifices

Figure 3. Examples of full MEMS wafer and port plate fabricated in Fall 2014.

- The new actuator arrays include the first attempts at actuator geometries which are not cantilever beams. Specifically, some of the actuators utilize fixed-fixed beams, which introduce the possibility of generating substantially higher forces (at the expense of lower deflection).



Device mounted to standard 24-pin package.

Deformation of piezobenders (visible as warping of center of beams).

Figure 4. Testing of first style "2P" device harvested from the wafer illustrated in Fig. 3(a).

- The first device successfully harvested from the December 2014 wafers was tested in January 2015 (see Fig. 4). A deflection of the fixed-fixed beams of approximately 30 μm was observed before a wire bond between a main device bus and a supporting package separated.
- Several compounding drift problems that had plagued the electronics of our ISO 6358-compatible test stand were tracked down and resolved. The stand is now being utilized to fully map the performance of the meso-scale valve described in previous years. It can also now be used to test complete MEMS valves as they become available.
- We have previously reported on difficulty etching precisely through the 500 μm thick silicon wafer, which provides the foundation to our MEMS valves, to release approximately 2 μm thick actuators. New processing methods have been developed to overcome this problem[3].

C. Plans

<u>Plans for next year</u>

Plans for February 2015-January 2016 are listed in chronological order below:

- Develop processes to align and bond actuator arrays to port plates: Alignment requires accuracy of about 20 μm in the x- & y- directions, 0.5 μm in the z-direction and 0.5° in angular orientation. Three alignment strategies have been considered. The first was to develop our own alignment fixtures, which we abandoned due to the discovery of less resource intensive solutions. The second was to utilize photolithographic contact alignment machines available in the Minnesota Nanofabrication Center, which we abandoned because they are designed to manipulate complete wafers rather than individual devices. We are instead pursuing utilizing a "chip bonding" machine that we have located in a nearby industrial facility. Our current bonding strategy consists of tack-bonding the actuator array to the port plate during alignment, then mechanically clamping the parts together in a clam shell package. We will continue to investigate alternative adhesive bonding solutions.
- Performance map the first complete MEMS pneumatic valve: The first assembled actuator array and port plate package will be mounted in the UMN test stand to enable mapping its flow versus actuation voltage performance.
- Optimize MEMS valve design for application to the Test Bed 6 Ankle-Foot Orthosis: The prototype actuator arrays and orifice plates illustrated in Fig. 3 will have a maximum pressure capacity of 5.5 bar and a maximum flow capacity of 3.7 slpm, which are below the specifications required for the Ankle-Foot Orthosis. Performance parameters determined from the previous test will be integrated with our models to develop a new valve design with higher pressure and flow capacities. Improved prototype valves will then be fabricated.
- Develop leakage strategies: Leakage of the MEMS valves will be studied when the first actuator array/port plate assemblies become available, and the findings will be applied to reduce leakage in future designs.

[3] A 0.5 μm thick SiO_2 layer still remains attached to the bottom of the actuators, but this is less problematic.

- Develop on-board displacement sensing strategies for MEMS valves: As time permits, methods for adding circuitry to the MEMS devices to enable displacement sensing will be explored. The addition of displacement sensing strategies would enable the implementation of MEMS servo-valves.

1. Expected Milestones and Deliverables
   - Demonstrate first complete packaged MEMS device [3/15/15]
   - Demonstrate MEMS pneumatic valve on Ankle-Foot Orthosis (Test Bed 6) [8/31/15]
   - Demonstrate MEMS valve with reduced leakage [1/31/16]

D. Member company benefits

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

E. References

1. Fikru N and Chase, T R A Review of MEMS Based Pneumatic Valves, in press for 52nd National Conference on Fluid Power (Paper 11.2), Las Vegas, NV, March.
2. Kim, H., In, C., Yoon, G., and Kim, J., 2005, "A Slim Type Microvalve Driven By PZT Films", Sensors and Actuators A, Vol. 121, pp. 162-171.
3. Vandelli, N. Wroblewski, D., Velonis, M., and Bifano, T., 1998, "Development of a MEMS Microvalve Array for Fluid Power Control", Journal of Microelectricomechanical Systems, Vol. 7, No. 4, pp. 395-403.
4. Koch, M., A. G R Evans, and A. Brunnschweiler. "Characterization of Micromachined Cantilever Valves." Journal of Micromechanics and Microengineering 221-223 7.1997 (1997): n. pag. Web. 26 Feb. 2014.
5. Lee, Dong Gun. "Large Flow Rate / High Frequency Microvalve Array for High Performance Actuators." Sensors and Actuators 257-263 134.2007 (2007): n. pag. Web. 26 Feb. 2014.
6. 2011ISO 6358:1989(E), Pneumatic fluid power – Components using compressible fluids – Determination of flow-rate characteristics, First edition, 1989-10-01.
7. Yang, E-H., Hishinuma, Y., Cheng, J-G., Trolier-McKinstry, S., Bloemhof, E., and Levine, M-B., 2006, "Thin-Film Piezoelectric Unimorph Actuator-Based Deformable Mirror with a Transferred Silicon Membrane", Journal of Microelectromechanical Systems, Vol. 15, pp. 1214-1225.
8. Sanchez, L., and Polcawich, R., 2008, "Optimization of PbTiO3 Seed Layers for PZT MEMS Actuators", Army Research Laboratory, ARL-TR-4697.

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

Research Team

Project Leader:	Elizabeth Hsiao-Wecksler, MechSE, UIUC
Other Faculty:	Girish Krishnan, Industrial & Enterprise Sys Eng, UIUC
	Sameh Tawfick, MechSE, UIUC
	Placid Ferreira, MechSE, UIUC
	Brooke Slavens, Occupational Sci & Tech, UW-Milwaukee
Graduate Students:	Deen Farooq and Gaurav Singh, UIUC
Undergraduate Students:	Chenzhang Xiao, Ye Oo, Michael Rouse, UIUC
Industrial Partners:	Enfield Technologies, Parker Hannifin

1. Statement of Project Goals

This newly-funded project has two main goals: to develop novel high-force, energy storing, miniature soft pneumatic actuators, and to directly integrate them as the structure for soft robotic upper extremity orthoses for pediatric patients that use crutches for ambulation. While walking with crutches, peak loads observed in the wrist typically approach 50% of body weight and wrist postures experience extreme extension angles ~35° (Fig. 1) [7-9]. 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; therefore lowering the risk for joint injury such as carpal tunnel syndrome, while allowing for normal wrist and arm range of motion when not used for load bearing. 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) [5]. We will expand the range and functionality of current contracting McKibben muscles, which are based on simple equal and opposite fibers, by developing a robust analysis framework to generalize the construction and operating principles for FREE actuators to yield different deformation patterns. Further, we will develop a new manufacturing process where flat elastomeric sheets patterned with variable angle vascular microchannels and high strength fibers will be rolled into generalized FREE actuators to provide higher energy density at the same operation pressure and additional deformation patterns: expansion, rotation, and spiraling snake-like motion to produce compressive forces, torque, and constriction forces, respectively.

(a) (b)

Figure 1: (a) Crutch user during swing-through gait [Slavens, 2009]. (b) Hyper-extension wrist posture

2. Project Role in Support of Strategic Plan

The development of miniature soft pneumatic actuators and soft pneumatic arm orthosis directly address one of the 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 the nine technical barriers to fluid power: compact energy storage (5), compact integration (6), safe and easy-to-use (7), and quiet (9). Further, the pediatric 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 orthosis. The testbed for this application will focus on developing a lightweight soft wrist orthosis for pediatric patients that use crutches for ambulation. The repetitive, high loads and poor wrist postures associated with crutch use have been shown to lead to joint pain and injury, carpal tunnel syndrome, arthritis, or joint deformity. Currently, the natural progression finds pediatric crutch users often transitioning to using wheelchairs, as their arms cannot support their body weight as they grow and the effects of these secondary injuries become unsustainable. This transition reduces mobility, fitness, and quality of life. Creating an effective orthosis would be beneficial for these pediatric patients or any assistive mobility device users, whom are susceptible to overuse injury and pain (those with acute limb injury or surgery, elderly, adult pathology populations).

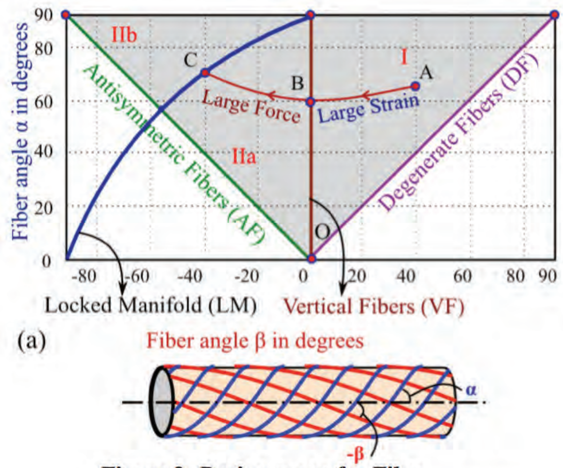


Figure 2: Design space for Fiber-Reinforced Elastomeric Enclosure (FREE) actuators based on fiber orientation angles.

The key enabling building block for soft pneumatic actuators in this projects are known as Fiber Reinforced Elastomeric Enclosures (FREEs) as shown in Fig. 2. FREE actuators are inspired in operating principle and construction by Pneumatic Artificial Muscles (PAMs) or McKibben's actuators. This project aims to expand the capabilities of McKibben actuators by generalizing its construction and operating principle to yield different deformation patterns. A FREE actuator has two families of helical fibers with arbitrary orientation reinforced on a hollow elastomer tube that is actuated by pressurized fluid (air or liquid). The orientation or the helical angles of the two families of fibers α and β respectively, span the design space of FREE actuators as shown in Fig. 2 [5]. The popular configuration of McKibben actuators spans just a line (shown in green in Fig. 2 as Antisymmetric fibers). FREEs can have different deformation patterns such as pure extension, contraction, axial rotation and more generally a screw motion or simultaneous translation and rotation [1, 5]. These deformation patterns are co-related to the fiber orientations using the kinematic governing equations that result from the inextensibility of fibers.

This project will conduct the research necessary to develop working prototypes of the soft pneumatic actuators (Task 1) and pediatric wrist orthosis (Task 2).

In Task 1, we will leverage the understanding of generalized FREE actuators to create novel building blocks and structural embodiments for soft exoskeletons. We will first develop a robust analysis framework to evaluate forces exerted and the stiffness of different FREEs constructions as functions of applied pressure. This framework will be used to evaluate and objectively compare various design concepts and optimize the design to match functional requirements. We will explore the development compact fluid powered torsional actuators, which will be optimized to maximally overcome the trade-off between maximum angular displacement and obtained moment. We will also explore the use a generalized FREE actuator in conjunction with a compliant MEMS spring as an energy storage unit or accumulator. The compliant MEMS spring can be designed to have a specified nonlinear force vs. displacement behavior to control the energy release rate. We will develop a new diverse manufacturing process to enable the systematic miniaturization of FREE actuators to < 100 μm diameter with tunable fiber orientation in a time and labor efficient process.

In Task 2, the actuators will undergo bench-top testing and will be integrated into multiple generations of wrist orthoses for improved performance. Product design and user operational specifications will be assessed. We will determine appropriate operational specifications for user safety, comfort and efficiency. The wrist orthosis will be tested on able-bodied adults and children during Lofstrand crutch mobility. Time permitting, testing will extend to children with orthopedic disabilities.

B. Achievements

This new project was funded starting in 6/1/14. Work to date has resulted in four invention disclosures [2-4, 10] and one conference presentation [6].

Task 1 (Soft FREE Actuator Design and Manufacturing):

We have developed a method to analyze the large deformation behavior of FREEs. This methodology aspires to maximally decouple the kinematics and kinetostatics, without the compromising on the accuracy of the deformed shape including the stroke length and axial rotation. This allows us to determine the actuator's deformation behavior (Fig. 3) without considering material properties, thereby making the analysis simpler and more suitable for extending to design. A FREE is essentially a cylindrical hyperelastic membrane with two families of inextensible fibers wound helically on its outer surface. Upon pneumatic actuation, the actuator tries to maximize its enclosed volume while the fibers maintain their constant length. Therefore, we have posed the analysis as a volume maximization problem with constraints due to the inextensibility of fibers.

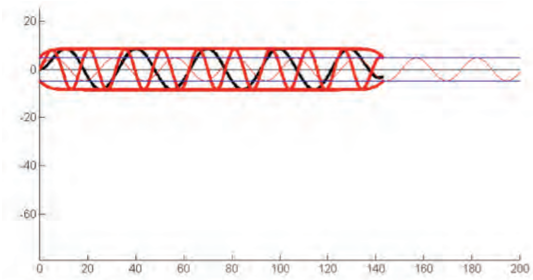


Figure 3: Deformed (red and black) and undeformed (blue and red) shape of a rotational FREE

After carrying out the kinematic analysis, we have added the material model of the hyperelastic membrane to carry out the elastokinetic analysis of the actuator. This analysis allows us to obtain force vs displacement and torque vs rotation relationships (Fig. 4), when the actuator is pressurized to different pressures. While this offers an alternative, yet faster technique to analyze McKibben actuators (Fig. 4a), which have well-established mechanics-based models in literature, it also analyzes FREEs with asymmetric fiber angles for which there are no known models (Fig. 4b). These plots can be used to redesign the FREE geometry and the material for a specific stroke and force requirement.

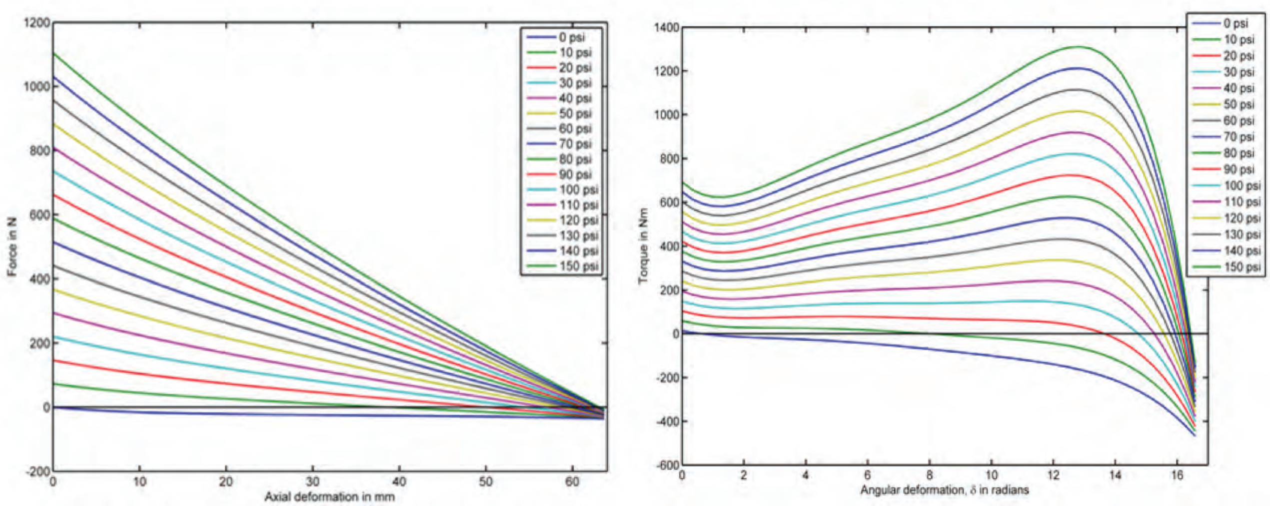


Figure 4: (a) Force vs displacement data at different actuation pressures for a contracting FREE actuator. (b) Torque vs angular deformation data at different actuation pressures for a rotational FREE

We have built upon an existing macro-scale manufacturing process of FREEs. This process involves embedding fiber networks on latex elastomer tubes. A binding agent such as rubber cement is used to adhere the fibers to the elastomer. One end of the tube is rigidly shut with end caps and the other is fixed to an air hose using appropriate fittings. Once manufactured, we experimentally tested the deformation behavior of the actuators and compared it with finite element analysis. Our emphasis was to test the stroke and the fiber orientations throughout the range of the FREE deformation space and found good agreement between the various analysis models for a rotating actuator (Fig. 5) and the fiber orientations throughout the range of the FREE deformation space and found good agreement between the various analysis models for a rotating actuator (Fig. 5).

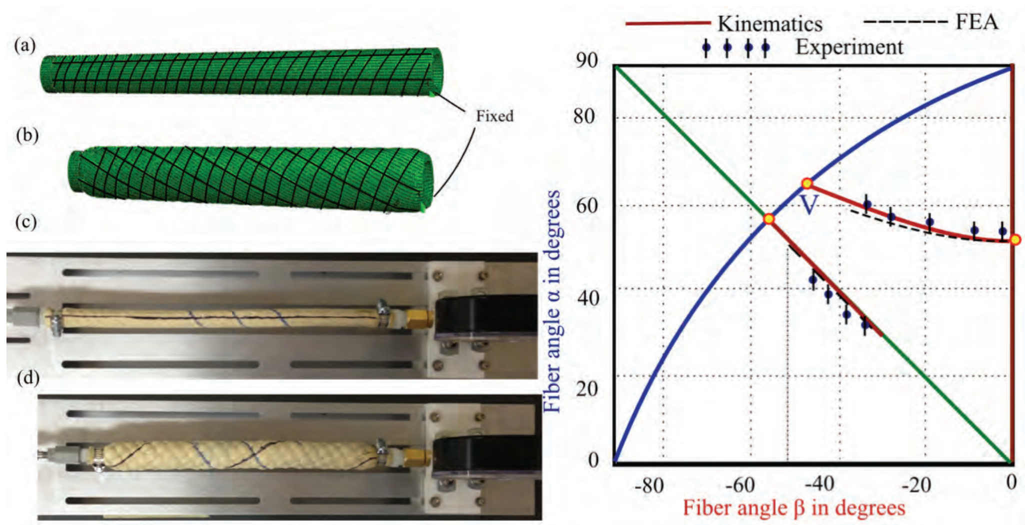


Figure 5: Finite element analysis of the (a) underformed,and (b) deformed and experimental testing (c) underformed and (d) deformed fiber angle orientations of a rotational FREE. These angles are also plotted in a FREE design space that spans the two fiber angles.

We are working on a new manufacturing process to enable the systematic miniaturization of FREE actuators as well as the quick prototyping of highly complex fiber architectures. During the past year, we were able to fabricate a 1x1" coupon with complex internal stiff ribs. (Fig. 6) This design was done using Kapton sheets as the stiff layers, and 3M VHB tape as the soft elastomeric layers. Both were cut using CO2 Laser cutters and laminated and sealed by the double sided acrylic tape. Challenges: Sealing the very small ribs (< 1 mm width) remains a challenge and eventually the sealing fails.

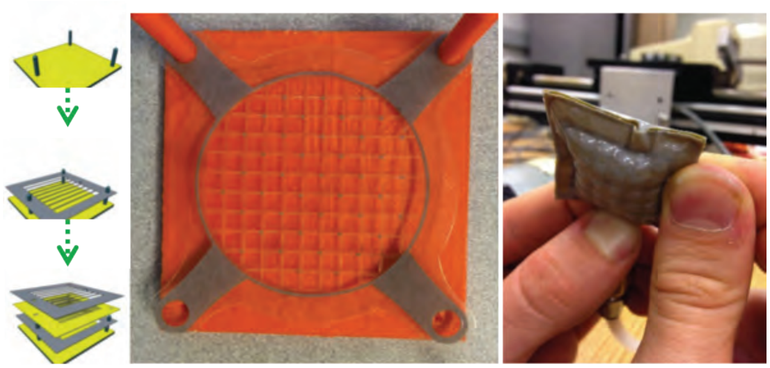


Figure 6: Flat actuator made by stacking and sealing alternating layers of Kapton sheets and 3M VHB tape.

Also we realized that the minimum realistic feature size with the laser cutter is 1mm. We are currently using this technique to make larger size flat McKibben like actuator that can curl when pressurized to be fixed to the crutch bracket. We believe that the sealing challenges will be overcome by making the rib size > 5mm. We expect to have a first prototype in May 2015.

Task 2 (Wrist Orthosis Prototypes)

To minimize poor joint alignment and loading of the arm during crutch-assisted gait, we have recently proposed orthotic supports to improve wrist posture and transfer loading from the hand and palm to the forearm during forearm, or Lofstrand, crutch use. We realized that to prevent wrist hyper-extension and maintain neutral wrist orientation, it was not necessary to create a powered orthosis to orient and maintain wrist posture. Rather, a simple, lightweight, inexpensive, passive wrist support has been designed (Fig. 7a) [3]. This design can be easily retrofitted to any crutch and does not require the arm to be secured to the crutch; thereby allowing immediate freedom of arm movement when not used for ambulation. To reduce loads transmitted to the hand and arm, a powered soft pneumatic sleeve orthosis has been proposed to partially transfer loading to the forearm (Fig. 7b) [2]. This sleeve takes advantage of the soft and pliable yet strong FREE actuators (Fig 7c). By attaching to the crutch cuff, the sleeve and wrist support allow the hand and arm free movement for reaching, similar to a traditional crutch design.

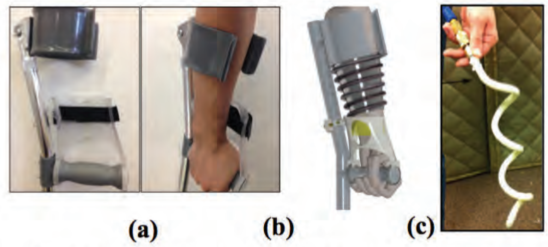


Figure 7:. (a) Passive wrist support
(b) Proposed soft pneumatic sleeve orthosis
(c) FREE actuator that coils when powered by air

To power the pneumatic sleeve, we are also pursuing the harvesting of pneumatic energy during ambulation by designing a pneumatic pump mounted in the tip of the crutch (Fig. 8) [4]. The harvested gas can be used as a replacement to an external pneumatic power supply or as a supplement to such a power supply. The pumping action will also provide shock absorption and added compliance to the crutch to improve user comfort.

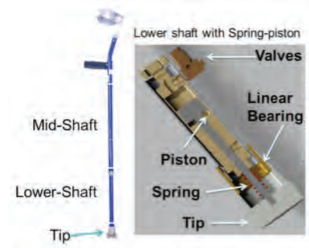


Fig 9. Pneumatic power harvesting with crutch tip

Plans for the next year.

Task 1.a: Design of FREE actuators

a. Design customized FREE actuators, whose kinematics maximizes area of wrap around the proposed pneumatic sleeve.
b. Extend FREE analysis models to estimate and optimize wrapping force on the sleeve.

Task 1.b: Manufacturing of FREE actuators

a. Get flat actuator to work on larger sizes to use it as the actuating sleeve and fit it to the bracket of the crutches
b. Work on developing micro- soft actuators by making silicon microfabricated molds in the cleanroom.

Task 2: Develop orthosis prototypes

a. Design and test Gen 1.0 pneumatic sleeve and passive wrist support with crutch tip pump on bench and on healthy subjects
b. Refine design and test Gen 2.0 design on bench and on healthy subjects

Expected milestones and deliverables.

Task 1.b. Design of FREE actuators

- First design of FREE wrapping actuators on a sleeve (March 2015)
- Analysis tools to estimate wrapping kinematics and force (August 2015)
- Optimization and redesign (October 2015)
- Scaling down the FREE actuators and evaluating its functional implication (January 2016)
- A user-interactive FREE design tool (February 2016)

Task 1.c. Manufacturing of FREE actuators

- First prototype made by undergraduate assistant for flat sleeve (~10x10" size) (May 2015)
- Second prototype by (August 2015)
- For the micro actuators, done with micro-fabricated molds (Oct 2015)
- Start fabricating the actuators (August 2015)
- Testing of micro actuators will begin (February 2016)

Task 2: Develop orthosis prototypes

- Complete tip pump and Gen 1.0 prototype sleeve designs (May 2015)
- Complete passive wrist support testing (June 2015)
- Complete Gen 1.0 healthy testing by (August 2015)
- Complete Gen 2.0 prototype sleeve design (Oct 2015) and healthy testing by (May 2015)

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. The manufacturing processes will allow for possible automated fabrication approaches and customizable actuators. 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.

D. References [* supported by CCEFP NSF funds]

1. Bishop-Moser, J., Krishnan, G., Kim, C., & Kota, S. Design of Soft Robotic Actuators using Fluid-filled Fiber Reinforced Elastomeric Enclosures in Parallel Combination, ,in proceedings of the IEEE International Conference for Intelligent Robot And Systems (IROS), Vilamoura, Algarve (Portugal), October 7-12, 2012.
2. Hsiao-Wecksler, E.T., Farooq, D., Krishnan, G., Singh, G., Tawfick, S.H. "Soft Pneumatic Sleeve Support for Lofstrand Crutch Users", Invention Disclosure submitted October 10, 2014a.
3. Hsiao-Wecksler, E.T., Farooq, D., Xiao, C. "Passive Wrist Support for Crutch Users", Invention Disclosure submitted October 10, 2014b.
4. Hsiao-Wecksler, E.T., Farooq, D., Xiao, C., Oo, Y.L. "Harvesting Pneumatic Energy for Crutch Users", Invention Disclosure submitted October 10, 2014c.
5. Krishnan, G., Bishop-Moser, J., Kim, C., & Kota. Evaluating the Mobility Behavior of Fluid Filled Fiber Reinforced Elastomeric Enclosures, proceedings of the 2012 ASME-IDETC/CIE, Chicago, IL, August 15-17, 2012.
6. Singh, G., Farooq, D., Hsiao-Wecksler, E.T., Krishnan, G., Tawfick, S.H. “Soft pneumatic actuator for arm orthosis,” in 1st Fluid Power Innovation and Research Conference, Nashville, TN, Oct 13-15, 2014.
7. Slavens, B.A., Sturm, P.F., Bajorunaite, R., Harris, G.F. Upper extremity dynamics during Lofstrand crutch-assisted gait in children with myelomeningocele. Gait and Posture 30, 511–517, 2009.
8. Slavens, B.A., Sturm, P.F., Harris, G.F. Upper extremity inverse dynamics model for crutch-assisted gait assessment. Journal of Biomechanics 43 (10), 2026–2031, 2010.
9. Slavens, B.A., Schnorenberg, A., Graf, A., Krzak, J., Smith, P. and Harris, G.F. Assisted Mobility Device Usage in Pediatric Orthopaedic Disabilities. Presented at the American Academy of Cerebral Palsy and Developmental Medicine (AACPDM) as part of Preconference Workshop 3: New Clinical Horizons and Emerging Mobility Technologies-A Research Driven Process. October 16-19, 2013.
10. Tawfick, S.H. and Ferreira, P. “Invention disclosure: Soft actuator from layered and rolled-up sealed films,” October 10 2014.

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

Research Team

Project Leaders:	Robert Webster and Eric Barth, Mechanical Engineering, Vanderbilt Jun Ueda, Mechanical Engineering, Georgia Tech
Other Faculty:	Vito Gervasi, Rapid Prototyping Center, MSOE
Graduate Students:	David Comber, Vanderbilt Melih Turkseven, Lauren Lacey, Euisun Kim, Georgia Tech Charles Williams, MSOE
Undergraduate Student:	Ilya Kovalenko, Georgia Tech
Summer REUs:	Emily Matijevich, Vanderbilt; Johnathan Williams, Georgia Tech
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 will develop 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 9

MRI-compatible Actuators and Surgical Robots

Invention of novel, non-invasive approach to access and treat the hippocampus

Together with our collaborating neurosurgeon at VU Medical Center, we have designed a radiofrequency (RF) ablation electrode and an accompanying concentric tube needle [3]. This device is designed to enable a novel, non-invasive access path through the foramen ovale, a natural opening in the skull base at the top of the patient's cheek. This access path is a new approach and is highly advantageous since the soft tissue will seal the access path and prevent contamination of the brain through it. Our new steerable needle system will provide a percutaneous treatment by deploying through a straight outer cannula, which is manually inserted beneath the cheek skin and docked to the foramen ovale. A helically curved, shape-memory alloy needle, actuated at its distal end by a precision pneumatic robot, will maneuver the RF ablation electrode from the foramen ovale to and through the hippocampus from head to tail. MR imaging and thermometry will guide the needle along the planned path, and monitor the delivery of thermal ablative therapy.

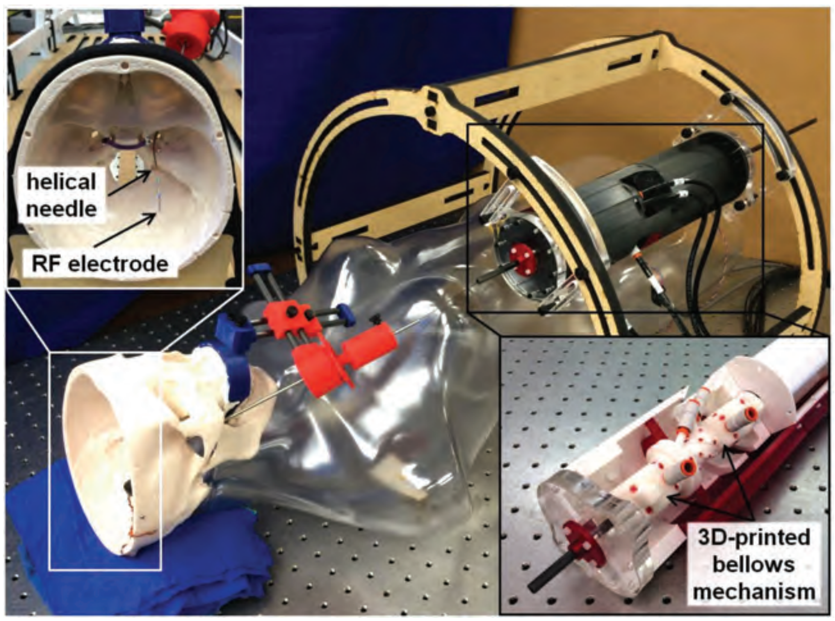


Figure 1. 3D-printed robot and outer cannula fixture are compactly positioned with a patient manikin. This layout fits inside an MRI magnet opening of 60 cm

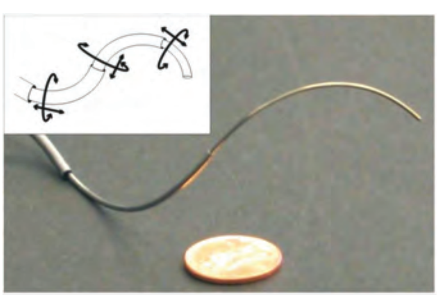


Figure 2. Steerable needle of concentric, telescoping, curved elastic tubes.

Our work has resulted in mature hardware, and the complete system to enable the transforamenal ablation approach consists of a precision pneumatic robot, mounting devices, a robotic steerable needle, and MRI guidance. Using existing prototypes, the photograph in Fig. 1 portrays the general layout we envision for positioning the robot inside the MRI scanner with the patient. It should be noted that all components in Fig. 1 are functional and are not mock-ups. The robotic steerable needle idea that enables our proposed transforamenal ablation approach is the concentric tube needle concept (see Fig. 2). The needle is made from several nested tubes that telescopically extend from one another. Because each individual tube is curved and made of shape-memory alloy (nitinol, the same alloy used in cardiac stents), the needle can bend controllably when axial insertions and rotations are applied at tube bases.

Invention of intrinsically-safe, MRI-compatible pneumatic stepper actuator

For traditional piston-cylinders, there are failure contingencies in which the piston could travel the full stroke of the cylinder and potentially endanger the patient. Therefore, we have created our own fluid power actuator that is intrinsically safe and MRI compatible. Building upon prior results of the Project 2G collaboration between Vanderbilt and MSOE [5], this prototype was jointly designed at both institutions by a novel approach for manufacture by selective laser sintering (SLS); this additive manufacturing process enabled compact integration of actuator components, resulting in a small footprint for the device, shown in Fig. 3. It is designed to both translate and rotate the base of a single tube of the steerable needle. Because the steerable needle is made of multiple, nested tubes, the actuator design is modular, allowing for several modules to be cascaded together, one for each tube of the needle. Employing an inchworm-like behavior, the actuator translates and rotates the needle bi-directionally in discrete steps, and is thereby intrinsically safe. When inflated, one bellows expands linearly to translate the needle, and another bellows expands rotationally to exert torque on the needle. These forces and torques are imparted to the needle using diaphragm-actuated clamps that, when inflated, firmly grasp the needle. The actuating bellows and gripper diaphragms were manufactured as a single assembly on an SLS machine at MSOE. They are hermetically sealed (i.e. no sliding seals) to prevent contaminants such as blood or cerebrospinal fluid from entering pneumatic circuitry. A provisional patent on this invention was jointly filed by Vanderbilt and MSOE [6]. Building upon prior work in Project 2G on precision pneumatic controls for MRI-compatible devices [9-12], a novel hybrid controller for the pneumatic system was designed and tested. As shown in Fig. 4, this controller has demonstrated precision positioning of the needle: 0.013 mm and 0.29 degrees.

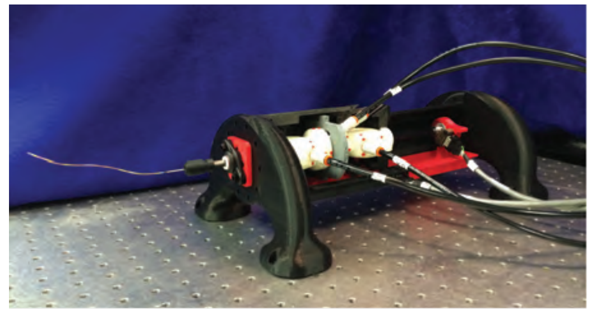


Figure 3. Prototype with helix-shaped concentric tube needle. One half of the device housing is not shown, to expose inner working parts.

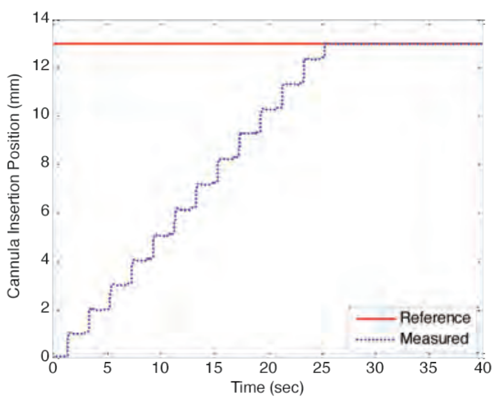


Figure 4. Hybrid control of needle insertion to reference depth. Steady state error: 0.013 mm.

Rehabilitation via Pneumatically Driven MRI-Compatible Systems

Pressure Observation for Tele-Operated Pneumatic Systems Using Force Sensor

Prior studies at Georgia Tech, made in Y8, have depicted the key factors that characterize the pressure dynamics of the actuator. A long transmission line induces a delay in mass transportation and introduce a pressure gradient through its length. MRI compatible pneumatic actuators have low friction; yet, they present a significant gas leakage and resistance at the connection ports which lead to an important difference between the valve and actuator pressures that could potentially destabilize the closed-loop control. An accurate feedback on the actuator pressure states is crucial for high-bandwidth operations that involve human interaction [14].

A non-linear, asymptotically stable pressure observer that utilizes interaction force measurements for error correction was proposed and tested in Y9 [18]. 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 7, 13]. The goal of the proposed observer is to provide accurate pressure estimations where standard pneumatic system modeling methods fail to characterize the system dynamics. Primarily the systems with complicated pneumatic hardware, such as MRI compatible robots, are targeted.

The accuracy of the observer was verified by performing typical force control experiments on a typical tele-operation setup with 7.25 meters long transmission line. Comparisons were made between the proposed observer and the following two conventional approaches: Pressure measurements at the valve and a standard pneumatic system model. The valve is the only location for pressure measurement on a typical MRI-compatible system. The standard model does not involve any form of feedback and estimates the chamber pressures in a purely open-loop manner.

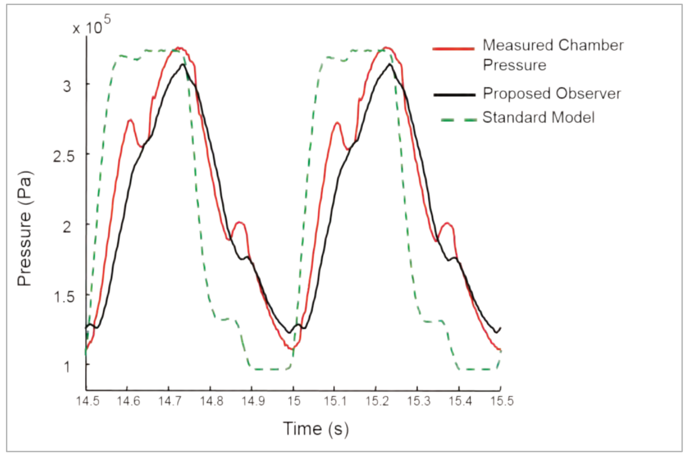


Figure 5. Pressure Estimations vs. True Actuator Pressure

The proposed observer based on force sensing achieves a quick response and substantially reduces the estimation errors in the transient phase. This improvement can be observed in Fig. 5 where the transient pressure fluctuations during a 2 Hz force controlling experiment are shown. The time delay and attenuation in the mass flow rate introduced by transmission lines are not captured by the standard model as expected. The observer attained a more accurate estimation, enforcing the estimation to satisfy the measured actuator force.

	Mean Squared Error (J^2/sec)		
	Valve Pressures	Standard Model	Proposed Observer
1 Hz Force Control	5.068	6.47	**3.213**
2 Hz Force Control	30.55	31.12	**3.769**

Table 1 - Averaged Sum of Squared Errors in the State Variables [18]

Estimation performances are evaluated quantitatively by the averaged sum of squared errors (MSE) in the potential energy within one cycle in the steady-state condition. Table 1 presents the calculated errors (MSE) for each method and indicates a significant improvement in the estimation accuracy by the use of the observer. In the presence of such factors, the observer based on force sensing appears to be beneficial and effective in reducing estimation errors.

<u>Modeling of pneumatic line transmission delay and attenuation:</u>

In addition to novel methods for pressure observation, a pneumatic system model, exclusively developed for tele-operated systems, has been established in Y8 [16]. The transmission line and the actuator were regarded as two separate chambers serially connected to the valve. It improved the accuracy of system characterization, which is projected to be used on non-linear controllers. The impact of the proposed model was observed on fixed-volume chamber tests with a 7.25 meters long tube up to 1 Hz valve input signal. In Y9, the accuracy of the model was further improved by accounting the friction on the transmission lines. This extended model was shown to maintain its accuracy up to 5 Hz, as shown in Fig. 6 where the model's pressure estimation is compared to that of the standard model.

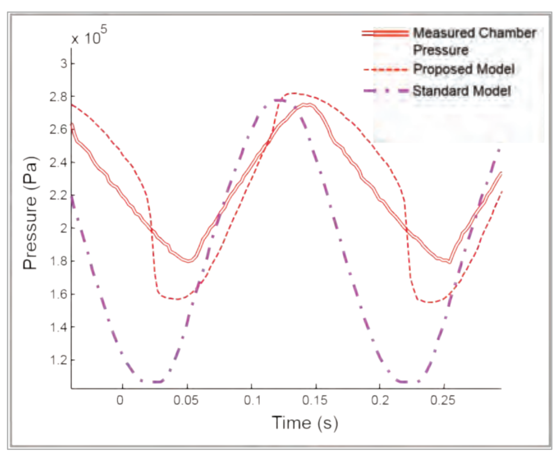


Figure 6. Pressure estimated by the developed model

Facilitation Exercise using a Pneumatic Device

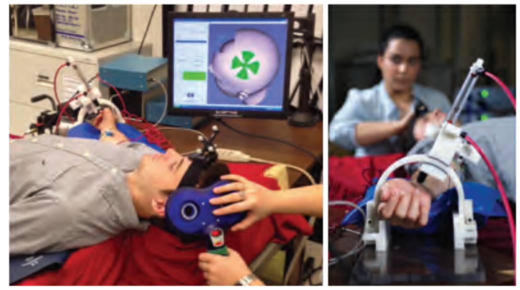


Figure 7. TMS tests with the developed MRI-compatible prototype

An fMRI-compatible rehabilitation device with a pneumatic tendon hammer has been designed in Georgia Tech to study the neural mechanisms of Repetitive Facilitation Exercise (RFE) [8, 15]. The developed system facilitates a myotatic reflex by applying a mechanical impact in synchronization with the patient's intention to move the hemiparetic limb. An MRI-compatible rotary actuator for wrist pronation was designed and integrated to the developed prototype to enhance its functionality [17]. Timing precision of the new system was confirmed to be satisfactory for RFE which is a reflex-based facilitation therapy that requires a high temporal precision. Following MRI-compatibility checks and preliminary conceptual tests that have started in Y8, studies on human subjects have started in Y9. The functionality of the device was elaborated on a healthy human subject using transcranial magnetic stimulation (TMS), a magnetic stimulator that generates a local neural signal on the subject's brain [16, 19]. The device was shown to provide a satisfactory temporal precision for inducing a reflex signal synchronized to the TMS related weak neural activity, confirming its suitability for the intended therapy.

Plan for next 2 years

The MRI scanners at Vanderbilt University Institute for Imaging Science (VUIIS) are available to all CCEFP investigators as Test Bed β, a zero maintenance, zero capital investment test bed. PIs Webster and Barth will continue collaboration with Dr. Joseph Neimat, a neurological surgeon at VU Medical Center, for clinical insight and guidance of the surgical robot project, and full integration of the surgical robot with Test Bed β. PI Ueda has been collaborating with Dr. Shinohara in Applied Physiology at GA Tech and Dr. Butler at Georgia State University so that project results can be seamlessly transitioned to clinical settings. Results may also be applicable to PI Ueda's stroke rehabilitation robot project in collaboration with Drs. Kawahira and Shimodozono at Kagoshima University, who invented a new therapeutic procedure for hemiplegic limbs. Study on the neuroscientific aspect of the rehabilitation procedure is currently supported by the Georgia Tech Neuro Engineering Center Seed Grant Program. Outcomes of this project will be used to improve the design of the rehabilitation robot. PI Ueda has submitted a NSF Smart and Connected Health (SCH) grant proposal with Drs. Shinohara, Butler, and King to characterize the neural facilitation during the robotic rehabilitation using fMRI. Furthermore, PI Ueda has submitted another NSF National Robotics Initiative (NRI) grant proposal with Drs. Wagner (PI), Borensterin, and Howard to apply the established pneumatic actuation technology to exoskeletons for children.

C. Member company benefits

Among the CCEFP member companies, some valve and actuator companies, including Enfield Technologies, NetShape, Inc; Hoowaki, LLC, have agreed to support the project at VU. In addition, KYB Corporation, a NFPA member, Enfield Technologies and DTI Robotics USA Inc. have agreed to support the project at GT. In addition, PI Ueda visited the KYB Corporation R&D Center, an industry collaborator of this project, and agreed to work with them to investigate the potential of their water hydraulic technology for developing future clean rehabilitation robots. During Y9-10, PIs Webster and Barth will collaborate with Enfield Technologies in the area of precision pneumatic controls research. This collaboration will include an annual working meeting for the team at Enfield's facilities in Shelton, CT.

D. References

1. Jun Ueda and Melih Turkseven, MRI Compatible Force Sensor, Provisional Patent Application, GTRC ID 5652, Filed April 26, 2011
2. Melih Turkseven and Jun Ueda, "Design of an MRI Compatible Haptic Interface," Proceedings of the 2011 IEEE International Conference on Intelligent Robots and Systems (IROS 2011), 2139-2144, 2011.

3. D. B. Comber, R. J. Webster III, E. J. Barth, and J. S. Neimat. “System, Method and Apparatus for Performing Transforamenal Therapy,” Non-provisional patent filed Nov 18, 2014.
4. D. B. Comber, R. J. Webster III, and E. J. Barth, 2013. “Open-Loop Tip Accuracy of an MRI-Compatible Active Cannula Robot,” *The Hamlyn Symposium on Medical Robotics*, London
5. D. B. Comber, J. E. Slightam, V. R. Gervasi, R. J. Webster III, and E. J. Barth, 2013. “Design and Precision Control of an MR-Compatible Flexible Fluidic Actuator,” *Proc ASME/Bath 2013 Symposium on Fluid Power & Motion Control*, Sarasota, FL.
6. D. B. Comber, E. J. Barth, J. Slightam, and V. Gervasi. “A Modular, Two Degree-of-Freedom, MRI-Compatible Pneumatic Stepper Actuator.” Provisional patent filed Jun 12, 2014.
7. Jun Ueda and Melih Turkseven, "Development of a Pneumatically Driven MRI-compatible Haptic Device," Proceeding of the 29th Annual Conference of the Robotics Society of Japan, International Session, September 7-9, Tokyo, Japan.
8. Lacey L, Buharin V, Turkseven M, Shinohara M, Ueda J. "Control of voluntary and involuntary nerve impulses for hemiparesis rehabilitation and MRI study”, 6th Annual Dynamic Systems and Control Conference (2013).
9. D. Comber, and E. J. Barth. “Precision Position Tracking of MR-Compatible Pneumatic Piston-Cylinder Using Sliding Model Control*”. 2011 ASME Dynamic Systems and Control Conference & Bath/ASME Symposium on Fluid Power and Motion Control.* pp. 1-7, Oct 31-Nov 2, 2011, Arlington, VA.
10. D. B. Comber, D. Cardona, R. J. Webster III, and E. J. Barth, 2012, "Precision Pneumatic Robot for MRI-Guided Neurosurgery," ASME Journal of Medical Devices, vol. 6, p.017587-1, March 2012. Best Paper Award at *2012 ASME Design of Medical Devices Conference*.
11. D. B. Comber, D. Cardona, R. J. Webster III, and E. J. Barth, 2012. “Sliding Mode Control of an MRI-Compatible Pneumatically Actuated Robot”. Bath/ASME Symp. Fluid Power & Motion Control, D. N. Johnston and A. R. Plummer, eds., Centre for Power Transmission & Motion Control, University of Bath, UK, pp. 283-293.
12. D. B. Comber, R. J. Webster III, and E. J. Barth, “Design and Control of a Magnetic Resonance Compatible Precision Pneumatic Robot,” *ASME J Medical Devices*, 8(4):011003-1 to -7, 2014.
13. Melih Turkseven and Jun Ueda, "Analysis of an MRI Compatible Force Sensor for Sensitivity and Precision," IEEE Sensors Journal, Vol.13, No.2, pp.476-486, Feb. 2013.
14. J. Ueda, D. B. Comber, J. Slightam, M. Turkseven, V. Gervasi, R. J. Webster III, and E. J. Barth, 2013. “MRI-Compatible Fluid-Powered Medical Devices,” *Dynamic Systems and Control Magazine*, **1**(2):13-16
15. Lauren Lacey, Arnold Maliki, Debapriya Bhattacharjee, James Veldhorst and Jun Ueda, “Design of MRI-Compatible Hemiparesis Rehabilitation Device,” *ASME Journal of Medical Devices*, 8(2), April 28, 2014
16. J. Ueda, L. Lacey, M. Turkseven, M. Shinohara, A. Maliki, I. Kovalenko, “Robotic Rehabilitation Exercise in Hemiparetic Limbs Based on Functional Synchronization of Voluntary and Involuntary Nerve Impulses”, IEEE International Workshop on Advanced Robotics and Its Social Impacts, 2014
17. I. Kovalenko, J. Lai, J. Williams, A. Maliki, J. Ueda, “Design and Testing of a Pneumatic Hemiparesis Rehabilitation Device for a Neurofacilitation Exercise”, Design of Medical Devices Conference, 2015
18. M. Turkseven, J. Ueda, “An asymptotically Stable Pressure Observer Based on Load and Displacement Sensing for Pneumatic Actuators with Long Transmission Lines”, IEEE Transactions on Mechatronics, submitted in November, 2014
19. J. Ueda, L. Lacey, M. Turkseven, M. Shinohara, I. Kovalenko, E. Kim, F. Sulejmani, “Robotic Neuromuscular Facilitation for Regaining Neural Activation in Hemiparetic Limbs”, ASME 2015 International Design Engineering Technical Conferences (IDETC/CIE), 2015.

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

Research Team

Project Leader:	Wayne Book, Mechanical Engineering, Georgia Tech
Other Faculty:	JD Huggins, Mechanical Engineering, Georgia Tech
	Eui Park, Industrial Engineering, NCAT
Graduate Student:	Samuel Seifert
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.

Achievements in the past year

Simulation Improvement: Head Tracker

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. Problems due to calibration and tracking accuracy arose, and were overcome. 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.

Simulation Improvement: Collision with Physical Environment

During the pilot study for a test designed to quantify the differences between 2D and 3D display, it became apparent that a simulation simplification that was previously ignored needed to be corrected because it was tainting results. This 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 worst culprits were the bins that operators were asked to dump spoil into: because running into the bins offered no impedance, users were not penalized for misjudging the locations of the end effector relative to the bins. The concept behind the 3D TV was that it would give the operators a better sense of where the end effector was in the environment, helping them to avoid running into things and allowing them to complete the same task in less time. To measure that advantage (or lack there of), operators needed to be penalized for running into objects. The implemented penalization is 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 we're 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.

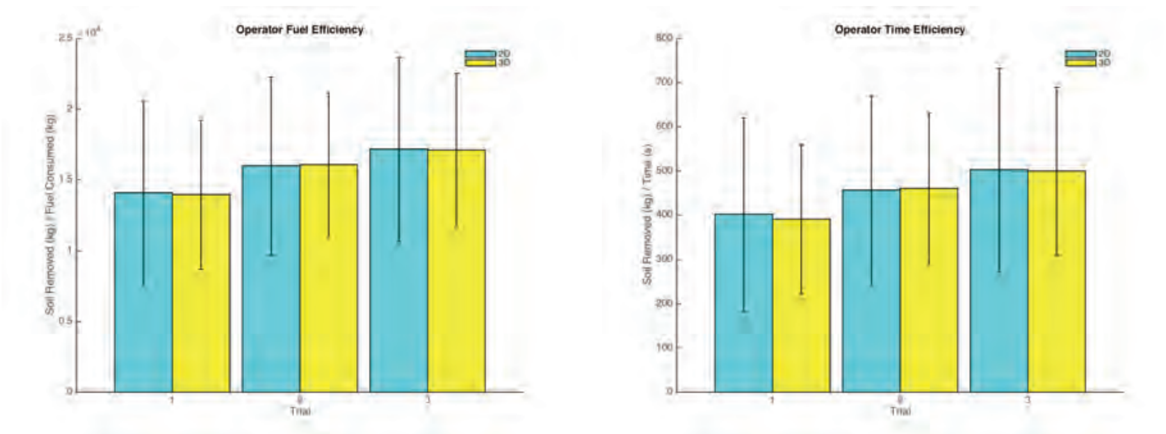


Figure 1: Comparing 2D, 3D Efficiency Metrics

Figure 1 illustrates no conclusive difference between operator performance on 2D and 3D screens. The left to right increase in each graph is associated with the user learning as the session progresses; with each trial the operators perform better and better. The error bars show the standard deviation of each distribution, the giant standard deviations illustrate a large variety in operator skill level. The main takeaways from Figure 1 is that 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.

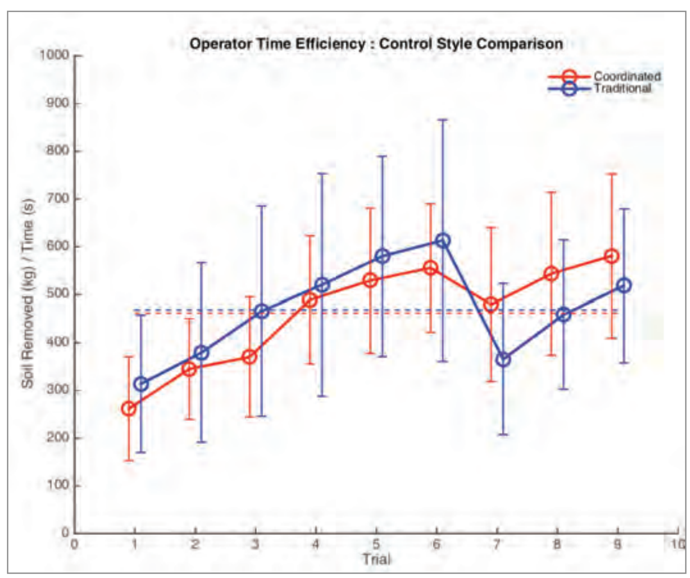


Figure 2: Control Style Comparison

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 2 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.

C. Plans

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

Data analysis for the study that was completed in December is unfinished. Those results will be further analyzed and compared with previous results to draw conclusions about the coordinated rate controller. We are interested in performing a new study that measures operator finesse (as opposed to speed). Details are still unclear, however there is a possibility this study will be performed on live hardware.

<u>Expected milestones and deliverables</u>

1. Paper on benefits of 3D display on excavator simulator
2. Paper on coordinated velocity control of excavator
3. Complete the evaluation of selected coordinated control interfaces
4. Completion of experiments on actual hardware (dependent on coordination with industry and CCEFP test beds)
5. 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.

E. References

1. Lyons, L., Nuschke, P., Jiang, X., “Multimodal interaction in augmented reality of fluid power applications: current status and research perspective”, The 7th Human in Complex Systems and the 1st Topical Symposium on Sensemaking, Greenbelt, MD. November 17-18, 2006.
2. Elton, Mark and Wayne Book, “An Excavator Simulator for Determining the Principles of Operator Efficiency for Hydraulic Multi-DOF Systems,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, March 23-25 2011.
3. Elton, Mark and Book, Wayne, “Comparison of Human-Machine Interfaces Designed for Novices Teleoperating Multi-DOF Hydraulic Manipulators,” 20th IEEE International Symposium on Robot and Human Interactive Communication, Atlanta, Aug. 1-3, 2011.
4. Zhu, M., S. Salcudean, "Achieving Transparency for Teleoperator Systems under Position and Rate Control," Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems, vol.2, pp.7-12, Aug 1995.
5. Kim, W., Tendick, F., Ellis, S., Stark, L., “A Comparison of Position and Rate Control for Telemanipulations with Consideration of Manipulator System Dynamics,” IEEE Journal of Robotics and Automation, vol.3, no.5, pp. 426-436, Oct. 1987.
6. Elton, Mark “Matching Feedback with Operator Intent for Effective Human-Machine Interfaces,” PhD Dissertation, Georgia Institute of Technology, Atlanta, GA, December, 2012.
7. Winck, Ryder C., Mark Elton, and Wayne J. Book. "A practical interface for coordinated position control of an excavator arm." Automation in Construction 51 (2015): 46-58.

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

Research Team

Project Leader:	Steven Jiang, Industrial and Systems Engineering, NCA&T
Other Faculty:	Zongliang Jiang, Industrial and Systems Engineering, NCA&T
	Eui H. Park, Industrial and Systems Engineering, NCA&T
Graduate Students:	B. Jimmerson, D. Davis, D. Stajsic
Undergraduate Students:	A. Bouncer, S. Breeze, K. Sanders

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 play a very important role in fluid power systems ranging from interface design to operator performance and safety. In this project, we studied the impact of the auditory feedback on excavator operator performance and investigated the impact of various factors on nurses operating a patient transfer device. Traditionally, engineers have designed products from a technology-centric perspective. Unfortunately, the technology driven approach has led to information overload and errors causing products to be ineffective [1]. Consequently, operators are usually blamed for 60% to 85% of all accidents [2, 3]. However, accidents/errors are not always the fault of the operator, rather, the design of the product itself [1]. Human factors research has shown that the users' perspective must be included in the design and development process to achieve effective and efficient results [4]. Human performance plays a significant role in overall system performance. This can be evidenced by the patient transfer device. Work related musculoskeletal disorders (MSD) have become a challenge and financial burden for employers in the United States because of the negative impact on worker's compensation claims, absenteeism and productivity. In 2011, MSD accounted for 33% of all worker injury and illness cases reported [5]. Healthcare was the industry with the most reported cases [5]. Since 2006, nursing occupations have been reported as one of the top ten highest risks for work-related MSD in the United States [6]. MSD cases involving patient handling accounted for 98% of all reported cases [7]. 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. The American Nursing Association reported that the lower back followed by shoulders and knees are the most affected body parts when handling patients [8]. The Center for Disease Control reported that lower back injuries are also the most costly MSD [9]. The direct and indirect costs associated with only back injuries in the health care industry are estimated to be $20 billion annually, according to the U.S. Department of Labor [6]. Therefore, with nursing personnel currently leading the nation in work related back injuries, more research is needed to identify and provide safe guidelines for patient handling that will decrease the potential risk of MSDs. The objective of this study is to use the user-centered design (UCD) approach and human

performance modeling tools to gain knowledge about healthcare worker's goals, capabilities, and limitations to design an effective, efficient, and safe patient transfer assist device.
The following approach was used in this study:

1. A user centered design approach was applied:
    - Identified customer needs through observation of expert users and focus group
    - 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. Human performance modeling was applied:
    - Digital human modeling tools, Jack® simulation software with standard tools that use human factors, anthropometry, and physiology of the human body to evaluate the movements a person has been built to conduct a biomechanics evaluation.
    - 3D virtual human modeling + Kinect to mimic work and safety issues

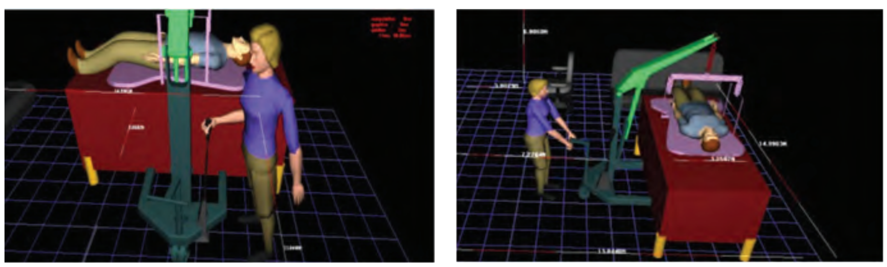


Figure 1: Simulation of caregiver transferring patient from bed using Hoyer lift

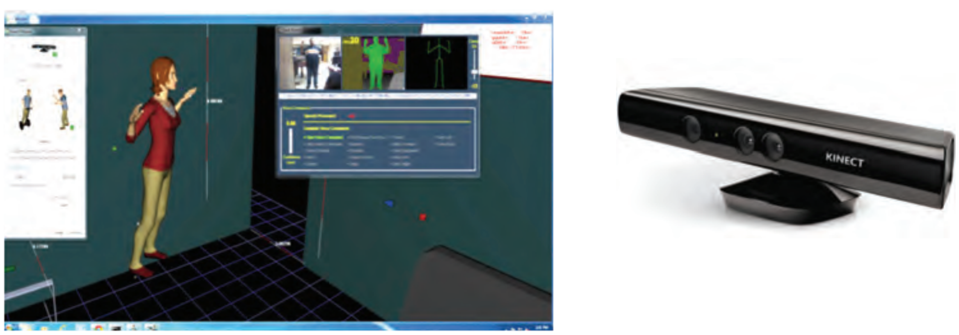


Figure 2: Simulation of Kinect capturing postures in Jack software

B. Achievements

Achievements prior to February 2015:

- Revised haptic-controlled excavator simulator in preparation for the auditory experiment
- Conducted an empirical study on auditory feedback using the simulator
- Conducted literature review on MSDs related to patient transfer
- Conducted task analysis for patient transfer device

- Developed apparatus for patient transfer experimentation
- Conducted an empirical study on patient transfer

Achievements in this reporting period:

- Developed Digital human models to mimic caregivers performing a transfer task
    - **1**. 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 50^{th} Percentile of the male population
    - 2. 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
    - 3. Import CAD drawings of two lift designs
        - Hoyer lift
    - 4. Create Environment
        - 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
    - 5. Use Tool Kit to Collect Data
        - 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

- Environment 1 was populated with the caregiver, the patient, and the bed.
    - Low back analysis from the simulations involving turning the patient to their side revealed the following:
        - The compression forces was as high as 6860 N, which exceeds the maximum permissible limit of safety standard of 6300 N
        - at higher bed heights, pushing the patient produced much more favorable results
        - if pushing the patient is an available option to the caretaker it should be used
        - When pushing the patient, the majority of the load is handled by the shoulders
        - When pulling the patient, additional bend is needed thus causing more low back strain
    - SSP estimated the percentage of 50th percentile female nurse population that can actually perform this task:
        - Trunk strength capability was analyzed
        - the percentage of population able to perform the task is as low as 6.73% and 14.86%
        - Pushing shows a higher spread of the population is able to perform the task
        - Higher bed height yields more preferable results, especially when pushing the patient
        - Improper sling fitting can occur, due to lack of trunk strength to handle the load

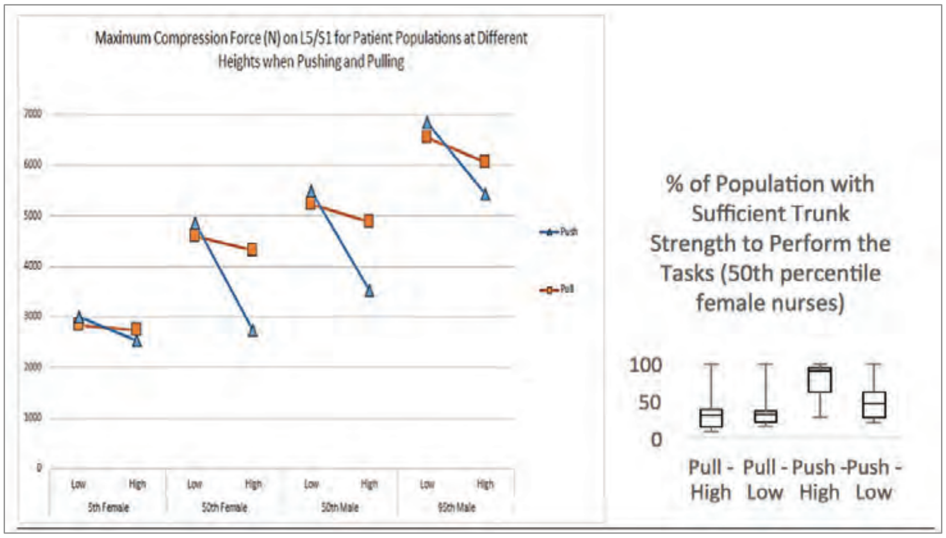


Figure 3: Low back and SSP analysis for environment 1

- Environment 2 was populated with the caregiver, the patient, Hoyer lift, chair, and the bed.
    - Lower Back Analysis::The results for simulations involving transferring the patient from bed to wheel chair focusing on the pushing and pulling motion revealed:
        - the compression forces was as high as 6100 N, which exceeds NIOSH Limit of 3400N and just below the maximum of 6300 N
        - the pushing motion produced much more favorable results than pulling wheel type and location can have a positive effect of reducing the compression force when maneuvering the lift and relieve some of the patient load.
    - SSP Analysis: SSP estimated the percentage of 50th percentile female nurse population that can actually perform this task:
        - trunk strength capability was analyzed
        - the percentage of population able to perform the task is as low as 21.37% and 25.24%.
        - pushing shows a higher spread of the population is able to perform the task
        - Design improvements to the boom (extension), powered wheels, and swing of the base could potentially increase the number of caregivers that can perform the task

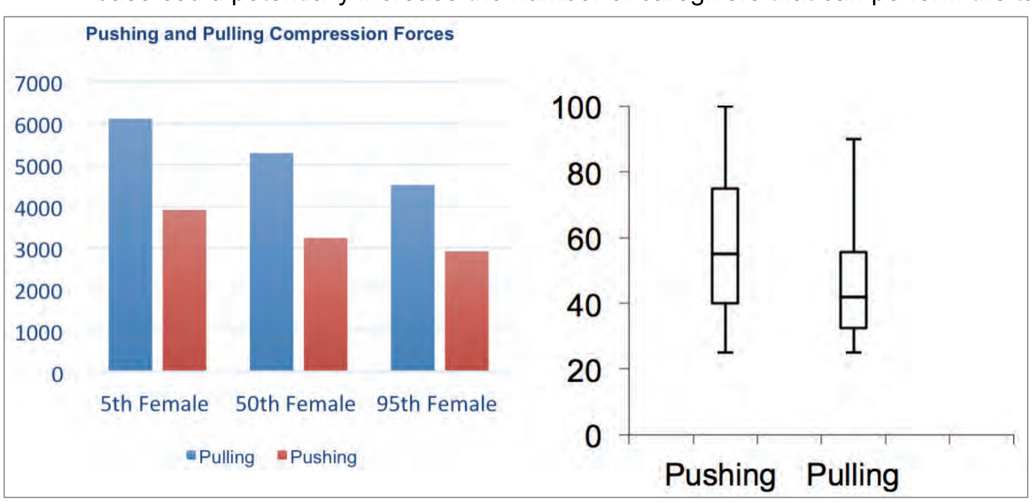


Figure 4: Low back and SSP analysis for environment 2

Plans for the Next Five Years

- Identify usability goals for the patient transfer device
- Develop prototype interface for the patient transfer device
- Conduct usability study on the prototype interface of the patient transfer device
- Revise the interface design for the patient transfer device
- Develop human performance models for the patient transfer device
- Conduct empirical study on operator performance using human subjects for the patient transfer device

Expected Milestones and Deliverables

- 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

C. Member company benefits

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

D. References

1. Endsley, M. R., 2003, Designing for situation awareness: An approach to user-centered design, Taylor & Francis, US.
2. Nagel, D. C., 1988, “Human error in aviation operators,” appears in Human factors in aviation, Weiner, E., Nagel, D. (eds.), Academic Publishers, New York, 263-303.
3. Sanders, M., and McCormick, E., 1992, Human Factors in Engineering and Design, McGraw Hill, New York.
4. Adams, J. A., 2002, “Critical considerations for human-robot interface development,” appears in Schultz A. C. (ed.), Human-robot interaction: Papers from the 2002 fall symposium, Menlo Park, CA: American Association for Artificial Intelligence, 2-8.
5. United States Bureau of Labor Statistics, 2001. Economic News Release, Retrieved from http://www.bls.gov/news.release/osh2.nr0.htm
6. Collins J.W, Menzel N.N., 2006, “Safe patient handling and movement: a practical guide for health care professionals,” Scope of the problem. In: Nelson A, editor. New York: Springer Publishing, 1–26.
7. Owen, B.D., Garg, A., Jensen, R.C., 1992, “Four methods for identification of most back-stressing tasks performed by nursing assistants in nursing homes,” Int. J. Ind Ergon. 9, 213-220
8. NIOSH 1981, Work practices guide for manual load lifting. National Institute for Occupational Safety and Health, Cincinnati, Ohio, USA.
9. American Nursing Association., 2013, Retrieved from http://www.nursingworld.org/

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

Research Team

Project Leader: Andrea Vacca, ABE/ME, Purdue University
Graduate Students: Guido, Francesco Ritelli, Davide Cristofori (Graduated)
Undergraduate Students: Two REU/year: Roy Fisher (Summer 2012), Bixing Yan (Summer 2013)
Industrial Partners: Parker Hannifin, CHN

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

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

3. Project Description

A. Description and explanation of research approach

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

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

Pure hydraulic technology

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

Electro-Hydraulic (EH) technology

EH technology is based on an optimal management of the power source with respect to a feedback signal representative of the oscillation extent. EH technology has often been combined with PH technology, to extend the range of stability of the hydraulic system and/or to limit the contribution of pure-hydraulic techniques drawbacks on the entire system. Examples are: active suspensions; earthquake simulators, vehicles braking systems; hydraulic robots; active damping seats.

This research particularly investigates the pressure feedback control methodology, in which the pressure signal is used to indirectly quantify the oscillation. In this case a control based on real-time identification of the relationship between pressure and oscillations is required. Some interesting results obtained in the past have not reached practical application because of the complexity of the proposed controllers and of its model-based nature, which makes it difficult to extend to other applications.

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

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

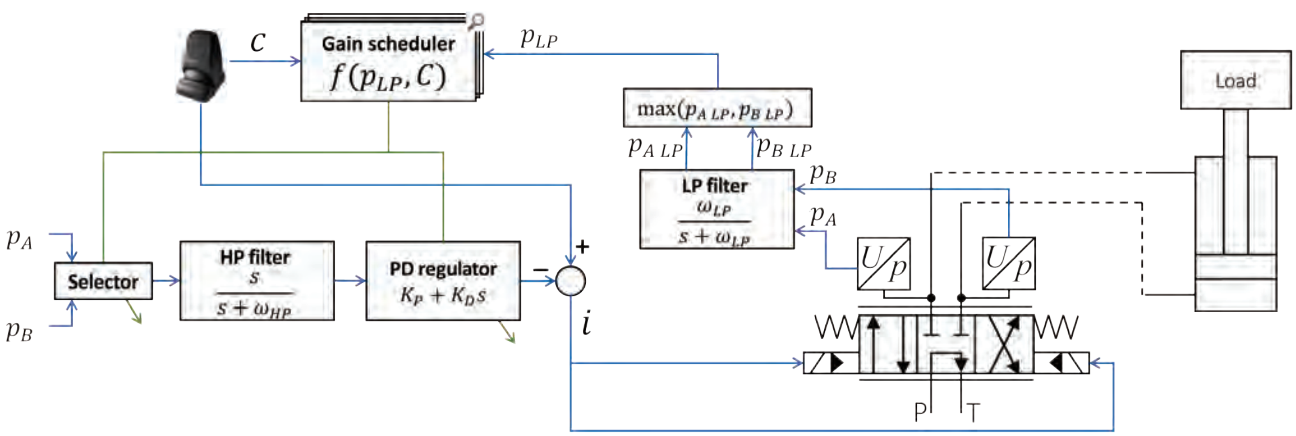


Figure 1: Detailed control loop implementation for a general linear hydraulic actuator

The proposed control solution and its innovative contents

This research applies for the first time to FP applications the adaptation/optimization scheme using the Extremum Seeking (ES) theory. ES is an algorithm able to identify the set of parameters that can seek for the maximum or minimum of a given function. Figure 1 and Figure 3 describe the idea under the proposed control approach. A controller is used to control the input signals of the control elements (flow control valves, for the case considered in this research), Figure 2. The input parameters of the controller are signals given by pressure sensors installed near the actuator for which the oscillations have to be minimized. The tuning of the control parameters is achieved through online or offline optimization methods. Figure 3 represents the idea for the optimization according to the offline scheme. A cost function associated to the oscillation is evaluated using real experiments or computer simulations. The ES algorithm is used to achieve minimum oscillation through a fast convergence loop.

B. Achievements

a) Achievements in previous years

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

Control strategy achievements

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

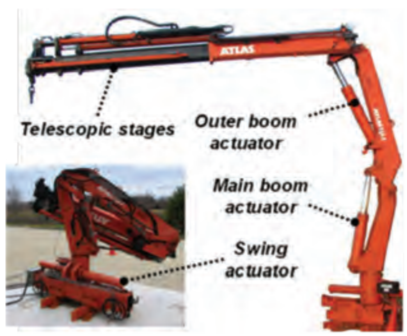


Figure 2: Experimental setup of the reference hydraulic crane instrumented at Maha Center of Purdue University

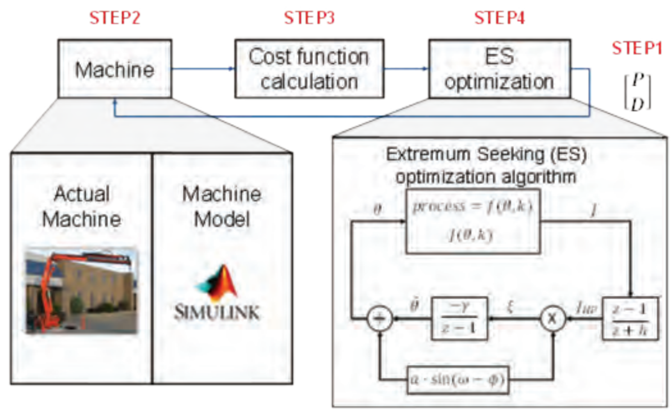


Figure 3: Controller tuning optimization process

The controller parameters obtained by this procedure were tested on the actual experimental crane equipped with accelerometers on the end of the mechanical arms. Results show a significant improvement in the machine dynamics (about 30% settling time and overshoot reduction), [5]. Such oscillation reduction was obtained using the standard and energy inefficient machine configuration. A more significant result was obtained when the setting of the counterbalance valve were changed in order to achieve a better overall energy efficiency. The controller implementation and results were published in [6].

Energy consumption estimation

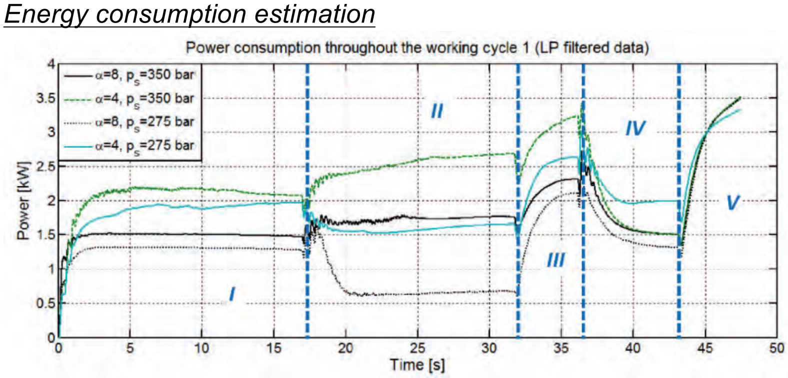


Figure 1: Overall energy consumption comparison for a working cycle using different counterbalance valve settings

In order to perform an estimation of the energy consumption and its possible improvement, a study was conducted on the reference machine, Figure 2, by changing the settings of the CBV. Two typical operating cycles were considered for the study, in order to investigate the overall operation of the machine (lifting/lowering, with/without load). A detailed AMESim model, created to model the behavior of the valve, supported this activity. First an analytic study on CBV was performed with the goal of deriving a relationship between the valve settings and the machine energy consumption/dynamics. The main results have been published in [7]. In this work a graphical method to study the operation of CBV was presented. Different valve settings were also experimentally tested and results showed that the overall energy consumption of the entire system can be reduced by up to 34% using more energy efficient counterbalance valve settings. The results for one working cycle are given in

Figure 4. As Figure 5 shows, the dynamic response of the machine is greatly affected by the valve setting changes. However the application of the control strategy showed the ability of bringing the machine response back to an acceptable behavior while utilizing the more efficient configuration, [6,7].

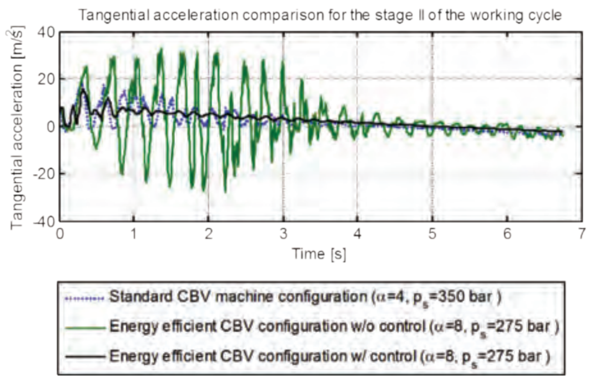


Figure 5: Dynamic response of the standard machine CBV settings and of the energy efficient machine CBV settings with and without control applied

b) Achievements in the past year

During the last year (02/1/2014-01/31/2015), the following activities were completed.

<u>*Experimental-Auto-Tuning Method for Active Vibration Damping Controller*</u>

Part of the effort was put in demonstrating the effectiveness of the optimization-based approach in a real world scenario. One key factor for an experimental application is the fast convergence property of the optimization algorithm when its parameters are properly set. This reduces the number of iterations needed and therefore populates the gain scheduler more quickly. The results of the experimental application of the control technique proposed are published in [8]. Figure 6 shows the optimization results for a particular operating condition. The controller parameters reach convergence in about 40 iterations. This shows the possibility of applying the control method to the actual experimental setup.

<u>*Generalization of the Control Strategy for Vibration Damping*</u>

The success of the optimization, Figure 3, lies on the efficient quantification of the vibration extend which is the objective to be minimized. To extent the generalization of the control method proposed a new cost function was introduced. It does not require a priori knowledge of the working cycle. This approach enables the control strategy to be potentially applied to any kind of working scenario and does not require the intervention of a control designer. In particular the accelerometer was not used for the cost function calculation anymore. The new cost function is composed of two cost functions. One utilizes the pressure information to quantify the oscillation content, while the second one utilize the command to the control element. The latter cost function guarantees a good operator command tracking. In doing it also the speed of the actuation is kept. The results of this new approach are presented in [9].

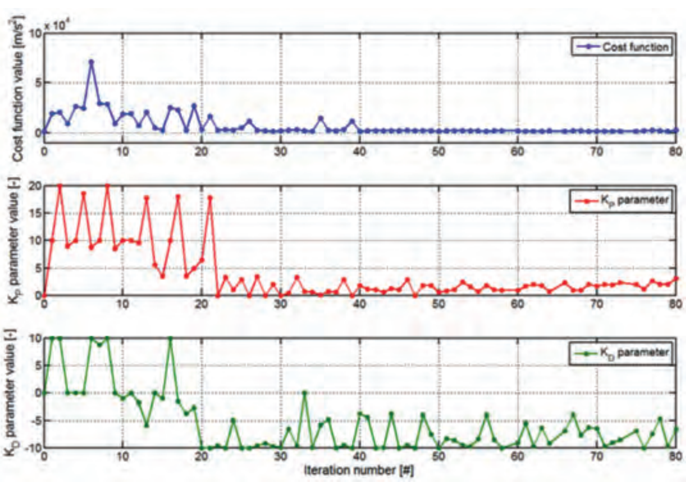


Figure 6: Optimization results for a particular operating condition performed using the actual experimental setup

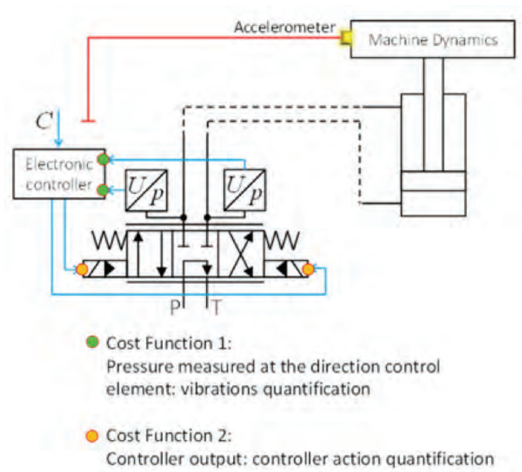


Figure 7: Graphical representation of the new cost function calculation method

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

- Improvement of the experimental setup:
  - Crane oscillating platform construction
- Formulation of a novel frequency based control method for payload oscillation reduction
  - Controller structure formulation
  - Preliminary experimental test activity
  - Control method application and results analysis

D. Member company benefits

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

E. References

1. Chapple, P. and Tilley, D., *Evaluation Techniques For The Selection of Counterbalance Valves*, in *The Expo and Technical Conference for Electrohydraulic and Electropneumatic Motion Control Technology*. 1994: Anaheim, USA.
2. Handroos, H., Halme, J., and Vilenius, M., *Steady State and Dynamic Properties of Counterbalance Valves*, in *The Third Scandinavian International Conference on Fluid Power*. 1993: Linköping.
3. Miyakawa, S., *Stability of a Hydraulic Circuit With a Counterbalance-Valve.* Bulletin of the JSME, 1978. Vol.**21**(162).
4. Overdiek, G., *Design and Characteristics of Hydraulic Winch Controls by Counterbalance Valves*. 1981.
5. Cristofori, D., Vacca, A., and Ariyur, K., *A Novel Pressure-Feedback Based Adaptive Control Method to Damp Instabilities in Hydraulic Machines.* SAE Int. J. Commer. Veh., 2012. Vol.**5**(2) DOI: 10.4271/2012-01-2035.
6. Ritelli, G.F. and Vacca, A., *Energy Saving Potentials of a Novel Electro-Hydraulic Method to Reduce Oscillations in Fluid Power Machines: The Case of a Hydraulic Crane.* SAE Int. J. Commer. Veh., 2013. Vol.**6**(2) DOI: 10.4271/2013-01-2345.
7. Ritelli, G.F. and Vacca, A., *Energetic and dynamic impact of counterbalance valves in fluid power machines.* Energy Conversion and Management, 2013. Vol.**76**: p. 701-711 DOI: http://dx.doi.org/10.1016/j.enconman.2013.08.021.
8. Ritelli, G.F. and Vacca, A., *Experimental-Auto-Tuning Method for Active Vibration Damping Controller. The Case Study of a Hydraulic Crane*, in *9th IFK 2014*. 2014: Aachen, Germany.
9. Ritelli, G.F. and Vacca, A. *A General Auto-Tuning Method for Active Vibration Damping of Mobile Hydraulic Machines*. in *8th FPNI Ph.D Symposium on Fluid Power*. 2014. Lappeenranta, Finland: ASME.

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

Research Team

Project Leader:	Richard F. Salant, Georgia Institute of Technology
Graduate Student:	Yuli Huang
Industrial Partners:	Trelleborg Sealing Solutions, Freudenberg NOK, Bosch-Rexroth, John Deere, Caterpillar, Concentric AB, R. T. Dygert

1. Statement of Project Goals

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

2. Project Role in Support of Strategic Plan

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

3. Project Description

A. Description and explanation of research approach

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

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

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

B. Achievements

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

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

The results of the simulations have revealed much about the basic physics of rod seal operation. They show that these seals do indeed operate with mixed lubrication, and for a given set of operating conditions and seal design, there is a critical seal surface roughness below which there will be zero net leakage per cycle, and above which the seal will leak. They also show that for a given stroke length, net leakage decreases with rod speed and above a critical rod speed there will be zero net leakage. Comparison of simulations of non-leaking and leaking seals show that the following characteristics are conducive to zero or reduced net leakage: a thinner lubricating film, a larger film thickness during instroke than during outstroke, cavitation in the sealing zone during outstroke, reduced or no cavitation during instroke. The viscoelastic model has produced results similar to those from the elastic model for moderate to long cycle time applications. However, for short cycle time applications, the viscoelastic effects become important and produce cycle to cycle variations.

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

A major effort has been directed toward developing a model to investigate engineered micro-patterned rod surfaces to reduce seal friction while maintaining zero net leakage. The past simulation work done on this project has shown that extremely large friction forces are exerted by the rod seal on the rod, in agreement with experimental measurements by a seal manufacturer (Trelleborg). For a 50 mm diameter rod, these forces are in the range of 1000-1500 N. For energy conservation and control purposes, there is therefore an obvious need to reduce this friction while still maintaining the sealing effectiveness. Over the last several years there has been substantial tribological research on reducing friction by the application of micro-patterns on mating surfaces using laser texturing and photolithography. This has been applied to such machine elements as journal bearings, piston rings and mechanical seals. The present project takes a similar approach, applied to rod seals, initially considering a pattern of micron-scale triangular cavities in the surface of the rod.

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

The research generated by this project thus far has been published in 10 archival journal papers, presented in 3 plenary and 1 keynote lecture, 2 invited papers, 28 additional conference presentations and 5 seminars.

Progress During the Reporting Period

All of the seal simulation results generated over the past several years assume flooded lubrication conditions in the interface between the seal and the rod. Using the new approach, described above, in addition to flooded conditions, starved conditions have also been considered. In practice, whether flooded or starved conditions actually exist, depends on the particular sealing application.

With a smooth rod, it has been found that starved conditions result in just a portion of the sealing zone being lubricated, so that contact pressures are increased and there is a much higher friction force than under flooded conditions.

The effect of the plunge-ground rod finish has been re-examined under starved conditions. For the U-cup seal, it was found that the effect is just the opposite as that under flooded conditions: the plunge ground rod yields a lower friction force than a smooth rod. This agrees with published experimental work.

Extensive studies have been performed, under both flooded and starved conditions, of the effects of rods with micro-cavities and micro-protrusions on friction. It has been found that under flooded conditions, such micro-patterns can significantly reduce friction. However, under starved conditions, the opposite occurs and they increase friction. The details of these results are contained in the thesis of Yuli Huang.

Planned Progress

This project terminated at the end of year 9. However, work is underway to publish two to three additional journal papers.

C. Member company benefits

Leakage is a major barrier to expanding the benefits of fluid power to many new applications. Reducing, ideally eliminating, leakage will improve the system's performance and lessen maintenance costs in existing applications. The models created by this research can be used by industry to help minimize component and system leakage.

D. References

1. Nikas, G. K., "Research on the Tribology of Hydraulic Reciprocating Seals," Tribology Research Trends, Hasegawa, T. editor, Nova Science Publishers Inc., Hauppauge, NY, 11-56, 2008.
2. Salant, R. F., Maser, N. and Yang, B., "Numerical Model of a Reciprocating Hydraulic Rod Seal, Including Seal Roughness and Mixed Lubrication," Plenary Lecture, 14th International Sealing Conference, Stuttgart, Germany, 2006.
3. Salant, R. F., Maser, N. and Yang, B., "Elastohydrodynamic Model of a Reciprocating Hydraulic Rod Seal," AITC-AIT 5th International Conference on Tribology, Parma, Italy, 2006.
4. 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.
5. Nikas, G. K., "Elastohydrodynamics and Mechanics of Rectangular Elastomeric Seals for Reciprocating Piston Rods," J. of Tribology, 125, pp. 60-69, 2003.
6. Nikas, G. K, "Transient Elastohydrodynamic Lubrication of Rectangular Elastomeric Seals for Linear Hydraulic Actuators," J. of Engineering Tribology, 217, pp. 461-473, 2003.

7. Öngün, Y., André, M., Bartel, D. and Deters, I., “An Axisymmetric Hydrodynamic Interface Element for Finite-Element computations of Mixed Lubrication in Rubber Seals,” ImechE Journal of Engineering Tribology, Vol. 222, pp. 471-481, 2008.
8. Schmidt, T., Andre, M. and Poll, G., “A Transient 2D-Finite-Element Approach for the Simulation of Mixed Lubrication Effects and Wear Progress of Reciprocating Hydraulic Rod Seals,” Leeds-Lyon Symposium on Tribology, Lyon, France, 2009.
9. Stupkiewicz, S. and Marciniszyn, A., “Elastohydrodynamic Lubrication and Finite Configuration Changes in Reciprocating Elastomeric Seals, Tribology International, Vol. 42, pp. 615-627, 2009.

Project 3D.2: New Directions in Elastohydrodynamic Lubrication

Research Team

Project Leader:	Scott Bair, School of Mechanical Engineering, Georgia Institute of Technology
Industrial Partners:	Lubrizol, Afton Chemical, John Deere, Caterpillar
University Collaborators:	Ashlie Martini, University of California, Merced, simulation
	Ivan Krupka, Brno University, Czech Republic, film thickness measurement
	Riccardo Casilini, George Mason Univ, measurements of relaxation time
	Michael Khonsari, Louisiana State University, simulation
	Punit Kumar, National Institute of Technology, India, simulation
	Philippe Vernge, INSA Lyon, France, film thickness and traction
	Paul Michael, MSOE, lubricant formulation
	Arno Laesecke, NIST Boulder, viscosity correlations
	Wassim Habchi, Lebanese American University, simulations
	Roland Larson, Lulea University of Technology, traction measurements

1. Statement of Project Goals

Progress in the classical field of elastohydrodynamic lubrication (EHL) has for decades been paralyzed by the assumption that shear-thinning should be indistinguishable from the shear dependence of the viscosity of a liquid heated by viscous dissipation and that the parameters of this simple shear dependence can be obtained from the shape of a friction curve. As a result of this project, in the last few years, by abandoning these assumptions and employing real viscosity measured with viscometers, there has been revolutionary progress in predicting film thickness and friction. The goal of the project is to transform elastohydrodynamic lubrication into a quantitative field, able to provide solutions to problems in fluid power. This is a basic research program intended to support applied research in fluid power. There are now five thrusts to this project-two are new for this year. Much of the work will be done concurrently since progress depends upon collaborators in laboratories scattered around the world working on different schedules.

1) *Extending the pressure range for shear-dependent viscosity measurement-with INSA Lyon*

   Shear-thinning of base oils can only be observed in steady shear at very high pressures. The problem arises from viscous dissipation that results in thermal softening which masks the constitutive response when the viscosity is low. Viscosity may be increased by reducing the temperature or by increasing the pressure. High pressure is also required to prevent shear cavitation, making this the obvious strategy. A new 1.1 GPa Couette viscometer will be jointly developed with INSA-Lyon. This instrument will provide the capability of measuring shear dependence of the low viscosity base oils that are widely used today in formulating hydraulic oils.

2) *Demonstrating the prediction of friction from primary properties-with Brno University and Lebanese American University*

   A commercial polymer-thickened oil, supplied by Caterpillar, will be tested for the temperature, pressure and shear dependence of viscosity at Georgia Tech. Film thickness and friction will be measured at Brno to be compared with simulations performed at LAU.

3) *Rheology of degraded oil-with MSOE and Afton*

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

4) *Accurate prediction of minimum film thickness in EHL-with Brno and LAU*

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

5) *Solution of Navier-Stokes for piezoviscous liquids-with LSU*

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

2. Project Role in Support of Strategic Plan

Compactness

More compact components must necessarily have smaller radius of curvature of the contacting elements. A clear strategy for making more compact components is also to increase the operating pressure. The resulting increase in load and decrease in radius of curvature of the sliding/rolling elements will result in diminished film thickness. The reduced film must impact the reliability. New insights into the effects of scale [2,7], load [8] and lubricant degradation [16,27] are being provided by this project.

Efficiency

Surprisingly, there has been little progress within EHL over the last forty years in explaining the mechanism of mechanical dissipation in full EHL films. In very recent related work [20,23,26] using the temperature/pressure correlation for viscosity devised by this project [4,5,6,10,17], the first experimentally validated EHL friction calculations were performed which included thermal-softening and shear-thinning. Fragility has been shown to be the principal property controlling friction at very high contact pressures. Thermal conductivity of the liquid becomes important at high sliding speeds.

3. Project Description

A. Description and explanation of research approach

What sets this program of fundamental research into EHL apart from any previous approach is the use of primary measurements of liquid transport properties under the actual conditions of EHL. A significant opportunity to investigate the elastohydrodynamic lubrication (EHL) problem using experimental film measurements, high pressure rheological measurements and numerical analysis (quantitative elastohydrodynamics) has recently appeared as a result of this project. In an exciting departure from previous methods, new film behavior regarding the effects of scale [2,7], load [8], rheology [1,13,20,23,24,26], thermal properties [23,26,28] and shear degradation [16,17] has been predicted from EHL simulation using measured rheological properties and the predictions have subsequently been experimentally validated. Both film thickness and friction may now be predicted [23,26,28] from primary properties rather than from fictitious properties adjusted to fit analysis to measurements of film thickness or friction. Film thickness may now be calculated from the properties of mixtures. Thermal EHL calculations using measured rheology have revealed the importance of the high-pressure thermal properties of lubricants in calculations which have been experimentally validated.

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

The present time is propitious for the EHL field to embrace a quantitative description of the temperature and pressure dependence of viscosity since there has been, over the last decade, an interest by the physics community in the pressure evolution of the dynamic properties of the supercooled liquids such as lubricants.

New high pressure measurement techniques are being developed and data gathered. New correlations are being developed to apply these data to numerical simulations. The numerical strategies are being developed to understand and to predict film-forming and friction.

B. Achievements

a. Achievements in previous years

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

The achievements of this project may best be summarized by a list of resulting publications. Thirty-nine papers have resulted from the seven years of work; nine have been written, submitted or published within the last year alone. They are listed below. For examples: The effects of scale and load on film thickness were accurately described. New viscosity correlations have been derived. New accurate film thickness equations have been derived and tested with real viscosity. The dimensionless numbers delineating friction regimes were derived.

The high productivity of this program has been mostly due to collaborations but also due to the unstructured plan. Each new discovery has opened the possibility of new opportunities. The same approach will be employed in future work. For example, work this year has emphasized the need for improved modelling of rheological properties, especially shear-thinning, at EHL pressure levels. Therefore, next year, a new viscometer will be constructed in collaboration with INSA-Lyon for measurements at higher pressures. Increasing the pressure will allow measurements on ultra-low-viscosity base oils.

b. Achievements in the past year

1) A new thermal conductivity cell has been completed for 700 MPa pressure and a density scaling rule has been investigated for a mil spec oil.
2) The first normal stress difference and the shear dependent viscosity have both, for the first time, been measured under pressure for a polymer-blended oil and the principal of time-temperature-pressure superposition was validated for normal stress differences.
3) The Cox-Merz rule was used to predict friction from oscillatory shear measurements for the first time.
4) The principal of time-temperature-pressure superposition was validated for oscillatory shear for the first time.

C. Plans

a. Plans for the next year.

1) Extend the pressure range for shear-dependent viscosity measurement-with INSA Lyon
2) Demonstrate the prediction of friction from primary properties-with Brno University and Lebanese American University
3) Rheology of degraded oil-with MSOE and Afton
4) Accurate prediction of minimum film thickness in EHL-with Brno and LAU
5) Solution of Navier-Stokes for piezoviscous liquids-with LSU

b. Expected milestones and deliverables.

Results will be reported in journal papers and conference presentations. This project supports education and outreach through collaborations with faculty and students in ten universities. The

39 journal papers written or published have broadened public awareness of fluid power research.

D. Member company benefits

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

E. References

Nine journal papers were written or published this last year alone.

1. Kumar, P., Khonsari, M.M. and Bair, S., "Full EHL Simulations Using the Actual Ree-Eyring Model for Shear Thinning Lubricants", J. Tribol., 2009, Vol. 131, Issue 1, 011802, 6 pages.
2. 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.
3. 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
4. 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.
5. Bair, S and Michael, P., "Modeling the Pressure and Temperature Dependence of Viscosity and Volume for Hydraulic Fluids", ASME paper IJTC2008-71028, 2008.
6. Bair, S., "Rheology and High Pressure Models for Quantitative Elastohydrodynamics", Proc. I. Mech. E., Part J, J. Engineering Tribology, Vol.223, 2009, pp.617-628.
7. Krupka, I., Bair, S., Kumar, P., Khonsari, M.M. and Hartl, M. "An experimental Validation of the Recently Discovered Scale Effect in Generalized Newtonian EHL", Tribology Letters, Vol. 33, No.2, 2009, pp.127-135.
8. Krupka, I., Kumar, P., Bair, S., Khonsari, M.M. and Hartl, M. "The Effect of Load (Pressure) for Quantitative EHL Film Thickness," Tribology Letters, Vol.37, No. 3, 2010, pp.613-622.
9. Martini, A. and Bair, S., "The role of Fragility in EHL Entrapment," Tribology International, Vol. 43, 2010, pp.277–282.
10. Bair, S., "The Dependence of the Dynamic Properties of Elastohydrodynamic Liquids on Temperature and Pressure (Volume)," Proc. I. Mech. E., Part C, Journal of Engineering Science 224(C12), 2010, pp.2568-2576.
11. Kumar, P., Khonsari, M.M. and Bair, S., "Anharmonic Variations in Elastohydrodynamic Film Thickness Resulting from Harmonically Varying Entrainment Velocity", Proc. I. Mech. E., Part J, J. Engineering Tribology, 224(J3), 2010, pp.239-248.
12. Bair, S and Michael, P., "Modeling the Pressure and Temperature Dependence of Viscosity and Volume for Hydraulic Fluids", International Journal of Fluid Power, 11, 2010, pp.37-42.
13. Kumar, P., Bair, S. and Krupka, I., "Newtonian Elastohydrodynamic Film Thickness with Linear Piezoviscosity", Tribology International 43(11), 2010, pp.2159-2165.
14. Young, A. and Bair, S., "Experimental Investigation of Friction in Entrapped Elastohydrodynamic Contacts," Tribology International 43(9), 2010, pp.1615–1619.
15. Laeseke, A. and Bair, S., "High Pressure Viscosity Measurements of 1,1,1,2-Tetrafluoroethane," Int. J. Thermophys, Volume 32, Number 5, 2011, pp.925-941.
16. Krupka, I., Kumar, P., Bair, S. Svoboda, P. and Hartl, M., "Mechanical Degradation of the Liquid in an Operating EHL Contact," Tribology Letters, Volume 41, Number 1, 2011, 191-197.
17. Bair, S., and Laeseke, A., "Normalized Ashurst-Hoover Scaling and a Comprehensive Viscosity Correlation for Compressed Liquids," ASME J. Tribol, 2012, Vol.134.
18. Bair, S. (2012). A Critical Assessment of the Role of Viscometers in Quantitative Elastohydrodynamics. Tribology Transactions, 55(3), 394-399.

19. Michael, P. W., Garcia, J. M., Bair, S. S., Devlin, M. T., & Martini, A. (2012). Lubricant Chemistry and Rheology Effects on Hydraulic Motor Starting Efficiency. Tribology Transactions, 55(5), 549-557.
20. Habchi, W., Vergne, P., Fillot, N., Bair, S. and Morales-Espejel, G.E. “A Numerical Investigation of the Local Behavior of TEHD Highly Loaded Circular Contacts”, Tribology International, Vol.44, 2011, pp.1987-1996.
21. Bair, S., “Temperature and Pressure Dependence of Density and Thermal Conductivity of Liquids,” Chapter for the Springer Encyclopedia of Tribology.
22. Habchi, W., & Bair, S. (2013). Quantitative Compressibility Effects in Thermal Elastohydrodynamic Circular Contacts. Journal of Tribology, 135, 011502.
23. Habchi, W., Bair, S., & Vergne, P., On Friction Regimes in Quantitative Elastohydrodynamics. Tribology International, 58, 2013, 107-117
24. Habchi, W., Bair, S., Qureshi, F. and Covitch, M., “A Film Thickness Correction Formula for Double-Newtonian Shear-Thinning in Rolling EHL Circular Contacts,” Tribology Letters, DOI 10.1007/s11249-012-0078-6
25. Bair, S., Mary, C., Bouscharain, N., & Vergne, P. (2013). An improved Yasutomi correlation for viscosity at high pressure. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology.
26. Bjorling, Habchi, Bair, Larsson and Marklund, “Towards the True Prediction of EHL Friction”, Tribology International, 66, 2013, 19-26.
27. Bair, Krupka, Sperka and Hartl, “Quantitative Elastohydrodynamic Film Thickness of Mechanically Degraded Oil,” Tribology International, 64, 2013, 33-38.
28. Bjorling, Habchi, Bair, Larsson and Marklund, “Friction Reduction in Elastohydrodynamic Contacts by Thin-Layer Thermal Insulation”, Tribol Lett (2014) 53:477–486.
29. Bair, S. and Qureshi, F., “Time-Temperature-Pressure Superposition in Polymer Thickened Liquid Lubricants”, ASME, J. Tribology, Volume 136, 2014, 021505
30. Vergne, P., & Bair, S. (2014). Classical EHL Versus Quantitative EHL: A Perspective Part I—Real Viscosity-Pressure Dependence and the Viscosity-Pressure Coefficient for Predicting Film Thickness. *Tribology Letters*, *54*(1), 1-12.
31. Bair, S. (2014). Density Scaling of the Thermal Conductivity of a Jet Oil. *Tribology Transactions*, *57*(4), 647-652.
32. Bair, S., “The temperature and pressure dependence of the dynamic properties of branched perfluoropolyethers,” Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Volume 228, Issue 4, 2014 pp. 424 – 434.
33. Bair, Yamaguchi, Brouwer, Schwarze, Vergne and Poll, “Oscillatory and Steady Shear Viscosity of Liquid Lubricants: The Cox-Merz Rule, Superposition, and Application to EHL Friction,” Tribology International, 79, 2014, 126-131.
34. Ramasamy, Bair and Martini, “Predicting Pressure-Viscosity Behavior from Ambient Viscosity and Compressibility: Challenges and Opportunities,” accepted Tribology Letters
35. Bair, S., “A Critical Evaluation of Film-Thickness-Derived Pressure-Viscosity Coefficients,” accepted by Lubrication Science
36. Mary, C., Philippon, D., Devaux, N., Fillot, N., Laurent, D., Bair, S., & Vergne, P. (2014). Bridging high pressure rheology and film-forming capacity of polymer-base oil solutions in EHL. *Tribology International*.
37. Bair, S., “The First Normal Stress Difference in a Shear-Thinning Motor Oil at Elevated Pressure,” submitted to Tribology Transactions.
38. Bair, S., “The Temperature and Pressure Dependence of Viscosity and Volume for Two Reference Liquids,” submitted to Lubrication Science
39. Bair, Vergne, Kumar, Poll, Krupka, Hartl, Habchi, and Larsson, "Comment on "History, Origins and Prediction of Elastohydrodynamic Friction" by Spikes and Jie", submitted to Tribology Letters
40. Bair, S. Choosing Pressure-Viscosity Relations for Reference Correlations. High Temperatures - High Pressures 2015, submitted

Project 3E.1: Pressure Ripple Energy Harvester

Research Team

Project Leader:	Kenneth A. Cunefare, Woodruff School of Mechanical Engineering, Georgia Institute of Technology
Graduate Student:	Ellen Skow
Undergraduate Students:	Nalin Verma, Aaron Kranc, Zachary Koontz, Brian Hults, Karthika Poonammalla Venkatasubramanian, Tanya Johson, Chong Woo Han, Daniel Kim, Jeremy Savor
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; current funding is 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 past year

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 ranging from 150 μW to over 3.3 mW; given that low-data-rate wireless sensors may be expected to consume on the order of less than 100 μW, it is clear that HPEH devices have demonstrated the output power levels necessary to enable a wide variety of sensing applications.

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

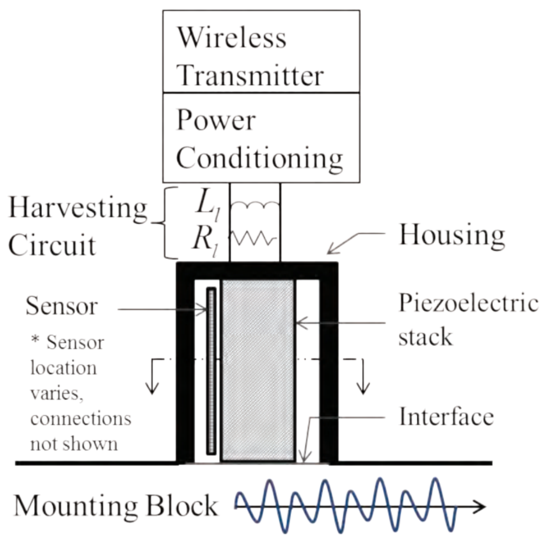
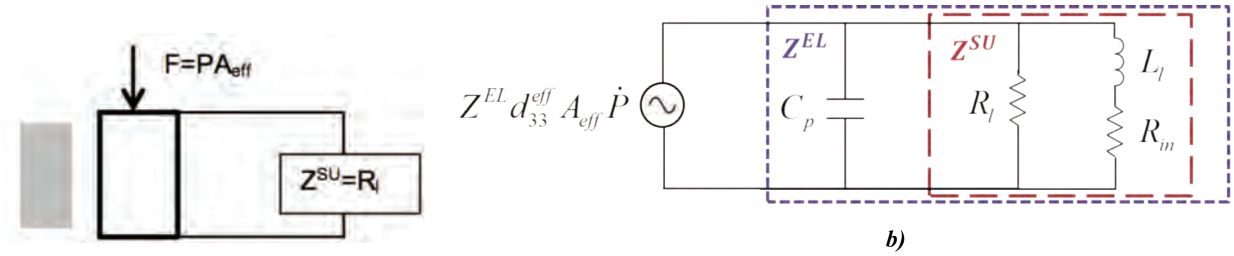


Figure 1: Simplified schematic of self-powered wireless hydraulic pressure energy harvester sensor, where the interface implements fluid-mechanical coupling between the piezoelectric stack and pressure ripple in a pressurized fluid.

Modeling

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



a) *b)*

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

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

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

where

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

and

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

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

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

from which the optimal load resistance is

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

and the optimal load inductance is

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

The analysis above enabled design analysis and optimization of HPEH devices for particular applications and available pressure ripple.

The bulk of the effort in the reporting period focused on validation of the predictive performance models described above, through design and testing of a number of proof-of-concept devices and sensor nodes. Several of the devices were developed in the prior reporting period, and their test and evaluation was completed in this reporting period.

Prototypes

Six generations of HPEH prototypes, depicted in Figure 3, have been developed through the project to date. The devices were designed to withstand a static pressure of up to 34.5 MPa (5000 psi). Of particular note, all of the devices were designed and fabricated by REU students. The REU students have also participated in the testing of the devices, and appear as co-authors on several of the project's publications.

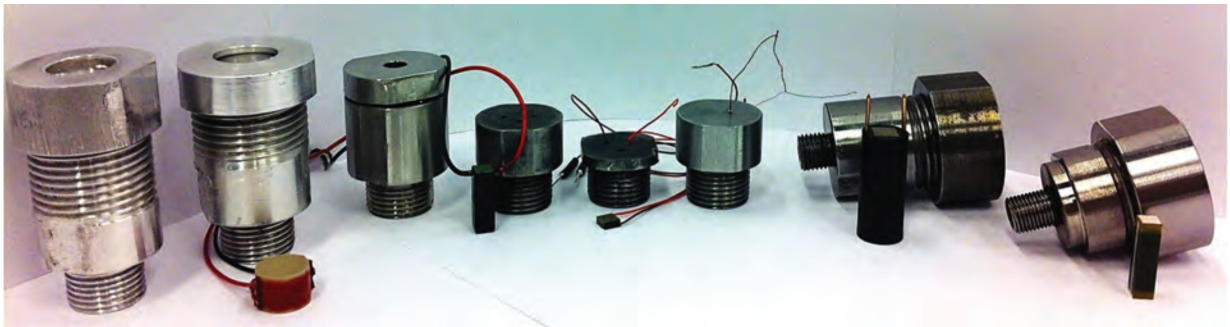


Figure 3. HPEH prototypes with threaded connector for attachment to fluid hydraulic systems; successive generations, left to right to the center of the picture, designed for smaller piezoelectric element and more compact packaging. Later generations, from center of the picture to the right side of the picture, designed for specific piezoelectric performance assessment and alternative seal designs (center),and HPEH integration with existing commercial hydraulic sensor housings (right two prototypes).

Results

Example results for five generations of devices are presented in Figure 4; the devices had different target output power per volume, and as such span the range of device sizes and outputs targeted by the project. The HEH devices have met or exceeded all of the performance and schedule targets for the project.

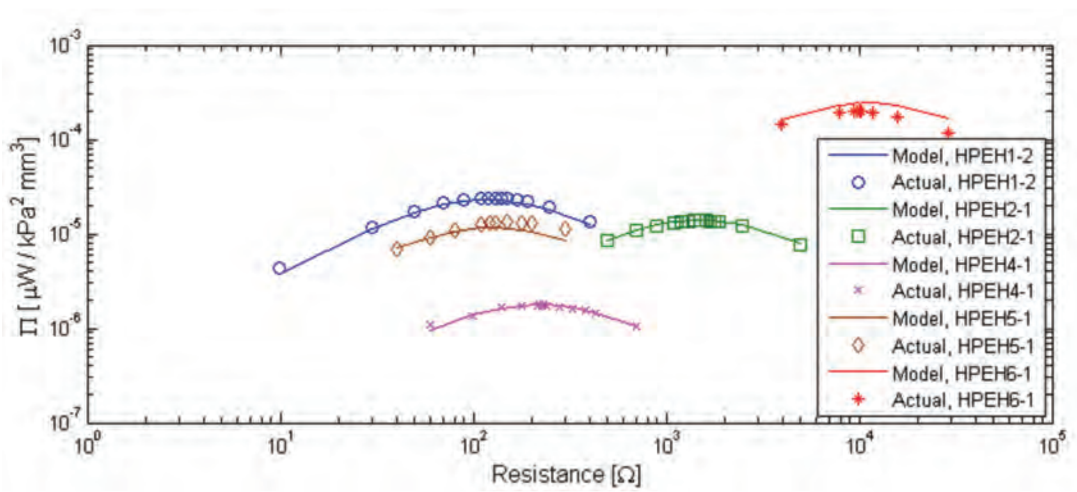


Figure 4. Power output vs. resistance in the harvester circuit for five generations of HPEH prototypes.

C. 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. An affiliated program explored the use of the technology to develop a HPEH-powered wireless pipeline leak detection system; this project was funded through an STTR; a Phase II proposal to continue the work was under preparation at the end of the reporting period.

D. References

1. K.A. Cunefare, E.A. Skow, and A. Erturk. Transduction as energy conversion; harvesting of acoustic energy in hydraulic systems. in *Joint 21st meeting of the International Congress of Acoustics and 165th Meeting of the Acoustical Society of America*. 2013. Montreal, Canada: ASA.
2. K.A. Cunefare, E.A. Skow, A. Erturk, J. Savor, N. Verma, and M.R. Cacan, Energy harvesting from hydraulic pressure fluctuations. *Smart Materials and Structures*, 2013. 22(2): p. 025036.
3. K.A.C. Ellen Skow, Alper Erturk, Power performance improvements for high pressure ripple energy harvesting. *Smart Materials and Structures*, submitted for review 2014.
4. Z.K. Ellen Skow, Chong Woo Han, Kenneth A. Cunefare, Alper Erturk. Pressure ripple energy harvester enabling autonomous sensing. in *International Fluid Power Exposition*. 2014. Las Vegas, NV.
5. K.A. Cunefare, A. Erturk, J. Savor, N. Verma, E. Skow, and M. Cacan. Energy harvesting from hydraulic pressure fluctuations. in *ASME 2012 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*. 2012. Stone Mountain, Georgia, USA: ASME.
6. S.R. Anton and H.A. Sodano, A review of power harvesting using piezoelectric materials (2003-2006). *Smart Materials & Structures*, 2007. 16(3): p. R1-R21.
7. S.P. Beeby, M.J. Tudor, and N.M. White, Energy harvesting vibration sources for microsystems applications. *Measurement Science & Technology*, 2006. 17(12): p. R175-R195.
8. K.A. Cook-Chennault, N. Thambi, and A.M. Sastry, Powering MEMS portable devices - a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems. *Smart Materials & Structures*, 2008. 17(4): p. 33.
9. S. Priya, Advances in energy harvesting using low profile piezoelectric transducers. *Journal of Electroceramics*, 2007. 19(1): p. 167-184.
10. R. Taylor, F. Liu, S. Horowitz, K. Ngo, T. Nishida, L. Cattafesta, and M. Sheplak, Technology Development for Electromechanical Acoustic Liners, in *Active 04*. 2004: Williamsburg, VA. p. paper a04_093.
11. F. Liu, A. Phipps, S. Horowitz, K. Ngo, L. Cattafesta, T. Nishida, and M. Sheplak, Acoustic energy harvesting using an electromechanical Helmholtz resonator. *Journal of the Acoustical Society of America*, 2008. 123(4): p. 1983-1990.
12. A. Phipps, F. Liu, L. Cattafesta, M. Sheplak, and T. Nishida, Demonstration of a wireless, self-powered, electroacoustic liner system. *Journal of the Acoustical Society of America*, 2009. 125(2): p. 873-881.
13. S.B. Horowitz, M. Sheplak, L.N. Cattafesta, and T. Nishida, A MEMS acoustic energy harvester. *Journal of Micromechanics and Microengineering*, 2006. 16(9): p. S174-S181.
14. W.-C. Wang, L.-Y. Wu, L.-W. Chen, and C.-M. Liu, Acoustic energy harvesting by piezoelectric curved beams in the cavity of a sonic crystal. *Smart Materials & Structures*, 2010. 19(4).
15. M. Lallart, D. Guyomar, C. Richard, and L. Petit, Nonlinear optimization of acoustic energy harvesting using piezoelectric devices. *Journal of the Acoustical Society of America*, 2010. 128(5): p. 2739-2748.
16. S.H. Kim, C.H. Ji, P. Galle, F. Herrault, X.S. Wu, J.H. Lee, C.A. Choi, and M.G. Allen, An electromagnetic energy scavenger from direct airflow. *Journal of Micromechanics and Microengineering*, 2009. 19(9).
17. R. Hernandez, S. Jung, and K.I. Matveev, Acoustic energy harvesting from vortex-induced tonal sound in a baffled pipe. *Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science*, 2011. 225(C8): p. 1847-1850.

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

Research Team

Project Leader:	Monika Ivantysynova, Purdue University, School of Mechanical Engineering, Dept. of Agricultural & Biological Engineering
Other Faculty:	Andrew Alleyne, UIUC Wayne Book, Georgia Tech Paul Michael, MSOE Kim Stelson, Minnesota
Test Bed Manager/ Staff:	Anthony Franklin
Graduate Student:	Enrique Busquets
Industrial Partners:	Bobcat, Caterpillar, Parker Hannifin, Moog, Husco, Sauer Danfoss, Sun Hydraulics.

1. Statement of Test Bed Goals

The compact excavator test bed was a demonstrator of throttle-less hydraulic actuation technology since the inception of the center through spring 2012. This technology, called displacement control (DC) or pump-controlled actuation (PCA), promises fuel savings for 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 toward transition of the test bed becoming a demonstrator of 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 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. Through project 1A.2 work was 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. In addition, the developments of project 1A.2 led to the theoretical development, simulation and formulation of appropriate control concepts for each of the aforementioned proposed technologies. 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 (LS), negative flow control (NFC), positive flow control (PFC) 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 across the control valves supplying all actuators other than the actuator operating at maximum pressure (in a typical cycle, only one or two actuators operate at high pressures, with the others at low or medium pressures). Further, energy from braking or lowering of actuators is either 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 was 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. 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 [1]. Competing throttle-less actuation technologies are open-circuit DC actuation and hydraulic transformers. 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.

Caterpillar has released a hydraulic hybrid version of a 37-t excavator (336E H) and has announced the release of a hydraulic hybrid front shovel. The 336E H excavator uses a parallel hybrid architecture, wherein an extra pump/motor is added to the engine shaft, in parallel to the pumps supplying the working actuators. The additional pump is responsible for charging and discharging the accumulator. Caterpillar has claimed 25% fuel savings over the 336E, it is claimed that swing braking energy is captured. However, the addition of another pump in the Caterpillar system will introduce additional power losses to the system. This is not the case in the in CCEFP series-parallel hybrid DC architecture. Also, due to the fact that all remaining functions are still valve-controlled, it is not possible to recover energy from other working functions like boom, arm or bucket in the current 336E-H Caterpillar machine.

<u>Achievements Prior to Reporting Period</u>

- Four variable displacement pumps were installed on test bed 1 along with associated sensors and electronic control hardware to retrofit the prototype with DC actuation and control laws for pump displacement, actuator position and actuator velocity control were developed and implemented.

- The DC hydraulic system was demonstrated by video at the CCEFP annual meeting and in person to a delegation from Caterpillar on 2009.
- Simulation and measurement results on test bed 1 determined that up to 50% of the cooling power capacity in the system could be reduced.
- Productivity and fuel test for test bed 1 with DC hydraulics was conducted in cooperation with Caterpillar, Inc.; test bed 1 consumed 40% less fuel on average than the standard machine while moving the same amount of dirt and productivity was increased by 16.6%, which lead to a fuel efficiency (tons/kg) improvement of 69%.
- A proposed optimal power management algorithm from project 1A.2 was evaluated using a pipe-laying cycle. Results showed 56.4% fuel efficiency improvement over the non-optimally managed.
- In April 2011, test bed 1 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 test bed 1 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 test bed 1.
- Control strategies were implemented with the goal of demonstrating the hydraulic hybrid functionality.

Achievements During 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. However, every approach so far assumes a constant pressure at the working port of the secondary unit. Efforts in this area for test bed 1 focus on the synthesis of a robust controller which achieves maximum actuator performance (good tracking of the cab velocity) while minimizing losses by actively controlling the secondary unit working pressure. The proposed controller design was carried out using the Robust Control Toolbox in MATLAB. Simulation of the proposed controller promised improved tracking for the actuator level control over a manually tuned PID controller. In reference to Figures 1 and 2, measurements of the pressure show greatly improved tracking for various inertia loads and commanded speeds. However, the speed tracking is only improved in certain areas displaying overshoots when decelerating. For illustration purposes, Figures 3 and 4 show the commanded and measured pressures and cabin speeds for a manually tuned PID controller.

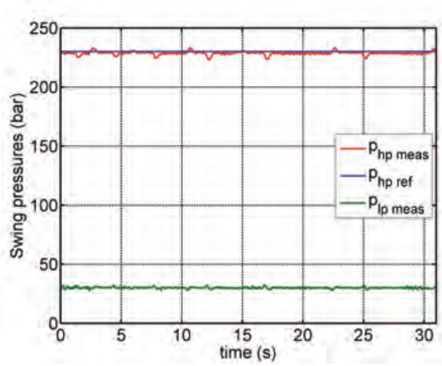


Figure 1: Proposed controller pressure tracking

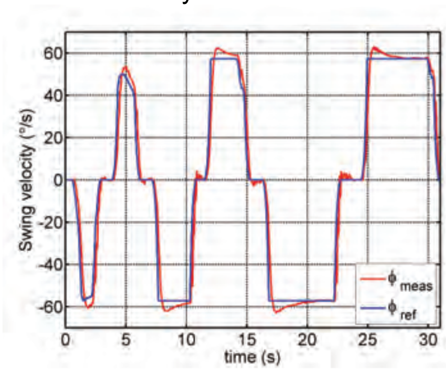


Figure 2: Proposed controller cab speed tracking

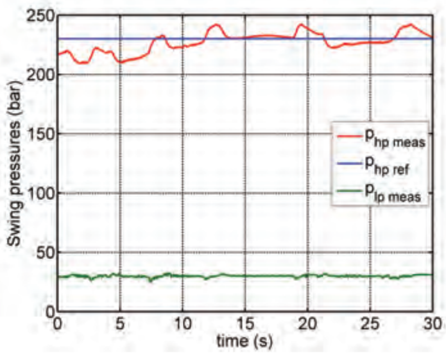


Figure 3: PID controller pressure tracking

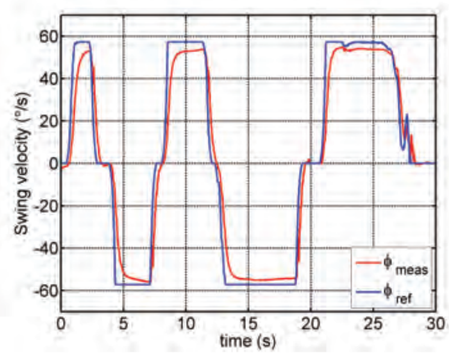


Figure 4: PID controller cab speed tracking

<u>Pump Switching</u>

With the developments from project 1A.2, the concept of pump switching was realized in test bed 1. Pump switching has the potential to minimize the number of pumps in a DC hydraulic system. However, this parameter will depend upon machine operation and operator demands. In the case of test bed 1, the limitation is imposed by the main purpose of an excavator: digging. This limitation exists since experienced operators use the swing, boom, arm and bucket simultaneously. The distributing manifold has been designed to distribute the flow from the hydraulic units to all of the actuators. Therefore, the coupling of a well-designed manifold and proper controls lead to the maximization of the number of actuator combinations which an operator may use. To demonstrate the operability of the actuators in test bed 1, the hydraulic manifold was manufactured by SunHydraulics and installed in the prototype. The aforementioned control concepts were implemented and studied for test bed 1. Measurements of pump switching for the boom actuator are presented under a large load to show the ability of the control algorithms to prevent undesired actuator transients (Figures 5 and 6). The intention of the obtained measurements is to present the most challenging operation which is to allow the valve to open while the operator commands very small increments in motion. In all measurements, an exaggerated miscalibration of the swash plate was imposed to force the wrong pilot-operated check valve to open.

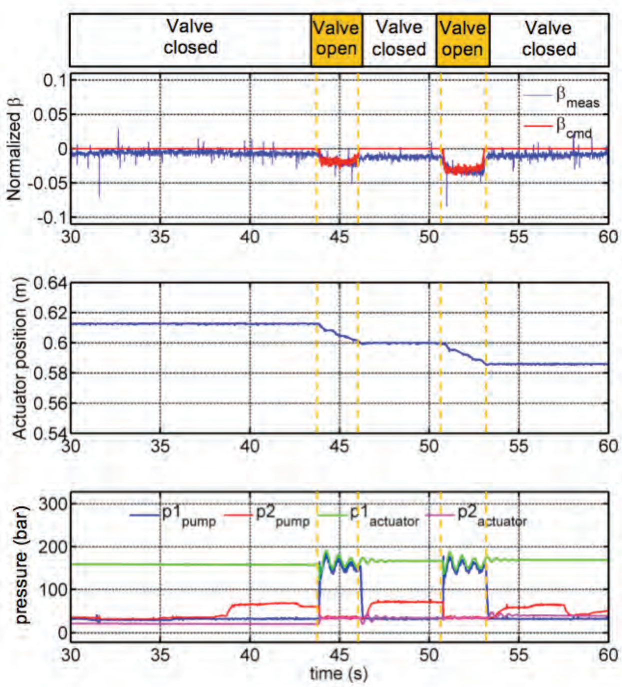


Figure 5: Pump switching without control using the boom actuator under a high load

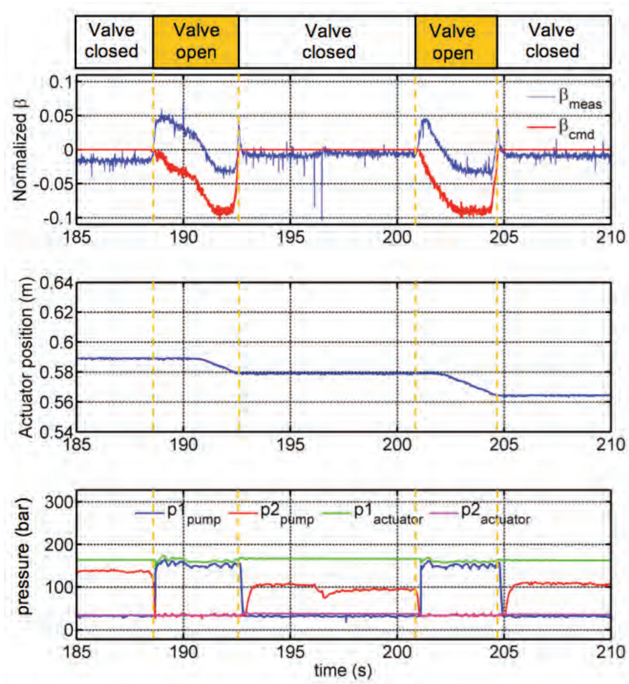


Figure 6: Pump switching with control using the boom actuator under a high load

Electronic Anti-stall Controller

One of the often overlooked challenges of fluid power systems is that in most cases hydraulic drives are extremely powerful relative to their primary movers. If not addressed properly, this condition can degrade performance, controllability, efficiency and even lead to complete system shutdown. To prevent engine overloading and its undesired effects, several hydraulic and electro-hydraulic anti-stall system have been proposed and commercialized. The main challenge for DC actuation is the one pump per actuator requirement. This condition complicates the conception and implementation of an anti-stall apparatus. For this reason, we have proposed for the first time an electronic anti-stall control for DC actuation. Similar to the majority of anti-stall controllers, the proposed scheme is enabled based on the error between the engine speed measurement and reference value. However, the operation of the DC actuation as well as its nonlinear behavior are taken into account. Since the hydraulic units in DC actuation may operate as pumps or motors they can contribute to loading or aid in unloading the engine.

The advantage of the proposed approach is that the displacement of the hydraulic units operating as motors is not affected by the anti-stall controller, maximizing their torque, while the displacements of the units operating as pumps are penalized depending on their torque level and the available torque from the engine. To deal with the nonlinearities in the system, a manually tuned gain scheduler takes into account the error between the measured and reference engine speeds and each units' differential pressure. The commanded unit displacements are limited according to the gain-scheduler. To show the validity of the controller approach, the strategy was implemented in test bed 1. An aggressive cycle was measured to show the controller working at extreme operating conditions. In reference to Figure 7, it can be observed that the engine speed error is maintained relatively small.

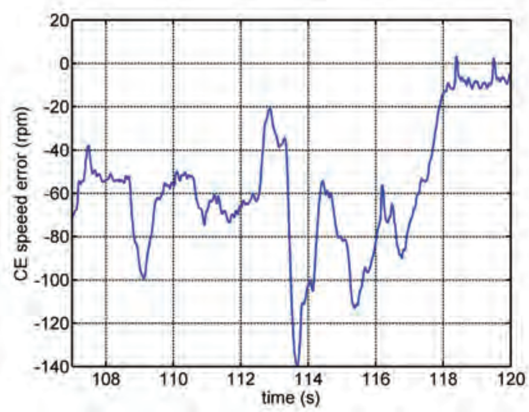


Figure 7: Engine speed error

Planned Achievements following the reporting period

- Synthesize smart controllers for pump switching to both optimize the entire system operability and increase DC system reliability through control redundancy
- Derive and implement advanced controls for the power management of the hydraulic hybrid swing drive.
- Improve the anti-stall control algorithm capabilities through the formulation of an algorithm that optimizes the gain values of the now manually tuned anti-stall gain schedule.

Member company benefits

The results gained from test bed 1 are directly transferable to industry and have already offered benefits to member companies. Below are some of these benefits:

- Test bed 1 was actively evaluated and tested by industry members (Caterpillar, Bobcat, Parker-Hannifin and CNH) during its time as a DC, non-hybrid prototype excavator. In the future, it can be tested and evaluated in its hybrid configuration. This saves them much time and money compared to building their own prototypes in order to evaluate the potential of DC actuation as well as that of the hybrid DC architecture.

- The results of this test bed have shown that up to 40% fuel savings can be achieved which would clearly be a benefit to OEM companies within the center.
- The improved efficiencies and potential for reduced engine power made possible by the hybrid DC excavator architecture being developed in this project will help OEMs meet upcoming regulations under the TIER emissions standards, together with providing the resulting monetary benefits.

References

[1] Williamson, C., Lee S. and Ivantysynova, M. 2009. Active Vibration Damping for an Off-Road Vehicle with Displacement Controlled Actuators. *International Journal of Fluid Power*, Vol. 10, No. 3, pp. 5-16.

Test Bed 3: Hydraulic Hybrid Passenger Vehicle

Research Team

Project Leader: Perry Y. Li, Mechanical Engineering, University of Minnesota
Other Faculty: Thomas R. Chase, Mechanical Engineering, University of Minnesota
Graduate Students: Kai-Loon Cheong, Tan Cheng
Industrial Partner(s): Bosch-Rexroth, Eaton, Parker, Danfoss, and others

1. Statement of Test Bed Goals

The overall goal of this project is to realize hydraulic hybrid power trains 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. Power trains produced in the scope of this project must demonstrate advantages over electric hybrids to be competitive.

2. Test Bed Role in Support of Strategic Plan

Test Bed 3 (TB3) 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 may be 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”) connected to an in-house built hydrostatic dynamometer. The vehicle has been outfitted with a modular power train. This enables experimenting with different pump, motor and energy storage technologies, including those developed in complementary CCEFP projects.

The “Generation 2” vehicle is being developed in partnership with Folsom Technologies International (FTI). It is built on the platform of a 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 two years has focused on the Generation 1 vehicle, although development of the Generation 2 vehicle has continued as resources permit. The Generation 2 vehicle is housed at the Folsom facility in Albany, NY.

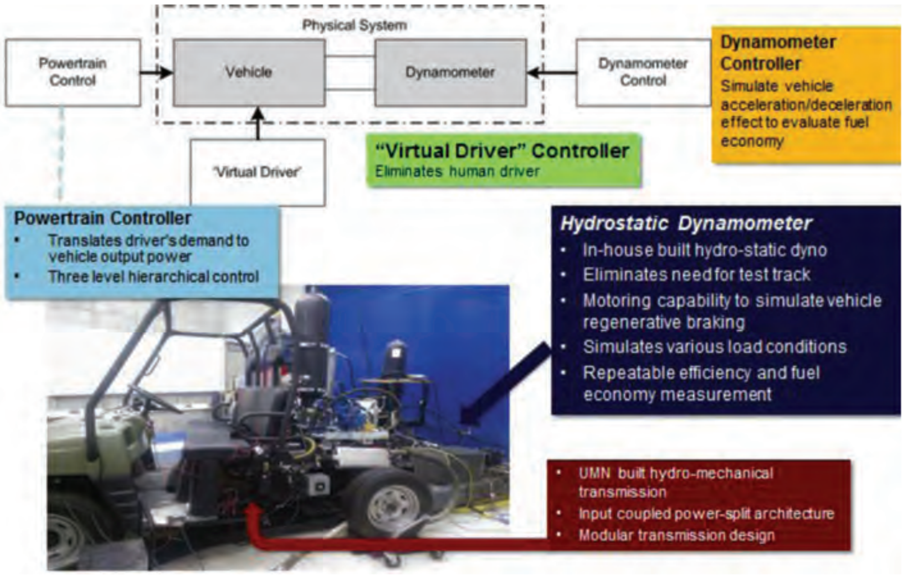


Figure 1: Overview of Test Bed 3 HHPV Generation 1 with hydrostatic dynamometer.

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 (2014).

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

Recent years' major achievements:

- *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.
- *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.
- *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.
- *Powertrain and dynamometer control systems*: Three controllers have been designed and implemented on the vehicle-dynamometer system (see Figure 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 also 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. The virtual driver controller replaces an actual driver. It makes it possible to track arbitrary drive cycles repeatably, which is necessary to gather reliable fuel efficiency data.

Major achievements in year 2014:

- *Clutch system redesign*: Now that we are able to program actual drive cycles, we learned that the transmission occasionally and briefly transmits torque to the vehicle's engine, rather than vice versa. The electric clutch that we formerly used to couple the engine to the transmission only had the ability to transmit torque in one direction. Therefore, instances of reverse torque transmission would damage the clutch. A new hydraulic clutch, with two way torque transmission capability, was purchased and installed. A small electrically driven hydraulic pump, originally intended for use on a convertible top, was adapted to enable engaging the clutch with an electric signal. This architecture eliminates the need to throttle hydraulic fluid from the main hydraulic system to power the clutch. The new clutch system now enables us to simulate complete drive cycles.

- *Sensors upgrade on vehicle*: Several sensors were added to the vehicle to enable better quantifying drive cycle efficiency. A wireless torque sensor was installed on the transmission input shaft to directly measure engine torque. At the suggestion of one of our industry mentors, pressure and temperature sensors were installed at the inlet and outlet ports of the two hydraulic pump motors to improve the assessment of their efficiency, particularly while experimenting with alternative hydraulic fluids.
- *Dynamometer controller improvement*: The dynamometer was previously modeled as a second order system. Further study of system identification results revealed that it is better modeled as a third order system. This improvement increased the bandwidth of the dynamometer controller from 6 rad/s to about 15 rad/s.
- *Energy management strategy implementation*: The top level of the three level vehicle controller was programmed to implement a rule based energy management algorithm developed in related Project 1A.1. Results for the urban and highway drive cycles are shown in Figure 3. (Preliminary results from the highway drive cycle were reported in Year 8.) As noted in "Dynamometer Hardware Upgrades", the vehicle inertia was artificially reduced to enable completing these drive cycles with an undersized hydraulic power unit available for the dynamometer at the time of testing. This is the first time that the HHPV has been tested in hybrid mode using an urban drive cycle. Unfortunately, the results showed little improvement in fuel economy over CVT mode. The likely reason is that the algorithm used was not designed to fit the Generation I vehicle. Improvement is expected for future hybrid algorithms such as Mild Hybrid and Lagrange multiplier.

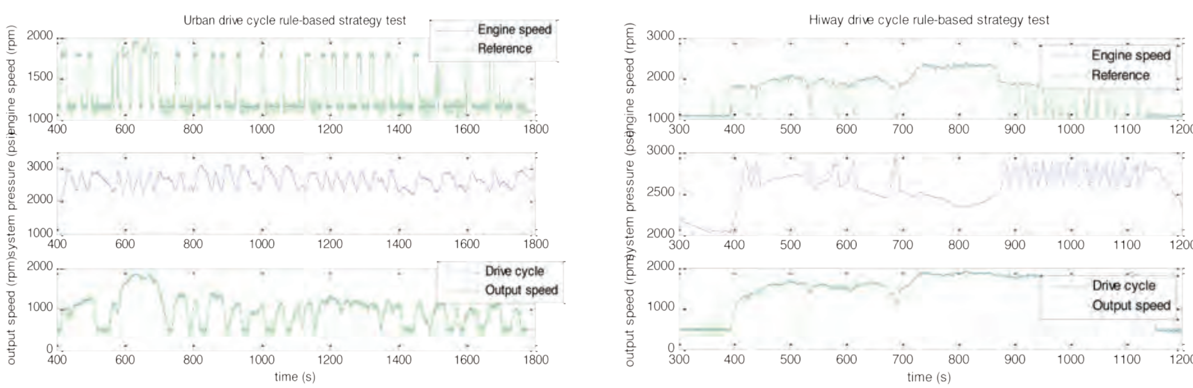


Figure 2: Hybrid powertrain operated with Rule-based strategy in urban (left) and highway (right) drive cycles

- *Dynamometer Hardware Upgrades*: Two improvements on the dynamometer were completed in December 2014. First, the dynamometer has not been able to simulate the full inertia of the Generation I vehicle due to an undersized power supply. The power supply was increased from 5.6 kW to 15 kW to overcome this problem. Second, the charge pump for the dynamometer was formerly attached in parallel with the main pump/motors, which are driven by the vehicle's drive shaft. As a result, the drive shaft could not be run at low speed, as charge pressure would be lost. As a consequence, note that the output shaft speed is not allowed to drop below 400 RPM in Figure 2. This problem was overcome by installing a separate 750 W electric motor to drive the dynamometer charge pump exclusively. This modification also removes a parasitic power loss on the dynamometer, further increasing its power capacity.

Achievements Applicable to the Generation 2

Recent years' achievements:

- *Transmission Characterization:* A method has been developed to determine the efficiency map for the FTI transmission under various hybrid operating conditions given limited data. This map is necessary for proper design of the vehicle operating strategy.
- *Effect of hydraulic oil*: The transmission efficiency depends on the hydraulic oil used. It has been demonstrated that replacing the low viscosity (5 cSt) Automatic Transmission Fluid (ATF) with a higher viscosity (15 cSt) fluid results in improved efficiency, especially at low transmission ratios.
- *Hardware preparation:* The FTI transmission has been re-installed on the Ford F-150 at Folsom. The signal conditioning and data acquisition system is installed on the vehicle. Hardware-in-the-loop testing has been completed at UMN.

Major achievements in year 2014:

- Visit #1: The control computer was interfaced with the vehicle. Access was established with the engine and transmission control inputs and sensors.
- Visit #2: System identification was performed on the drive train.
- Visit #3: The low level portion of the 3-level hierarchical vehicle controller was implemented. A free-spinning test of the CVT was performed; e.g., the wheels were raised off of the ground. Figure 3 illustrates that the controller maintains the engine speed at 900 rpm as the transmission ratio is changed by varying the pump/motor displacements.

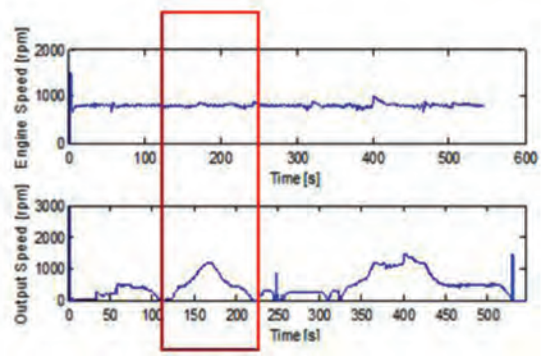


Figure 3: CVT free-spinning test

C. Plans

Plans for the Generation 1 Vehicle

Plans for the Generation 1 vehicle will focus on core project integration. It is noted that several of events from the Year 8 plan have been re-scheduled to Year 9. The reason is that power to the fourth floor lab space where the vehicle was housed was discontinued on short notice in August 2014 due to building remodeling, and power for operating the dynamometer in its new lab space was not made available until late December 2014. Nevertheless, two benefits resulted from the move. First, we were able to specify power in the new lab to accommodate the new 15 kW dynamometer power supply described earlier. Second, the new space is on the first floor and has a garage door, so the vehicle can be easily removed from the building for road demonstrations. The Year 9 plans are described in order below.

1. Additional high level hybrid energy management control strategies will be tested. The mild hybrid mode is now being implemented, which will be followed by the modified Lagrange multiplier strategy. The more complex Stochastic Dynamic Programming (SPD) and Model Predictive Control (MPC) algorithms developed in Project 1A.1 will be implemented and tested in Fall 2015.

2. For Project 1G.1 (Energy Efficient Fluids), a synthetic biodegradable ester will be utilized as the hydraulic fluid, which is expected to exhibit higher efficiency at low speeds [10]. The new oil will be compared with a baseline shear stable high viscosity index hydraulic fluid in Spring-Summer 2015. The modified Lagrange hybrid control strategy will be used if it shows improvement over CVT control.

3. A pulse width modulated virtually variable displacement pump/motor (VVDPM) designed in Project 1E.1 will be evaluated using torque and speed data provided by the Gen I vehicle. Simulations have been performed to optimize the gear ratios for the pulse width modulated

pump/motor [8]. The VVDPM will be evaluated on a test bench using the torque-speed data in a hardware-in-the-loop configuration. Performance will be compared with the baseline bent-axis unit (summer 2015).

4. A conventional accumulator is currently used on the low pressure side of the vehicle. When its pressure rises, vehicle efficiency declines, since the differential pressure across the pump/motors decreases. Strain energy accumulators being developed by Project 2C.2 introduce the potential for maintaining the low pressure at a constant low level. We are planning to replace the low pressure accumulator with a prototype provided by Project 2C.2, and we will measure the change in efficiency associated with this replacement (December 2015-January 2016).

<u>Plans for the Generation 2 Vehicle</u>

Much of the controller development that has been completed for the Generation 1 vehicle will be adapted to the Generation 2 transmission, and fine-tuned for the differences in architectures. After the Generation 2 vehicle is fully functional, the continuous variable transmission (CVT) strategy and a hybrid strategy will be tested.

1. Visit #1: Implement two high level control strategies: CVT and mild hybrid (regenerative braking, launch assist, CVT).
2. Visit #2: Implement full hybrid operation and prepare vehicle for dynamometer testing.

<u>Milestones and Deliverables</u>

Generation I:

- Task 1: Implement the mild hybrid and modified Lagrange multiplier method developed and compare their effectiveness. [4/15]
- Task 2: 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. [8/15]
- Task 3: Evaluate the 4 quadrant Virtually Variable Displacement Pump/Motor (VVDPM) developed in Project 1E.1 under a hardware-in-the-loop test (1E.1) [6/15]
- Task 4: Test efficiency gain attributable to installing a strain energy accumulator (2C.2) [1/16]

Generation II:

- Demonstrate CVT control strategy in Generation 2 vehicle [6/15]
- Demonstrate mild hybrid control strategy in Generation 2 vehicle [12/15]

D. Member company benefits

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

E. References

[1] Rannow, M., Li, P., Chase, T., Tu, H., and Wang, M., 2010. “Optimal design of a high-speed on/off valve for a hydraulic hybrid vehicle application”. Proceedings of the 7th International Fluid Power Conference, Aachen, Germany.

[2] Cheong, K. L., Li, P. Y., Sedler, S. P., and Chase, T. R., 2011, “Comparison Between Input Coupled and Output Coupled Power-Split Configurations in Hybrid Vehicles”, 52nd Nat Conf on Fluid Power (Paper 10.2), Las Vegas, NV.

[3] Richard Stone, “Introduction to Internal Combustion Engines”, SAE International; 3rd Edition, 1999.

[4] C. T. Li and H. Peng, 2010, “Optimal Configuration Design for Hydraulic Split Hybrid Vehicles”, Proceedings of the American Control Conference, Baltimore, MD, 2010.

[5] P. Y. Li and F. Mensing, 2010, “Optimization and control of hydro-mechanical transmission based hydraulic hybrid passenger vehicle”, Proceedings of the 7th International Fluid Power Conference (IFK), Aachen, Germany.

[6] D. R. Grandall, *Performance and Efficiency of Hydraulic Pumps and Motors*, M.S. Thesis, Department of Mechanical Engineering, University of Minnesota, January, 2010.

[7] T. P. Sim and P. Y. Li, 2009, "Analysis and Control Design of a Hydro-Mechanical Hydraulic Hybrid Passenger Vehicle", Proceedings of the ASME 2009 Dynamic Systems and Control Conference #2763, Hollywood, CA.

[8] Haink C. Tu, et. al., “High-speed 4-way rotary on/off valve for Virtually Variable Displacement pump/Motor Applications”, in *Dynamic Systems and Control Conference, Arlington*, VA, November 2011.

[9] Cheong, K. L., Li, P. Y., and Chase, T. R., 2011, “Optimal Design of Power-Split Transmission for Hydraulic Hybrid Passenger Vehicles”, 2011 American Control Conference, San Francisco, CA, pp. 3295-3300.

[10] Herzog, S., Zink, M. and Michael, P., 2009, “Hydraulic Fluid Viscosity Selection for Improved Fuel Economy”, *SAE Journal of Commercial Vehicles*, 2(2): 61-65.

[11] Michael, P., Wanke, T., Devlin, M., et al., 2010. “An Investigation of Hydraulic Fluid Properties and Low-Speed Motor Efficiency”. Proceedings of the 7th International Fluid Power Conference, Aachen, Germany, Vol. 3, pp. 341-353.

[12] Z. Du, K. L. Cheong, P. Y. Li and T. R. Chase, “Fuel Economy Comparisons of Series, Parallel and HMT Hybrid Architectures”, Proceedings of 2013 American Control Conference, Washington D.C., June 2013.

[13] K. Cheong, Z. Du, P. Y. Li and T.R. Chase, “Hierarchical Control Strategy for a Hybrid Hydro-Mechanical Transmission (HMT) Powertrain”, Proceedings of the 2014 American Control Conference, Portland OR, June 2014.

[14] Z. Du, K. L. Cheong, P. Y. Li and T.R. Chase, “Design and Experimental Validation of a Virtual Vehicle Control Concept for Testing Hybrid Vehicles Using a Hydrostatic Dynamometer”, ASME Dynamic Systems and Control Conference, San Antonio, TX, Nov. 2014.

Test Bed 4: Patient Transfer Assist Device

Research Team

Project Leader:	Wayne J. Book, Mechanical Engineering, Georgia Tech
Research Engineer:	James Huggins, Mechanical Engineering, Georgia Tech
Graduate Student:	Heather Humphreys, Mechanical Engineering, Georgia Tech
Undergraduate Student:	Zack Siegel, Mechanical Engineering, Georgia Tech
Industrial Partners:	Parker Hannifin, Eaton

1. Statement of Test Bed Goals

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

To benefit from the power and force density of fluid power, effective human interfaces and control algorithms are very important. It must be safe for humans in its workspace, allow for simple and intuitive operation of multiple degrees of freedom (DOFs) by a single caregiver, have smooth motion without vibration or oscillation, and be highly maneuverable. Related and client CCEFP projects include passivity based control (3A.2), control of vibration (3B.3), multi-modal human machine interfaces (3A.1), user-centered design (3A.3), the hydraulic transformer (1E.5), and potentially others. The research includes developing methods to allow for intuitive collaborative manipulation, managing external interaction forces with a powerful machine operating in a relatively delicate environment, and compensation for nonlinear and non-ideal characteristics resulting from lower-cost components.

2. Test Bed Role in Support of Strategic Plan

The CCEFP seeks to make fluid power ubiquitous. As such the power of hydraulics must be adapted to uses in the delicate situations which are epitomized by patient care. Affordable, quality care of mobility limited individuals is currently hampered by the need for multiple caregivers to perform transfers of patients that may occur a dozen times in a day. Obese, even moderately heavy patients are especially difficult to transfer. The needs for the patient transfer assist device application exemplify some primary CCEFP goals, such as the need for a safe and effective operator interface, a very compact and mobile design, and minimal noise and leakage, all in a multi-DOF system. This test bed provides an opportunity to explore how fluid power can be used in non-traditional environments such as homes and clinical institutions, with humans in the workspace. It also provides a system in which to test features needed for these fluid power applications. Contrary to prior concerns, the research is consistent with the goals of the center in that it demonstrates expansion of fluid power technology to a smaller than typical scale, in a more delicate environment. It addresses barriers that arise in these new applications, such as control with low-cost components with non-ideal characteristics, management of forces in any undesirable environmental interactions, and physical collaboration with humans.

3. Test Bed Description

Overview

A significant market need has been identified for an improved mobile assist device to aid in transferring mobility limited people, particularly bariatric patients [1]. With the increasing aging population and the increasing number of bariatric patients, the number of mobility limited patients is significantly increasing. Institutions have recognized the risks of injury to caregivers and most are implementing “no lift policies” which require the use of an assist device to lift the weight of a patient [2, 3]. However, current market lift devices are antiquated and insufficient for many patient and caretaker needs; transfers often require multiple personnel and as much as 10-20 minutes. Only a few projects have addressed the problem of patient transfers, and most do not consider bariatric patients. One example of a prototype patient transfer and rehabilitation device was developed by NIST [4]. This test bed concept stemmed from a related project with our collaborators at the Quality of Life Technology NSF ERC, which developed a wheelchair-mounted device for transferring patients. However, using electrical actuation, they were unable to achieve the desired lifting power [5]. Hydraulic actuation has the advantage of providing large force capability in a compact package, with the power source located at the base of the device. This is an ongoing test bed; currently it has four degrees of freedom fully functional. The next stage of the research focuses on various control techniques, operator interface design, and modeling and dynamic simulation.

Challenges & Technology Advancement Barriers

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

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

A. Achievements

Achievements in previous years

At the start of the project, a substantial needs assessment was completed, involving individual interviews, a focus group, and a benchmark operator study with current market patient lift devices. The assessments included patients who use current market lifts, engineers and salespeople in the patient lift industry, home caretakers, nurses, assisted living facility administrators, and physical therapists. The study shed light on a number of shortcomings of current market lifts. We learned that the new design needs to be much more maneuverable in tight spaces, such as transfers into cars and inside bathrooms, providing accessibility to more locations. The device needs to allow for a single caregiver to perform even complex transfers; often only one caregiver is available. Heavier or bariatric patients are particularly difficult for caretakers to maneuver; the device needs to provide forces sufficient to handle bariatric patients. Furthermore, the benchmark operator study demonstrated that the transfer operations often involve inadvertent small collisions with the environment. It is desirable for these unwanted interaction forces to be managed, considering the necessary high force capabilities of the machine.

Based on the information from the needs assessment, a design for the first prototype was developed. A design review meeting was held, including researchers from the assistive device industry, fluid power researchers, engineers from the current patient lift industry, and human factors researchers. It was determined that hydraulic actuation of multiple degrees of freedom would be beneficial. The first two degrees of freedom of the machine were fabricated and integrated, a main lifting scissor mechanism and a boom extension. The machine uses an electrohydraulic pump controlled architecture, intended to provide better efficiency than valve-controlled systems by eliminating throttling losses. The system includes a servo drive, reversible DC electric motor, small gear pump, and hydraulic actuator for each degree of freedom. The control input is the reference current for the servo drive. The operator input is measured from a force sensing handle mounted near the patient, providing intuitive coordinated control; the operator simply pushes on the machine in the desired direction of motion, and it moves the patient accordingly.

Additionally, some initial testing was performed on a pre-prototype patient transfer assist device, which used a valve-controlled vertical lifting cylinder to actuate a boom which lifted the patient sling. A force sensing handle was mounted to the boom, which provided the operator input. A passivity-based human power amplifier controller was implemented on the pre-prototype. This control approach uses feedback of both motion and actuator force, with the goal of acting as a mechanical tool to amplify the human input force, within passivity constraints. Preliminary operator experiments were performed using the passivity based human power amplifier controller [6].

Achievements in the past year

System Integration & Hardware

Two additional degrees of freedom have been added, the differential drive wheels. For the purpose of safety in testing controller designs, the wheels are currently mounted on a separate cart. The wheels are actuated by low speed high torque hydraulic motors. The wheel cart uses the same actuation system architecture as the first two degrees of freedom, with a servo drive, reversible DC electric motor, and hydraulic motor, for each wheel. The cart uses a separate onboard National Instruments Single Board Rio controller, which is similar to the controller used on the main lift and extension; when the wheels are integrated into the full machine, the control code will be easily portable. The cart also has a separate set of batteries and a force/torque sensing handle for the operator input (Figure 1).

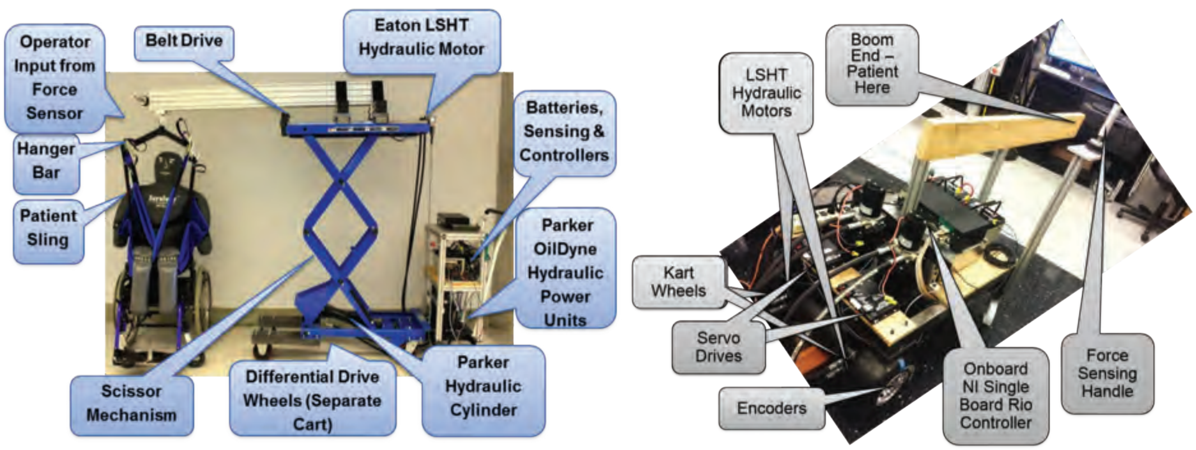


Figure 1. First prototype patient transfer assist device; left: main lifting and boom extension, right: differential drive wheels on separate testing cart

The operator input force maps to a reference patient velocity, and the kinematics calculations for conversion from patient motion to wheel motion are performed on the controller. Wheel position feedback is obtained from encoders, and feedback rate control is implemented on the controller. The cart is fully functional and ready for testing of more advanced control architectures, such as obstacle avoidance. Additional updates have also been made to the overall electrical system, including addition of a breakout board and electrical box to handle all sensing, including pressures on each side of each actuator, motor currents, actuator positions, operator input forces, and other system forces. A detailed description of the design of the patient transfer assist device is given in [7].

Dynamic System Modeling

A model has been created to simulate the mechanical dynamics of the main lifting scissor mechanism, boom extension, and actuation mechanisms, as well as a variable patient payload, in MATLAB [8]. A gray box model based on system identification by spectral analysis, roughly based on the form of a first principles based model, has been developed for the actuation systems, with input reference motor current and output actuator motion. Further investigation is in process to capture significant nonlinear or non-ideal features of the actuation systems, such as stiction, deadband, and other characteristics.

Control and Operator Interface

In order to allow for this powerful machine to operate safely in a relatively delicate environment with humans in the workspace, and to reduce the caretaker mental workload, it is desirable to manage any undesirable interaction forces. For the main lifting and boom extension, some interaction with the caretaker and patient is necessary. Therefore, it is desirable to develop controllers which manage both force and motion. A substantial literature study has been performed on various types of interaction controllers, particularly those that are well-suited for hydraulic actuation. Several forms of interaction control will be tested on the boom extension.

The first form of interaction control to be implemented on the hardware system is an impedance control [9], currently implemented in a mechanical dynamics simulation on the scissor lift and boom extension, and in the hardware system on the boom extension [8], shown in Figure 2. The controller uses a low level force control based on pressure measurements from the hydraulic motor. The required estimate of the external interaction force is estimated from pressure measurements and knowledge of the system dynamic properties, such as inertia and friction/damping.

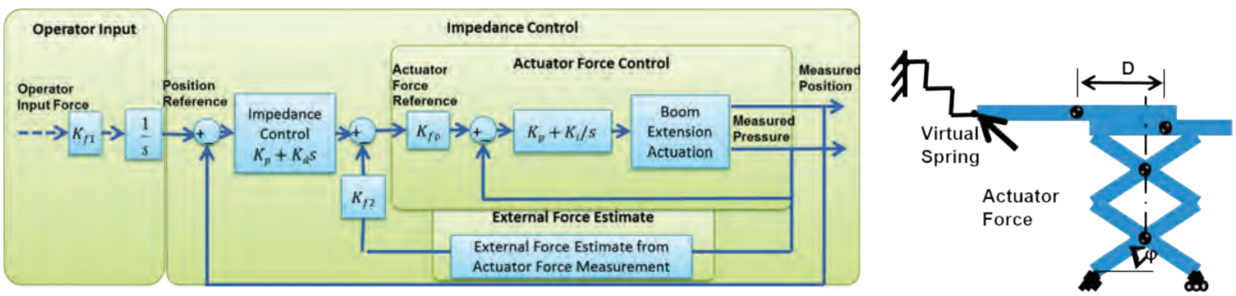


Figure 2. Interaction control; left: current impedance control implementation on boom extension, right: interaction concept of virtual spring in task space

The architecture shown in Figure 2 has been tested on the boom extension hardware system. Preliminary experiments demonstrate that the motion of the machine under closed loop control can be significantly affected by small external forces (less than 15 lbf), exerted by a human.

B. Plans

Plans for the next year

System Integration and Modeling

Once controller testing for the wheels is complete, the differential drive wheels will be integrated into the full patient transfer assist device system. The machine and electronics were designed to allow for integration with the additional actuators, sensors, and hydraulics. Four degrees of freedom, the wheels, the vertical lift, and the horizontal boom extension, will be controlled from the same operator input force sensing handle. Management of the redundancy between the boom extension and the wheeled base will be determined. An investigation on this base redundancy management, along with tipping stability, will be performed. Basic models of the hydraulic actuation system and mechanical dynamics for the boom and lift have been created. Models for the differential drive wheels will be added and integrated into the full system model. Also, further characterization of nonlinearities and other non-ideal features of the pump controlled actuation systems will be added, and the full system will be integrated in simulation.

Operator Interface and Control Design

The current focus for the control design is on interaction control, to manage any undesirable external interaction forces. It was apparent from the benchmark operator testing that unintentional interactions between parts of the machine and the environment are common, and with such large force capability, management of such forces is needed. First, a few different types of interaction control will be implemented on the horizontal boom extension, along with any needed compensation for nonlinearities or other non-ideal hardware system features. These include forms of the currently implemented impedance control (with low level force control), an admittance-based human power amplifier (with low level position control), and a passivity-based human power amplifier. The most suitable forms of interaction control will also be implemented on the vertical lifting degree of freedom. Obstacle avoidance algorithms based on ultrasonic sensing will be implemented on the wheeled base. The system will be integrated to provide coordinated control of all degrees of freedom of the machine from a single force sensing handle. The design of the caretaker physical interface will be improved, based on input from NCAT, including determining an appropriate ergonomic location for the input handle.

Operator Testing

Once the system integration is complete, a set of operator experiments will be performed. The experiments will include tests similar to those from the benchmark study, which included several transfer operations between a bed, a wheelchair, a chair and the floor, as well as a time study and survey. It will also include experiments to evaluate the performance of the obstacle avoidance / interaction control. Results will be evaluated by statistical methods, including ANOVAs, and the results will be presented. Improved or alternative caretaker physical interface designs will also be tested.

CCEFP Project Integration

Collaboration continues with NCAT on project 3A.3 on their modeling of the caretaker physical and mental interaction with the machine. CAD models of the prototype patient transfer assist device have been provided and are being used in their simulations. They are also providing input on the operator testing, evaluation, and interface design. A form of vibration control similar to that used in project 3B.3 with Dr. Vacca may provide a different method to compensate for an instability problem encountered in this test bed hardware system resulting from an overrunning load condition; they have provided some guidance toward our understanding and solution of this issue, and investigation on viability of implementation on Test Bed 4 will be pursued further. The graduated passivity-based human power amplifier controller developed in project 3A.2 was implemented on a pre-prototype of this test bed, and it continues to be a candidate controller and will be tested on the current prototype hardware. Finally, initial investigation and exchange of information has begun related to simulation of integration of a hydraulic transformer, project 1E.5, into Test Bed 4.

Longer Term Vision

In later years, this test bed can provide a platform in which to test additional small scale subsystem and component technologies and operator interface designs, as they further develop. Alternative hydraulic system architectures may be tested. This system is also a good candidate for testing regeneration.

Expected milestones and deliverables

- Preliminary testing with control strategies implemented in simulation and hardware completed [Month 10]
- First round of human operator studies completed [Month 13]
- Preliminary testing with additional actuated degrees of freedom completed [Month 15]
- Preliminary testing with alternative operator and patient interface designs completed [Month 19]
- Results of testing with other CCEFP component projects [Month 22]
- Final testing *and reporting** completed [Month 24]

  **Note: added after proposal*

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.

D. **References**

[1] P. L. Santaguida, M. Pierrynowski, C. Goldsmith, and G. Fernie, "Comparison of cumulative low back loads of caregivers when transferring patients using overhead and floor mechanical lifting devices," *Clinical Biomechanics,* vol. 20, pp. 906-916, 2005.

[2] A. Nelson, M. Matz, F. Chen, K. Siddharthan, J. Lloyd, and G. Fragala, "Development and evaluation of a multifaceted ergonomics program to prevent injuries associated with patient handling tasks," *International Journal of Nursing Studies,* vol. 43, pp. 717-733, 2006.

[3] R. Petzel, "Safe Patient Handling Program and Facility Design," Dept. of Veterans Affairs, Ed., Washington, DC, 2010.

[4] R. Bostelman, J. Albus, and T. Chang, "Recent Developments of the HLPR Chair," in *IEEE 10th International Conference on Rehabilitation Robotics*, Noordwijk, The Netherlands, 2007.

[5] R. Cooper, G.G. Grindle, J.J. Vasquez, J. Xu, H. Wang, J. Candiotti*, et al.*, "Personal Mobility and Manipulation Appliance - Design, Development, and Initial Testing," *Proceedings of the IEEE,* vol. 100.

[6] H. C. Humphreys, W.J. Book, and J. D. Huggins, "HYDRAULICALLY ACTUATED PATIENT TRANSFER DEVICE WITH PASSIVITY BASED CONTROL," presented at the Proceedings of the ASME/BATH 2013 Symposium on Fluid Power & Motion Control, Sarasota, Florida, USA, 2013.

[7] H. C. Humphreys and W. J. Book, "Advanced Hydraulically Actuated Patient Transfer Assist Device," in *8th FPNI Ph.D. Symposium on Fluid Power*, Lappeenranta, Finland, 2014.

[8] H. C. Humphreys, W. J. Book, J. D. Huggins, and B. Jimerson, "Caretaker-Machine Collaborative Manipulation with an Advanced Hydraulically Actuated Patient Transfer Assist Device," in *ASME 2014 Dynamic Systems and Control Conference*, San Antonio, TX, 2014.

[9] S. Buerger, "Stable, High-Force, Low-Impedance Robotic Actuators for Human-Interactive Machines," PhD, Mechanical Engineering, Massachusetts Institute of Techology, 2005.

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

Research Team

Project Leader:	Elizabeth Hsiao-Wecksler, MechSE, UIUC
Other Faculty:	Will Durfee, Mechanical Engineering, University of Minnesota 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
Undergraduate Students:	UIUC: Katie Neville, Chenzhang Xiao; Tim Anderson, Minnesota State Mankato (CCEFP REU); UMN: Faith Bradley, UIUC (CCEFP REU), Jon Nath (UMN)
Industrial Partner:	Parker Hannifin

1. Statement of Test Bed Goals

The goal of this test bed is to drive the development of enabling fluid power technologies by:

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

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

2. Project Role in Support of Strategic Plan

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

3. Test Bed Description

A. Description and explanation of research approach

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

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

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

Research Approach: We are following a roadmap for developing portable fluid powered AFO devices with increasing complexity and performance requirements. In 2008, the design and construction of an energy-harvesting AFO that selectively restricted joint motion using a pneumatically-driven locking mechanism was completed [6, 7]. Using a systems engineering approach, the fluid powered AFO system has been divided into four subsystems that align with our core system challenges: power supply, actuator/valving, structural shell, and control system (electronics, sensors, and HMI). The subsystems have target specifications that must be met to realize a fully functional device. The power supply must weigh < 500 g, produce at least 20 W of power, run continuously for ~1 hour, and be acceptable for use near the human body. The actuator and valving must weigh < 400g and provide a minimum of 10 Nm of assistive torque at a reasonable efficiency. The structural shell must weigh under 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. To achieve our goals we have pursued two parallel paths: a portable pneumatic AFO (the PPAFO) and an untethered hydraulic AFO (the HAFO). We report on each below.

B. Achievements

Portable Pneumatic AFO (PPAFO)

In 2010, the first generation PPAFO demonstrated device feasibility [8-10] and was an improvement over state-of-the-art passive and active systems [4, 5, 11] because it provided subject-specific motion control and torque assistance without tethered power supply or electronics. The device provided modest dorsiflexion (toes-up) and plantarflexion (toes-down) torque actuation at the ankle. Two U.S. patent applications on the PPAFO were filed with CCEFP students and faculty from UIUC, UMN, MSOE and GT as co-inventors [12, 13].

Since then, we improved the efficiency, compactness, control, usability, and applications of the PPAFO. The hardware includes an OTS pneumatic rotary actuator located at the ankle joint, a canister of compressed CO_2 at the waist (a placeholder for a future compact power source), and a waist-worn microcontroller (Figure 1d). The Gen 1.0 PPAFO could generate up to 12 Nm at 100 psig with run times less than 30 minutes with a 20 oz. bottle (Figure 1a). Theoretical and experimental component and system efficiencies of the PPAFO system suggested that the exhaust gas from the higher pressure plantarflexion actuation (100 psig) could be captured into an accumulator and recycled to power the lower pressure dorsiflexion actuation (30 psig) [14, 15]. Working with students at Vanderbilt on Project 2C.2 (strain energy accumulator), we constructed a pneumatic elastomeric accumulator for use with the regenerative pneumatic circuit that was tested during walking tests and we investigated the effect of two control algorithms on fuel efficiency. By increasing the net work output, a more intelligent, state estimation controller improved fuel efficiency by 72% compared to a basic controller with the regenerative circuit [15]. Using the state estimation controller and the regenerative pneumatic circuit, the run time for a 9 oz bottle was expanded from original 15 to 19 minutes.

For the 2012 Gen 2.0 PPAFO, we developed a lighter and simpler structural shell that allows for swapping of modular system components (Figure 1b). The shell has no metal vertical struts and no medial support. The weight of the PPAFO went from 1.86 kg to 1.60 kg. Multiple sized (S, M, L) foot and shank shells were fabricated to support testing on different sized test subjects. To reduce the size and increase the torque of pneumatic actuation, we have sponsored Mechanical Engineering capstone design teams at Bradley University from fall 2011 to spring 2014 as a CCEFP E&O capstone project. The 2014 team delivered a design with dual cylinders and gear train that achieves 40Nm @ 110 psig. We are currently integrating this actuator with the Gen 2.0 shells to create the Gen 3.0 design (Figure 1c).

To control the PPAFO in varied walking environments (level ground, stairs, ramps), we examined different actuation-timing control strategies, solenoid vs. proportional control, and recognition and control for different gait modes. Our initial controller for level ground walking was a simple direct event threshold-based control using just the heel and toe sensors [9]. To accommodate impaired gait, we developed a model-based state estimator controller that added the angle sensor [8]. We examined how work and fuel use were affected by the controllers and inclusion of a regenerative circuit using the elastomeric accumulator [15]. A simulation and bench-top study highlighted that proportional valve control has better tracking and efficiency compared to solenoid valves [10]; however due to the large size of commercial proportional vales, we have not implemented this on the PPAFO, but it does highlight technological barriers to compact fluid-powered orthoses. In 2011, we began work in recognition and control for different gait modes using a 6DOF inertial measurement unit (IMU) [16, 17]. Progress in 2012 and 2013 resulted in success rates of identifying level ground, stairs, or ramps of 97-99%. We determined that only stair or ramp descent require a different controller than level ground or stair/ramp ascent, and differential gait mode control has been implemented [18]. In Y9, we worked on improved control algorithms that use modified fractional time and Bayesian regularized artificial neural networks for estimating walking state.

In 2013, in collaboration with researchers at the Rehabilitation Institute of Chicago, we began testing the Gen 2.0 PPAFO compared to tibial stimulators and passive AFOs in post-stroke and multiple sclerosis (MS) subjects. At the end of Y9 we nearly completed a 20-person study on MS participants. Results suggest that walking with the PPAFO reduces stride length and velocity, but improves joint kinematics perhaps leading to less stress on compensating joints for ankle impairment [19]. In an associated project with the Movement Disorders Center at the University of Minnesota, we are investigating the use of the PPAFO as a gait initiation device for people with Parkinson's disease (PD). A pilot study on healthy young adults provided insight into the feasibility of this application [20], and an on-going study with people with PD began in 2013 [21]. Preliminary results suggest 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.

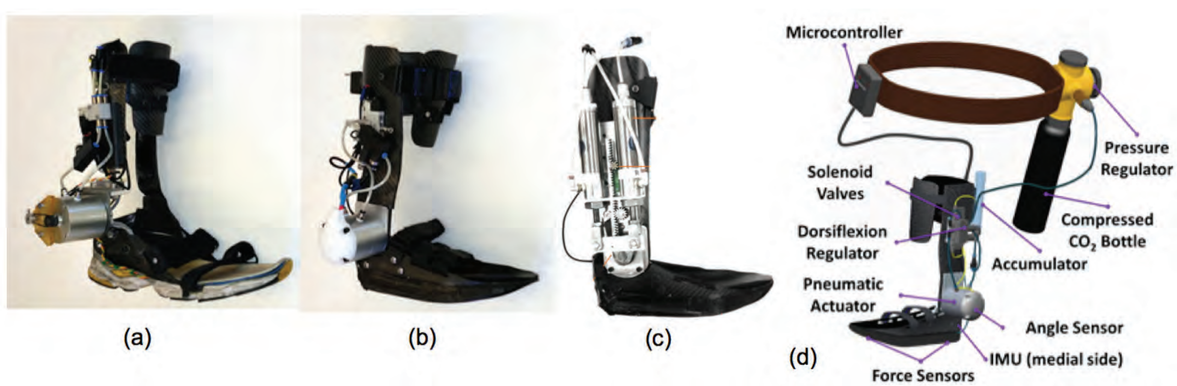


Figure 1: Three generations of the PPAFO (a) 1.0, (b) 2.0, (c) 3.0. (d) CAD rendering of Gen 2.0 system.

Untethered Hydraulic AFO (HAFO)

The research objective for the HAFO test bed is to understand the limits of small-scale hydraulics in the 10-100W range. The motivation is the need for small, untethered wearable robots. The rationale for using hydraulics is that the higher pressures that can be attained with hydraulics enables high-torque exoskeletons. From an analysis of small-scale system, we determined that the hydraulic pressure must be over 500 psi for high power-to-weight [22] and chose 2,000 psi as the nominal pressure for the HAFO. The key design requirements driving the test bed HAFO are: (1) 90 Nm torque, (2) 70 deg range of motion, (3) 100 deg/sec velocity, (4) fits under pants, (5) less than 1 Kg mass at the ankle, (6) 3,000 steps between recharge, (7) no tether. In Year 9 we completed the design and assembly of a wearable HAFO and met all of the key design requirements except requirement 6 that we have yet to test [23].

The configuration of the HAFO is: Battery ⇨ DC Motor ⇨ Pump ⇨ Hose ⇨ Cylinder. The system layout and prototype is shown in Figure 2. Performance bench testing of the prototype showed the system can reach the 90 Nm and 100 deg/s target and has about a 3 Hz bandwidth.

C. Plans, Milestones and Deliverables for Next Year

<u>PPAFO</u>: Complete longevity assessment of PPAFO with additional healthy test subjects to verify robust operation. Perform clinical trials on use of PPAFO on post-stroke, multiple sclerosis, and Parkinson's populations. Investigate new control schemes for state estimation and gait mode recognition. Implement new higher torque output pneumatic actuation system on Gen 3.0 PPAFO.

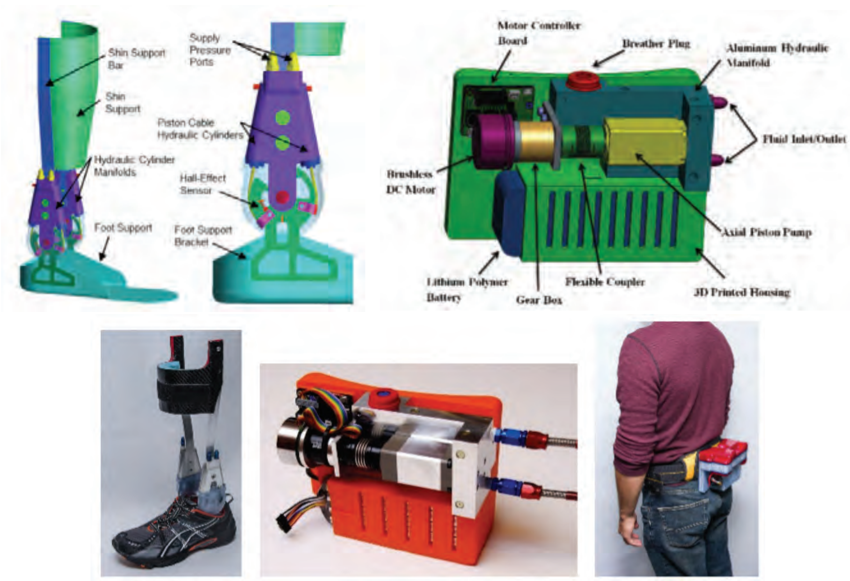


Figure 2: HAFO layout and prototype.

<u>HAFO</u>: Complete bench testing of the HAFO prototype. Complete walking testing of prototype. Develop new controllers. On the analysis side, we have begun to develop a comprehensive suite of design tools for small-scale hydraulic systems. Using static physics models of piston pumps, hoses and cylinders, we are able to predict the weight and efficiency of a system for a chosen operating point. During Y10 we will validate these models and will add in models for control valves.

D. Plans, Milestones and Deliverables for Next Five Years

<u>PPAFO</u>: Demonstrate the PPAFO on different patient populations (MS, PD, stroke) and seek external funding to support extended clinical research. To achieve these goals, we will conduct the following tasks:

Task 1: Improve torque to weight and torque to size performance, and a proportional MEMS valve. Integrate MEMS valve and higher torque actuation system. Milestones: Investigate control of Gen 3.0 PPAFO [June 2015]; Integrate MEMS proportional valve into PPAFO [December 2015].

Task 2: For a walking assistance application, design and implement control, including neural network state estimation and gait mode recognition. Milestones: ANN integration (computer driven) completed [June 2015]; Gait mode recognition and actuation without one-step delay completed [August 2015]; Concepts for energy harvesting completed [December 2015].

Task 3: For a seated rehabilitation therapy application, we will work with clinical stroke collaborators to identify testing protocols. Pressure and air flow control for torque and rotational velocity control will be examined to allow proper operation of the PPAFO. A post-stroke therapy system will be demonstrated. Milestones: Identify therapy requirements [June 2015]; Initial integration of clinician and patient user interfaces with PPAFO [September 2015]; Torque and rotational velocity control completed [March 2016]; Demonstration of post-stroke therapy [May 2016]

HAFO:

Task 1: Create suite of design tools for small hydraulic systems that predicts size, weight and efficiency.

Task 2: Examine selected fluid power circuit and control architectures for small hydraulic systems.

Task 3: Implement the HAFO in a child-size version for a research project involving children with cerebral palsy.

Task 4: Seek external funding to support application studies.

E. Member company benefits

New technologies that miniaturize components such as power sources, actuators, and valves will be developed. New design tools that simplify the process of small hydraulic systems. This could spawn new markets for miniature fluid power systems.

F. References (references after [5] are from work supported by this test bed)

1. Dollar, A.M. and H. Herr, "Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art". *Robotics, IEEE Transactions on*, 24(1): 144-158, 2008.
2. Ferris, D.P., J.M. Czerniecki, and B. Hannaford, "An ankle-foot orthosis powered by artificial pneumatic muscles". *Journal of Applied Biomechanics*, 21(2): 189-197, 2005.
3. Krebs, H.I. and N. Hogan, "Therapeutic robotics: a technology push". *Proceedings of the IEEE*, 94(9): 1727-1738, 2006.
4. Blaya, J.A. and H. Herr, "Adaptive control of a variable-impedance ankle-foot orthosis to assist drop-foot gait". *IEEE Trans Neural Syst Rehabil Eng*, 12(1): 24-31, 2004.
5. Hollander, K.W., R. Ilg, T.G. Sugar, and D. Herring, "An efficient robotic tendon for gait assistance". *J. Biomech. Eng.* , 128(5): 788-792, 2006.
6. Chin, R., E.T. Hsiao-Wecksler, E. Loth, G. Kogler, S.D. Manwaring, S.N. Tyson, K.A. Shorter, and J.N. Gilmer, "A pneumatic power harvesting ankle-foot orthosis to prevent foot-drop". *Journal of NeuroEngineering and Rehabilitation*, 6(19), 2009.
7. Chin, R., E.T. Hsiao-Wecksler, and E. Loth, "Fluid-Power Harvesting by Under-Foot Bellows During Human Gait". *Journal of Fluids Engineering*, 134(8): 081101-7, 2012.
8. Li, D.Y., A. Becker, K.A. Shorter, T. Bretl, and E.T. Hsiao-Wecksler, "Estimating System State During Human Walking With a Powered Ankle-Foot Orthosis". *IEEE-ASME Transactions on Mechatronics*, 16(5): 835-844, 2011.
9. Shorter, K.A., G.F. Kogler, E. Loth, W.K. Durfee, and E.T. Hsiao-Wecksler, "A portable powered ankle-foot orthosis for rehabilitation". *J Rehabil Res Dev*, 48(4): 459-72, 2011.
10. Shorter, K.A., Y. Li, T. Bretl, and E.T. Hsiao-Wecksler, "Modeling, control, and analysis of a robotic assist device". *Mechatronics*, 22(8): 1067-1077, 2012.

11. Shorter, K.A., J.C. Xia, E.T. Hsiao-Wecksler, W.K. Durfee, and G.F. Kogler, "Technologies for Powered Ankle-Foot Orthotic Systems: Possibilities and Challenges". *IEEE-ASME Transactions on Mechatronics*, 18(1): 337-347, 2013.

12. Hsiao-Wecksler, E.T., J.N. Gilmer, G. Kogler, E. Loth, K.A. Shorter, and J.E. Thomas, "Portable active fluid powered ankle-foot orthosis". United States Patent Application, US20110112447 A1, May 12, 2011

13. Hsiao-Wecksler, E.T., K.A. Shorter, V. Gervasi, D.L. Cook, R. Remmers, G.F. Kogler, and W.K. Durfee, "Portable active pneumatically powered ankle-foot orthosis". United States Patent Application, US20120289870 A1, Nov 15, 2012

14. Li, Y., E.A. Morris, K.A. Shorter, and E.T. Hsiao-Wecksler. "Energy Efficiency Analysis of A Pneumatically-Powered Ankle-Foot Orthosis". in *International Fluid Power Expo (IFPE)*. March 23-25, 2011. Las Vegas, Nevada. 2011

15. Boes, M.K., M. Islam, Y.D. Li, and E.T. Hsiao-Wecksler. "Functional Efficiency of a Portable Powered Ankle-Foot Orthosis". in *IEEE 13th International Conference on Rehabilitation Robotics (ICORR 2013)*. June 24-26. Seattle, WA. 2013

16. Li, Y.D. and E.T. Hsiao-Wecksler. "Gait Mode Recognition Using an Inertial Measurement Unit to Control an Ankle-Foot Orthosis". in *36th Annual Meeting of the American Society of Biomechanics,* . August 15-18. Gainesville, FL. 2012

17. Li, Y.D. and E.T. Hsiao-Wecksler. "Gait Mode Recognition Using an Inertial Measurement Unit to Control an Ankle-Foot Orthosis During Stair Ascent and Descent". in *ASME Dynamic Systems and Control Conference* October 17-19. Fort Lauderdale, FL. 2012

18. Li, Y.D. and E.T. Hsiao-Wecksler. "Gait Mode Recognition and Control for a Portable-Powered Ankle-Foot Orthosis". in *IEEE 13th International Conference on Rehabilitation Robotics (ICORR 2013)*. June 24-26. Seattle, WA. 2013

19. Boes, M.K., E.T. Hsiao-Wecksler, and R.W. Motl. "Evaluation of a Portable Powered Ankle-Foot Orthosis on Gait Function in Persons with Multiple Sclerosis". in *Consortium of Multiple Sclerosis Centers ACTRIMS Meeting*. Dallas, TX. 2014

20. Petrucci, M.N., C.D. MacKinnon, and E.T. Hsiao-Wecksler. "Mechanical Modulation of Anticipatory Postural Adjustments of Gait Using a Portable Powered Ankle-Foot Orthosis". in *IEEE 13th International Conference on Rehabilitation Robotics (ICORR 2013)*. June 24-26. Seattle, WA. 2013

21. Petrucci, M.N., C.D. MacKinnon, and E.T. Hsiao-Wecksler. "A Step Towards Reducing Freezing of Gait in Parkinson's Disease: Using a Portable Powered Orthosis". in *6th World Congress of Biomechanics* July 6-11. Boston, MA. 2014

22. J. Xia and W. Durfee, "Analysis of Small Scale Hydraulic Actuation Systems," *Journal of Mechanical Design*, 135(9):091001-1 - 091101-11, 2013.

23. Neubauer, B. C., Nath, J., & Durfee, W. K. "Design of a portable hydraulic ankle-foot orthosis", *Proceedings of the 36th Annual International Conference of the IEEE EMBS*, 2014.

CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

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

Thrusts, Projects and Program Objectives	Promote STEM learning	Promote awareness of fluid power	Fluid power dissemi-nation	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	X	X		X		X
Thrust B: Outreach Bringing fluid power education to K-12 students, with a focus on middle and high school outreach						
B.1 Research Experiences for Teachers (RET)	X	X	X	X		
B.3B Portable Fluid Power Demonstrator and Curriculum	X	X	X	X		
B.7 NFPA Fluid Power Challenge Competition	X	X			X	X
Thrust C: College Education Bringing fluid power education to undergraduate and graduate students						
C.1 Research Experiences for Undergraduates (REU)	X	X		X	X	
C.4 Fluid Power in Engineering Courses, Curriculum and Capstones	X	X	X	X	X	X
C.4A Capstone Senior Design Project: A Third-Generation Pneumatic Rotary Actuator Driven by Planetary Gear Train	X	X	X	X	X	X
C.4B Parker Hannifin Chainless Challenge	X	X	X	X	X	X
C.8 Student Leadership Council (SLC)	X	X		X	X	X
Thrust D: Industry Engagement Making connections between CCEFP and industry						
D.1 Fluid Power Scholars	X	X		X	X	X
D.2 Industry Student Networking	X	X		X	X	X
D.5 CCEFP Webcasts Series	X	X		X	X	X
Thrust E: Evaluation Measuring CCEFP program effectiveness	X	X	X	X	X	X

Introduction

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

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

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

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

The objectives of the Education and Outreach Program are to:

1. Motivate 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.

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

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

Thrust A: Public Outreach

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

Project A.1 Interactive Exhibits on Fluid Power The staff of the Science Museums of Minnesota (SMM) is creating, field-testing and displaying exhibits that demonstrate basic attributes of fluid power and highlight CCEFP research. These exhibits serve as models for dissemination to other science museums, student centers at technical universities, and/or lobbies at fluid power companies. Fluid Power exhibits currently on display at SMM include an axial piston pump, hydraulic hybrid car, hydraulic transmission, super-mileage car and a hydraulics lab. SMM has also developed a fluid power activity kit that volunteer staff use to introduce visitors to fluid power concepts. This project is now being extended in order to engage undergraduate engineering students, enrolled in Senior Capstone Design courses, in developing prototypes of interactive exhibits relevant to fluid power, working with industry mentors wherever possible. These prototypes will be further developed by SMM staff and eventually housed in industry and university sites around the country. [Project Leader: J Newlin, SMM]

Thrust B: Pre-College Education

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

Project B.1 Research Experiences for Teachers (RET) As a part of the National Science Foundation's RET program aimed at improving science, technology, engineering and mathematics (STEM) education, the CCEFP's RET program enables teachers in pre-college schools to introduce fluid power to their students, drawing on their summer-long experiences in CCEFP research labs. A special CCEFP RET focus is recruiting teachers from high schools participating in the Project Lead The Way program. [Project Leader: Alyssa Burger, CCEFP]

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

Thrust C: College Education

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

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

Project C.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. [Project Leader: Jim Van De Ven, UMN]

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 (CO_2). [Project Leader: Elizabeth Hsiao-Wecksler, UIUC]

C.4b Parker Hannifin Chainless Challenge Four of the seven CCEFP institutions have participated in the Parker Hannifin Chainless Challenge - an engineering design competition for undergraduates to design and create the most efficient and effective human-assisted green energy vehicle. The students are required to design and build the drive system for their vehicles, as well as participate in the final demonstration competition. They can utilize either off-the-shelf components provided by Parker Hannifin or design their own. The demonstration event includes a judging criterion, a straight sprint race, and distance/performance race. This final event is conducted over a two day period. Cash awards were given to the winning team in each specified category. The CCEFP provides supplemental funding to team who apply for the Center's Capstone Project Grant. [Project Leader: Brad Bohlmann, CCEFP]

Project C.8 Student Leadership Council (SLC) The Student Leadership Council is an independent board of the CCEFP. The SLC's current and proposed activities support the education and outreach program of the Center and impact all students within the CCEFP. An SLC officer is a member of the Center's Executive Committee and participates in the meetings of the Industrial Advisory Board. The SLC is managing a travel and project grant program used to support student travel between CCEFP institutions and to companies engaged in the fluid power industry. The travel grant program will foster greater communication between the research institutions as well as between students and industry partners. In addition, SLC members are responsible for the Center's webcast program, and provide recommendations and guidance for other Center programs including the annual student retreat and various networking opportunities with industry [Project Leaders: Alyssa Burger, UMN; SLC officers]

Thrust D: Industry

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

Project D.1 Fluid Power Scholars/Interns Internship programs bring opportunities for engineering students to gain practical experience working in the fluid power industry while providing host companies with access to a diverse pool of talented engineering students. Working with industry, the CCEFP created the Fluid Power Scholars/Intern program and launched it in the summer of 2010. Fluid Power Scholars/Interns receive a scholarship to an intensive three and one half-day instructional program in fluid power, taught at the Milwaukee School of Engineering's Fluid Power Institute, and then join a corporate supporter of the CCEFP for a paid summer internship. [Project Leader: Alyssa Burger, CCEFP]

Project D.2 Industry Student Networking The goal of this project is to provide CCEFP students with opportunities to network within the fluid power industry in a variety of ways. In doing so, there are multiple benefits to students and companies: all students will better understand the fluid power industry and the applications of fluid power technology; companies will be able to meet, interact, learn about Center research, and discuss potential employment opportunities with students, benefiting from the fresh insights and perspectives that students bring to these these exchanges; students' efforts to find internships and later job opportunities in the fluid power industry will be facilitated. Channels utilized in this project include company tours, poster sessions, and resume exchanges as well as additional opportunities that extend the Center's outreach to more students and companies. [Project Leader: Alyssa Burger, CCEFP, Student Leadership Council]

Project D.5 CCEFP Webcast Series The CCEFP hosts bi-weekly webcasts, each with two to three presenters describing either research projects or discussing Center-wide programs such as education an outreach projects, strategic planning initiatives, special topics, or project evaluation. The webcasts are open to all CCEFP students and faculty and to all CCEFP member companies. The webcasts are an important means for Center-wide communication and knowledge transfer. [Project Leader: Cherie Bandy, CCEFP, Alyssa Burger, CCEFP, Student Leadership Council]

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

Graduated E&O Programs and Projects

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

Project A.3 Multimedia Educational Materials The CCEFP leverages the use of 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.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.

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 Leaders: Alyssa Burger, UMN]

Project B.5 BRIDGE Project BRIDGE (Building Resources and Innovative Designs for Global Energy) is a project spearheaded by the National Society of Black Engineers (NSBE), the Innovative Engineers (IE), and the American Indians in Science and Engineering Society

(AISES) student groups at the University of Minnesota. 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.

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.

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 Outreach 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. Each research and test bed project in the Center has an E&O component. The E&O activities of individual research projects are reported in the project update reports.

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.

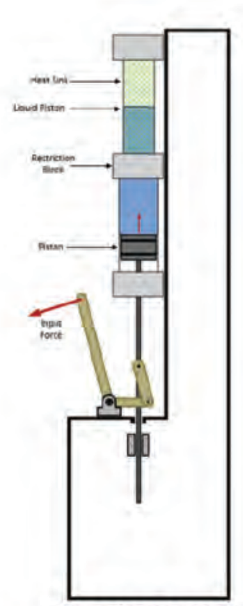


Figure 1: Cylinder assembly

Capstone Projects In 2007, 2008, 2011, 2012, and 2014 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

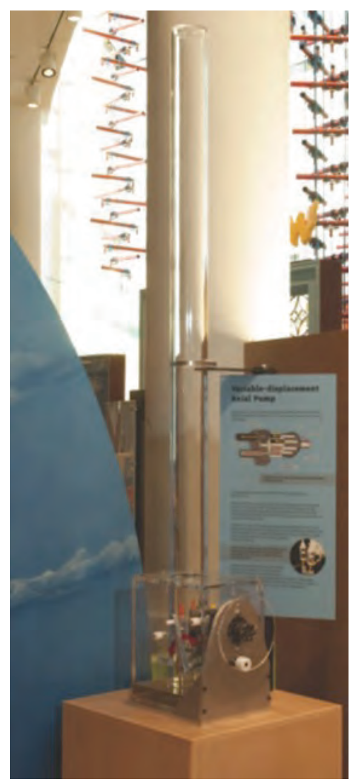
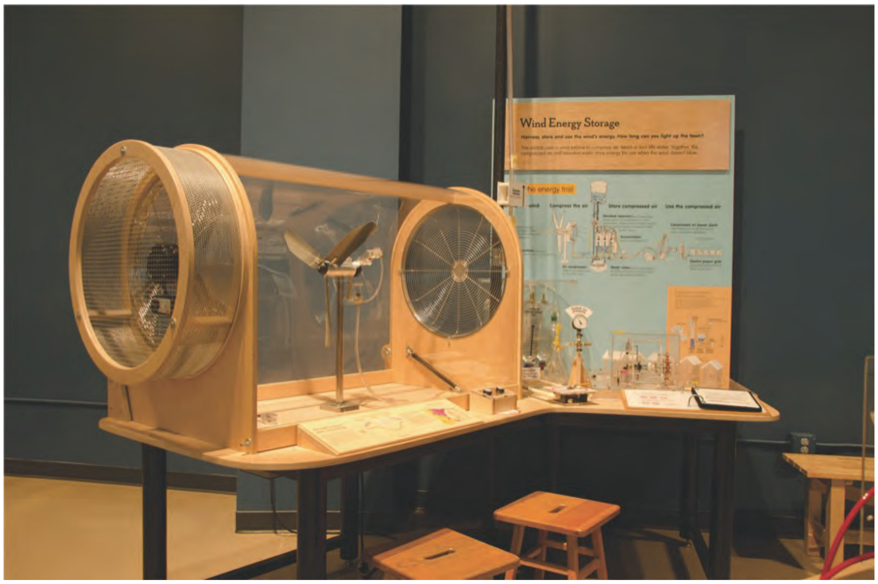


Figure 2: Axial Piston Pump

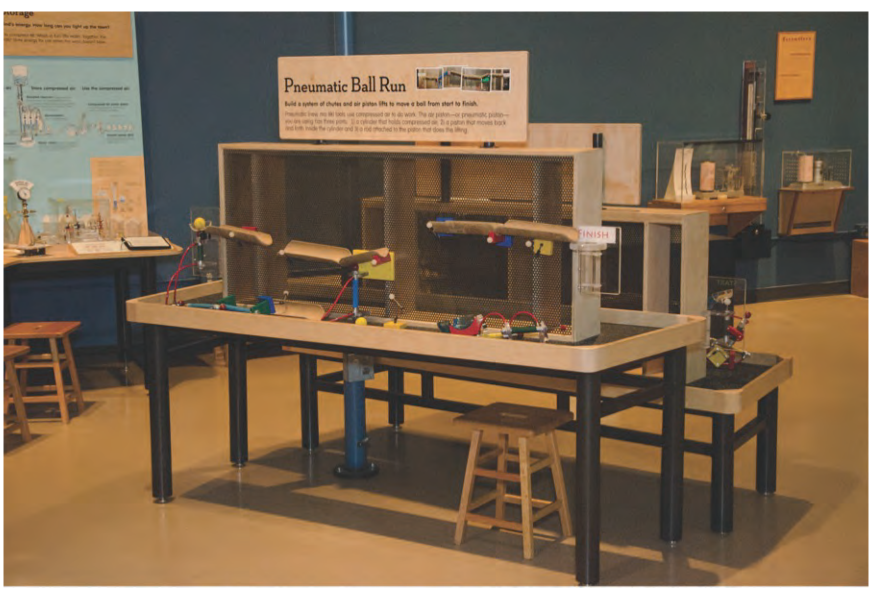
Figure 3: Hydraulics Lab (Left)

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

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

Project Team

Project Leader: Alyssa Burger, Education Outreach Director, CCEFP

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

1. Project Goals

The CCEFP's RET program enables teachers in pre-college schools to introduce fluid power to their students, drawing on their experiences in CCEFP research labs. In this six-week summer program, teachers learn first-hand about fluid power basics and are engaged in research through their work in the Center's university network. With these experiences as a foundation, teachers develop research-inspired curriculum modules to bring back to their classroom. Special efforts are made to recruit Project Lead The Way (PLTW) teachers to this program in geographic locations where the Center's RET program is hosted and where PLTW has a presence.

2. How Project Supports the EO Program Strategy

The RET program is an example of the CCEFP's strategy to maximize program impact: one teacher reaches many students; many teachers reach many classrooms. And, in sharing the curriculum modules they develop, RET teachers support another key CCEFP strategy—development of projects that can be replicated and/or adapted by other educators for new audiences. The work of RETs can be used by a host of teachers who have not participated in the RET program.

3. Achievements

- Four teachers participated as RETs in summer 2014, the either year of the program. Two at Purdue and two at NCAT, just as the year before.
- Four teachers participated as RETs in summer 2013, the seventh year of the CCEFP RET program: two at Purdue (returning RET teachers) and two at North Carolina A&T State University.
- Over 46 teachers have participated in the CCEFP RET program since it's inception, and several have been repeat participants, especially the established collaboration at Purdue and it's outreach program involving local teachers.
- The CCEFP requires that all RET participants submit their classroom curriculum to the TeachEngineering.com website which is a repository of evaluated and reviewed curriculum modules. The CCEFP encourages each RET to beta test the curriculum modules s/he has developed in the school year following the RET experience, modifying as necessary, and then submitting it as a final module at the end of the academic year. TeachEngineering.com then helps to review, edit and craft the curriculum for a well-rounded module. The modules are indicative of state standards as well.

- *Purdue Update:* In the Spring of 2014, the small wooden hydraulic claws were used in a local elementary school to determine how well the curriculum and devices worked and where improvements could be made. A high school FIRST robotics team is using these devices as part of their outreach activities they do at elementary school science nights for students and parents. In the Fall of 2014, a few high school student worked on developing a web based game using Scratch and an Android based App that would teach younger students, ages 6-10, about basic fluid power principles. The Scratch game is still being worked on by a senior student within the engineering department and attached are the preliminary designs and concepts for the app which will be worked on throughout the PLTW Computer Science and Engineering course at JHS. In January 2015, the same FIRST robotics team started redesigning the PFPD's that were used at the school for many years and will rebuild them to work as pneumatic based devices. It was determined that the water left in the PFPD's over time caused the seals to leak in the actuators and valves. The three devices were used for high school fluid power lessons, outreach activities at science nights, and as an exhibit at a local hands-on science museum for kids. The rebuilt devices will be used in the same capacity throughout 2015 and beyond.

- Other relevant work: In addition to their summer research experiences, the CCEFP encourages cross-collaboration with other activities within the Center such as outreach activities, workshops and piloting curricula. RETs are encouraged to remain a part of the Center by bringing their classrooms to campus for a tour, or other such opportunities. Several of these RET projects are connected to other E&O Projects. Also, further work has been invested in an on-line repository of teaching and learning materials at the CCEFP.org website. Materials can be found: *www.ccefp.org -> Get Involved -> Educators -> Teaching and Learning Materials*. Such materials include:
    - TeachEngineering.com fluid power curriculum by CCEFP RETs
    - Teaching Fluid Power video tutorials by Professor William Durfee, UMN
    - Fluid Power Demonstrator Kit and Curriculum by Professor John Lumkes, Purdue
    - Pneumatics Demonstrator Kit (Ball and Cup) and Curriculum by Professor Will Durfee, UMN
    - Fluid Power Hands-on Tools designed by the Science Museum of Minnesota Youth Science Team
    - Supply sources for fluid power teaching and learning materials

4. Plans, Milestones and Deliverables

- In 2015, the program will begin sunsetting as it is not slated to be a cornerstone of the future workforce development initiatives of CCEFP and NFPA.
- In the final year of the program, Y10, CCEFP commits to hosting two teachers within its university network.

5. Member Company Benefits

Following their RET experiences, teachers can bring their experiences in university research as well as their expanded understanding of fluid power concepts to their classrooms. New curricula stemming from these experiences should inspire and motivate a next generation of leaders in the engineering, corporate and/or academic arena.

Project B3.b: Portable Fluid Power Demonstrator and Curriculum

Project Team

Project Leader: Professor, John Lumkes, Purdue University

Other Personnel: Brian Bettag, Lafayette Jeff High School
Farid Breidi, Purdue University
Jordan Garrity, Purdue University
Tyler Helmus, Purdue University
Gary Werner, McCutcheon High School

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

Project Goals and Description

The Portable Fluid Power Demonstrator (PFPD) was developed for K-12 classrooms, with an initial focus on middle and high schools. The kits can enhance current and enable new activities for organizations that include PLTW, FIRST Robotics, science museums, children's museums, and for activities within the CCEFP. The PFPD is being used to promote awareness and/or increase interest of fluid power education in high school grades 8-12. Through the addition of microcontrollers the PFPD can be used to teach robotics and mechatronics.

Project Role in Support the EO Program Strategy

This project directly supports the CCEFP mission to "develop research inspired, industry practice directed education for pre-college, university and practitioner students; to integrate research findings into education; to educate the general public; and through active recruiting and retention, to increase the diversity of students and practitioners in the fluid power research and industry". Project B.3.b specifically targets the fifth component of the ERC's vision for education, to "increase public and K-12 student awareness of the importance of fluid power, and the excitement and possibilities that new technologies of the Center will bring".

Achievements

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

Since 2014 efforts have focused on a new multi-actuator smaller educational tool that can be easily transported, doesn't require any setup or water, can be plugged into any 110/220V outlet, and introduces students to fluid power and the interaction of electronics, microcontrollers, and actuators in fluid power systems. The original PFPDs at Purdue are still being used at various K-12 outreach programs, museums, high schools, and conferences. The previous demonstrators have been successful in classrooms, science museums, on campus programs and other engagement activities. However, their size, weight and large loose components make long-range travel, shipping, and transporting as baggage on airlines unnecessarily difficult.

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

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

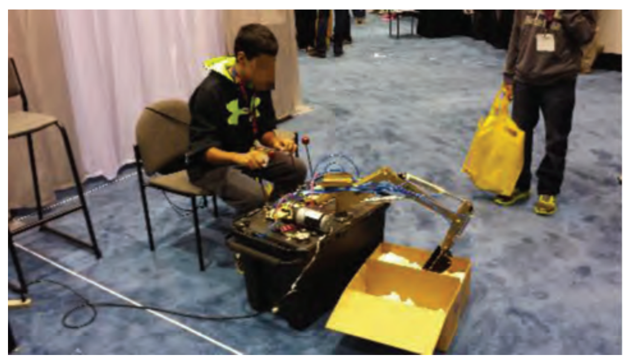
The small portable device demonstrates pneumatics, robotics, and programming in environments where these topics were previously only discussed.

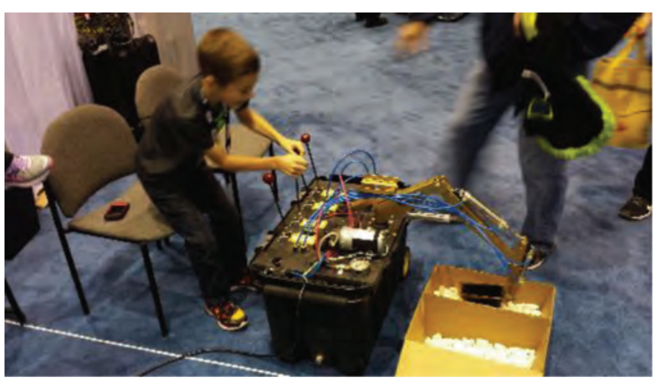
Summary of PFPD outreach activities to date

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

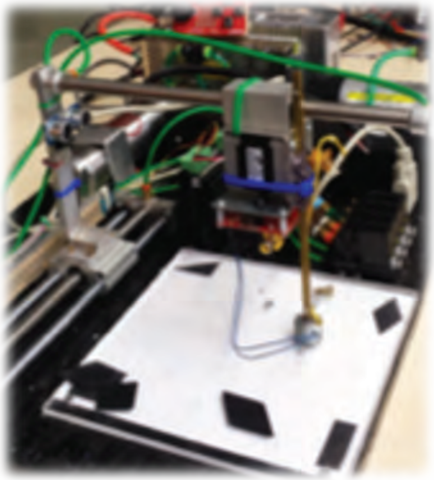
In September 2013 this project was nominated by the CCEFP and NSF to participate in the “CHANGE THE WORLD: Science & Engineering Careers Fair” in Washington D.C. The PFPDs were always busy and an estimated over 400 people stopped by during the 2-day event.

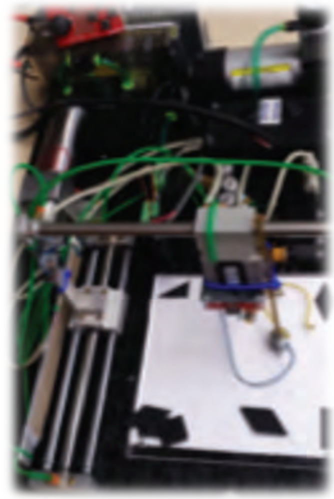
In September 2014 the PFPDs were brought to the Smartforce Student Summit at the International Manufacturing and Technology show in Chicago, IL. They were very popular and reached a wide range of ages many of whom were unaware of fluid power and its many uses and opportunities.





Since the project inception there have been multiple undergraduate students involved in the design, construction, and delivery (outreach programs), along with REU and RET participation in the summer and high school involvement on a variety of levels. The kits have been used at various high schools, state fairs, outreach events, tours, and workshops.





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

Member Company Benefits
This project will directly benefit member companies involved in fluid power by providing a methodology and demonstration kits to capture the imagination of future engineers, their future workforce. All reports and publications will be available to Center members

EO Project B.7 Fluid Power Challenge Competition

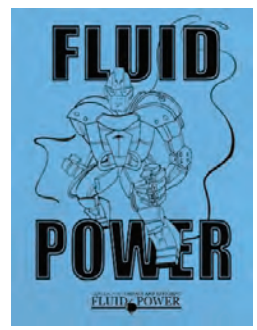
Project Team

Project Leader: Alyssa A. Burger, Education Outreach Director

Other Personnel: Don Haney, Communications Director
Ben Adams and Pieter Gagnon, Volunteers

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

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

Press Release

<u>Minneapolis, Wednesday, January 21, 2015</u> — The University of Minnesota will host the NFPA Fluid Power Challenge, a competition that gets middle school students excited about fluid power. A Workshop Day for the event was held on December 8, 2014, followed by a Competition Day, to be held on January 26, 2015.

During the Fluid Power Challenge, middle school students learn about fluid power technology (hydraulics and pneumatics) and gain hands-on experience while building a fluid power mechanism with real world applicability. The program is designed to introduce the students, and their teachers, to the world of engineering and fluid power careers.

During the Challenge Day at the University of Minnesota, 23 8th-grade teams (four students per team) will design and build fluid power mechanisms that pick an object from one platform and move it to another. In addition to the number of pick-and-place cycles a school's machine completes, a review of each team's design approach, teamwork and portfolio will be used in the final evaluation.

A student from a past competition said "This opens up more opportunities for engineering and careers kids aren't aware of. It's fun...you get to work with other kids and learn more math and science."

Through the Challenges, the Center for Compact and Efficient Fluid Power (CCEFP) at the U of MN and the National Fluid Power Association (NFPA) hopes to encourage students to select more mathematics and science courses in their high school curricula to keep their options open for technology-based post-secondary studies.

Highlights

- 2014/2015 CCEFP hosted and sponsored three Fluid Power Challenge events at University of Minnesota, Georgia Institute of Technology and Purdue University at Kokomo (to be held Spring, 2015).
- 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
- 2013/2014 Fluid Power Challenge Competition recruited 20 teams, over 80 students and teachers, from Minnesota, the majority coming from outside the Twin Cities. Only one veteran teacher returning with a new team of students. A school from Northern Minnesota brought five teams of girls, which won three of the five awards.
- 2012 / 2013 Fluid Power Challenge Competition recruited 18 teams from Minnesota, the majority from the Twin Cities of Minneapolis and St. Paul. Three teams joined the event from outstate western Minnesota.
- Typically, over half of the 8th grade student participants are female. Secondly, by observation, a highly diverse student body.

- Several of the teachers recruited were Project Lead the Way teachers, who have a fluid power module in their PLTW Principles of Engineering curriculum.

- Each sponsoring company provided one or two engineers to judge the competition.

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

- One of the 2013 corporate sponsors, Tolomatic, wrote a blog about the competition: http://info.tolomatic.com/linear-actuator-blog/.

4. Plans
Given the successful efforts by CCEFP to coordinate the Fluid Power Challenge, and the strong interest in industry sponsors and teachers alike, the CCEFP will plan to host a competition each Fall. Goals include gaining more industry sponsorship, to reduce the cost to the Center, including direct funding from NFPA. The sustainability of the project includes identifying external funding sources and continued support from NFPA.

- Host **three** competitions in the 2015/2016 academic year.

- Recruit more industry sponsors

- Identify additional funding sources for additional support

Related Projects

This project aligns well with the Center's former relationship with Project Lead The Way (PLTW), where CCEFP and NFPA provided content experts to design a fluid power curriculum module in PLTW's Principles of Engineering course. This competition provides the means and the applicability for PLTW teachers to teach hands-on hydraulics and pneumatics in a design environment.

5. Milestones and Deliverables?

- Host a Fluid Power Competition each Fall at two or more CCEFP location(s)

- Recruit a minimum of 20 teams to participate in any Fluid Power Challenge Competition

- Recruit a minimum of five industry sponsors

- Keep costs low by finding additional sources of sponsorship and funding support

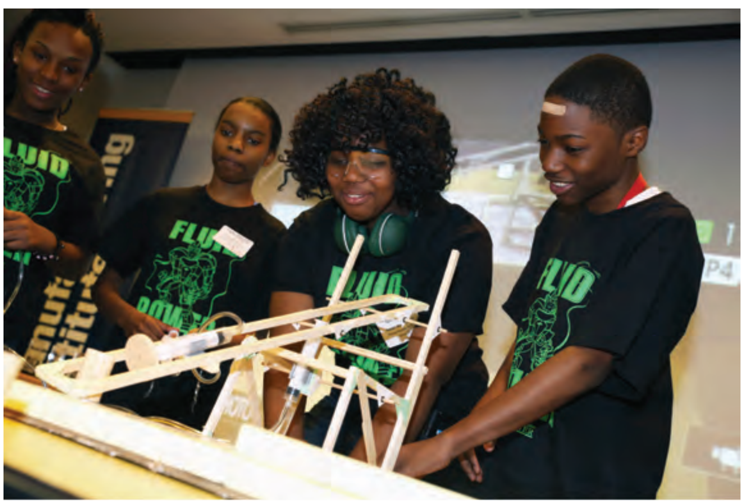
- Generate interest in fluid power at the K12 level and through teachers

- Market this program and create an investing group of teachers who anticipate participating in this program.

- This program has been identified as part of the CCEFP's future program portfolio.

6. Member Company Benefits
The 2014-2015 Fluid Power Challenge corporate sponsors include Eaton Corporation, FORCE America, International Fluid Power Society (IFPS), 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.

UMN Fluid Power Challenge



GT Fluid Power Challenge

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

Project Team

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

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

1. Project Goals

The REU program is aligned with several CCEFP goals: developing research inspired, industry practice directed education; facilitating knowledge transfer; integrating research findings into education; and increasing the diversity of students and practitioners in fluid power research and industry. Through its REU program, undergraduate engineering students from schools nationwide participate in cutting edge research under the mentorship of Center faculty. The program also provides professional development activities for these students.

2. How Project Supports the EO Program Strategy

REU students learn through the expertise of faculty mentors--an example of knowledge transfer. After completing their summer-long programs, REU engineering students are more likely to enroll in a graduate engineering program, often at the REU-hosting school. Further, the Center's efforts to recruit REUs from a diverse student population improve the likelihood of increased diversity among the students, faculty and industry professionals in fluid power.

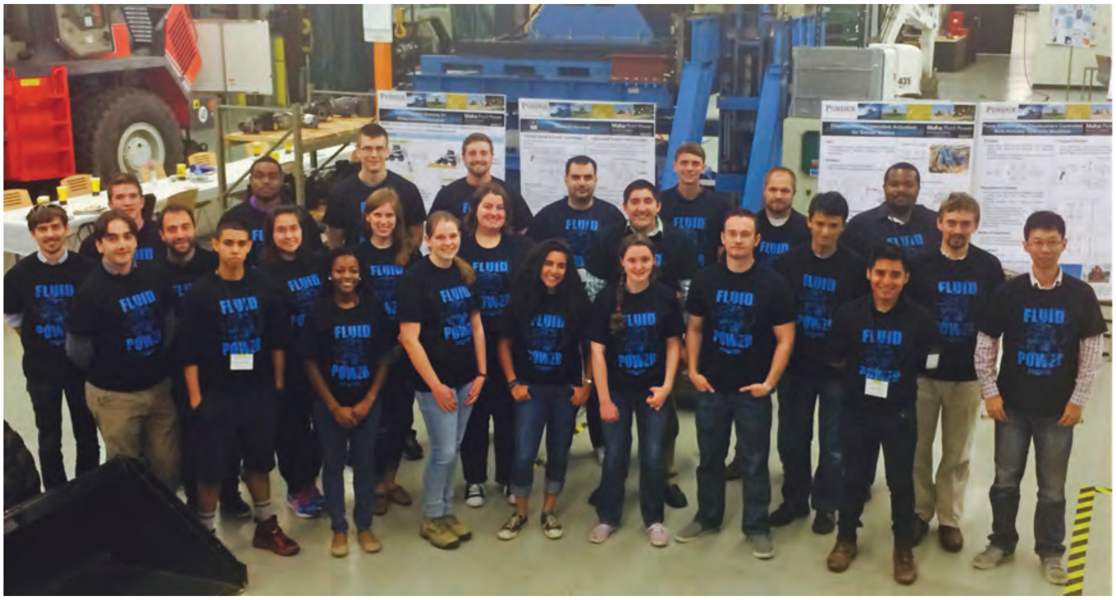
3. Achievements

- The CCEFP is pleased to announce it being the recipient of an NSF REU Site Award. Three years, a $390,000 grant.
- To date, the CCEFP has hosted over 170 undergraduate students in the highly successful REU program.
- Since revising the CCEFP REU program structure in 2008, the CCEFP REU Program has recruited, on average, over 35% women, and over 33% racially or ethnically underrepresented students into the program on a yearly basis. The CCEFP's recruiting strategy includes identifying institutions, programs and people with whom to develop relationships that, in turn, open pathways to CCEFP summer programs and beyond for underrepresented students.
- The CCEFP completed a longitudinal study of our past participants in early 2014. At the time of the report, 57% of all former CCEFP undergraduate researchers enter graduate school, and 25% of those are PhD candidates. Extremely positive statistics!

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

2013 REU Program:

- Eighteen REU students participated in summer 2013, the seventh year of the program. Six of the students were recruited from outside the CCEFP seven institutions.

2012 REU Program:

- Twenty-three REU students participated in summer 2012, the sixth year of the program: three at the University of Minnesota, one at the University of Illinois, nine at Purdue, two at MSOE, three at North Carolina A&T, two at Georgia Tech and three at Vanderbilt University. None of these REU students had previous experience with CCEFP. 10 of the 23 were recruited from outside the CCEFP's core institutions.
- Following a highly successful Fluid Power Bootcamp at the University of Minnesota in 2011, the CCEFP hosted the 2012 REU Fluid Power Bootcamp at Purdue University. Professor Andrea Vacca of Purdue orchestrated the bootcamp curriculum, which included three separate fluid power lab sessions led by CCEFP PU graduate students. Those lab sections are: Lab 1: Pump/system Characterization on Water Hydraulic Test Rig; Lab 2: Circuit Construction and Debugging; Lab 3: Displacement Control System. Students had an opportunity to socialize with each other as well as find themselves completely immersed in fluid power technology. The program at PU was so well received, the Center will host the 2013 REU Bootcamp at PU as well.
- Two REUs from North Carolina A&T State University received travel grants from NFPA to attend and present a poster at the Fall 2012 NFPA Workforce Summit and CCEFP Annual Meeting held at the University of Illinois, Urbana-Champaign.

4. Plans, Milestones and Deliverables

- In 2013, the CCEFP was awarded the NSF REU Site to support the program through the end of the NSF-funded ERC. Plans call for another proposal submission in 2015.

- The Center will promote the REU program to its collaborating partner, NFPA, to determine if additional programmatic funding can be offered in lieu of the end of the REU Site Award in future years, 2016 and beyond.
- The Center is committed to host between 14 and 20 REU students each summer -- two or three students at each university in the CCEFP network. (Some sites will host additional students due to leveraged funding from other sources.)
- The CCEFP will host its 2014 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 six CCEFP universities and that the overall REU program is nationwide in scope.
- Additionally, using its network and database of contacts, the CCEFP will strive to recruit and retain racially underrepresented students as well as women, those with disabilities and recent war veterans.
- The Center will continue to encourage education focused research topics.
- The Center will hold an REU Advisor orientation webcast prior to the start of the 2015 program.

5. Member Company Benefits

Member companies can participate in REU projects through project mentorship. Here, member companies get a first look at a bright, diverse pool of students trained in fluid power who may become future intern or permanent employees. More generally, the REU program contributes to the building of an informed and motivated student group—future leaders for industry and academia.

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

Project Team

Project Leader: Jim Van de Ven, University of Minnesota

Other personnel: Will Durfee, University of Minnesota
All CCEFP faculty

1. Statement of Project Goals

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 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:

- 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.
- 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.
- UIUC undergraduate course. UIUC.

Fluid Power Curriculum and Dissemination:

- Fundamentals of Fluid Power MOOC (Massive Open Online Course) developed and delivered on Coursera fall 2014 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
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	Eaton	Hydromechanical transmission

	2011		
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:

- 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.

Project C.4a Capstone Senior Design Project:
A second-generation, compact, light-weight, pneumatic actuation system for an ankle AFO

Project Team

Project Leader:	Prof. Elizabeth Hsiao-Wecksler, MechSE UIUC
Other Personnel:	Prof. Martin Morris, MechE, Bradley University UIUC Graduate Students: Morgan Boes, Matt Petrucci, Mazhar Islam, Ziming Wang

1. Project Goals and Description

This project is a continued collaboration between researchers and students at the UIUC and Bradley University on a project to develop prototype pneumatic actuators that can be useful in Testbed 6 on the portable pneumatic ankle-foot orthosis (PPAFO). Limitations of the current pneumatic actuator on the PPAFO are torque output and size of commercially available small pneumatic rotary actuators (example: 15 Nm @ 150 psi, dual vane, 2.5" dia, casing height 2.4"; model PRNA30D, Parker Hannifin Corp). (Figure 1)

Figure 1. PPAFO with current commercial rotary actuator

This E&O project has supported three capstone senior design project teams in the Mechanical Engineering Department at Bradley University in Peoria, IL. Bradley is a small, private university with undergraduate and graduate programs, and is located 90 miles from the UIUC campus. Their capstone design course covers two semesters. Prof. Martin Morris has an expertise in fluids and design, and runs the capstone design course in the ME department. CCEFP E&O funds have been used to support three different design teams, AY11-12, AY12-13, and AY13-14.

The objectives for the first team (AY11-12) were to: (1) increase torque output of pneumatic rotary actuators in a compact housing, (2) explore the possibility of using a planetary gear train constructed from plastic designed to increase the output torque, (3) examine the use of labyrinth sealing in the pneumatic actuator to minimize frictional losses, and (4) perform a thermodynamic analysis to determine if energy consumption of pneumatic fuel (compressed CO_2) could be improved with different design modifications to power source. (Due to the vaporization process of CO_2 from liquid to vapor, cooling of the CO_2 canister is observed. Temperature of a gas is negatively correlated with gas density, which could affect fuel efficiency.)

The original objectives for the second team (AY12-13) were to: (1) retain, as a minimum, the torque output generated by the compact, first-generation pneumatic rotary actuator while increasing the number of activation cycles, (2) explore the possibility of increasing the efficiency of the plastic planetary gear train, (3) improve the effectiveness of the labyrinth seal in the pneumatic actuator to maintaining low frictional losses, and (4) improve the utilization of the driving gas energy (the available energy). However, as the school year progressed and the students brainstormed alternate actuator designs, these original objects were not addressed since the team decided not to continue to focus on just modifying last year's design mainly due to leaking issues that were encountered with trying to develop their own pneumatic actuator. The team decided to use a single off-the-shelf linear pneumatic cylinder and convert the translational force to a rotary torque via a gear train.

The objectives of the third team (AY13-14) were similar to the previous year but modified for the linear system: (1) retain, as a minimum, the torque output generated by the compact, first-generation pneumatic linear actuation system, (2) explore the possibility of increasing the efficiency of the gear train, (3) maintain low frictional losses in the pneumatic cylinder, and (4) improve the utilization of the driving gas energy (the available energy). This team chose to use a dual linear cylinder design to increase torque capability and to decrease the depth of the actuation system relative to side of the leg.

For all teams, a working prototype actuator is the primary deliverable from the 9 month capstone senior design project experience.

2. How Project Supports the EO Program Strategy

The primary educational impact of this project was 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 were exposed to fluid power issues as they participated in the gated review process which included four oral progress report presentations by the design team. The results from the project were revealed to the entire campus community on both campuses during two campus-wide expositions. The project exposed the student teams to first-hand experiences with fluid power through pneumatic design issues such as torque generation, leakage and seals, fluid dynamics, and also thermodynamic analysis of dealing with expansion of compressed gas (CO_2).

3. Accomplishments

The first-generation prototype (Figure 2) was delivered at the end of AY11-12. It had a diameter of about 3.5” with a casing height of about 1.5”, and utilized labyrinth sealing. The torque output for the prototype actuator was designed to deliver 40 Nm of torque with a relative motion of 55° between the components using a supply pressure of 100 psig. The planetary drive train was designed to deliver a torque amplification of about 3. Actual testing of the design by the end of the 9 month period was not possible due to leakage in the system. The thermodynamic analysis found that if the power source (compressed CO_2 canister) was allowed to remain at an isothermal as opposed to isentropic condition, then the system could have a ~10% improvement in actuation duration.

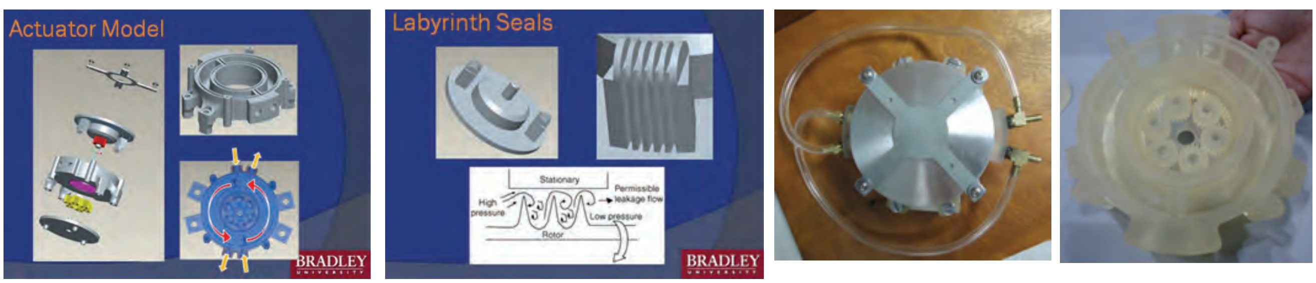


Figure 2. CAD and physical models of first-generation pancake pneumatic rotary actuator driven by planetary gear train that were completed by AY11-12 team

The second team used a commercially-available pneumatic actuator in order to avoid the leakage problem that can be encountered by designing one’s own actuator. Further, instead of designing a pancake rotary actuator, they decided to use a linear actuator combined with a limited range sector gear in order to convert translational motion to the linear actuator into rotation motion at the ankle (Figure 3). The final prototype was able to produce 23 Nm at 90 psi, range of motion of 55°, and mass of 588 g.

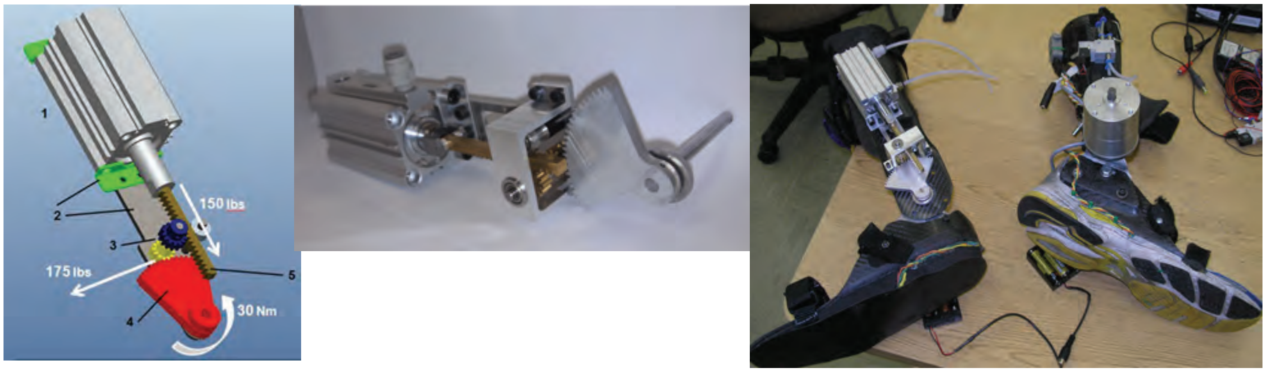


Figure 3. CAD and physical models of design which used an off-the-shelf linear actuator with sector gear to create torque about the ankle axis by AY12-13 team. Right panel: comparison of linear design with commercially available pneumatic rotary actuator

The third year team decided to select a dual cylinder design. The proposed design generated >40 Nm at 110 psi, has overall length of 8.8", width of 3.25", and depth of 2.2", and weigh 664 g.

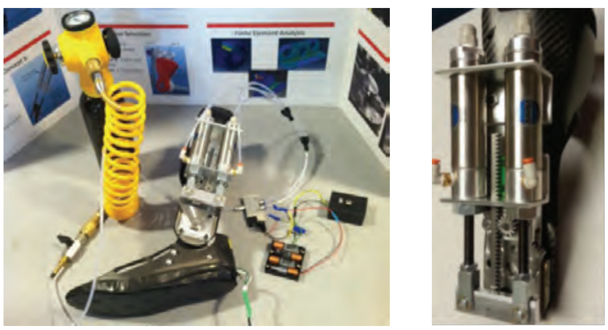


Figure 4. Actual design attached to orthosis lower leg shell. The design uses dual off-the-shelf linear actuators with yoke and sector gear by AY13-14 team.

The Bradley design teams for all years have consisted of four Mechanical Engineering students. For AY11-12 and AY112-13, both teams had two women for each year. The AY13-14 team had one woman.

Bi-weekly/weekly teleconference meetings were held between UIUC and Bradley team members throughout this project. UIUC faculty and students also virtually attended staged gateway review presentations, which were used to evaluate team progress and deliver concurrent feedback by clients, Bradley faculty, and other design teams.

AY11-12 Bradley students presented their design during the University of Illinois' College of Engineering Open House in March 2012 (Figure 5). Engineering Open House weekend attracts thousands of students (K-college), teachers, and the general public from across Illinois and the Midwest. The Bradley students also presented their results as part of the annual Bradley University Student Exposition during Parents Weekend in May 2012.
AY12-13 Bradley students also presented a poster on the first generation design and thermodynamic analysis at the CCEFP Annual Conference in September 2012 (Figure 5). The AY13-14 team also presented their design at the 2014 University of Illinois' College of Engineering Open House event.

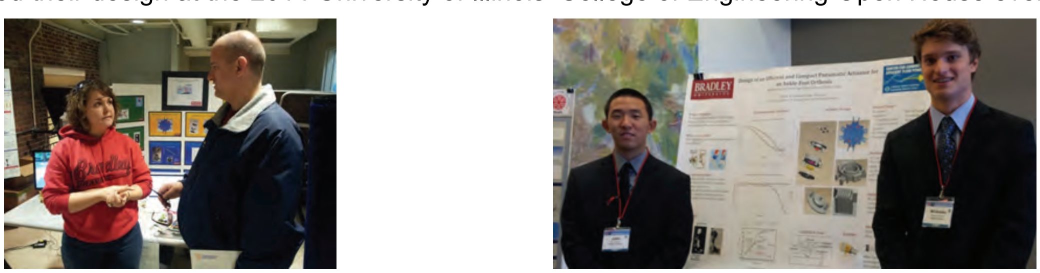


Figure 5. (left) Bradley student presenting team's work during the 2012 University of Illinois' Engineering Open House weekend. (right) Bradley students at 2013 CCEFP Annual Meeting student poster show.

4. Plans

The project has been completed. The AY13-14 team delivered a prototype that will be integrated into Testbed 6. A graduate student, Ziming Wang, has been working with the prototype since June 2014 to ensure its function and integration into the Gen 2.0 PPAFO shell designs.

5. Milestones and Deliverables?

The milestones for the project align with the milestones defined by the Bradley ME department's senior design curriculum:

1) 1st Oral Presentation (Gateway 1)	Before September 31, senior year
2) Proposals to the Client	Before October 31, senior year
3) 2nd Oral Presentation (Gateway 2)	Before October 31, senior year
4) Written Progress Report	Due end of Fall semester
5) 3rd Oral Presentation (Gateway 3)	Before February 28, senior year
6) 4th Oral Presentation (Gateway 4)	Before April 31, senior year
7) Written Final Report & Deliverables	Due end of Spring semester

For all teams, a working prototype actuator was the expected primary deliverable at the end of the course. Additional deliverables were interim and final reports. These reports include performance characterization of the actuator at a range of pneumatic pressures, engineering drawings of the components, and details about the actuator construction.

6. Member Company Benefits

This project does not have corporate sponsors, although the students on both teams have worked with Winzler Gear, a plastic gear engineering and manufacturing firm in Chicago, which has worked with the students to design appropriate gear trains. The AY12-13 team worked with engineers at Bimba Manufacturing on the linear pneumatic actuator. We would be happy to share the design ideas with CCEFP or NFPA industry members.

EO Project C.4b: Parker Hannifin Chainless Challenge

Project Team

Project Leader:	Brad Bohlmann, University of Minnesota
Other personnel:	Elizabeth Hsiao-Wecksler, University of Illinois, Urbana-Champaign
	Andrea Vacca, Purdue University
Industry partners:	Parker Hannifin

1. Project Goals

The Parker Hannifin Chainless Challenge is a design competition for undergraduate college students. The focus is creating a human powered vehicle (typically bicycles or recumbent or upright tricycles) in which the conventional chain drive is replaced with a hydraulic transmission. Elements of the competition include the design (creativity/novelty, functionality, presence of renewable energy systems), fabrication (quality, aesthetics), design process (design report, cost analysis) and a three event competition (efficiency, acceleration and distance events). The goal of this project is to provide students with an opportunity to learn about fluid power, apply their knowledge to a real world open-ended design project and compete in a national competition to demonstrate their work.

2. How Project Supports the EO Program Strategy

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 Center schools with training and experience in fluid power (20-25 students from Center schools per year).

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.

There are typically about a dozen teams in the competition. In 2011-12, CCEFP was represented by Illinois, Illinois Tech, Minnesota and Purdue. Minnesota took second place overall. In the 2012-13 competition, teams from Illinois, Minnesota and Purdue participated. Illinois took first place overall. In the 2013-14 competition, CCEFP was represented by teams from Illinois, Minnesota and Purdue. Purdue and Minnesota took second and third place, respectively

4. Plans

The Chainless Challenge is a fun and educational experience for the students and advisors. It provides a unique opportunity for students to learn about fluid power. All of the schools currently participating have found it to be a meaningful experience for their students and they plan to continue fielding teams for the competition. We hope to expand CCEFP's participation in Chainless Challenge ideally having teams from each of our seven schools in future competitions.

5. Member Company Benefits

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

Parker Hannifin benefits directly by meeting and working with the students on the project team. They have an opportunity to observe students in a job-like situation which can help find potential employees. It also provides a way to get bright minds on an engineering problem of interest to the company.

EO Project C.8: Student Leadership Council

Project Team

Project Leader:	Alyssa Burger, Education Outreach Director, CCEFP
Other Personnel:	SLC Officers SLC University Representatives Student Members of the CCEFP

1. Project Goals and Description

The primary role of the CCEFP's Student Leadership Council is to serve as one of five advisory boards to the CCEFP. The SLC also functions as a service organization, a social club, and a student government entity for all students within the CCEFP. The SLC promotes inter-university and industrial collaboration directly with CCEFP students through a travel grant program, provides students with funding opportunities to conduct outreach programs at their local universities through a project grant program, organizes and produces the Center's bi-weekly webcast and is also responsible for planning the annual student retreat.

Each university nominates one graduate student representative to serve on the student leadership council. The SLC members elect four individuals to serve in officer roles: President, Vice President, Secretary, and Treasurer. In addition to university representatives from each CCEFP partner institution. The SLC serves as a liaison between the student body and the senior CCEFP leadership providing guidance, voicing concerns and relaying important information between these two groups.

2. Project Role in Support the EO Program Strategy

The SLC serves a vital role in meeting the EO program's goal of providing fluid power education and awareness for pre-college, university, and practitioner students. At the university level, the SLC strives to make the education and research resources of each member university accessible to all CCEFP students through the creation of student directed travel grant program. For pre-college students, the SLC supports programs to have current CCEFP students teach basic fluid power concepts to future engineers and students. Although a wide platform of methods exists to educate young students about science, technology and specifically fluid power, the importance of a human connection cannot be overstated. In this aspect, the student body of the CCEFP is potentially the greatest asset to inspire pre-college students of all ages. Presently the SLC itself sponsors project grants which allow individuals at member universities to pursue projects that allow them to connect with and educate the youth within their communities.

3. Achievements

To fulfill the mission of the Student Leadership Council, a number of distinct efforts are undertaken by the SLC membership supported by this EO project:

Travel Grants

The SLC Travel Grant Program aims to provide funds for students to travel to another project or industry location, making collaboration more accessible. Twice a year the SLC solicits proposals for travel by contacting all CCEFP students and faculty. Member students are invited to submit short written proposals and the SLC discusses and votes on which travel grants to approve based of funding resources and proposal strength. The maximum grant for any trip is $1,000, and preference is given to collaboration between projects over collaboration with industry. In addition to providing an outstanding collaborative opportunity for CCEFP graduate students, it also provides an experience for members of the SLC who must review and vote on a variety of differing proposals.

A total of two travel grants were awarded in the reporting period. It should also be noted that there were 5 other travel grants from Y9 which were unused and still were valid for the reporting period. In order to make the SLC travel grant program more accessible to the students and to improve their usage, the SLC has now taken measures to have a rolling application program wherein the members of the CCEFP will be able to apply for the travel grant as and when the need for the travel arises. Proposals may be submitted throughout the year, however they must be proposed at least two months prior to intended travel. In this way, the student members of the CCEFP need not wait for the regular callout for the proposals, and hence will promote more appropriate usage of the funds for the travel.

Project Grants

The SLC project grant program is intended to fund outreach or social activities in which primarily CCEFP students will be involved. This may include activities such as building hydraulic demonstration kits, travel to an elementary school to teach about fluid power, or lunch for biweekly webcast presentations. Projects may be one-time or recurring, but should be presented in a single proposal as long as recurrence occurs in the same fiscal year. Proposals are limited to $500 per request.

One project grant was intended to improve the "camaraderie and communication between the different research labs" that are part of the CCEFP at Purdue University. This event invited research assistants, visiting researchers, professors, etc., in fluid power to attending a basketball game followed by dinner.

> *"I am proud to report 17 Purdue students (inclusive of 2 visiting scholars from China) attended a men's basketball game –Purdue vs. Michigan– and dinner at a campus "pizza joint". And, 5 additional students joined the group at the restaurant since they had an exam during the game. This group of 22 fluid power researchers represented over 6 countries and 3 professors, and introduced several non-CCEFP members to the opportunities available with CCEFP. As a reminder, the goal of this project outing was to increase interaction between fluid power students, both CCEFP and not, at Purdue. [...] Since the CCEFP is so dependent on furthering research, it is critical that students are aware of other projects and problems being solved, especially at the same university.*
>
> *Additionally, to incorporate outreach into the event, there was no discrimination against non-CCEFP members attending; however, all invited were in fluid power. [...]*
>
> *Fun conversation and new friends kept the event going strong with 3 even staying until midnight. [...] The goals were met and surpassed, the event was well below budget, and everyone had a wonderful evening thanks to the generous sponsorship of the NSF, CCEFP, and SLC. THANK YOU!"*

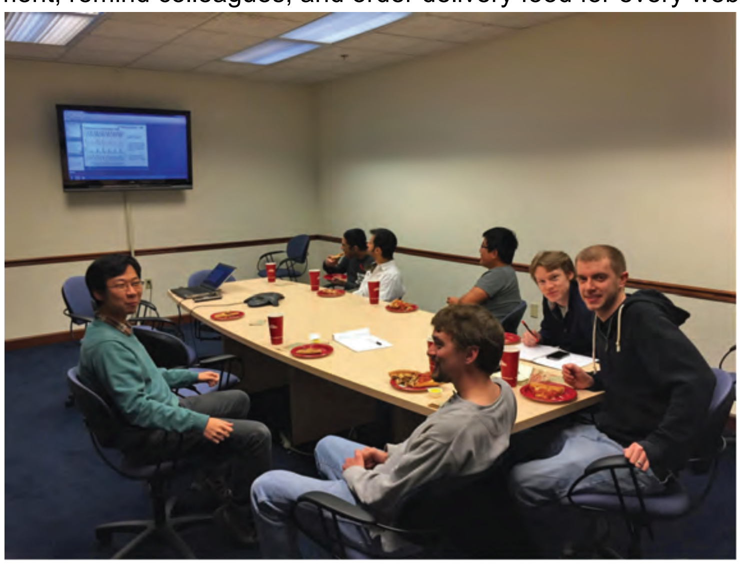
- SLC Project Grant Report submitted by Natalie Spencer

Purdue Project Grant - February 26, 2014

CCEFP Bi-Weekly Webcasts
The Center estimates between 50 - 75 participants view each webcast on a regular basis. Participants include industry, faculty, staff and students. In addition to including an audio feedback component, the Center has greatly improved its efficiency and effectiveness with the CCEFP webcasts. The SLC's vice president hosts each webcast, creating seamless transitions between each presenter.

Presentations are not just project-specific information; they also include information on how each project is aligned with the Center's strategic plan. For research, presentations describe how work is demonstrated on the Center's test beds, how current research aligns with what has been done previously as well as how it is breaking new ground, etc. These inclusions have added important new dimensions to the webcasts and have provided another avenue where students, faculty and Center leadership can continue to strategize on the direction of the research projects across the Center. Additionally, webcasts now include special topics, education outreach presentations and "State of the CCEFP" discussions presented by Center Leadership.

Project grant food monies have been shown to clearly improve student webcast attendance. Thus, the center decided from this year forward, a blanket provision will be made to fund food for the bi-weekly webcasts. Although this now relieves individual institutions from submitting project grant proposals for webcast food, SLC representatives at each member institution must still reserve meetings rooms, setup teleconference equipment, remind colleagues, and order delivery food for every webcast.



Webcast attendance at Purdue - Maha - January 28, 2015

SLC SWOT Analysis
Every year the SLC conducts a Strengths, Weaknesses, Opportunities, and Threats analysis of the student body to identify what efforts are working and identify what areas need continued improvement. The SLC analysis can be found in the SLC SWOT analysis in section 5 Infrastructure, sub-section 5.1 Configuration and Leadership Effort.

4. Plans, Milestones and Deliverables
The deliverables of the SLC efforts this past year have been clear. Through the hard efforts of many of its members, travel and project grants were awarded and processed, bi-weekly webcasts continue to educate CCEFP student members and external companies of recent research developments. Additionally, the SLC sponsors and promotes social events to encourage the development of strong

relationships between fellow researchers at SLC student retreats and any other event where many CCEFP students are present.

Plans for the future continue to promote and expand the travel and project grant programs, enabling CCEFP students to continue collaboration with their colleagues at other institutions. The SLC will work to ensure that a student lunch or dinner is scheduled for CCEFP meetings where students will already be present to take advantage of the opportunity.

5. Member Company Benefits

- SLC funded travel grants enable CCEFP students to travel to industrial locations for training or further education.
- The SLC organizes industrial tours at locations near-by to conferences or retreats.
- The SLC is looking to promote and foster internships between CCEFP graduate students and member companies.
- The SLC hosted Webcasts continues to be the primary means by which industry members can receive continuous updates on CCEFP research projects and Testbeds.
- Student retreats offer significant networking opportunities for companies wishing to get to know students or hire them.

EO Project D.1: Fluid Power Scholars/Interns Program

Project Team:

Project Leader: Alyssa Burger, CCEFP Education Outreach Director

Industry Partners: Members of the IEC Committees

1. Project Goals

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

2. How Project Supports the EO Program Strategy

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

3. Achievements

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

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

- The history of the Fluid Power Scholars Program demonstrates that 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.

Essentially, 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.

2015 Fluid Power Scholars Program:

- The MSOE course has an upper limit of 16 participants, due to the number of hydraulic trainers available for use. As of this writing, the Fluid Power Scholars Program has reach capacity, 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 (new), Caterpillar, Inc., Danfoss, Deere & Company, Deltrol Inc., FORCE America, HUSCO International, Poclain Hydraulics (new), SunHydraulics and Pall Corporation (new).

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.

5. Member Benefits

- Internships provide companies with opportunities to directly participate in educating and training a next generation of engineers.
- Fluid power interns provide an excellent way to locate motivated, short-term engineering help.
- Long term, internships are viewed by many in industry as an invaluable tool for identifying talented candidates for future full-time employment. And the program has proven to do just that; sponsoring companies have established a track record of hiring fluid power scholars.

Project D.2: Industry Student Networking

Project Team

Project Leader: Alyssa A. Burger, Education Outreach Director

Other Personnel: Student Leadership Council
CCEFP Graduate Students
NFPA Pascal Society Members

Industrial Partner: All CCEFP Industry Members

1. Project Goals and Description

The goal of this activity is to provide CCEFP students with opportunities to network with industry representatives through a variety of channels. In doing so, there are multiple benefits: students will better understand the fluid power industry's needs and its markets; interested students will be able to find internships and later job opportunities upon graduating; companies will be able to meet, interact, and discuss potential employment opportunities with students. Channels utilized in this project include company tours, poster sessions, and resume exchanges as well as additional opportunities that extend the Center's outreach to more students and companies.

2. Project Role in Support the EO Program Strategy

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

3. Achievements

- Student Retreats: Each year a student retreat is held for all CCEFP students. These have been held at member institutions, as well as in conjunction with the National Fluid Power Association's (NFPA) 2009 and 2011 Industry and Economic Outlook Conference. Retreats provide students with the opportunity to expand their networking connections as they present their research to company representatives, some of whom are not members of the CCEFP but work in fluid power.
  - 2013: Caterpillar, Inc., Joliet, IL.
  - 2012: Sauer-Danfoss, Ames, IA.

- CCEFP Annual Meetings: Since 2006, the CCEFP has held an annual meeting at each Center's partner institutions. Representatives of the Center's industry members attended each of these meetings. Corporate kiosks and "resume exchange / speed meetings", poster sessions and presentations allow for regular networking opportunities for industry members and students.
  - Fall of 2014, the CCEFP's Fluid Power Innovation & Research Conference (FPIRC) is borne, held at Vanderbilt University in Nashville, TN.
  - Plans are underway for FPIRC15 in Chicago, IL, in conjunction with ASME/BATH Fluid Power Symposium.
  - 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.

- IEC Summits (formerly IAB Summits): Added to the Center's agenda in 2012, the CCEFP hosts Industry Engagement Committee (IEC) 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, and 2014. 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, 42+ Fluid Power Scholars have been supported through the program. Over 75% of Scholars transition to full-time employees after the internship.
- The CCEFP supports 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 in 2009, 2012, 2013, and 2014 (at UMN, GT and PU). Over 600 8th grade students engaged through this program and dozens of corporate sponsors participating.
- The Student Leadership Council (SLC) hosts a Research Webcast every other week. Students and faculty from CCEFP institutions participate, along with industry supporters. These webcasts are intended to keep everyone in the Center informed about research progress, give and receive suggestions, and generally promote inter-university collaboration as well as cooperation between academia and industry. These webcasts are well attended, with an average of 73 participants per week.

4. Plans, Milestones and Deliverables

- Holding retreats at company facilities will provide students the chance to interact with practicing engineers and will facilitate opportunities for knowledge transfer.
- 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.
- A workforce development steering committee will be 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.

5. Member Company Benefits

This project, with its current and planned programs and activities, enables CCEFP member companies to interact on many levels with engineering students, some of whom will join their work forces, others of whom will work within the fluid power industry's customer base; and still others who will find their way to the classroom where they will teach a next generation of engineers, instilling in them a knowledge of and interest in fluid power.

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

EO Project D.5: CCEFP Webcast Series

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

1. Project Goals and Description

The goal of the webcast series is to maintain a consistent means of technology transfer throughout the Center—students, faculty and industry supporters. On a regular basis, the CCEFP hosts a webcast featuring two presentations, each discussing either research projects or other Center-wide programs (e.g., special topics, strategic planning, education and outreach, project evaluation, etc.). These webcasts are open to all CCEFP students, faculty, and industry supporters through the NFPA Pascal Society and more broadly. The webcasts are presentation based, with audio and visual capabilities. A brief question and answer session after each presentation allows the audience to ask for clarifications and give feedback to the presenter. Each webcast is recorded and archived for retrieval and is posted and available on a members-only secured section of the Center's web site.

2. Project Role in Support the EO Program Strategy

This program aligns well with the mission, vision, and strategy of the CCEFP by creating widespread awareness of its research and education projects as well as the Center's administrative and evaluative work. Since many of the webcast presentations are made by Center students, participation in this project fosters professional development as they "learn by doing" how best to communicate—describing their work and also responding to and benefiting from the input of faculty, their peers and industry. 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 are invited to present. In addition, guest presenters from industry are invited to give talks on interested concepts or technology in the field.
- The Center estimates between 50 - 75 participants join the webcast on a regular basis. Participants include industry, faculty, staff, and students including special invitations to the Scientific Advisory Board.
- The Center continues to find ways to improve the efficiency and effectiveness of the webcasts. In addition to including an audio feedback component, the Student Leadership Council emcees each webcast, making for seamless transitions between presenters.
- The CCEFP has awarded the Student Leadership Council funding to host lunch at each partner site to encourage participation and attendance.
- Presentations are not just project-specific information; they also include information on how each project is aligned with the Center's strategic plan. For research, presentations describe how work

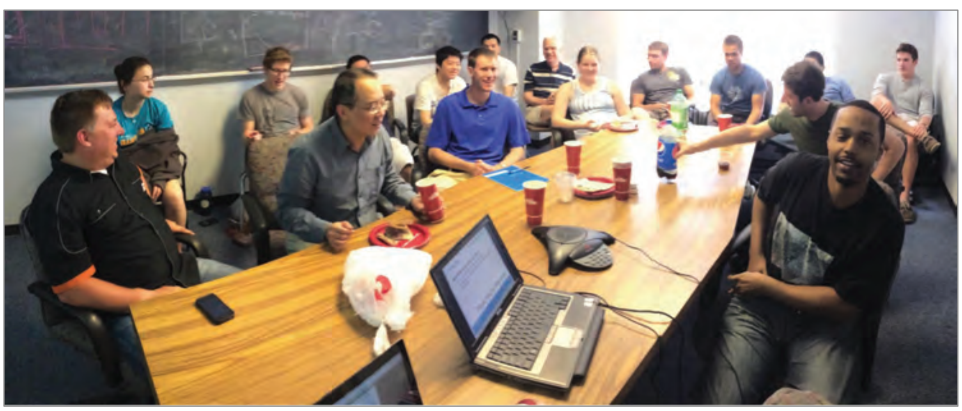
is demonstrated on the Center's test beds, how current research aligns with what has been done previously as well as how it is breaking new ground, etc. These inclusions have added important new dimensions to the webcasts and have provided another avenue where students, faculty and Center leadership can continue to strategize on the direction of the research projects across the Center.

4. Plans, Milestones and Deliverables

- The CCEFP will introduce new technology within the next year. Also, plans are underway to collaborate more directly with NFPA.
- Every effort will be made to expand participation among all audiences. The Center will continue to gather input from current and potential participants as we seek out ways to enhance this key Center project.
- The CCEFP Webcast 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 webcasts, which are a proven success, popular within the Center network and among its industrial members.

5. Member Company Benefits

All Center participants—faculty, SAB, students, industry, and staff—have opportunities to get first-hand updates on research, education, and management level activities from project leaders. Webcasts also foster a sense of “community” throughout the Center network as all constituents regularly have opportunities to hear and learn from each other.



Screenshot of a webcast presentation

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

Project Team

Project Leader: Quality Evaluation Designs (QED)

Personnel: Gary Lichtenstein, Principal, Quality Evaluation Designs
Jenifer Helms, Senior Research Associate, Quality Evaluation Designs

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) Related to #2, above, identify pathways students take into fluid power in order to 1) recognize and leverage opportunities to attract and retain qualified students with experience and interest into the fluid power field, and 2) enable CCEFP/NFPA to create a database populated with names and emails of those interested in learning more about fluid power research, industry, and jobs.

2. How Project Supports the EO Program Strategy

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

3. Achievements

In FY9, QED deployed a survey that assesses each of 6 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. A total of 762 people participated in E&O programs during summer and fall 2014, representing 6 programs and several courses. The MOOC accounted for 194 survey takers of approximately 650 dedicated course takers. Subtracting out MOOC students, responses were received from 88 respondents of approximately 112 E&O program participants overall, reflecting a 78% survey response rate. Response rate by program ranged from 79% to 100%, except for the MOOC (30%) and Fluid Power Scholars (44%).

Ratings of cross-cutting objectives across E&O programs were uniformly high, averaging about 4 on a 5-point scale, with 4 being *Extensive* and 5 *To A Great Extent*. Eighty-seven percent of respondents rated *Overall Value* as *Extensive* or *Greatly Valuable* (average 4.2/5.0). Respondents were asked whether they are interested in working in the Fluid Power industry. Thirty-three percent reported *Moderate* interest and 56% reported Extensive or Great interest. Email addresses were provided by 60% of respondents in order to receive more information about Fluid Power activities and/or job opportunities. Findings are summarized in Volume II.

In a Sponsor Study conducted by QED in FY7, industry supporters reported that their primary goal in participating in CCEFP is to access a talent pool of potential fluid power employees. If FY8 and FY9, QED has conducted interviews and surveys to help determine pathways potential workforce candidates travel that bring them into contact with fluid power industry and/or research.

Through surveys and interviews conducted in summer and fall 2014, QED mapped the pathways of 95 students and industry employees. Findings, which are summarized in Volume II, show that faculty provide more influence in the early careers of fluid power employees and researchers than any other group (including family). Currently, faculty advising in this regard is informal, so that there is no means of tracking students who demonstrate aptitude for and interest in fluid power, nor a means for faculty to know the effects of their advising or the decisions made by most students who they advise. Formalizing this channel and providing support and possibly mentoring for such students could have significant benefits in two ways by 1) enhancing the talent pool for fluid power at the 2-year, 4-year and graduate level, and 2) creating an actual pool of names and email addresses of those interested in fluid power, as opposed to a hypothetical pipeline, which exists today.

Goals for 2014-2015 are to:

1) Complete the E&O Survey analysis for spring term (2015) and implement the survey beginning summer term.
2) Complete the Fluid Power Pathways study by including more 2-year students and faculty respondents.
3) Advise and assist CCEFP and NFPA in acting on findings from the E&O survey and Fluid Power Pathways study to strengthen fluid power programs and professional pathways.

4. 2014-15 Implementation and Deliverables

Month	**Activities**
Aug 2014	QED met with E&O taskforce to finalize E&O Survey objectives and items
Sept 2014	E&O Survey Deployed
Sept-Oct 2014	QED develops unique Fluid Power Pathway survey and interview protocols
Oct 2014	QED attends the CCEFP Fluid Power Research & Innovation Conference in Nashville, conducting over 50 interviews, presenting at a well-attended session, and leading a poster session.
Nov-Dec 2014	Fall term data analysis: Survey and FPP Study data
Jan 2015	Submit interim reports to E&O (E&O Survey and FPP study)
Feb 2015	Complete FPP Data Collection (target 2-Yr students and faculty)
Mar 2015	Completed FPP Data Analysis
Apr 2015	QED presents at NSF Site Visit
May 2015	Complete Spring Quarter E&O Survey Analysis
May 2015	QED submits annual report

This page is intentionally left blank

Associated Project Abstracts: Research

Thrust 1 – Efficiency

A Characterization of the Pressure-Viscosity and Compressibility Response of Five Oils for a Wide Range of Temperatures
Project Leader: Scott Bair
Sponsors: Confidential
Abstract: *Unavailable due to confidentiality of project*

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: *Unavailable due to confidentiality of project*
Abstract: *Unavailable due to confidentiality of project*

Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump
Project Leader: Andrea Vacca
Sponsors: Dae Jin Hydraulics – TECPOS
Abstract: A radial piston pump for high pressure application is investigated

EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage
Project Leader: Perry Li, Terry Simon
Sponsors: National Science Foundation (NSF)
Abstract: "The goal of this project is to develop an efficient, powerful and cost effective localized_x000D_ energy storage concept for off-shore wind power using high pressure compressed air. The_x000D_ system is to be capable of storing several hours worth of wind energy. Research involves heat_x000D_ transfer improvement, efficient machine element, and system optimization and control."

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

Energy Saving Hydraulic System Architecture Utilizing Displacement Control
Project Leader: Monika Ivantysynova
Sponsors: Confidential
Abstract: *Unavailable due to confidentiality of project.*

Evaluation and Design Improvements for a Hydraulic Pump
Project Leader: Monika Ivantysynova
Sponsors: Confidential
Abstract: *Unavailable due to confidentiality of project.*

Evaluation 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.*

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 and Analysis of Swash Plate Type Piston Motor
Project Leader: Monika Ivantysynova
Sponsors: Confidential
Abstract: *Unavailable due to confidentiality of project.*

Modeling and Analysis of Swash Plate Axial Piston Pump
Project Leader: Monika Ivantysynova
Sponsors: Confidential
Abstract: *Unavailable due to confidentiality of project.*

Modeling of Lubricating Features of External Gear Machines and Development of Quieter Solutions
Project Leader: Andrea Vacca
Sponsors: Casappa S.p.A.
Abstract: This project explores new solutions for improved axial balance of pressure compensated external gear machines for reduced power losses. Novel modeling technique is developed in aid to the design of the pressure compensation areas in the lateral bushes. The lateral bushes are also modified to permit lower pressure pulsation, thus reduced noise emissions.

MRI: Development of a Controlled-Trajectory Rapid Compression and Expansion Machine
Project Leader: Zongxuan Sun, David Kittleson, Kim Stelson
Sponsors: National Science Foundation
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. The proposed instrument utilizes high pressure and high speed hydraulic actuation system and unique motion control methodologies to achieve precise and flexible compression and expansion processes. This new design and control approach provides three key advantages of the proposed instrument. It offers added flexibility with piston trajectory control, better repeatability with real-time feedback, and improved throughput without the need for physical adjustment of the mechanical system. Furthermore, the most unique feature of the proposed instrument is the capability of tailoring the temperature and pressure history during the combustion processes by controlling the piston trajectory and therefore the combustion chamber volume in real-time, which can create new experimental conditions and enable real-time measurement that are not possible with conventional rapid compression machines.

New Geometries for External Gear Machines towards the Reduction of Noise Emissions
Project Leader: Andrea Vacca
Sponsors: Casappa S.p.A
Abstract: This project is aimed at studying unconventional gear profiles for external gear machines. Profiles different than the standard involute profiles will be investigated by using the HYGESim simulation tool. Experimental activity based on both noise and flow measurements on prototype pumps is also included in the project. The goal is to formulate designs for high pressure applications characterized by low noise emissions.

Numerical Modeling of GEROTORs Unit
Project Leader: Andrea Vacca
Sponsors: Thomas Magnete GmbH
Abstract: This project is about the formulation of a multi-domain simulation model for internal gear ring pumps (gerotors). The model has to be capable to simulate the flow through the unit accepting a large range of geometries of the inner and outer rotor. The model is aimed at predicting the outlet flow fluctuations, instantaneous shaft and will be instrumental to formulate the optimal design solution for any given application.

Thrust 3: Effectiveness

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.

Model Predictive Control of Pneumatic Actuators
Project Leader: Wayne Book
Sponsors: National Defense Science and Engineering Graduate Fellowship (NDSEG)
Abstract: Pneumatic actuators possess a number of qualities that make them potentially versatile actuators: they have high power and force density, are clean, safe, and low cost, and possess inherent compliance and potentially adaptable stiffness that make them useful for contact and interaction tasks. However, control of pneumatic actuators has proven difficult, limited by the inherent compliance of the actuator, friction in the cylinder, and third order dynamics that are both nonlinear and discontinuous. In general, past controls solutions have had limited application, applied where position tracking is not critical, or using high-gain PD controllers to transform the system into a stiffer one that succeeds in precision tracking but possesses high output impedance and lacks compliance. Of the variety of advanced controllers that have been tested, the most successful have been sliding mode controllers, which add robustness criteria to simpler feedback controllers. Input shaping has shown that the tracking problem can be solved in the open-loop case without sacrificing compliance and impedance goals. Model predictive control offers the potential to extend this concept to the pseudo-closed-loop case, by effectively iteratively solving a feed forward problem to achieve good tracking performance of a system with high compliance and low output impedance that interacts safely and securely with its surroundings. A predictive observer can then be used to compensate for friction â€“ and especially stiction â€“ proactively, rather than using an additive compensation term at each instant. This may improve performance for a pneumatic system, which has generally slow dynamics. Finally, the predictive control enables the user to place constraints on the optimization, thereby enabling the controller solution to operate closer to the optimal capability of the system, which is subject to dynamic and mechanical limits. The resultant system resembles the increasingly common series elastic and variable stiffness actuators, coupled with a new method to achieve control of compliant actuators for use in robots that require both good tracking and environmental interaction.

New Generation Of Green, Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology

Project Leader: Monika Ivantysynova, 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.

Rheology Modeling for Mechanical Face Seals

Project Leader: Scott Bair

Sponsors: John Crane

Abstract: Rheological models are developed for the very high shear conditions of a mechanical face seal.

Self-Powered Leak Detection System for Pipeline Monitoring

Project Leader: Kenneth Cunefare

Sponsors: Veraphotonics, Mistras

Abstract: In collaboration with the Georgia Institute of Technology and Mistras Inc., Veraphotonics proposes to harvest the energy of hydraulic pressure ripple in pipeline systems by piezoelectric transduction to enable self-powered wireless leak and damage detection systems toward sustainable energy transmission and monitoring. The pressure ripple present within most hydraulic systems, or within any fluid system subject to pumping action, is commonly viewed as an annoyance or a detriment to system performance; however, the pressure ripple may also represent a high-intensity power source for energy harvesting. In a pipeline system, an energy harvesting technology might be further integrated with health-monitoring sensors and eliminate the need for batteries or wires providing power to individual sensors; this would reduce maintenance contact and eliminate potential points of failure. Distributed sensors are common in hydraulic systems, and health-monitoring systems are being deployed within the hydraulics industry, and remote sensing and monitoring is common in processing industries, such that there are immediate applications for the technology. Whereas the commonly explored â€œenergy harvesterâ€ technologies developed to date have been applied to energy sources of relatively low power intensity, the pressure ripple in a hydraulic system represents a relatively high power intensity by comparison. In this STTR Phase I project, the hydraulic pressure harvesting mechanism will be combined with four-channel acoustic emission (AE) based leak and damage detection hardware along with power management electronics to enable self-powered wireless health monitoring in pipeline systems. By combining our theoretical simulation and experimental testing, hydraulic pressure energy harvester systems will be designed and optimized for characteristics of typical oil pipeline systems. Wireless AE-based leak detection and energy harvester systems will be integrated with impedance matching and optimal power management to achieve the maximum efficiency.

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

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, Robert Webster
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.

Modulation of Anticipatory Postural Adjustments in Parkinson's disease Using a Portable Powered Ankle-Foot Orthosis
Project Leader: Elizabeth Hsiao-Wecksler
Sponsors: NSF IGERT Student Fellowship
Abstract: Two of the most debilitating symptoms in Parkinson's disease are freezing of gait (FOG) and start hesitation. Previous research has shown that presenting an extra sensory cue can alleviate FOG symptoms, however the results have been inconsistent. To date, mechanical assistance given as a cue (or during another cue) has been under explored. We are testing the efficacy of providing mechanical assistance at the ankle through the portable powered ankle-foot orthosis to alleviate FOG symptoms in Parkinson's disease.

Wearable eMbots to Induce Recovery of Function

Project Leader: William Durfee

Sponsors: NIH, 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.

This page is intentionally left blank

Associated Project Abstracts: Education & Outreach

Through cooperation and collaboration, the CCEFP leverages its work with the following university and organizational programs and the funding each has received. These efforts follow from the CCEFP's strategy of seeking out strong partners in developing its educational and outreach programs.

NSF REU Site Award

REU Site: Research Experiences for Undergraduates in Fluid Power
Source: National Science Foundation
Location: University of Minnesota
PI: Kim A Stelson
Funding: $390,000. 6/1/13 - 5/31/16

The Center received the competitive NSF Research Experiences for Undergraduates (REU) Site Award for Years 8 – 10. The goal of NSF REU programs are to kindle the interest of diverse participants in attending graduate school. Additionally, CCEFP's goal also includes increasing the number of undergraduate students knowledgeable in fluid power, a positive outcome from industry's point of view as well. To date, more than 145 REU students have participated in the CCEFP program -- more than in many REU site programs. Based on responses by 54 undergraduates to a 2012 longitudinal study, 55% of all former CCEFP REU students enter graduate school and 33% eventually become PhD candidates. Since revising the CCEFP REU program structure in 2008, the CCEFP REU Program has recruited, on average, over 35% women, and over 33% racially or ethnically underrepresented students into the program on a yearly basis. The CCEFP's recruiting strategy includes identifying institutions, programs, and people with whom to develop relationships that, in turn, open pathways to CCEFP summer programs and beyond for underrepresented students.

NFPA Foundation Grant

NFPA Fluid Power Challenge Competition
Source: NFPA Foundation
Location: University of Minnesota
PI: Alyssa A Burger
Funding: $10,000. 9/1/14 - 5/31/15

The Center received an earmarked donation of $10,000 to launch and host two new Fluid Power Challenge Competitions at Georgia Institute of Technology and Purdue University at Kokomo. The Challenge is a skills-based design competition for eighth grade students. The program challenges students to solve a real life engineering problems using hydraulics and pneumatics. The NFPA Fluid Power Challenge is a competition that challenges eighth grade students to solve an engineering problem using fluid power. They work in teams to design and build a fluid power mechanism, and then compete against other teams in a timed competition. The NFPA Fluid Power Challenge:

- Actively engages students in learning about fluid power
- Gives support and resources to teachers for science and technology curriculum
- Creates a learning environment where math and science are fun
- Encourages students to acquire a diversity of teamwork, engineering and problem-solving skills
- Introduces either graders to careers in the fluid power industry
- Helps build a strong workforce for tomorrow

<u>NC A&T State University Regional Collaborations for Excellence in STEM</u>

Lead Personnel: Eui Park

Funding: $500,000 over 2 years

Abstract: The North Carolina A&T State University Regional Collaborative for Excellence in STEM is a comprehensive and inclusive project that targets the enhancement of STEM education and learning outcomes for middle school aged children in five counties in Eastern North Carolina: Bertie, Edgecombe, Gates, Pitt, Wilson. In particular, this project focuses on cohorts of 6th grade students 2012. The project will follow these students with programming until high school graduation. In each year following the first cohort, an additional 6th Grade cohort will be added to the project creating a pipeline into high school and post-secondary education.

The approach to this project is to collaboratively assess design and implement programs focused on STEM education tailored to the needs and capacities of the identified rural areas. The needs and the capacities of these localities will differ; however, given the array of partners, the resources in this collaborative, coupled with its comprehensive approach, each locality will be able to improve the educational experience and outcomes in STEM areas, particularly in math and science.

Publications

Thrust 1: Efficiency

Agarwal, P. and Vacca A., "A Numerical Model for the Simulation of Flow in Radial Piston Machines", Proceedings of International Fluid Power Exhibition, International Fluid Power Expo, Las Vegas, NV (March 2014)

Agarwal, P., Vacca, A., Wang, K., Kim, K., Kim, T., "An Analysis of Lubricating Gap Flow in Radial Piston Machines", SAE International Journal of Commercial Vehicles, 7(2): 524-534 (October 2014)

Altare, G. and Vacca, A., "A Design Solution for Efficient and Compact Electro-Hydraulic Actuators", Proceedings of the Second International Conference on Dynamics and Vibroacoustics of Machines, Samara, Russia (September 2014)

Altare, G.; Vacca, A.; Richter, C., "A Novel Pump Design for an Efficient and Compact Electro-Hydraulic Actuator", Proceedings of the 2014 IEEE Aerospace Conference, Big Sky, Montana (March 2014)

Bair, S., "The temperature and pressure dependence of the dynamic properties of branched perfluoropolyethers", Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Volume 228, Issue 4, pp. 424-434 (2014)

Barth, E. and Pedchenko, A., "Elastic Hydraulic Accumulator/Reservoir System", U.S. patent #8,434,524

Bramer, J.; Puzzuoli, A.; Michael, P.; 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)

Breidi, F.; Helmus, T.; Holland, M.; Lumkes, J., "The Impact of Peak-and-Hold and Reverse Current Driving Strategies on the Dynamic Performance of Commercial Cartridge Valves", Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control, Bath, UK (2014)

Busquets, E. and Ivantysynova, M., "A Robust Multi-Input Multi-Output Control Strategy for the Secondary Controlled Hydraulic Hybrid Swing of a Compact Excavator with Variable Accumulator Pressure", Proceedings of the ASME/BATH Symposium on Fluid Power & Motion Control, Bath, UK (2014)

Busquets, E. and Ivantysynova, M., "An Adaptive Robust Control for Displacement-controlled End-effectors", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (September 2014)

Busquets, E. and Ivantysynova, M., "The World's First Displacement Controlled Excavator Prototype with Pump Switching - A Study of the Architecture and Control", 9th JFPS International Symposium on Fluid Power (October 2014) **Best Paper Award**

Chacon, R. and Ivantysynova, M., "An Investigation of the Impact of Micro Surface Shaping on Cylinder Block/Valve Plate Interface Performance", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (2014)

Cook, D., "Heat and Efficiency Considerations in Fluid-Powered Co-Robotics Applications", Proceedings of the International Fluid-Power Exposition (IFPE) Technical Conference, Las Vegas, NV (March 2014)

Cummins, J.; Maurice, C.; Song, Y.; Sanchez, F.; Barth, E.; Adams, D., "Elastomeric Evolution: A New Look at Carbon Nanotube Reinforced Elastomers", Proceedings of the 40th European Rotorcraft Forum (September 2014)

Daher, N. and Ivantysynova, M., "An Indirect Adaptive Velocity Controller for a Novel Steer-by-Wire System", ASME Journal of Dynamic Systems, Measurement, and Control (2014)

Daher, N. and Ivantysynova, M., "Energy Analysis of an Original Steering Technology that Saves Fuel and Boosts Efficiency", Energy Conversion and Management (July 2014)

Daher, N. and Ivantysynova, M., “A Steer-by-Wire System that Enables Remote and Autonomous Operation”, SAE Commercial Vehicle Engineering Congress, Rosemount, IL (2014)

Daher, N. and Ivantysynova, M., “A Virtual Yaw Rate Sensor for Articulated Vehicles Featuring Novel Electro-Hydraulic Steer-by-Wire Technology”, Control Engineering Practice (June 2014)

Devendran, R. and Vacca, A., “A novel design concept for variable delivery flow external gear pumps and motors”, International Journal of Fluid Power, 15:3, pp. 121-137 (2014)

Devendran, R., Vacca, A., "Experimental Characterization of External Gear Machines with Asymmetric Teeth Profile", Proceedings of IFPE 2014, Int. Fluid Power Expo, Las Vegas, NV (March 2014)

Dhar, S. and Vacca, A., "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 82, pp. 162-175 (October 2014)

Dhar, S., Vacca, A., Lettini, A., "An Experimental Investigation of the Lateral Lubricating Gaps in External Gear Machines with Axially Balanced Lateral Bushes", Proceedings of the International Fluid Power Conference (9 IFK), Aachen, Germany (March 2014)

Johnston, M.T., W.P. King, R.H. Ewoldt, "Shear stress characteristics of microtextured surfaces in gap-controlled hydrodynamic lubrication", Tribology International, 82, 123-132 (2015)

Krause, M. and Michael, M., "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)

Lee, S. and Li, P., "Trajectory Tracking Control Using a Hydraulic Transformer", Proceedings of ISFA 2014 International Symposium on Flexible Automation (July 2014)

Li K.; Zhang C.; Sun, Z., "Precise Piston Trajectory Control for a Free Piston Engine", Control Engineering Practice. vol. 34 pp. 30-38 (January 2015)

Miller, M.; Khalid, H.; Michael, P.; Guevremont, J.; Garelick, K.; Pollard, G.; Whitworth, A.; Devlin, M., “An Investigation of Hydraulic Motor Efficiency and Boundary Lubrication Additive Effects”, Proceedings of the 9th International Fluid Power Conference, Aachen, Germany, Vol. 1, 266-277 (March 2014)

Miller, M.; Khalid, H.; Michael, P.; Guevremont, J.; Garelick, K.; Pollard, G.; Whitworth, A.; Devlin, M.. “An Investigation of Hydraulic Motor Efficiency and Tribological Surface Properties”, Tribology Transactions, 57: 622-630 (2014)

Mizell, D. and Ivantysynova, M., "Material Combinations for the Piston-Cylinder Interface of Axial Piston Machines: A Simulation Study", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (June 2014)

Naseem, D. and Ivantysynova, M., "New Steering Concept for Wheel Loaders", Proceedings of the International Fluid Power Conference (9 IFK), Aachen, Germany (March 2014)

Padovani, D. and Ivantysynova, M., "Energy Efficient Hydraulic Rotary Drive: Analysis and Comparison of Two Different Displacement Controlled Solutions", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (2014)

Pena, O.R., Leamy, M.J., "A Self-Contained Architecture for Energy Recovery in Hydraulic Elevators", Proceedings of the ASME 2014 International Mechanical Engineering Congress & Exposition, Montreal, Canada (November 2014)

Qin, C.; Loth, E.; Li, P.; Simon, T.; Van de Ven, J., "Spray-cooling concept for Wind-Based Compressed Air Energy Storage", Journal of Renewable and Sustainable Energy, Vol.6 043125 (2014)

Saadat, M. and Li, P., "Modeling and Control of an Open Accumulator Compressed Air Energy Storage (CAES) System for Wind Turbines", Applied Energy [http://dx.doi.org/10.1016/j.apenergy.2014.09.085] (2015)

Saadat, M.; Shirazi, F.; Li, P., "Revenue Maximization of Electricity Generation for a Wind Turbine Integrated with a Compressed Air Energy Storage System", Proceedings of 2014 American Control Conference (2014)

Schenk, A. and Ivantysynova, M., "A transient fluid structure interaction model for lubrication between the slipper and swashplate in axial piston machines", Proceedings of the 9th International Fluid Power Conference (2014)

Schenk, A. and Ivantysynova, M., "A transient thermoelastohydrodynamic lubrication model for the slipper / swashplate in axial piston machines", ASME Journal of Tribology (January 2015)

Shirazi F.; Gagnon P.; Li, P.; Van de Ven, J., "Design, modeling and control of a lab- scale compressed air energy storage (CAES) testbed for wind turbines with simulated input and demand power variability", Proceedings of the ASME Dynamic Systems and Control Conference (2014)

Skelton, D.; Xiong, S.; Lumkes, J.; Breidi, F., "High Performance Actuation Systems Enabled by Energy Coupling Mechanisms", SAE Commercial Vehicle Engineering Congress, Rosemont, Illinois (October 2014)

Skelton, D.; Xiong, S.; Lumkes; J., "Design of High Performance Actuation System for High Speed Valves", Proceedings of the 9th International Fluid Power Conference, Aachen, Germany (March 2014)

Skow, E.; Cunefare, K.; Erturk, A., "Power performance improvements for high pressure ripple energy harvesting: Smart Materials and Structures, vol. 23, p. 104011 (2014)

Skow, E.; Koontz, Z.; Han, C.; Cunefare, K.; Erturk, A., "Pressure ripple energy harvester enabling autonomous sensing", Proceedings of IFPE 2014, International Fluid Power Expo, Las Vegas, NV (March 2014)

Sprengel, M. and Ivantysynova, M., "Hardware-in-the-Loop Testing of a Novel Blended Hydraulic Hybrid Transmission", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (2014) **Backe Medal for Best Paper**

Sprengel, M. and Ivantysynova, M., "Investigation and Energetic Analysis of a Novel Blended Hydraulic Hybrid Power Split Transmission", Proceedings of the 9th International Fluid Power Conference (9IFK) (March 2014)

Sprengel, M. and Ivantysynova, M., "Recent Developments in a Novel Blended Hydraulic Hybrid Transmission", 2014 SAE Commercial Vehicle Engineering Congress, Rosemount, IL (September 2014)

Thiagarajan, D.; Dhar, S.; Vacca, A., "A Novel Fluid Structure Interaction-EHD Model and Optimization Procedure for an Asymmetrical Axially Balanced External Gear Machine", Tribology Transactions, Vol. 58(2), pp. 274-287 (2015)

Thiagarajan, D.; Vacca, A., "A Numerical Procedure to Design the Optimal Axial Balance of Pressure Compensated Gear Machines", 8th FPNI Ph.D. Symposium on Fluid Power (2014)

Wang, F.; Bissen, M.; Ward, W.; Stelson, K., “Modeling and Design of a Hybrid Bicycle with Hydraulic Transmission,” The Ninth JFPS International Symposium on Fluid Power, Matsue, Japan (October 2014)

Wang, F. and Stelson, K., "Midsize wind turbines with hydraulic transmissions", Proceedings of the 53rd National Conference on Fluid Power, Las Vegas, NV (2014)

Wang, F., Stelson, K., "A Novel Pressure Controlled Hydro-mechanical Transmission", Proceedings of the ASME/BATH Symposium on Fluid Power & Motion Control, Bath, UK (September 2014)

Wilhelm, S., and Van de Ven, J., "Adjustable Linkage Pump: Efficiency Modeling and Experimental Validation", Journal of Mechanisms and Robotics, v. 7, n. 3. (2015)

Wilhelm, S., and Van de Ven, J., "Design of a Variable Displacement Triplex Pump", National Conference on Fluid Power, International Fluid Power Exposition, Las Vegas, NV (March 2014)

Wilhelm, S., and Van de Ven, J., "Efficiency Testing of an Adjustable Linkage Triplex Pump", ASME/BATH 2014 Symposium on Fluid Power & Motion Control, Bath, UK, FPMC2014-7856. (September 2014)

Winkelmann, A. and Barth, E., "System Dynamic Model and Design of Stirling Pump", Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control, Bath, UK, (2014)

Wondergem, A. and Ivantysynova, M., "The Impact of the Surface Shape of the Piston on Power Losses", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (June 2014)

Xiong, S. and Lumkes, J., "Coupled Physics Modelling for Bi-Directional Check Valve System", International Journal of Fluid Power, 15:2, 55-67 (2014)

Zhang, C.; Li, K.; Sun, Z., "Modeling of Piston Trajectory-based HCCI Combustion", Applied Energy [http://dx.doi.org 10.1016/j.apenergy.2014.11.007] (2015)

Zhang, C.; Li, K.; Sun, Z., "Modeling of Piston Trajectory-based HCCI Combustion", Proceedings of the 2014 ASME Dynamic Systems and Control Conference (October 2014)

Zhang, C.; Shirazi F.; Yan, B.; Simon T., "Design of an Interrupted-Plate Heat Exchanger Used in a Liquid-Piston Compression Chamber for Compressed Air Energy Storage", ASME Summer Heat Transfer (June 2014)

Zhang, C.; Yan, B. ; Wieberdink, J. , Li, P.; Van de Ven, J.; Loth, E.; Simon, T., "Thermal analysis of a compressor for application to compressed air energy storage", Applied Thermal Engineering, V. 73,:2, pp. 1402-1411 (2014)

Zhou, J.; Vacca, A.; Casoli, P., “A Novel Approach for Predicting the Operation of External Gear Pumps under Cavitating Conditions”, Simulation Modeling Practice and Theory (Elsevier), Vol. 45, pp. 35-49 (2014)

Zhou, J.; Vacca, A.; Casoli, P.; Lettini, A., "Investigation of the impact of Oil Aeration on Outlet Flow Oscillations in External Gear Pumps", Proceedings of IFPE 2014, International Fluid Power Expo, Las Vegas, NV (March 2014)

Thrust 2: Compactness

Cummins, J.; Pedchenko, A.; Barth, E.; Adams, D., “Advanced Strain Energy Accumulator: Materials, Modeling and Manufacturing”, Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control, Bath, UK (2014)

Lacey, L.; Maliki, A.; Bhattacharjee, D.; Veldhorst, J.; Ueda, J., "Design of fMRI-Compatible Hemiparesis Rehabilitation Device", Proceedings of the 2014 ASME Medical Device Conference (April 2014)

Lacey, L.; Maliki, A.; Bhattacharjee, D.; Veldhorst, J.; Ueda, J., "Design of MRI-Compatible Hemiparesis Rehabilitation Device", ASME Journal of Medical Devices, 8(2) [10.1115/1.4027028] (April 2014)

Strohmaier, K., Cronk, P., Knutson, A., and Van de Ven, J., 2014, "Experimental Studies of Viscous Loss in a Hydraulic Flywheel Accumulator", Proceedings of the National Conference on Fluid Power, International Fluid Power Exposition, Las Vegas, NV, 0369-000017, (March 2014)

Thrust 3: Effectiveness

Bair, S. and Qureshi, F., "Time-Temperature-Pressure Superposition in Polymer Thickened Liquid Lubricants", ASME Journal of Tribology 136(2), 021505 (February 2014)

Bair, S. and Vergne, P., "Classical EHL versus Quantitative EHL: A Perspective Part I: Real viscosity-pressure dependence and the viscosity-pressure coefficient for predicting film thickness", Tribology Letters, Volume 54, Issue 1, pp. 1-12 (April 2014)

Bair, S., "A Critical Evaluation of Film-Thickness-Derived Pressure-Viscosity Coefficients", Lubrication Science [DOI: 10.1002/ls.1284] (2014)

Bair, S., "The pressure and temperature dependence of volume and viscosity of four Diesel fuels", Fuel 135 pp. 112-119 (2014)

Bair, S.; Yamaguchi, T.; Brouwer, L.; Schwarze, H.; Vergne, P.; Poll, G., "Oscillatory and steady shear viscosity: The Cox-Merz rule, superposition, and application to EHL friction", Tribology International Volume 79, pp. 126-131 (November 2014)

Bair, S., "Density Scaling of the Thermal Conductivity of a Jet Oil", Tribology Transactions, Volume 57, Issue 4 (April 2014)

Cunefare, K.; Skow, E.; Erturk, A., "Design and modeling of hydraulic pressure energy harvesters for low dynamic pressure environments", Proceedings of ASME 2014 International Mechanical Engineering Congress and Exposition, Montreal, Canada, paper IMECE2014-38684 (November 2014)

Daepp, H. and Book, W., "Model Predictive Control for compliant pneumatic systems", Proceedings of the 2014 ASME Dynamic Systems and Control Conference (October 2014)

Daepp, H. and Book, W., "Predictive friction compensation for control of pneumatic actuators", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (June 2014)

Daepp, H. and Book, W., "Value of a high fidelity actuator model for dynamic simulation of a pneumatic rescue robot", 19th International Federation of Automatic Control (IFAC) World Congress (2014)

Davis, D.; Jimerson, B.; Stajsic, D.; Jiang, Z., "Trunk Kinematics of Pulling at or Below Sub-waist Height", Proceedings of the 2014 Industrial and Systems Engineering Conference (2014)

Desai, Y.; Davis, D.; Jiang, S.; Ward, A., "The Effect of Auditory Cues on Haptic-Controlled Excavator Operator Performance", Proceedings of the 2014 Industrial and Systems Engineering Conference (2014)

Huang, Y. and Salant, R., "Numerical Modelling of a Hydraulic Rod Seal with a Micro-Patterned Rod", Proceedings of the 18th International Sealing Conference, Stuttgart, pp.611-623 (October 2014)

Humphreys, H. and Book, W., "Advanced Hydraulically Actuated Patient Transfer Assist Device", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (June 2014)

Humphreys, H.; Book, W.; Huggins, J.; Jimerson, B., "Caretaker-Machine Collaborative Manipulation with an Advanced Hydraulically Actuated Patient Transfer Assist Device", Proceedings of the 2014 ASME Dynamic Systems and Control Conference (October 2014)

Kim, T.; Kalbfleisch, P.; Ivantysynova, M., "The Effect of Cross Porting on Derived Displacement Volume", International Journal of Fluid Power (June 2014)

Li, P. and Wang, M., "Natural Storage Function for Passivity Based Trajectory Control of Hydraulic Actuators", IEEE/ASME Transactions on Mechatronics [10.1109/TMECH.2013.2266916] (June 2014)

Ritelli, G. and Vacca, A., "Experimental-Auto-Tuning Method for Active Vibration Damping Controller. The Case Study of a Hydraulic Crane", Proceedings of the International Fluid Power Conference (9 IFK), Aachen, Germany (March 2014)

Winck, R.; Elton, M.; Book, J., "A practical interface for coordinated position control of an excavator arm", Automation in Construction, pp. 46-58 (2015)

Test Beds and General

Beccani, M.; Di Natali, C.; Sliker, L.; Schoen, J.; Rentschler, M.; Valdastri, P., “Wireless Tissue Palpation for Intraoperative Detection of Lumps in Soft Tissue”, IEEE Transactions on Biomedical Engineering, Vol. 61, N. 2, pp. 353-361 (2014) **This paper was featured by IEEE Spectrum, IEEE TBME Highlights, and was on the cover of the February issue of IEEE Transactions on Biomedical Engineering**

Breidi, F.; Helmus, T.; Lumkes, J., "Development of Portable Pneumatic Educational Tool for STEM Education", Proceedings of IFPE 2014, International Fluid Power Expo, Las Vegas, NV (March 2014)

Chase, T.; Cheong, K.; Du, Z.; Li, P., "Design and Experimental Validation of a Virtual Vehicle Control Concept for Testing Hybrid Vehicles Using a Hydrostatic Dynamometer", Proceedings of the 2014 ASME Dynamic Systems and Control Conference (October 2014)

Cheong, K.; Du, Z.; Li, P.; Chase, T., "Hierarchical Control Strategy for Hybrid Hydro-Mechanical Powertrain", Proceedings of 2014 American Control Conference (2014)

Du, Z.; Cheong, K.; Li, P.; Chase, T., "Energy Management Strategy for a Power-Split Hydraulic Hybrid Vehicle Based on Lagrange Multiplier and Its Modifications", IEEE Transactions on Vehicular Technology (January 2015)

Garcia, J., Kuleshov, Y., and Lumkes, J., "Using fluid power workshops to increase STEM interest in K-12 students", Proceedings of the 2014 American Society for Engineering Education Annual Conference and Exposition, (June 2014)

Neubauer, B.; Nath, J.; Durfee, W., "Design of a portable hydraulic ankle-foot orthosis", Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society (2014)

Petrucci, M.; MacKinnon, C.; Hsiao-Wecksler, E. "A Step Towards Reducing Freezing of Gait in Parkinson’s Disease: Using a Portable Powered Orthosis", Proceedings of the 6th World Congress of Biomechanics, Boston, MA, (July 2014)

Xia, J. and Durfee, W., "Experimentally validated models of O-ring seals for tiny hydraulic cylinders", Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control, Bath, England (2014)

Data Management Plan

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

Expected Types of data

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

Format and Content Standards

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

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

Additional information includes the following:

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

Access and Sharing

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

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

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

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

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

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

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

Professional Preparation

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

Appointments

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

Closely Related Products

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

Significant Products

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

Synergistic Activities

Recent Patent Activities:

(a) Peroulis, D., Kovacs, A., Koester. D., Sadeghi, F., Scott, S., and Adams, D. E., "Highly-Reliable Micro-Electromechanical System Temperature Sensor," August 2013, US 2013/0202012 A1.

(b) Calhoun, K., Kiser, R., Adams, D., Gul, K., Yoder, N., Bruns, C., and Yutzy, J., "System and Method for Detecting Fault Conditions in a Drivetrain Using Torque Oscillation Data," May 2013, US 2013/0116937 A1.

(c) Adams, D. E., Yutzy, J., and Dana, S., "Load Shape Control of Wind Turbines," December 2012, US 2012/029254.

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

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

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

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

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

Collaborators & Other Affiliations

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

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

Ph.D. Students Supervised:

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

Ph.D. and M.S. Advisors:

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

Research Visitors:

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

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

Professional Preparation

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

Research Areas

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

Appointments

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

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

Closely Related Products

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

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

Significant Products

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

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

Collaborators within the past 48 Months:
Kim Stelson, Perry Li, Will Durfee (U. of Minnesota); Lucy Pao (Univ of Colorado); Placid Ferreira, John Rogers, Mark Shannon, Paul Kenis, Kent Choquette, Ilesami Adesida, Qin Zhang, Amy Wagoner Johnson, Elizabeth Hsiao-Wecksler, Eric Loth, Bill King, Jennifer Berhnard, William King (UIUC), Jakob Stoustrup (Aalborg), Maarten Steinbuch (TUEindhoven)

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

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

Professional Preparation

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

Appointments

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

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

Bair, S., "The High Pressure Rheology of Some Simple Model Hydrocarbons," Proc. I. Mech. E., 216, J, 2002, pp. 139-150.

Bair, S., McCabe, C. and Cummings, P., "Calculation of Viscous EHL Traction for Squalane using Molecular Simulation and Rheometry," Tribology Letters, 13, 4, pp. 251-254, 2002.

Bair, S., "Pressure-Viscosity Behavior of Lubricants to 1.4 GPa and Its Relation to EHD Traction," STLE Tribology Transactions, 43, 1, pp 91-99, 2000.

Bair, S. and Qureshi, F., "The Generalized Newtonian Fluid Model and Elastohydrodynamic Film Thickness," ASME, J. Tribology, 125, 1, pp. 70-75, 2003.

Significant Products
Bair, S., "Normal Stress Difference in Liquid Lubricants Sheared Under High Pressure," Rheologica Acta, 35, 13, pp 13-23, 1996.

Bair, S., Qureshi, F., and Khonsari, M., "Adiabatic Shear Localization in a Liquid Lubricant Under Pressure," Trans. ASME, Journal of Tribology, 116, 4, 1994.

Bair, S. and Winer, W.O., "A New High-Pressure, High Shear Stress Viscometer and Results for Lubricants, "Tribology Transactions, 36, 4, pp. 721-725, 1993.

Bair, S., Qureshi, F., and Winer, W. O., "Observations of Shear Localization in Liquid Lubricants Under Pressure," Trans. ASME, Journal of Tribology, 115, 3, 1993.

Bair, S., Green, I., and Bhushan, B., "Measurements of Asperity Temperatures of a Read/Write Head Slider Bearing in Hard Magnetic Recording Disks," Trans. ASME Journal of Tribology, 113, No. 3, 1991.

Synergistic Activities
Awards
Co-Recipient of the 1983 Best Paper of the Year for the Tribology Division/ASME
Co-Recipient of the 1991 Best Paper of the Year for the Tribology Division/ASME
Jacob Wallenberg Foundation, 1996
Recipient of the 2000 Alfred Hunt Award from STLE for best paper
Fellow of ASME
Fellow of STLE

Co-Recipient of the 2006 Alan Berman Research Publication Award (with Roland and Casalini)
Recipient of the 2007 Alfred Hunt Award from STLE for best paper
Recipient of the 2009 Naval Research Laboratory Chemistry Division Alan Berman Research Publication Award (with Roland, Bogoslovov, Casalini, Ellis, Rzosca, Czuprynski, and Urban)
Recipient of the International Award for 2009, the highest honor given by the Society of Tribologists and Lubrication Engineers.

US Patents

4,349,130	Liquid Metering Pump
4,347,643	Power Assist Drive Upright Vacuum Cleaner and Power Assist Drive System
4,391,018	Vacuum Cleaner with Wheel and Nozzle Height Adjusting Mechanism [with Vermillion and Gromek]
4,998,228	Drinking Water Filter [with Eager]
5,562,692	Fluid Jet Surgical Cutting Tool
5,643,299	Hydrojet Apparatus for Retractive Surgery
5,735,815	Method of Using Fluid Jet Surgical Cutting Tool
5,853,384	Fluid jet Surgical Tool and Aspiration Device
5,865,790	Method and Apparatus for Thermal Phaco-emulsification by Fluid Throttling
6,126,668	Microkeratome
6,527,766	Instrument and Method for Phacoemulsification by Direct Thermal Irradiation

Collaborators And Other Affiliations
Collaborators Over The Last 48 Months:
Ashlie Martini, Purdue University, CCEFP
Ivan Krupka, Brno University, Czech Republic, Elastohydrodynamic film thickness measurements
Riccardo Casilini, George Mason University, Viscosity correlations
Mike Roland, Naval Research Laboratory, Viscosity correlations
Michael Khonsari, Louisiana State University, Elastohydrodynamic numerical simulations
Punit Kumar, National Institute of Technology Kurukshetra, Elastohydrodynamic numerical simulations
Paul Michael, MSOE, CCEFP
Kees Venner, U. of Twente, Netherlands, Elastohydrodynamic numerical simulations
Arno Laesecke, NIST Boulder, Viscosity correlations
Philippe Vergne, INSA de Lyon, Elastohydrodynamic numerical simulations
Wassim Habchi, Lebanese American University, simulations
Hubert Schwarze, Technische Universität Clausthal, high-frequency viscosity measurements under pressure

Eric J. Barth
Department of Mechanical Engineering
Vanderbilt University

Professional Preparation

University of California Berkeley	Engineering Physics	B.S., 1994
Georgia Institute of Technology	Mechanical Engineering	M.S., 1996
Georgia Institute of Technology	Mechanical Engineering	Ph.D., 2000
Vanderbilt University	Mechanical Engineering	Post Doc, 2002

Appointments

2010 – present	Associate Professor of Mechanical Engineering, Vanderbilt University
2002 – 2010	Assistant Professor of Mechanical Engineering, Vanderbilt University
2000 – 2002	Research Assistant Professor of Mechanical Engineering, Vanderbilt University

Closely Related Products

1. D. B. Comber, 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. N. Gulati, E. J. Barth. "A Globally Stable, Load Independent Pressure Observer for the Servo Control of Pneumatic Actuators". *IEEE/ASME Transactions on Mechatronics*, vol. 14, issue 3, pp.295 – 306, DOI 10.1109/TMECH.2008.2009222, June 2009.
2. M. A. Adams, E. J. Barth. "Dynamic Modeling and Design of a Bulk-Loaded Liquid Monopropellant Powered Rifle". *ASME Journal of Dynamic Systems, Measurement and Control*, vol. 130, issue 6, pp.061001-1 – 061001-8, November 2008.
3. C. Yong, J. A. Riofrio and E. J. Barth. "Modeling and Control of a Free-Liquid-Piston Engine Compressor," *Bath/ASME Symposium on Fluid Power and Motion Control (FPMC 2008)*, pp. 245-257, Bath, U K, September 10-12, 2008.
4. Y. Zhu, E. J. Barth. "Passivity-based Impact and Force Control of a Pneumatic Actuator". *ASME Journal of Dynamic Systems, Measurement and Control*, vol. 130, issue 2, pp.024501-1 – 024501-7, March 2008.
5. M. Goldfarb, E. J. Barth, M. A. Gogola, J. A. Wehrmeyer. "Design and Energetic Characterization of a Liquid-Propellant-Powered Actuator for Self-Powered Robots". *IEEE/ASME Transactions on Mechatronics*, vol. 8, no. 2, pp. 254-262, June 2003.

Synergistic Activities

1. 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): 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*: Alexander Pedchenko, Vanderbilt University, Dave Comber, Ph.D. Student, Anna Winkelmann, M. S. Student., Edward Pitt, Ph.D. Student, Josh Cummins, Ph.D. Student.

Bradley F. Bohlmann
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

University of Minnesota	Mechanical Engineering	B.S., 1985
University of Michigan, Dearborn	Mechanical Engineering	M.S., 1988
University of Saint Thomas	Business	M.B.A., 2000

Academic/Professional Appointments

12/10-5/11 & 10/12-1/13	Acting Industrial Liaison Officer, National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power, University of Minnesota
2012-present	Teaching Specialist, Mechanical Engineering, University of Minnesota
2010	Adjunct Professor, Mechanical Engineering, University of Minnesota
2009-present	Sustainability Director, National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power, University of Minnesota
1997-2009	Business Development Manager, Advanced Technology, Eaton Fluid Power Group
1990-1997	Manager, Technical Services, Cummins Power Generation
1986-1989	Project Engineer, Lead Engine Engineering, Chrysler Motors

Closely Related Products

Rahul Dutta, Feng Wang, Bradley Bohlmann, Kim Stelson, "Analysis of Short-term Energy Storage for Mid-size Hydrostatic Wind Turbine", in Proceeding of the 2012 ASME Dynamic Systems and Control Conference, DSCC-2012-8815, Fort Lauderdale, FL, USA, 2012 (selected as a top 20 outstanding paper).

Synergistic Activities

REU Advisor, 2012

Advisor, ME 4054W Capstone Design Projects course, University of Minnesota

- Fall 2011-Spring 2012: Advised a team of 5 undergraduate students working on a fluid power capstone design project. The project focused on a national competition funded by Parker Hannifin called the Chainless Challenge. The competition required that the mechanical link between the pedals and the drive wheel(s) of a bike be replaced with a hydraulic transmission. Twelve universities participated in the competition and the UMN team took second place overall. One of the 5 students is a graduate student at the University of Minnesota working with Prof Perry Li. Another is at the University of California, Santa Barbara pursuing a PhD in biomedical engineering.
- Fall 2012-Spring 2013: Advised a team of 5 undergraduate students working on a fluid power capstone design project focused on improving the previous year's bike in the Chainless Challenge. The 2012-13 competition will be held in April 2013. Two of the five students have expressed an interest in studying fluid power in graduate school.

Collaborators And Other Affiliations

Kim Stelson, University of Minnesota, Feng Wang, PostDoc, University of Minnesota

Member, Technical Advisory Group, CALSTART (2005-2011)

This page is intentionally left blank

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

This page is intentionally left blank

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 ν_e Appearance (NOνA) Experiment, responsible for the design of approximately $2 million of components for neutrino detector modules (an experiment of the Fermi National Accelerator Laboratory).
3. Director of Undergraduate Studies, Mechanical Engineering Department, 2009-present.
4. Level 3 Manager for Scintillator Module Design, Main Injector Neutrino Oscillation Search (MINOS) Experiment, responsible for the design and purchase of over $1 million of components for neutrino detector modules. The MINOS Collaboration includes approximately 32 institutions internationally.
5. Member, Executive Committee, Design Engineering Division of the American Society of Mechanical Engineers, 1998-2004 (Chair, 2002-03).

Collaborators & 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) – NOνA Experiment
P. Li (Univ of Minnesota Mechanical Engineering Dept) – CCEFP Projects 1E.1, 1E.4 & TB3
E. Hsiao-Wecksler (UIUC Mechanical Engineering Dept) – CCEFP Project 2F
S. Trolier-McKinstry (PSU Dept of Materials Science & Engineering) – CCEFP Project 2F
H. Conrad & W.-J. Seong (Univ of Minnesota Dental School) – Dental Implant Study
F. Kelso (Univ of Minnesota Mechanical Engineering Department) – Textbook project

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:

1. Gopinath Venkatesan, Post-Doctoral Research Associate, 2013-14
2. Edward Sandberg, MSME, 2013
3. Henry Kohring, MSME (John Deere), 2012
4. Stephen Sedler, MSME, 2012
5. Ross Makulec, MSME, 2011
6. Tyler Kuhlmann, MSME (MTS Systems Inc.), 2010
7. Anne Fundakowski, MSME, 2010
8. David Grandall, MSME (Stefan Maier Organbuilding), 2010
9. John Robelia, MSME, 2009
10. Benjamin Nitti, MSME, 2008

Total Number of Graduate Students advised: 37 (completed)

Graduate and Postdoctoral Advisors
Ph.D. Advisor: Professor Arthur G. Erdman, University of Minnesota
M.S.M.E. Advisor: Professor Richard Budynas, Rochester Institute of Technology

Douglas L. Cook
Research Engineer, Rapid-Prototyping Research
Milwaukee School of Engineering

Professional Preparation

Milwaukee School of Engineering	Engineering	M.S.	2007
Milwaukee School of Engineering	Mechanical Engineering	B.S.M.E.	1998
Milwaukee School of Engineering	Electrical Engineering	B.S.E.E.	1998
Fachhochschule Luebeck	Elektrotechnik	Dipl.-Ing.	1998

Academic/Professional Appointments

2006 – present	Research Engineer
2005 – 2006	Principal Investigator
1998 – 2003	Graduate Research Asst.
1996 – 1998	Undergrad Research Asst.

Closely Related Products

1. **Douglas Lee Cook**. “Actuation System for a Joint.” ***US 2014/0260950 A1***, published September 18, 2014. http://www.google.com/patents/US20140260950
2. **Douglas Cook**. “Heat and Efficiency Considerations in Fluid-Powered Co-Robotics Applications,” Proceedings of the 53rd International Fluid Power Expo (IFPE) Technical Conference, Las Vegas, NV (2014).
3. **Douglas Cook**, Samuel Newbauer, Adam Leslie, Vito Gervasi and Subha Kumpaty, Ph.D., P.E. “Unit-Cell-Based Custom Thermal Management through Additive Manufacturing.” Proceedings of the 23rd Annual International Solid Freeform Fabrication (SFF) Symposium, Austin, Texas (2012). http://utwired.engr.utexas.edu/lff/symposium/proceedingsArchive/pubs/Manuscripts/2012/2012-09-Cook.pdf
4. **Douglas Cook**, Vito Gervasi. “High-Performance, Multi-Functional, Fluid-Power Components Using Engineered Materials,” Proceedings of the 52nd National Conference On Fluid Power. Las Vegas, Nevada (2011).
5. **Douglas Cook**, Samuel Newbauer, Devin Pettis, Bradley Knier and Subha Kumpaty, Ph.D., P.E. “Effective Thermal Conductivities of Unit-Lattice Structures for Multi-Functional Components” Proceedings of the 22nd Annual International Solid Freeform Fabrication (SFF) Symposium. Austin, Texas (2011). http://utwired.engr.utexas.edu/lff/symposium/proceedingsArchive/pubs/Manuscripts/2011/2011-54-Cook.pdf

Significant Products

6. 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." ***US 2012/0289870 A1***, published November 15, 2012. http://www.google.com/patents/US20120289870
7. **Douglas Cook**, Vito Gervasi, Robert Rizza Ph.D., Sheku Kamara, Xue-Cheng Liu, Ph.D., M.D. “Additive Fabrication of Custom Pedorthoses for Clubfoot Correction,” Rapid Prototyping Journal, vol. 16, issue: 3, pp. 189-193, 2010, http://dx.doi.org/10.1108/13552541011034852
8. **Douglas Lee Cook**, and Thomas E. Bray. "Flux Concentrator for Biomagnetic Particle Transfer Device." ***U.S. Patent 7,799,281***, issued September 21, 2010. http://www.google.com/patents/US7799281
9. John R. Brauer, **Douglas L. Cook**, Thomas E. Bray. “Finite-Element Computation of Magnetic Force Densities on Permeable Particles in Magnetic Separators,” IEEE Transactions on Magnetics, Vol. 43, No. 8, pp. 3483-3487, August 2007, http://ieeexplore.ieee.org

Synergistic Activities

REU advisor for the summers of 2010 through 2014, and co-advisor for the summers of 2007 and 2008. RET advisor for the summers of 2008 & 2009. Funded by NSF's Center for Compact and Efficient Fluid Power. http://www.msoe.edu/reu/

Collaborating on the design of a "sleep pod" for infant safety with UW Milwaukee.

Past voting member of ASTM's Technical Committee F42 on Additive Manufacturing, contributor on the Design subcommittee.

Led the development of foam inserts for custom orthoses for children with club feet in a collaborative project between the Medical College of Wisconsin and MSOE (U.S. Dept. of Education, Grant No. H133G060142).

Outreach presentations: Altair-Northwestern University Symposium for Design Optimization 2008, SIAM Mathematics in Industry 2009, SME-RAPID 2011.

Collaborators & Other Affiliations

Collaborators within the last 48 months (other than students listed):
Matt Anderson, Vito Gervasi, Sheku Kamara, Subha Kumpaty and James Mallmann, all from the Milwaukee School of Engineering. Elizabeth Hsiao-Wecksler (U. Illinois); William Durfee and Tom Chase (U. Minnesota); Geza Kogler (Georgia Institute of Technology); and, Eric J. Barth (Vanderbilt University). Jennifer Doering (U.W. Milwaukee) and Tim Herman (3D Molecular Designs, LLC & MSOE). Sam Newbauer (RFA Engineering); Devin Pettis (Bucyrus International, Inc./Caterpillar Inc.); and, Josh Rocholl (McNeilus Truck & Manufacturing). Bradley Knier, Adam Leslie and Gunnar Vikberg, all unknown.

M.S. Advisors:
Ph.D.: A. James Mallmann, Dept. of Physics and Chemistry, Milwaukee School of Engineering
Ph.D.: Steven E. Reyer, Retired
Thomas E. Bray, Applied Research and Grants, Milwaukee School of Engineering

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).

<u>Collaborators and other Affiliations</u>
Collaborators and Co-Editors: Dr. Krishan Ahuja (Georgia Tech), Dr. Mark Allen (Georgia Tech), Dr. Yves Berthelot (Georgia Tech), Scott Crane (General Electric), Brian Dater (Northrup-Grumman), Sergio DeRosa (University of Naples), Dr. Stephen Elliott (ISVR, Southampton, U.K.), Steve Engelstad (Lockheed Martin), Dr. Francesco Franco (Post Doc, University of Naples), Dr. Jerry Ginsberg (Georgia Tech), Dr. Ari Glezer (Georgia Tech), Dr. Marty Johnson (VPI), Dr. Greg Larson (Georgia Tech), Dr. Chris Lynch (UCLA), Keith Oglesby (Ford Motor Co.), Dr. Huang Pham (Newport News Shipyard), Eugene Powell (Lockheed Martin), Dr. Nader Sadegh (Georgia Tech), Dr. Manuel Collet (CNRS), Dr. Chan Il Park (Kangnung National University)

Graduate and Post-Doctoral Advisors: Dr. Ashok Belegundu (Penn State), Dr. Courtney Burroughs (Penn State, retired), Dr. Prof. Manfred Heckl (Post-Doctoral Sponsor, Technical University of Berlin, deceased), Dr. Gary Koopmann (Penn State, retired), Dr. Alan Pierce (University of Boston).

Thesis Advisor and Postgraduate-Scholar Sponsor: Dr. Anne Marie Albanese-Lerner (University of Wisconsin), Scott Crane (General Electric), Dr. Noelle Currey (Currey Acoustics), Brian Dater (Northrup-Grumman), Sergio DeRosa (Post-Doc, University of Naples), Muwali Dzirasa (Johns Hopkins), Jesse Ehnert (Arpeggio Acoustic Consulting), Mark Fowler (SY Technology), Dr.Francesco Franco (Post-Doc, University of Naples), Aaron Graf (General Motors), Dr. Mark Holdhusen (University of Wisconsin Marathon County), Dr. Wayne Johnson (Armstrong State University), Janeen Jones (deceased), Dr. Heungsoeb Kim (post-doc, Hangyang University, Korea), Dr. Nila Montbrun (Post-doc, Universidad Simon Bolivar), David Moon (Ford Motor Company), Keith Oglesby (Ford Motor Company), Dr. Victor Rastelli (Post-doc, Universidad Simon Bolivar), Ryan Rye (Motorala), Dr. William Steven Shepard, Jr. (University of Alabama), Dr. Michael Michaux (University of Southern California), Dr. Manuel Collet (post-doc, CNRS), Dr. Chan Il Park (post-doc, Kangnung National University), Tina Famighetti (Arpeggio Acoustics), Alex Michaud (Cerami & Associates), John Arata, Ken Marek (current PhD student), Nick Earnhart (current PhD student), Ben Beck (current PhD student), Flaviano Tateo (current PhD student), Ellen Skow (current PhD student), Elliott Gruber (Current MS student).

Summary: 11 Ph.D., 22 M.S., 7 Post-Doc

William K. Durfee
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

Harvard University, Cambridge, MA	A.B.	1976	Eng. & Applied Physics
M.I.T., Cambridge, MA	M.S.	1981	Mechanical Eng.
M.I.T., Cambridge, MA	Ph.D.	1985	Mechanical Eng.

Appointments

1976	Laboratory Supervisor, Harvard University.
1976-1978	Project Engineer, Harvard-MIT Rehabilitation Engineering Center.
1978-1985	Research Assistant, Department of Mechanical Engineering, MIT.
1985-1990	Assistant Professor, Department of Mechanical Engineering, MIT.
1986-1988	W. M. Keck Foundation Assistant Professor of Biomedical Eng., Dept. of Mech. Eng., MIT.
1990-1991	Associate Professor, Department of Mechanical Engineering, MIT.
1991-1993	Brit and Alex d'Arbeloff Associate Prof. of Engineering Design, Dept. of Mech. Eng., MIT.
1993-2001	Associate Professor and Director of Design Education, Dept. of Mechanical Eng., University of Minnesota.
2001-present	Professor and Director of Design Education, Dept. of Mechanical Eng., University of Minnesota. Additional appointments to the Graduate Faculty in the Department of Biomedical Engineering, the program in Human Factors and the program in Product Design.

Closely Related Products

1. KA Shorter, GF Kogler, E Loth, WK Durfee, ET Hsiao-Wecksler, A portable powered ankle-foot orthosis for rehabilitation, *J Rehab Res Dev*, 48(4):459-472, 2011.
2. L Tian, DB Kittelson and WK Durfee, Experimental tests and simulations of a 1.5 cc miniature glow-ignition two-stroke engine, *SAE 2010-32-0018, Proceedings of Small Engine Technology Conference*, Linz, Austria, 2010.
3. W Durfee, J Xia, E Hsiao-Wecksler, Tiny hydraulics for powered orthotics, *IEEE International Conference on Rehabilitation Robotics*, 1-6, 2011.
4. Tian L, Kittelson DB, Durfee WK, Miniature HCCI free-piston engine compressor for orthosis application, *Proceedings of the SAE Small Engine Technology Conference*, 2009-32-0176/20097176, 2009.
5. Durfee W, Rivard A, Design and simulation of a pneumatic, stored-energy, hybrid orthosis for gait restoration. *J Biomechanical Eng*, 127(6):1014-1019, 2005.

Significant Products

1. Durfee, W.K. and P.A. Iaizzo. Rehabilitation and muscle testing. In: *Encyclopedia of Medical Devices and Instrumentation, 2nd ed*. J.G. Webster, ed., Vol 6, pp 62-71, Hoboken, John Wiley & Sons, 2006.
2. Durfee WK, Weinstein SA, Bhatt E, Nagpal A, Carey JR, Design and usability of a home telerehabilitation system to train hand recovery following stroke. *Journal of Medical Devices*, 3(4):041003, 2009.
3. Goldfarb, M, K Korkowski, B Harrold, W Durfee, Preliminary evaluation of a controlled-brake orthosis for FES-aided gait. *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* 11(3):241-248, 2003.
4. Durfee WK, Savard L and Weinstein S, Technical feasibility of remote assessments for rehabilitation. *IEEE Trans. Neural Systems and Rehabilitation Engineering*, 15(1):23-29, 2007.

5. H Deng, WK. Durfee, DJ Nuckley, B Rheude, AE Severson, KM Skluzacek, KK Spindler, C Davey and JR Carey, Complex versus simple ankle movement training in stroke using telerehabilitation: a randomized controlled trial, *Physical Therapy*, 92(2):197-209, 2012.

Synergistic Activities

1. Technical Program Chair and co-founder, annual Design of Medical Devices Conference.
2. Former Education Co-Director, Center for Compact and Efficient Fluid Power (CCEFP), an NSF Engineering Research Center
3. Project co-leader for Test Bed 6, Wearable Fluid Power Devices in the 10 to 100 W Range, a project of the CCEFP and Project co-leader for 2B2; HCCI Engine-Compressor, a project of the CCEFP
4. Work on passive and active exoskeletons for rehabilitation
5. Collaborate with companies on product development, projects with 3M, Micro-Medical Devices, Toro, Aetrium, Augustine Medical, Donaldson, Spinal Designs, Honeywell, Select Comfort, Sulzer Medica, Enhanced Mobility Technologies, Medtronics, EnduraTEC, Machine Magic, Scimed, Sulzer Spine Tech, Andersen Windows, Hormel, Introspective, Geodigm, VivaCare, Comedicus, Hearing Components, Newco, Pando, IMI Visions, Tennant, Devicix, Lake Regent Medical , Best Buy, Graco, Nesos, Boston Scientific and others.

Collaborators & Other Affiliations

(i) Collaborators:
A. Erdman (UMN), P. Iaizzo (UMN), K. LaBat (UMN), E. Bye (UMN), K. Stelson (UMN), P. Li (UMN), C. Adams (UMN), B. Hammer (UMN), T. Ebner (UMN), J. Carey (UMN), D. Kittleson (UMN), E. Stern (UMN), E. Davis (Sister Kenny), T. Rosenthal (Systems Technology), J. Wachtel (Veridian Group), Lars Oddson (Sister Kenny) ("UMN" = University of Minnesota)

(ii) Graduate Advisor:
Dr. Michael J. Rosen, University of Vermont

(iii) Thesis and post-doc advisees in past 5 years:
A. Dittli, L. Tian, J. Xia, R. Dolid, S. Swaminathan, J. Prosise, T. Corrigan, S. Pasalar, D. Waletzko, C. Monnier, D. Bonta, D. Celotta, G. Brahmbhatt, S. Ponkshe, M. Steckler, S. Freeman, K. Vedula, P. Johnson, A. Srivasta, B. Koch, N. Carlson, J. Young, A Kangude, B. Burgstahler, R. Dargus, E. Leingang, K. Braun, M. Waddell, B. Krueger, B. Koch

Total number of advisees: 14 Ph.D., 72 MS, no post-docs

Randy H. Ewoldt
Department of Mechanical Science & Engineering
University of Illinois at Urbana-Champaign

Professional Preparation

Iowa State University	Mechanical Engineering	B.S., 2004
Massachusetts Institute of Technology	Mechanical Engineering	S.M., 2006
Massachusetts Institute of Technology	Mechanical Engineering	Ph.D., 2009
University of Minnesota – Twin Cities	Institute for Math. and its Apps. & Dept. Chem. Engr. and Matl. Sci.	Post-Doc, 2009-2011

Appointments

Assistant Professor, University of Illinois at Urbana-Champaign	Aug 2011 – Present
Postdoctoral Fellow, University of Minnesota – Twin Cities	Sept. 2009 – Aug. 2011

Products (selected)

[1] Ewoldt, R.H., "Extremely soft: Design with rheologically-complex fluids," *Soft Robotics*, 1(1) (2013) (**invited review for inaugural issue**)

[2] Johnston, M.T. and R.H. Ewoldt, "Precision rheometry: Surface tension effects on low-torque measurements in rotational rheometers," Journal of Rheology, 57(6), 1515-1532 (2013)

[3] Ewoldt, R.H., N.A. Bharadwaj, "Low-dimensional intrinsic material functions for nonlinear viscoelasticity", *Rheologica Acta*, 52(3) 201-219 (2013)

[4] Ewoldt, R.H., "Defining nonlinear rheological material functions for oscillatory shear," *Journal of Rheology*, 57(1) 177–195 (2013)

[5] Felts, J., S. Somnath, R.H. Ewoldt, W.P. King, "Nanometer-scale flow of molten polyethylene from a heated atomic force microscope tip," *Nanotechnology*, 23 (21) 215301 (2012)

[6] Hyun, K., M. Wilhelm, C.O. Klein, K.S. Cho, J.G. Nam, K.H. Ahn, S.L. Lee, R.H. Ewoldt, and G.H. McKinley "A review of nonlinear oscillatory shear tests: Analysis and application of Large Amplitude Oscillatory Shear (LAOS)," *Progress in Polymer Science*, 36(12), 1697-1753 (2011)

[7] Ewoldt, R.H., P. Tourkine, G.H. McKinley, and A.E. Hosoi, "Controllable adhesion using field-activated fluids," *Physics of Fluids*, 23, 073104 (2011)

[8] Celli, J.P., B.S. Turner, N.H. Afdahl, S. Keates, I. Ghiran, C. Kelly, R.H. Ewoldt, G.H. McKinley, P. So, S. Erramilli, and R. Bansil, "Helicobacter pylori moves through mucus by reducing mucin viscoelasticity," *Proceedings of the National Academy of Sciences*, 106 (34) 14321-14326 (2009)

[9] Ewoldt, R.H., A.E. Hosoi and G.H. McKinley, "New measures for characterizing nonlinear viscoelasticity in large amplitude oscillatory shear," *Journal of Rheology* 52(6), 1427-1458 (2008); **highest number of citations among all articles published in Journal of Rheology 2004-present**

[10] Ewoldt, R.H., C. Clasen, A.E. Hosoi, and G.H. McKinley, "Rheological fingerprinting of gastropod pedal mucus and synthetic complex fluids for biomimicking adhesive locomotion," *Soft Matter* 3(5), 634-643 (2007)

Synergistic Activities

[1] *Industrially-relevant short courses on rheology*: Lecturer for seven rheology short courses for practicing users of rheology (Minneapolis, San Francisco, Boston, Belgium, Montreal).

[2] *The Rheology Zoo:* Outreach and educational effort to encourage diversity and broad participation of underrepresented groups in engineering (funding from NSF-BRIGE Award #1342408 and NSF-CAREER Award #1351342). The Zoo is a hands-on curated library of rheologically interesting

materials that will serve as a platform for outreach, engagement, and undergraduate research opportunities.

[3] *School of Art+Design Collaborative teaching:* For three semesters, collaborative teaching to use rheology as a disruptive technology in industrial design studio projects, and integrate design and creativity into a graduate-level course on non-Newtonian fluids and rheology.

[4] *Software Development:* **MITlaos**, a fully-documented and free software to calculate rheological properties from data, based on Ewoldt et al. J. Rheol. 2008. Requested by over 145 corporate and academic groups across the world.

[5] *Manuscript reviewer* for 49 journal articles 2009-present

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), Kwang Soo Cho (Kyungpook National University, Korea), C. Clasen (KU-Leuven), Karin Dahmen (UIUC), C. J. Dimitriou (MIT), J. Felts (UIUC), Douglas Fudge (U. Guelph, Canada), Francisco Galindo-Rosales (University of Porto, Portugal), A. Kate Gurnon (U. Delaware), Sascha Hilgenfeldt (UIUC), Anette "Peko" Hosoi (MIT), Gavin Horn (UIUC), W. Hu (Minnesota), Kyu Hyun (Pusan National University, Korea), Iwona Jasiuk (UIUC), William King (UIUC), Seung Jong Lee (Seoul National University, Korea), Carlos Lopez-Barron (ExxonMobil), Chris Macosko (Minnesota), Luca Martinetti (U. Minnesota), Gareth McKinley (MIT), Leslie D. Morgret (Wrigley), Eric Morrison (EarthClean), Florian Nettesheim (DuPont), T.S.K. Ng (MIT), Martin Ostoja-Starzewski (UIUC), F.J. Rubio-Hernandez (University of Málaga, Spain), A. Sevilla (Universidad Carlos III de Madrid, Spain), Cliff (S.S.) Shin (UIUC), H. Craig Silvis (Dow Chemical), S. Somnath (UIUC), J. Song (Dow Chemical), Johannes Soulages (ExxonMobil), James W. Swan (MIT), P. Tourkine (Ecole Normale Superieure), Norman J. Wagner (U. Delaware), Manfred Wilhelm (Karlsruhe Institute of Technology), T. M. Winegard (U. Guelph, Canada)

2. Graduate and Postdoctoral Advisors

Post-Doctoral: Christopher Macosko (Minnesota)

Ph.D. Gareth McKinley and Anette “Peko” Hosoi (MIT);

S.M. Anette “Peko” Hosoi and Gareth McKinley (MIT)

3. Thesis Advisor and Post-Scholar Sponsor (last five years)

N. Ashwin Bharadwaj, Brendan Blackwell, Rebecca Corman, Michael Johnston (now Boeing, CA), Jeremy Koch, Arif Nelson, Jonathon Schuh, Piyush Singh (all UIUC)

Total Graduate Students Advised: 8 **Total Postdoctoral Scholars Sponsored: 0**

Vito R. Gervasi
Research and Development
Milwaukee School of Engineering

PROFESSIONAL PREPARATION

Milwaukee School of Engineering	Manufacturing Engineering Technology	B.S, 1996 Milwaukee
School of Engineering	Mechanical Engineering	M.S., 2003

APPOINTMENTS

1993-present Director, Research & Development, Rapid Prototyping Research, Milwaukee School of Engineering
1985-1990 United States Air Force, honorable discharge

Closely Related Products

1. Gervasi, Vito R., Josh Rocholl, Adam J. Schneider, Doug C. Stahl. "Casting Process." U.S. Patent 8,312,913, issued November 20, 2012. (CMP-Hybrid Casting Process, licensed).

2. Gervasi, Vito R. "Three dimensional object." U.S. Patent 6,641,897, issued Nov 4, 2003. (TetraLattice structure).

3. Douglas Cook, Bradley Knier, Vito Gervasi, Douglas Stahl, Ph.D. "Automatic Generation of Strong, Light, Multi-Functional Structures from FEA Output." Proceedings of the 21st Annual International Solid Freeform Fabrication (SFF) Symposium. Austin, Texas (2010).

4. Gervasi, Vito R. "Method of making three dimensional object." U.S. Patent 6,309,581, issued Oct 30, 2001. (Method of producing lattice structure, licensed).

5. Douglas L. Cook, Vito R. Gervasi," High-Performance, Multi-Functional, Fluid-Power Components Using Engineered Materials," International Fluid Power Expo, Las Vegas, NV, March 2011.

Significant Products

6. Gervasi, Vito R., Douglas Cook, "Reduction Of Complex Objects Into Manufacturable Elements Using The Shell-Slice Approach," Solid Freeform Fabrication Symposium Proceedings, Austin, Texas, August 2009.

7. Gervasi, Vito R., Adam Schneider, and Joshua Rocholl. 2005. "Geometry and Procedure for Benchmarking SFF and Hybrid Fabrication Process Resolution." Rapid Prototyping Journal 11(1), 4- (1st place poster for entire symposium)

8. Gervasi, Vito R., Robert S. Crockett, "Process of making three dimensional object." U.S. Patent 6,623,687, issued Sep 23, 2003 (Intertwined three dimensional lattice structure, licensed).

9. Hsiao-wecksler, Elizabeth T., Alex K. Shorter, Vito Gervasi, Douglas L. Cook, Richard Remmers, Geza F. Kogler, and William K. Durfee. "Portable Active Pneumatically Powered Ankle-Foot Orthosis." U.S. Patent 20,120,289,870 A1, published November 15, 2012.

10. Gervasi, Vito R., Douglas Cook, Robert Rizza, Sheku Kamara, Xue Cheng Liu, "Fabrication of Custom Dynamic Pedorthoses for Clubfoot Correction Via Additive-based Technologies," Solid Freeform Fabrication Symposium Proceedings, Austin, Texas, August 2009 (SFF Symposium Outstanding Paper).

SYNERGISTIC ACTIVITIES

MSOE's executive committee representative for the NSF Center for Compact and Efficient Fluid Power, started June 2006. Primarily involved in research related to thrust area II, "compactness." Former 2D Project leader. Now 2G Co-project leader (ranked #1 among Center projects) and member of the CCEFP Executive Committee. Led hosting of several CCEFP events at Milwaukee School of Engineering. Supports center projects related to additive manufacturing.

Through collaborative efforts between industry and MSOE aimed at bringing innovations to market a number of novel processes, designs and methods invented or co-invented by Gervasi (as well as many trade secrets) are commercially available in the form of many products through three companies, including: DSM-Somos (US patents 6,309,581, 6,641,897, 6,623,687), Orbital Technologies Corporation (Orbitec, US patent 8,312,913), 3DMolecular Designs (US patents 6,793,497, US6,471,520). Products include education molecular models, AM-based patterns for investment casting, reduced-mass components, FGM's, harsh environment components and DoD components.

Promotes activities and education of the Rapid Prototyping Consortium (RPC) industrial membership in areas of additive manufacturing. 1) Educated and trained industrial members and MSOE community on RP related topics at consortium meetings as well as at member locations. 2) Suggested and arranged numerous RPC guest speakers for monthly meetings. 3) Conducted applied research with consortium membership on numerous RP related projects

Contributor to the NIST Measurement Science for Metal-Based Additive Manufacturing Roadmap and participant in ASTM F42 (AM Technologies). Partook in evolving SME's Rapid Prototyping Association (RPA) to the current Rapid Technologies and Additive Manufacturing (RTAM) Community, a significant progression for the education and integration of additive technologies toward the "factory of the future." Currently contributing to the "NAMII/SME additive manufacturing body of knowledge project." Currently involved in the RTAM Masters Exam Committee.
Contributes to several sections of Wohler's Additive Manufacturing and 3D Printing State of the Industry Annual Worldwide Progress Report.

COLLABORATORS & OTHER AFFILIATIONS

Thomas Bray, Doug Cook, Shajan John, Sheku Kamara , A. James Mallmann Ph.D., Subha Kumpaty Ph.D. PE, Eric Durant Ph.D., Paul Michael, Matey Kalchev Ph.D., Robert Rizza Ph.D., Douglas Stahl, Tim Herman Ph.D.(3DMD), Josh Rocholl (Orbital Technologies Corporation), Liu Xue-Cheng Ph.D. M.D. (Medical College of Wisconsin), T. Wohler (Wohler's & Associates, Mark Abshire (DSM), Eric Barth Ph.D. (Vanderbilt University), Tom Chase Ph.D. (University of Minnesota), William Durfee Ph.D. (University of Minnesota), Elisabeth Hsiao-Wecksler Ph.D. (University of Illinois Urbana-Champaign), Geza Kogler Ph.D., C.O., L.O. (IL), L.Ped. (IL), B.C.O. (University of Illinois Urbana-Champaign), Richard Remmers (Bucyrus International, Inc./Caterpillar Inc.), Arthur Sauer (Orbital Technologies Corporation), Dan Maas (X-One), Robert Webster Ph.D.(Vanderbilt University), Kim Stelson Ph.D. (University of Minnesota)

GRADUATE ADVISORS

G. Hoffmann (Retired), Matthew Panhans Ph.D. (Milwaukee School of Engineering), William Howard Ph.D. (East Carolina University)

THESIS ADVISOR

Graduate Students: Richard Remmers (Bucyrus International, Inc. /Caterpillar Inc.)

Elizabeth T. Hsiao-Wecksler
Dept of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

PROFESSIONAL PREPARATION

Cornell University	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 Professor, Dept of Mechanical Science and Engineering, 08/09 – present
Associate Professor, Information Trust Institute, 08/09 – present
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; 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 47 journals and 12 ext conf proceedings)*work supported by NSF

Select Related Products:

1. *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).
2. *Shorter, K.A., Hsiao-Wecksler, E.T., Kogler, G.F., Loth, E., and Durfee, W.K., "A Portable-Powered-Ankle-Foot-Orthosis for rehabilitation." J Rehab Res Dev, 48(4): 459-472, 2011. http://www.rehab.research.va.gov/jour/11/484/pdf/shorter484.pdf
3. *Chin, R., Hsiao-Wecksler, E.T. and Loth, E. "Fluid-Power Harvesting by Under-Foot Bellows During Human Gait" Journal of Fluids Engineering, 134(8): 081101, 2012. (Number 1 Most Downloaded Article in JFE for August 2012) http://dx.doi.org/10.1115/1.4005725
4. *Boes, M.K., Hsiao-Wecksler, E.T., and Motl, R.M. "Evaluation of a Portable Powered Ankle-Foot Orthosis on Gait Function in Persons with Multiple Sclerosis", 2014 Consortium of Multiple Sclerosis Centers ACTRIMS Meeting, Dallas, TX, May 28-31, 2014.
5. 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.

Select Significant Products:

1. *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.
2. Hsu, M-K. I., Moon, Y., Jayaraman, C., Rice, I.M., Sosnoff, J., and Hsiao-Wecksler, E.T., "Variability Of Upper Extremity Kinematics And Shoulder Pain During Wheelchair Propulsion: A Vector Coding Analysis", 37th Annual Meeting of the American Society of Biomechanics, Omaha, NE, September 4-7, 2013. (Nominated for Clinical Biomechanics Award.)
3. *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
4. *Hsiao-Wecksler, E.T., Polk, J.D., Rosengren, K.S., Sosnoff, J.J., and Hong, S. "A Review of New Analytic Techniques for Quantifying Symmetry in Locomotion". *Symmetry*, 2(2), 1135-1155, May 2010

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

- *REU sponsorship:* Since 2002, I have actively included over 80 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 and involved in specialized REU training programs. Their contributions have been acknowledged through authorship on conference papers, journal articles, and patents.
- *Development of research tools:* Developed techniques for (a) quantitatively assessing patterns of motion in dynamic systems with specific interest in analyzing asymmetric gait behaviors (NSF #0727083), and (b) assessing postural responses to impulse perturbations.
- *Engineering education:* UIUC College of Engineering Strategic Instruction Initiatives Program (SIIP) grant to revise Machine Design I & II Course (ME 370 / 371): flip lectures to create project-based courses, develop hands-on projects, created new Innovation Studio which is student project space with 3D printers, laser cutters, and machine tools, 2013-2015, co-PI. *Course development:* Whole-body Musculoskeletal Biomechanics. Elective senior/first-year grad student lecture course for engineering and advanced kinesiology students. Taught every fall semester since 2003. 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 & science team of 4th-8th grade students 2011-2014 (advanced to State tournament twice). Faculty advisor for national Chainless Challenge fluid powered bicycle design competition 2011-2015 (1st place in 2013). Continually contribute hands-on activities to learn about movement biomechanics at my laboratory with UIUC College of Engineering Girls' Adventures in Mathematics, Engineering, and Science (GAMES) summer camp for 9th-12th grade girls, and 4H Extension for Advanced Science Siesta weekends for 7th -10th 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 organization at UIUC).

COLLABORATORS & OTHER AFFILIATIONS (at UIUC unless otherwise noted)

Collaborators and Co-Editors: (Total Collaborators43, Total Co-Editors: 0) CL Beck, A Becker (UT Houston), MK Boes, T Bretl, R Chin (Unknown), H Dankowicz, S Downing, WK Durfee (UMN), I Ensari, P Ferreira, JT Gilmer (Enfield Tech), S Hong, GP Horn, MK Hsu (unemployed), P Hur (Texas A&M), A Hutchinson, M Islam, C Jayaraman, RE Klaren, LM Klump (unknown), GF Kogler (Georgia Tech), G Krishnan, Y Li (Western Digital), E Loth (UVA), CD MacKinnon (UMN), P Mehta, Y Moon, EA Morris (Caterpillar), RM Motl, K Park (Trine U), MN Petrucci, JD Polk, JH Pula, IM Rice, KS Rosengren (Wisconsin), KA Shorter (UMichigan), B Slavens (U Wisc-Milwaukee), DL Smith (Skidmore College), MJ Socie (Rehab Inst of Chicago), JJ Sosnoff, S Tawfick, JA Thomas (Unknown), A Tilton, J Xia (Seagate Technology)

Graduate Advisors and Postdoctoral Sponsors: (Total Graduate Advisor: 1, Total Postdoctoral Sponsor: 3)
Stephen N. Robinovitch, Simon Frasier (Grad)
Lewis A. Lipsitz, Harvard Medical School
James J. Collins, Boston University
D. Casey Kerrigan, University of Virginia

*Thesis Advisor and Postgraduate-Scholar Sponsor (*at UIUC unless noted)*:* Grad students advised: 33 (total; 7 PhD, 4 MS/PhD, 22 MS), Postdoc sponsored: 1 (none in past 5 years). Z An (FoxConn), MJ Angelini, MK Boes, AJ Bosilijevac (Proctor & Gamble), R Chin (Unknown), SC Daigle (IntelliWheels), LA DiBerardino (Ohio Northern U), RJ Doyle (Unknown), BA Duiser (Rolls-Royce), D Farooq, AJ Gaglio, MK Hsu (unemployed), P Hur (Texas A&M), M Islam, J Jang, RM Kesler, Y Li (Western Digital), J Liang, EA Morris (Caterpillar), MJ Major (Northwestern U), KM McHugh (Unknown), K Park (Trine U), MN Petrucci, K Rajendran (Unknown), C Imbs Ragetly (Paris, France private practice), A Ramachandran (Boeing), R Riemer (Ben Gurion U), KA Shorter (UMichigan), MJ Socie (Rehab Inst of Chicago), JA Thomas (Unknown), D Wajda, Z Wang, MJ Wineman (Watlow)

Paul Imbertson
University of Minnesota
Department of Electrical and Computer Engineering
200 Union Street S.E.,
Keller Hall 4-146
Minneapolis, MN 55455
Phone: (612) 625-6529 Fax: (612) 625-4583
Email: imbertson@umn.edu

Professional Preparation
PhD, 1997, University of Minnesota, Electrical Engineering,
MS, 1994, University of Minnesota, Electrical Engineering,
BS, 1983, University of Minnesota, Electrical Engineering,

Positions

Teaching Professor (current title), Electrical and Computer Engineering, University of Minnesota,	1997-Present
Education Director, Center for Compact and Efficient Fluid Power (CCEFP)	2011-Present
Consultant in Power Electronics and Motor Drives	1988-1997
Electrical Engineer, Power Conversion, Sperry Univac-Unisys Corp.	1983-1988

Professional Activities
Institute of Electrical & Electronic Engineers
American Society for Engineering Education
Faculty Advisor, National Society of Black Engineers (NSBE), Student Branch
Faculty Advisor, Innovative Engineers (IE), University of Minnesota
Faculty Advisor, Solar Vehicle Project
Faculty Advisor, Kappa Eta Kappa, Electrical Engineering Fraternity
Faculty Advisor, Mad Scientists Club

Awards
Award for Global Engagement; University of Minnesota, 2013
Senator Amy Klobuchar's Carbon Buster Award, December 2008
Ten times awarded "Best Professor Award" from IT/CSE Student Board
Most Inspirational Professor Award, Eta Kappa Nu, 2004
Recognized by the University of Minnesota Board of Regents for contributions to Community-University Partnerships. Noted for activity with communities throughout Minnesota on issues related to sources of renewable energy and hydroelectric power, June 2002

Patents
U.S. Patent #5,245,520: Asymmetrical Duty Cycle Power Converter

Activities
Developing novel active-learning classroom models and methods in engineering curriculum in collaboration with researchers at the University of Minnesota STEM Education Center.

EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Targeted Mathematics-Science Partnership, NSF-MSP.
Co-PI and Content Director working in the area of K-12 STEM education.

Initiated “Bridges Project” who’s mission is to build local empowerment here and abroad through collaborations with the Universidad Nacional de Ingenieria (UNI) in Managua, Nicaragua, Universidad La Salle (ULSA) in Leon, Nicaragua, Villanova University, and communities in Nicaragua.

Prime contributor and initiator of signed Memorandum of Agreement between the Electrical and Computer Engineering Department at the University of Minnesota and the National Engineering University of Nicaragua.

Consultant to the nonprofit Bright New Ideas and the for-profit ValuLamp. Both entities founded by UMN engineering graduate, Patrick Delany, which has developed, produced, and distributed several thousand solar lanterns for citizens of developing nations. Worked with Patrick from the inception of the project.

Member of working group to develop a graduate engineering program in Tanzania.

Dusome Foundation: Board Member. The Dusome Foundation is working to build libraries in Tanzania.

Developing collaborative outreach/development program uniting a tribal school, an inner-city minority school, and a technical school in Nicaragua to advance STEM education, and personal empowerment using renewable energy projects as a foundation.

Developed the BRIDGE program (Building Resources and Innovative Designs for Global Energy) with the National Society of Black Engineers (NSBE), an international outreach program with activities in Minnesota, Nicaragua, and Tanzania featured in articles in “Inventing Tomorrow” the magazine of the Institute of Technology, University of Minnesota.

Founding advisor to Applied Environmental Solutions (AES) student group.

Founding advisor to Innovative Engineers student group.

Founded an international branch of the Innovative Engineers at Universidad Ibero Americano in Mexico City, Mexico.

Education and curriculum development:

1. Developed new undergraduate course “Alternative Energy in Scandinavia”, three week May-term study abroad course to Iceland Norway and Denmark. Course has been executed six times 2004 to 2013 with plans to continue with yearly offerings. Informal survey of 145 past participants suggests that 75% of those who took the course are currently working in the energy field.
2. Curriculum Integration -- Study Abroad Participant, visiting Scotland and England to further study-abroad opportunities.
3. Developed new undergraduate course “Energy, Environment, and Society”.
4. Developed new senior/graduate level course in electrical and computer engineering “Energy Conversion and Storage Technologies: Theory and Applications”.

Regional Sustainable Development Partnership UMN (RSDP): Active engagement with Minnesota communities to develop and plan for local energy needs and to heighten energy awareness. This involved numerous speaking engagements, panel discussions, and one-on-one discourse at community meetings throughout Minnesota, and over 4000 travel miles.

Regional Sustainable Development Project - Distributed Energy Project: A site study to determine the financial feasibility of reactivating the hydro-electric power facility located on the Fish Hook Dam, Park Rapids, MN.

Presentation – “Power to the People: Building Citizen Leadership for a Sustainable Energy Future” Joint International Summit on Community and Rural Development, July 2001.

Technical Consultant, “Designing a Clean Energy Future: A Resource Manual” for the Clean Energy Resource Teams (CERTS).

Presenter at numerous NSF-sponsored faculty workshops on Teaching Electric Power Curriculum including Power Electronics and Electric Drives, 2003 to present.

Presentation – “Sharing the Load: Local Electric Energy Generation and Distribution” A Citizens’ Action Congress, March 2001.

Invited Speaker, IEEE-USA Annual Meeting in STEM track, 2010.

Reach for the Sky: STEM outreach program for the White Earth Indian Reservation.

University on the Prairie, Southwest Research and Outreach Center (SWROC), a unit of the University of Minnesota, Lamberton, MN; 2007 to present.

Technical consultant to University of Minnesota-DOE Solar Decathlon, 2009 competition.

Arranged outreach program at North High School, an inner city, minority high school in Minneapolis, MN, involving university members of the National Society of Black Engineers (NSBE).

Technical consultant to Bakken Museum’s Green Energy Art Garden; 2013, 2012, Renewable Energy Sculpture Garden; 2010, and “Electrifying Minnesota” exhibit; 2007.

Panelist, ASEE Annual Meetings; 2010, 2013.

Planning committee, Minnesota Power Systems Conference, MIPSYCON 2009, 2010.

Tutorial: “Motors 101”, MIPSYCON 2009.

Eagle Bluff Environmental Learning Center (ELC).
Concept and specifications for Zero-Energy-House demonstration/experimental project.

Prairie Woods Environmental Learning Center (ELC)
Concept, specifications, and construction of solar powered yurt classroom.

Publications

1. J. Ling, P. Imbertson, T. Moore, “Introducing an Instructional Model in Undergraduate Electric Power Energy Systems Curriculum-Part (II): Authoritative vs. Dialogic Discourse in Problem-Centered Learning,” ASEE 2014 Annual Conference (accepted).

2. J. Ling, P. Imbertson, T. Moore, “Introducing an Instructional Model in Undergraduate Electric Power Energy Systems Curriculum-Part (I): Authoritative vs. Dialogic Discourse in Problem-Centered Learning,” ASEE 2013 Annual Conference.

3. Jia-Ling Lin, Paul Imbertson, and Tamara Moore, “Applying design-based research to investigate instructional strategies for problem-centered learning in undergraduate electric energy systems curriculum,” TRUES Conference, June 3, 2012.

4. P. Imbertson, A. Sonnenburg, and M. Masoud “Connecting the Dots Between Engineering, Developing Nations, and Inner-City Youth with Sustainable Energy”, 2010 ASEE Annual Conference.

5. P. Imbertson, M. Masoud, and A.Sonnenberg, “Energy: Bridging Developing Nations and Inner-City Youth,” Minnesota Power Systems Conference (MIPSYCON), 2009.

6. T. Das, P. Imbertson, and N. Mohan, “Collaborative Learning in Laboratory Oriented Courses Using Web Conferencing for Shared Control of Physical Laboratory Experiments,” ASEE Annual Conference, 2007.

7. N. Mohan, W. Robbins, P. Imbertson, R. Ayyanar, and B. Oni, "Successes with NSF CCLI-EMD and CLI-ND Grants", Proc. of the 2004 ASEE Annual Conference and Exposition, Salt Lake City, Utah, June, 2004.

8. Ned Mohan, William P. Robbins, Paul Imbertson, Tore M. Undeland, Razvan C. Panaitescu, Amit Kumar Jain, Philip Jose, and Todd Begalke, "Restructuring of First Courses in Power Electronics and Electric Drives That Integrates Digital Control", IEEE Trans. on Power Electronics, Vol. 18, No. 1, pp. 429-437, Jan. 2003.

9. P. Imbertson, “Local/Community Aspects of Generation,” Minnesota Power Systems Conference (MIPSYCON), 2002.

10. Rohit Tirumala, Paul Imbertson, Ned Mohan, Chris Henze and Russ Bonn, “An Efficient, Low Cost DC-AC Inverter for Photovoltaic Systems with Increased Reliability,” IECON 2002.

11. N. Mohan, M. Riaz, P. Imbertson, and T. Brekken, “A Strategy for the Revival of Electric Machines and Drives Courses,” IEEE PELS web resources, 2001.

12. P. Imbertson, and N. Mohan, “New Directions in DC-DC Power Conversion Based on Idealized Concepts Leading Ultimately to the Asymmetrical Duty-Cycle Power Converter,” IEEE Transactions on Circuits and Systems, Aug 1997.

13. P. Imbertson and N. Mohan, “A Novel Asymmetrical Duty-Cycle Soft-Switching DC-DC Converter with Lower Conduction Losses Than in Hard-Switched PWM Converters,” PEDES 1996.

14. N. Mohan, P. Imbertson, and G. Kamath, “Panel Discussion on Future Trends in Power Electronics: Power Converters,” International Power Electronics Conference (IPEC), 1995.

15. P. Imbertson and N. Mohan, “Asymmetrical Duty Cycle Permits Zero Loss Switching in PWM Circuits With No Conduction Loss Penalty,” IEEE Transactions on Industry Applications (IEEE/IAS), Jan/Feb 1993.

16. P. Imbertson and N. Mohan, “New PWM Circuits Combining Zero Switching Loss with Low Conduction Loss,” International Telecommunications Energy Conference (INTELEC), 1990.

17. P. Imbertson and N. Mohan, “Square-wave Resonant Power Converter,” International Power Electronics Conference (IPEC), Tokyo, Japan, 1990.

18. P. Imbertson and N. Mohan, “A Method for Estimating Switch-Mode Power Supply Size,” Applied Power Electronics Conference (APEC), 1989.

Dr.h.c. Monika Ivantysynova, Ph.D
MAHA Professor Fluid Power Systems
School of Mechanical Engineering & Agricultural and Biological Engineering
Purdue University

Professional Preparation

Slovak Technical University of Bratislava, CZ	Mechanical Engineering	M.S.E.	1979
Slovak Technical University of Bratislava, CZ	Mechanical Engineering	Ph.D.	1983

Appointments

August 2004 – present	Maha Professor Fluid Power Systems, Director Maha Fluid Power Research Center, School of Mechanical Engineering and Agricultural and Biological Engineering, Purdue University
1999 – 2004	Professor Mechatronic Systems, Institute for Aircraft Systems Engineering, Technical University of Hamburg-Harburg, Germany
1996 – 99	Professor Fluid Power and Control, Department of Mechanical Engineering, Duisburg University, Germany
1992 -1996	Senior Researcher and Managing Director of the Institute for Aircraft Systems Engineering at Technical University of Hamburg-Harburg, Germany
1990 -1992	Senior Researcher and Project Manager at the Institute for Machine Design at Technical University of Hamburg-Harburg, Germany
1989 -1990	Project Manager for Mobile Hydraulics, Commercial Hydraulics, Hamburg, Germany
1988– 1990	Assistant Professor, Institute of Robotics, Technical University Bratislava, Czechoslovakia,
1984 – 1988	R & D Project Engineer for design and development of pumps, motors and hydraulic drive systems at ZTS VUHYM in Dubnica, Czechoslovakia
1983 - 1984	Product Development Engineer, Head of Department of Automation Systems at VEB Elektronik Gera, Germany

Closely Related Products

1. Pelosi, M. and Ivantysynova, M. 2012. A Geometric Multigrid Solver for the Piston-Cylinder Interface of Axial Piston Machines. Tribology Transactions, Vol. 55, Issue. 2, pp. 163 - 174.
2. Pelosi, M. and Ivantysynova, M. 2012. Heat Transfer and Thermal Elastic Deformation Analysis on the Piston/Cylinder Interface of Axial Piston Machines"; ASME Journal of Tribology. Vol. 134, October 2012, pp. 1- 15.
3. Zecchi, M. and Ivantysynova, M. 2012. A novel approach to predict the cylinder block / valve plate interface performance in swash plate type axial piston machines. ASME/Bath Symposium on Fluid Power and Motion Control (FPMC 2012), Bath, UK, pp. 13-28.
4. Pelosi, M. and Ivantysynova, M. 2011. Surface Deformation Enables High Pressure Operation of Axial Piston Pumps. ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VI, USA. **Best paper award**
5. Schenk, A. and Ivantysynova, M. 2011. An Investigation of the Impact of Elastohydrodynamic Deformation on Power Loss in the Slipper Swashplate Interface. 8th JFPS International Symposium on Fluid Power, Okinawa, Japan.- **Best paper award.**

Significant Products

1. Sprengel, M. and Ivantysynova, M. 2012. Coupling Displacement Controlled Actuation with Power Split Transmissions in Hydraulic Hybrid Systems for Off-Highway Vehicles. ASME/Bath Symposium on Fluid Power and Motion Control (FPMC 2012), Bath, UK, pp. 505-517.
2. Hippalgaonkar, R., Zimmerman, J. and Ivantysynova, M. 2011. Investigation Of Power Management Strategies For A Multi-Actuator Hydraulic Hybrid Machine System. SAE 2011 Commercial Vehicle Engineering Congress, , Sep 13-14 2011, Rosemont, IL, USA. SAE Technical Paper 2011-01-2273

3. Hughes, E.C., Williamson, C.A., Zimmerman, J.D. Ivantysynova, M.M. 2012. Displacement – controlled hydraulic system for multi-function machines. US Patent No: US 8,191,290 B2 issue June 5, 2012.
4. Ivantysynova, M. and Baker, J. 2009. Power Loss in the Lubricating Gap Between Cylinder Block and Valve Plate of Swash Plate Type Axial Piston Machines. International Journal of Fluid Power, Vol. 10, No. 2, pp. 29 - 43.
5. Ivantysyn, J. and Ivantysynova, M. 2000. Hydrostatic Pumps and Motors, Principles, Designs, Performance, Modelling, Analysis, Control and Testing. New Delhi. Academia Books International., 512 pages, ISBN 81-85522-16-2.

Synergistic Activities

- Co-founder and member of scientific board of Fluid Power Net International http://fluid.power.net 1999 – present
- Member of European Fluid Power Research Centre FPCE, http://www.fpce.net 2002 - 2005
- Executive Committee Member, Thrust and Test Bed Leader, Engineering Research Center for Compact and Efficient Fluid Power (CCEFP), 2006 – present
- Founder and Editor-in-Chief of the International Journal of Fluid Power since 2000
- Developed and taught two new graduate courses in the field of Fluid Power 2005 – present

Collaborators and Other Affiliations

(a) Collaborators in last four years:
All PI's of the CCEFP (Kim Stelson, Perry Li and Will Durfee, University of Minnesota, Wayne Book and Richard Salan, Gerogia Tech, Mike Goldfarb and Eric Barth, University of Vanderbuilt, Andrew Alleyne and Eric Loth, University of Illinois, John Lumkes Steve Frankel and Ashlie Martini, Purdue University)), Wayne John Book (Georgia Institute of Technology), Richard Burton (University of Saskatchewan), Peter John Chapple (NTNU Norwegian University of Science and Technology), Richard Kimbel (Parker Hannifin), Joe Kovach (Parker-Hannifin), Noah Manring (University of Missouri), Jean-Charles Mare (INSA Toulouse), Massimo Milani (University of Modena), Takao Nishiumi (National Defense Academy, Japan), Petr Noskievic (Technical University of Ostrava), Roberto Paoluzzi (IMAMOTER - C.N.R), Robert Rahmfeld (Sauer-Danfoss), Jari Rinkinen (Tampere University of Technology), Rudolf Scheidl (University of Linz), Scott Schuh (Bobcat), J. Weber (TU Dresden), Andrzej Sobzyk (Krakow University), Matti Vilenius (Tampere University of Technology), Howard Zhang (Parker-Hannifin).

(b) Thesis and Dissertation Advisor for Prof. Ivantysynova:
Prof. Paciga (TU Bratislava)

(c) Thesis or Dissertation Advisor in last five years:
Jonathan Baker, Shekhar Degaonkar, Reece Garret, Andrew Fredrickson, Najoua Jouini, Richard Klop, Kyle Williams, Christopher Wiliamson, Matteo Pelosi, Ganesh Seeniraj, Josh Zimmermann, Rajneesh Kumar, Shinok Lee, Rohit Kumar, Matteo Pelosi, Micheal Cross, Brent Warr, Jess Rose, Matt Kronlage, Domgjune Albert Kim

Total number of graduate students supervised: 87 Postdoctoral scholars: 6 Undergraduate Research Students: 25

Steven X. Jiang
Department of Industrial and Systems Engineering
North Carolina A&T State University

Professional Preparation

East China Institute of Technology	Mechanical Engineering	BS, 1992
Nanjing University of Science & Technology	Manufacturing Engineering	MS, 1998
Clemson University	Industrial Engineering	Ph.D. 2001

Appointments
Associate professor, Department of Industrial and Systems Engineering, North Carolina A&T State University, 2008-Present
Assistant Professor, Department of Industrial and Systems Engineering, North Carolina A&T State University, 2002-2008

Closely Related Products
Publications Most Closely Related to Proposal:
Hughes, K., Jiang, X. (2010), "Using Discrete Event Simulation to Model Excavator Operator Performance", International Journal of Human Factors and Ergonomics in Manufacturing and Service Industries, 20(5), 408-423.

Chung, C.,Jiang, X., Jiang, Z., Udoka, S. (2010), "Using Digital Human Modeling to Predict Operator Performance of a Compact Rescue Crawler", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Lee, A., Jiang, S. (2010), "Assessing Operator Workload for a Fluid Powered Rescue crawler", The journal of Management and Engineering Integration, 3(2), 48-53.

Hughes, K., Jiang, S., Jiang, Z., Park, E., and Mountjoy, D. (2011), "Assessment of Excavator Operator Performance Using an Integrated Human Performance Model", The journal of Management and Engineering Integration, 4(1), 88-98.

Franklin, C., Jiang, Z., Jiang, X. (2011), "Learning Curve Analysis of a Haptic Controller", The journal of Management and Engineering Integration, 4(1), 63-70.

Synergistic Activities
Hughes, K., Jiang, X., Jiang, Z., Mountjoy, D., Park, E. (2010), "A Preliminary Study of an Integrated Human Performance Model", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Delpish, R., Jiang, X., Park, E. , Udoka, S., Jiang, Z., (2010), "Development of a User-Centered Framework for Rescue Robot Interface Design", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Jenkins, Q., Jiang, X. (2010), "Measuring Trust and Application of Eye Tracking in Human Robotic Interaction", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Liu, Y., Jiang, X., Jiang, Z., Park, E. (2010), "Predicting Backhoe Excavator Operator Performance Using Digital Human Modeling", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Osafo-Yeboah, B., Elton, M., Jiang, X., Book, W., Park, E. (2010), "Usability Evaluation of a Coordinated Excavator Controller with Haptic Feedback", Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9,2010.

Synergistic Activities

- Co-chair of Human Factors and Ergonomics Track, 2007 Industrial Engineering Research Conference (IERC)
- Co-chair of Human Factors and Ergonomics Track, 2008 Industrial Engineering Research Conference (IERC)
- Editorial Board, International Journal of Industrial Ergonomics
- Editorial Board, Journal of Management and Engineering Integration

Collaborators And Other Affiliations

Collaborators Over The Last 48 Months:
Drs. Zongliang Jiang, Eui Park, Udoka Silvanus, NCA&T, CCEFP
Dr. Wayne Book, Georgia Institute of Technology, CCEFP
Drs. Lauren Davis and Salil Desai, NCA&T
Dr. Kevin Taaffe, Clemson University

Graduate and Postdoctoral Advisors:
Dr. Anand Granmopadhye, Clemson University

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
Khaliah Hughes (SAS), Gerald Watson (US Navy), Edem Tetteh (Paine College), Paul Nuschke (Electronic Ink), Porsche Williamson (GE), Ritson Delpish (NCA&T), Yang Liu (NC A&T), Benjamin Osafo-Yeboah (NCA&T), Quaneisha Jenkins (NCA&T), Charlie Chung (Virginia Tech), Antonio Lee (NCA&T)

Total Number of Graduate Students advised: 20

Zongliang Jiang
Department of Industrial and Systems Engineering
North Carolina Agricultural and Technical State University

Professional Preparation

Shanghai Jiao Tong University (China)	Engineering Mechanics	B.S, 1999
North Carolina State University	Computer Science	M.S., 2003
North Carolina State University	Industrial Engineering	Ph.D., 2008

Appointments

2008-present	Assistant Professor, Department of Industrial and Systems Engineering, North Carolina Agricultural and Technical State University (NCAT)
2007-2008	Postdoctoral Associate, Department of Industrial and Manufacturing Systems Engineering, Iowa State University
2003-2007	Research Assistant, Teaching Assistant, Department of Industrial and Systems Engineering, The Ergonomics Laboratory, North Carolina State University

Closely Related Products

1. Franklin, C., Z. Jiang, and S. Jiang, "Learning Curve Analysis of a Haptic Controller", *Journal of Management and Engineering Integration*, 4(1): 63-70, 2011.

2. Hughes, K., S. Jiang, Z. Jiang, E. Park, and D. Mountjoy, "Assessment of Excavator Operator Performance Using an Integrated Human Performance Model", *Journal of Management and Engineering Integration*, 4(1): 88-98, 2011.

3. Liu,Y., Z. Jiang., and X. Jiang, "Development of Digital Human Model to Evaluate Excavator Operator Performance", *Journal of Management and Engineering Integration*, 2(2): 67-74, 2009.

4. Shu, Y., Z. Jiang, X. Xu, and G. A. Mirka, "The Effect of a Knee Support on the Biomechanical Response of the Low Back", *Journal of Applied Biomechanics*, 23(4), pp. 275-281, 2007.

5. Jiang, Z., Y. Shu, J. Drum, S. Reid, and G. A. Mirka, "Effects of Age on Muscle Activity and Upper Body Kinematics during a Repetitive Forearm Supination Task", *International Journal of Industrial Ergonomics*, 36(11), pp. 951-957, 2006.

Synergistic Activities

Reviewer for International Journal of Industrial Ergonomics (2007 – Present)

Reviewer for Human Factors (2010 – Present)

Collaborators & Other Affiliations

Collaborators and Co-Editors: E. Codjoe (NCAT), C. Franklin (Nuclear Regulatory Commission), E. Hsiao-Wecksler (UIUC), K. Hughes (SAS), X. Jiang (NCAT), A. Lee (NCAT), Y. Liu (NCAT), G. A. Mirka (Iowa State Univ.), C. Ntuen (NCAT), E. Park (NCAT), B. Ram (NCAT), S. Udoka (NCAT)

Graduate and Post Doctoral Advisors: S-C Fang (NCSU), G. A. Mirka (Iowa State Univ.), C. D. Savage (NCSU).

Thesis Advisor or Postgraduate-Scholar Sponsor: M.S. Students: C. Franklin; Ph.D. Students: Y. Liu, R. Pope-Ford.

This page is intentionally left blank

William P. King
Department of Mechanical Science and Engineering
University of Illinois Urbana-Champaign

Professional Preparation

University of Dayton	Mechanical Engineering	B.S. 1996
Stanford University	Mechanical Engineering	Ph.D. 2002

Appointments

Professor, Mechanical Science and Engineering	University of Illinois	2010-present
Associate Professor, Mechanical Science and Engineering	University of Illinois	2006-2010
Assistant Professor, Mechanical Engineering	Georgia Institute of Technology	2002-2006

Closely Related Products

1. Wei, Z., D. Wang, S. Kim, S.-Y. Kim, Y. Hu, M.K. Yakes, A.R. Laracuente, Z. Dai, S.R. Marder, C. Berger, W.P. King, W.A. deHeer, P.E. Sheehan, and E. Riedo, "Nanoscale Tunable Reduction of Graphene Oxide for Graphene Electronics," *Science* 328, 1373-1376, 2010.

2. Lee, W. K., Z. Dai, W. P. King, and P. E. Sheehan, "Maskless Nanoscale Writing of Nanoparticle-Polymer Composites and Nanoparticle Assemblies using Thermal Nanoprobes," *Nano Letters* 10, 129-133, 2010

3. Cannon, A. H., and W. P. King, "Microstructured Metal Molding Tools Fabricated via Investment Casting," *Journal of Micromechanics and Microengineering* 20, 025025, 2010.

4. Lee, J., A. Liao, E. Pop, and W. P. King, “Electrical and Thermal Coupling to a Single-wall Carbon Nanotube Device using an Electro-thermal Nanoprobe,” *Nano Letters*, 0:4, 1356-1361, 2009.

5. Park, K., Z. M. Zhang, and W. P. King, “Experimental Investigation on the Heat Transfer Between a Heated Microcantilever and a Substrate,” *Journal of Heat Transfer,* 130, 102401-1-102401-9, October 2008.

Significant Products

1. Rowland, H. D., W. P. King, J. B. Pethica, and G. L. W. Cross, “Molecular Confinement Accelerates Deformation of Entangled Polymers During Squeeze Flow,” *Science*, 322, 720-724, October 2008.

2. Szoszkiewicz, R., T. Okada, S. C. Jones, T.-D. Li, W. P. King, S. R. Marder, and E. Riedo, “High-Speed, Sub-15 nm Feature Size Thermochemical Nanolithography,” *Nano Letters,* 7, 1064-1069, 2007.

3. Lee, J., T. L. Wright, T. Beecham, B. A. Nelson, S. Graham, W. P. King, “Electrical, Thermal, and Mechanical Characterization of Silicon Microcantilever Heaters,” *Journal of Microelectromechanical Systems*, 15, 1644-1655, 2006.

4. King, W. P., S. Saxena, B. A. Nelson, and B. Weeks, “Nanoscale Thermal Analysis of an Energetic Material,” *Nano Letters,* 6, 2145-2149, 2006.

5. King, W. P., T. W. Kenny, K. E. Goodson, G. L. W. Cross, M. Despont, U. Dürig, H. Rothuizen, G. Binnig, and P. Vettiger, “Atomic Force Microscope Cantilevers for Combined Thermomechanical Data Writing and Reading,” *Applied Physics Letters*, 78, 1300-1302, 2001.

Synergistic Activities

- Co-founder of Hoowaki LLC (www.hoowaki.com), a company based on technology from King's laboratory.

- Founding scientific advisor to Anasys Instruments Inc (www.anasysinstruments.com), a company based on technology from King's laboratory.

- Member, DARPA's Defense Sciences Research Council.

Collaborators And Other Affiliations

Collaborators Over The Last 48 Months:
Paul Sheehan (Naval Research Laboratory); Samuel Graham, Yogendra Joshi, Elisa Riedo (Georgia Institute of Technology); Blake Simmons (Sandia National Labs); Paul Braun, David Cahill, Joe Lyding, Eric Pop, Mark Shannon (University of Illinois Urbana-Champaign); Rob Carpick (U Penn); Jim Deyoreo (LBL Molecular Foundary); Brandon Weeks (Texas Tech).

Graduate and Postdoctoral Advisors:
Kenneth Goodson, Stanford University

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
Current: Bikram Bhatia, Andrew Cannon, Elise Corbin, Zhenting Dai, Jonathan Felts, Patrick Fletcher, Matthew Kasper, Andrew Gardner, Kyle Grosse, Patrick Harrell, Hoe-Joon Kim, Beomjin Kwon, Nicholas Maniscalco, Ryan Maclaren, James Pikul, Natasha Privorotskya, Suhas Somnath. Former: Joseph Charest, Siva Gurrum, Shinyong Eom, Marcus Elisason, Tanya Wright Haberman, Kyoung Joon Kim, Jungchul Lee, Brent Nelson, Keunhan Park, Jessica Remmert, Jun Suk Rho, Harry Rowland, Shubham Saxena, Yan Wu, Fuzheng Yang.

David B. Kittelson
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

University of Minnesota	Mechanical Engineering	B.S.	1964
University of Minnesota	Mechanical Engineering	M.S.	1966
University of Cambridge, England	Chemical Engineering	Ph.D	1972

Appointments

2009 Spring	Bye Fellow, Churchill College, Cambridge University
2003-2004	Overseas Fellow, Engineering Department, Cambridge University
2003-present	Frank B. Rowley Professorship in Mechanical Engineering
1996-present	Director, Center for Diesel Research.
1987-2005	Director, Power and Propulsion Division
1985-1986	Overseas Fellow, Engineering Department, Cambridge University
1980-present	Professor, Department of Mechanical Engineering
1976-80	Associate Professor, Department of Mechanical Engineering
1970-76	Assistant Professor, Department of Mechanical Engineering

Closely Related Products

1. Tian, L., Kittelson, D.B., Durfee, W.K., 2011. "Model based design of a miniature free-piston engine compressor". Proceeding of the IFPE conference, Las Vegas, U.S., 2011.
2. Tian, Lei, David B. Kittelson, William K. Durfee, 2009. Miniature HCCI Free-Piston Engine Compressor for Orthosis Application, JSAE paper number 20097176.
3. Aichlmayr, H. T. Kittelson, D. B. and Zachariah, M. R., 2003 "Micro-HCCI Combustion: Experimental Characterization and Development of a Detailed Chemical Kinetic Model with Coupled Piston Motion" Combustion and Flame Vol. 135, No. 3, pp. 227-248, 2003.
4. Aichlmayr, H. T., D. B. Kittelson, and M. R. Zachariah, "Miniature Free-Piston Homogeneous Charge Compression Ignition Engine-Compressor Concept-Part I: Performance Estimation and Design Considerations Unique to Small Dimensions," Chemical Engineering Science Vol. 57 No 19, pp. 4161-4171, 2002.
5. Aichlmayr, H. T., D. B. Kittelson, and M. R. Zachariah, "Miniature Free-Piston Homogeneous Charge Compression Ignition Engine-Compressor Concept-Part II: Modeling HCCI Combustion in Small-Scales with Detailed Homogeneous Gas Phase Chemical Kinetics," Chemical Engineering Science Vol. 57 No. 19 pp. 4173-4186, 2002.

Significant Products

6. Lucachick, Glenn, Aaron Avenido, David Kittelson, and William Northrop, 2014." Exploration of Semi-Volatile Particulate Matter Emissions from Low Temperature Combustion in a Light-Duty Diesel Engine," SAE paper number 2014-01-1306.
7. Fang, Wei, David B. Kittelson, William F. Northrop, and Junhua Fang, 2013. "An Experimental Investigation of Reactivity-Controlled Compression Ignition Combustion in a Single-Cylinder Diesel Engine Using Hydrous Ethanol," Proceedings of the ASME Internal Combustion Engine Division 2013 Fall Technical Conference, ICEF2013.
8. Bika, Anil Singh, Luke Franklin, and David B. Kittelson, 2012. "Homogeneous charge compression ignition engine operating on synthesis gas," International Journal of Hydrogen Energy, v 37, n 11, p 9402-9411, June 2012
9. Bika, Anil Singh; Luke Franklin, David B. Kittelson, 2011. Engine Knock and Combustion Characteristics of a Spark Ignition Engine Operating with Varying Hydrogen and Carbon Monoxide Proportions, International Journal of Hydrogen Energy, v 36, n 8, p 5143-5152, April 2011
10. Bika, Anil Singh, Luke Franklin, Helmer Acevedo, and David Kittelson, 2011. Hydrogen Fueled Homogeneous Charge Compression Ignition Engine, SAE paper number 2011-01-0672.

Synergistic Activities

- Directs Center for Diesel Research
- Highly recognized for developing key understanding about engine-generated nanoparticles
- PI or Co-PI on a variety of projects aimed at understanding combustion and emissions of alternative fuels

Collaborators and Other Affiliations

Collaborators and Co-Editors:
Aichlmayr, H. T., Sandia National Labs; Andrews, Gordon, Leeds University; Collings, Nick, Cambridge University; Durbin, Tom, UCR: Durfee, William K., U of Mn: Fang, Junhua, U of MN; Fang, Wei, U of MN; Goersmann, C., Johnson-Matthey; Kraft, Markus, Cambridge U.; Johnson, Kent, UCR; Johnson, Tim, TSI, Inc.; Johnson, Tim, Corning; Jung, Heejung, UC Riverside; Liu, Z. Gerald, Fleetguard; Lucachick, Glenn, U of MN; McMurry, P. H., University of Minnesota; Miller, Arthur, NIOSH ; Northrop, William, U of MN; Twigg, Martyn, Johnson-Matthey, plc.; Walker, A. P., Johnson-Matthey; Warrens, C. P., British Petroleum; Watts, W., Univ. of Minnesota; Zachariah, Michael R.. University of Maryland; Zarling, Darrick D., University of Minnesota; Zheng, Zhongqing, UCR; Ziemann, Paul J., UCR.

Graduate and Post Doctoral Advisors: M.S. – Edward Fletcher, University of Minnesota
Ph.D. – Alan Hayhurst, Cambridge University

Thesis Advisor and Postgraduate-Scholar Sponsor: (last 5 years)
Avenido, Aaron, TSI Inc.; Bennett, David, self-employed; Thul, Dain, Donaldson; Tian, Lei, Polaris; Patwardhan, Udayan, Schlumberger; Hathaway, Brandon, post-doc, Univ. of Minn.; Sweeney, Joe, ACS; Kirk Johnson, Polaris; Ryan Becker, Honeywell; Aaron Collins, MSP; Andre Olson, Scania; Ragatz, Adam, NREL; Mathew Kenitzer, Deere; David Gladis, Cummins; Franklin, Luke, Dow; Anil Bika, GMR; Jason Johnson, TSI Inc.; Jeffrey Campbell, US State Department; Jacob Swanson, MSU; Andy Tan, Cummins; David Hall, Phillips Temro; Brad Dana, MTS; John Dixon, Cummins

Thomas R. Kurfess, P.E.

HUSCO Ramirez Distinguished Chair in Fluid Power and Motion Control
and
Professor
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia USA

Professional Preparation:

M.I.T., Cambridge, MA	Mechanical Engineering	**S.B.** (1986)
M.I.T., Cambridge, MA	Mechanical Engineering	**S.M.** (1987)
M.I.T., Cambridge, MA	Electrical Engineering and Computer Science	**S.M.** (1988)
M.I.T., Cambridge, MA	Mechanical Engineering	**Ph.D.** (1989)

Appointments:

2012-Present, HUSCO Ramirez Distinguished Chair in Fluid Power and Motion Control and Professor, Woodruff School of Mechanical Engineering, GA Tech, Atlanta, GA.
2012-2013, Assistant Director for Advanced Manufacturing, Office of Science and Technology Policy, Executive Office of the President of the United States of America, Washington, DC.
2005-2012, Professor and BMW Chair of Manufacturing Integration, Department of Mechanical Engineering, Clemson University, Clemson, SC.
2000-2005, Professor, Woodruff School of Mechanical Engineering, GA Tech, Atlanta, GA.
1993-2000, Associate Professor, Woodruff School of Mechanical Eng., GA Tech, Atlanta, GA.
1993, Associate Professor of Mech. Eng. and Engineering and Public Policy, Carnegie Mellon University (CMU), Pittsburgh, PA.
1989-93, Assistant Professor of Mech. Eng. and Engineering and Public Policy, CMU, Pittsburgh, PA.
1992-present, participating guest in the Precision Engineering Program at the Lawrence Livermore National Laboratory (LLNL), Livermore, CA.
1992-93, Summer Faculty LLNL, in the Precision Engineering Program, Livermore, CA.

Products

1. Carter J. A., Tucker, T. M., Kurfess, T. R., “3-Axis CNC Path Planning Using Depth Buffer and Fragment Shader,” Computer-Aided Design & Applications, Vol. 5, No. 5, pp. 612-621, 2008.
2. Panyam, M., Tucker, T. M., Kurfess, T. R., “Least-Squares Fitting of Analytic Primitives on a GPU,” Journal of Manufacturing Systems, Vol. 27, No. 3, pp. 130-135, July 2008.
3. Tarbutton, J. A., Kurfess, T. R., Tucker, T. M., “Graphics Based Path Planning for Multi-Axis Machine Tools,” Computer-Aided Design & Applications, Vol. 7, No. 6, pp. 612-621, 2010.
4. Tarbutton, J. A., Kurfess, T. R., Tucker, T. M., “Machining by Ray-Casting into Voxel Models, Proceedings of 2010 International Symposium on Flexible Automation,” Tokyo, Japan, July 12-14, 2010 UPL-2503.

Products (other)

1. Kurfess, T. R., “CMMs Are Key to Auto Quality” Manufacturing Engineering, Vol. 137, No. 3, pp. 131-140, September 2006.
2. Roth, J.T., Mears, L., Djurdjanovic, D., Yang, X. and Kurfess, T. R., “Quality and Inspection of Machining Operations: CMM Integration to the Machine Tool,” ASME Journal of Manufacturing Science and Engineering, Vol. 131, No. 5, October 2009.
3. Kurfess, T. R. (Editor), Robotics and Automation Handbook, 2005, CRC Press, Inc., Boca Raton, FL.
4. A. J. Henderson, C. Bunget, and T. R. Kurfess, "On-machine monitoring of tool wear with touch probes," *Proceedings of NAMRI/SME,* vol. 39, p. 8, 2011.
5. M. Estrems, H. T. Sanchez, T. R. Kurfess, C. Bunget, A. J. Henderson, and B. J. Richardson, “Influence of size effect and radial runouts on the end milling of a nickel-based superalloy," *Proceedings of NAMRI/SME,* vol. 39, p. 8, 2011.

Synergistic Activities

1. Board of Director MT Connect Institute.
2. Co-Chair National Network for Manufacturing Innovation Working Group, Advanced Manufacturing Partnership 2.0.
3. Board of Directors, Society of Manufacturing Engineers.
4. Board of Directors, National Center for Manufacturing Sciences.
5. Board of Directors, National Center for Defense Manufacturing and Machining.
6. Board of Editors, International Journal of Engineering Education.
7. Member National Academies Panel on Manufacturing Engineering.

Collaborators & Other Affiliations

Collaborators and Co-Editors:

Douglass Chinn (Sandia National Laboratories), R. Cowan* (Georgia Tech), Steven Danyluk (Georgia Tech), Levent Degertekin (Georgia Tech), Craig Henderson (Sandia National Laboratories), Steven Liang* (Georgia Tech), Shreyes Melkote* (Georgia Tech), Mark L. Nagurka* (Marquette University)

Graduate Advisors:

C. L. Searle (M.I.T.), D.E. Whitney (M.I.T)

Thesis Advisor:

M.S: R. Anderson, K. Aravalli, P. Aussaguel, S. Billington, S. Bittle, V. Bobba, J. Bradon, Z. Brooks*, S. Burns, A. Caccialupi, J. Ceremuga, A. Chen, W. Choi, I. Chuckpaiwong, A. Claudet, R. Coulter, R. Cowan, M. Crudele, M. Cummings, T. Dawson, C. Gallagher, S. Gamble, M. Greene, O. Karhade, B. Kim, H. Kohli, K. Laughlin, M. Leclerc, T. Lloyd, D. Longanbach, R. Lopez, J. Miller, C. Moore, J. Morrisette, J. Nichols, P. Padmanabhan, M. Panyam, J. Rayner, J. Reyer, B.J. Richardson, U. Sadiq, M. Schmittdiel, M. Shilling, M. Shilling, J. Shiroishi, J. Sills, W. Stone, J. Stuhlfire, J. Tarbutton, G. Toledo, T. Tucker*, J. Tucker, B. Ulmer, J. Whidby, T. Williams, A. Wilson, M. Yang, S. Yim.

Ph.D.: M. Aminzadeh*, P. Amy, M. Arant, M. Bowler*, Aoyu Chen*, Austin Chen, W. Choi, I. Chuckpaiwong, A. Claudet, T. Dawson, D. Delorenzis, A. Henderson, Hodge Jenkins, O. Karhade, B. Kim, D. Konobrytskyi, K. Kreuger, J. Limroth, D. Longanbach, L. Mears, P. Murray, J. Nichols, H. Razavi, M. Shilling, W. Stone, J. Tarbutton, T. Tucker*, H. Vasseur, S. K. Wang

Post-Graduate Scholars: A. Bryan, C. Bunget, G. Bunget, S. De Rosa (University of Naples "Federico II"), Manuel Estrems (Universidad Politécnica de Cartagena, Spain), P. Gutheil (Fachhochschule Trier, Germany), Y. Jung (Pusan National University, Korea), J. Karandikar* (Georgia Tech), D. Kim (Kumoh National University of Technology), P. Kerstiens (Fachhochschule Gelsenkirchen, Bocholt, Germany), J. Marquez (ETSII. Polytechnic University of Madrid), H. Razavi (Georgia Tech)

Number of MS students: 55, Number of Ph.D. students: 25, Post-doctoral scholars sponsored: 11
* Indicates current

Michael J. Leamy
G. W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology

PROFESSIONAL PREPARATION

Clarkson University, Potsdam, NY	Mechanical Engineering	B.S. 1993
University of Michigan, Ann Arbor, MI	Mechanical Engineering	M.S. 1995
University of Michigan, Ann Arbor, MI	Mechanical Engineering	Ph.D. 1998
Technion, Haifa, Israel	Nonlinear Mechanics	1998-1999
NASA Langley Research Center	Computational Mechanics	1999-2000

APPOINTMENTS

Jul. 2012 – Present	Georgia Institute of Technology, Associate Professor
Aug. 2007 – Jul. 2012	Georgia Institute of Technology, Assistant Professor
Sep. 2004 – Aug. 2007	MITRE Corporation, Research Scientist
Sep. 2003 – Aug. 2004	University of Maine, Assistant Professor
Jun. 2000 – Aug. 2003	United States Military Academy, West Point, Assistant Professor

CLOSELY RELATED PROJECTS

1. Leamy, M.J., 2012, "Exact Wave-Based Bloch Analysis Procedure for Investigating Wave Propagation in Two-Dimensional Periodic Lattices," *Journal of Sound and Vibration*, **331**: 1580-1596.
2. Narisetti, R.K., Ruzzene, M., Leamy, M.J., 2011, "A Perturbation Approach for Analyzing Dispersion and Group Velocities in Two-Dimensional Nonlinear Periodic Lattices," *Journal of Vibration and Acoustics*, **133** (6): 061020, pp. 1-12.
3. Farzbod, F., Leamy, M.J., 2011, "Analysis of Bloch's Method in Structures with Energy Dissipation," *Journal of Vibration and Acoustics*, **133** (5): 051010, pp. 1-8.
4. Manktelow, K., Leamy, M., Ruzzene, M., 2011, "Multiple Scales Analysis of Wave-Wave Interactions in a Cubically Nonlinear Monoatomic Chain," *Journal of Nonlinear Dynamics,* **63**: 193-203.
5. Narisetti, R.K., Leamy, M.J., Ruzzene, M., 2010, "A Perturbation Approach for Predicting Wave Propagation in One-Dimensional Nonlinear Periodic Structures," *Journal of Vibration and Acoustics*, **132** (3): 031001, pp. 1-11.

SIGNIFICANT PRODUCTS

1. Kulpe, J.A., Lee, C.-Y., Leamy, M.J., 2011, "Computation of Acoustic Absorption in Media Composed of Packed Microtubes," *Journal of the Acoustical Society of America*, **130** (2): 826-834.
2. Lee, C.-Y., Leamy, M.J., Nadler, J.H., 2010, "Frequency Band Structure and Absorption Predictions for Multi-Periodic Acoustic Composites," *Journal of Sound and Vibration*, **329**: 1809-1822.
3. Farzbod, F., Leamy, M.J., 2009, "The Treatment of Forces in Bloch Analysis," *Journal of Sound and Vibration*, **325**: 545-551.
4. Leamy, M.J., DiCarlo, A., 2009, "Phonon Spectra Prediction in Carbon Nanotubes Using a Manifold-Based Continuum Finite Element Approach," *Computer Methods in Applied Mechanics and Engineering*, **198** (17-20): 1572-1584.
5. Leamy, M.J., Lee, C.-Y., 2009, "Dynamic Response of Intrinsic Continua for Use in Biological and Molecular Modeling: Explicit Finite Element Formulation," *International Journal for Numerical Methods in Engineering*, **80** (9): 1171-1195.

SYNERGISTICS ACTIVITIES

Associate Editor, *Journal of Vibration and Acoustics* (2012-Present)
Elected Member of the Technical Committee on Vibration and Sound, ASME (2011-present)
Member of ASME, SAE

SESSION/SYMPOSIA ORGANIZER (MOST RECENT)

- Technical Track Co-Chair, 'Multiscale Mechanics of Materials,' *49th Annual Society of Engineering (SES) Technical Meeting*, 2012, Atlanta, GA.
- Symposium Co-Organizer, 'Emerging Applications in Dynamic Systems,' *24th Conference on Vibration and Noise*, 2012 ASME IDETC Conference, Chicago, IL.
- Member of Scientific Advisory Board, *Phononics 2011 – International Conference on Phononic Crystals, Metamaterials & Optomechanics*, 2011, Santa Fe, NM.
- Topic Chair, 'Structural Dynamics,' *ASME IDETC Conference*, 2011, Washington, DC.
- Minisymposium Organizer, 'Computational Mechanics of Phononic Metamaterials and Phononic Crystals,' *11th U.S. National Congress on Computational Mechanics*, 2011, Minneapolis, MN.

COLLABORATORS & OTHER AFFILIATIONS

Collaborators: Prof. Thomas Bradley, Dr. Gary Caille (Colorado State University), Prof. Ken Cunefare, Prof. Aldo Ferri, Prof. Peter Hesketh, Prof. David Hu, Prof. Massimo Ruzzene, Prof. Karim Sabra, Prof. David Taylor (Georgia Institute of Technology), Dr. Mahmoud Hussein (University of Colorado), Prof. Mario Encinosa, Prof. Mark Jack (Florida A&M University), Prof. Chiara Daraio (Cal Tech).

Post Graduate Advisors: Prof. Ahmed Noor (NASA Langley Research Center, University of Virginia), Prof. Oded Gottlieb (The Technion, Israel).

Thesis Advisor and Postgraduate-Scholar Sponsor (Previous 5 Years)

Graduate Students (11): Dr. Farhad Farzbod, 01/2008 – 11/2010, Dr. Raj Narisetti, 06/2008 – 11/2010, Mr. John Arata, 01/2010 – 11/2011, Mr. Kevin Manktelow, 08/2009 – Present
Mr. Kyle Karlson, 08/2009 – Present, Mr. Jason Kulpe, 08/2010 – Present, Mr. Kamil Kocak, 08/2011 – Present, Mr. Dekun Pei, 08/2011 – 12/2012, Mr. Ryan Hopman, 01/2008 – 08/2009, Ms. Dooroo Kim, 09/2007 – 08/2009, Mr. Thibaut Autrusson, 09/2007 – 05/2009

Postdoctoral Scholars (1): Dr. Chang-Yong Lee (01/2008-01/2010).

Perry Y. Li
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)

Gary Lichtenstein, Ed.D.
Evaluation and Assessment
Quality Evaluation Designs

Professional Preparation

B.A. Honors in Rhetoric, University of California, Berkeley, 1983
M.A. Education, Curriculum & Teacher Education, Stanford University, 1989
Ed.D. Administration and Policy Analysis, School of Education, Stanford University, 1997

Appointments

1996-present **Sole Proprietor, Quality Evaluation Designs (QED)**
QED is a successful evaluation and research firm that has conducted research and evaluation throughout the United States for over a decade.

Jan 2011-Dec 2014 **Project Director, University of Colorado, Denver, CO**, *Rocky Mountain Prevention Research Center*. Implementation and evaluation of a 3-year grant to reduce obesity among school children in southern and eastern Colorado

2005-present **Consulting Associate Professor, Stanford University, Stanford, CA**
Consulting professor of research methods in the School of Engineering. From 2005-2008, responsible for analyzing and reporting qualitative and quantitative data in the Center for the Advancement of Engineering Education (CAEE), part of a national, NSF-funded study looking at factors that correlate with academic persistence and professional intention among undergraduate engineers.

1996-2007 **Adjunct Professor, University of Denver, Denver, CO**
Professor of research, evaluation, and community-based research in the College of Education.

2002-2004 **Director of Research & Evaluation, Colorado Small Schools Initiative, Denver, CO.**
Provided program direction and evaluation to high schools engaged in small school reform.

2000-2002 **Research Associate, Carnegie Foundation for the Advancement of Learning**
Responsible for data collection and analysis for nationwide study of undergraduate engineering majors. PI: Dr. Sheri Sheppard

Closely Related Products

1. Retention and Persistence of Women and Minorities Along the Engineering Pathway in the U.S., Gary Lichtenstein, Helen Chen, Karl Smith, & Theresa Maldonado, in *Cambridge Handbook of Engineering Education Research*, Eds. Aditya Johri & Barbara Olds (forthcoming, 2013).
2. Final Evaluation Report of Research Experiences for Teachers (RET):*What factors influence high school seniors to pursue STEM majors in college?* Unpublished Technical Report by G. Lichtenstein & Martin L. Tombari (Dec 2012). Colorado: Quality Evaluation Designs.
3. Cost of an Engineering Major, by Gary Lichtenstein, Alex McCormick, Sheri Sheppard & Jini Puma, JEE Selects Column in *PRISM*, a magazine for engineers and engineering educators, December, 2010, p.47.
4. An Engineering Major Does Not (Necessarily) an Engineer Make: Career Decision-making Among Undergraduate Engineers. Gary Lichtenstein, Heidi Loshbaugh, Brittany Claar, Helen Chen, Sheri Sheppard, Kristyn Jackson. *Journal of Engineering Education*, July 2009, pp.227-234.
5. Persistence, Engagement, and Migration in Engineering Programs. Matt Ohland, Sheri Sheppard, Gary Lichtenstein, Ozgur Eris, Debbie Chachra, Richard Layton. *Journal of Engineering Education (JEE). Special edition: How People Learn Engineering*, v97, n3, pp. 259-278. July 2008.

Significant Products

Development of a National Survey to Assess Student Outcomes of Community-Based Research, by Gary Lichtenstein, Trisha Thorme, Nick Cutforth and Martin L. Tombari. Journal of Higher Education Outreach & Engagement, v15,n2, pp.7-33, 2011.

Is the Supply of Engineering Majors a Problem of Many Losses or Few Gains? Persistence and Migration of Engineering Majors Compared to Other Fields. Alex McCormick, Gary Lichtenstein, Sheri Sheppard, Jini Puma (in preparation).

Comparing the Undergraduate Experience of Engineers to All Other Majors: Significant Differences are Programmatic, by Gary Lichtenstein, Alex McCormick, Sheri Sheppard & Jini Puma. Journal of Engineering Education, v99, n4, pp.305-317, October 2010.

"Graduation and Dropout Statistics: Time to Tell Hard Truths." Gary Lichtenstein. The Term Paper (formerly HeadFirst Colorado), The Piton Foundation, v4, #2, April/May 2005.

A Call for High School Reform. Gary Lichtenstein (technical research report). CO: Colorado Children's Campaign, April 2003.

Synergistic Activities

1. Quality Evaluation Designs (QED), the firm conducting the external evaluation, is a sole-proprietorship with a single owner. For over 20 years, Gary Lichtenstein has designed and conducted educational research and evaluation nationwide. Lichtenstein collected data for the Carnegie Foundation's book, *Educating Engineers* (Sheppard et al., 2009), conducted the evaluation of the National Academy of Engineering, *Frontiers of Engineering Education* and *"A Forum on Characterizing the Impact and Diffusion of Engineering Education Innovations"* grants, as well as Stanford's NSF-funded EESP grant, and has had several articles on engineering education published in the *Journal of Engineering Education*. Clients have included: The National Academy of Engineering, SRI International, EDC (Boston), Princeton University, the Carnegie Foundation for the Advancement of Learning, the Colorado Department of Education and others. Selected to write the chapter, *Persistence, Retention, and Motivation* in the Cambridge Handbook on Engineering Education (forthcoming, 2013).
2. Two-time recipient of the William Elgin Wickenden Award from the American Society for Engineering Education (ASEE) for the research articles, "Persistence, Engagement, and Migration in Engineering Programs," (July 2008) and "Comparing the Undergraduate Experience of Engineers to All Other Majors: Significant Differences are Programmatic," (October 2010) in the Journal of Engineering Education (JEE). The annual award recognizes authors whose article reflects the highest standards of scholarly research in engineering education among those articles published in JEE each year.
3. National Science Foundation panel reviewer (CAREERS grant 2011, and reverse site visit, 2012). ASEE member (division member: Evaluation and Research Methods, Minorities in Engineering, Women in Engineering.

Collaborators and Other Affiliations

Collaborators: Sheri Sheppard (Stanford U.); Helen Chen (Stanford Univesity); Karl Smith (University of Minnesota); Theresa Maldonado (National Science Foundation); Alex McCormick (Indiana University); Matt Ohland (Purdue).

Graduate Advisors: L. Cuban (Stanford University)

John H Lumkes Jr.
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
1987-1993	Applications Chemist, Benz Oil, Milwaukee, WI

Closely Related Products

Khalid, H. and Michael, P. “An Investigation of Hydraulic Motor Efficiency through Stribeck Analysis,” TLT,70:1, 20-23 (2014)

Michael, P. Garcia, JM. Bair, S. Devlin, MT, Martini, A. “Lubricant Chemistry and Rheology Effects on Hydraulic Motor Starting Efficiency,” Tribology Transactions, 55: 549-557, (2012)

Michael, P. Guevremont,J. K. Devlin, M. and Ziemer, C. “Tribological Film Formation in Hydraulic Motors,” Proceedings of the STLE/ASME International Joint Tribology Conference, Paper IJTC2011-61029 (2011)

Burgess, K. Michael, P. Wanke, T. and Ziemer, C. “Starting Efficiency in Hydraulic Motors,” Proceedings of the 52nd National Conference on Fluid Power – National Fluid Power Association, Paper NCFP I11-9.1, Las Vegas, NV (2011)

Bair, S. and Michael, P. “Modelling the Pressure and Temperature Dependence of Viscosity and Volume for Hydraulic Fluids,” International Journal of Fluid Power, Vol. 11, N 2, pp 37-42 (2010)

Michael, P. Wanke, T. Kimball, A. and Blazel, B. “Atomic Force Microscopy of Geroler Motor Wear Debris Ferrograms,” Journal of ASTM International, Vol. 6, N 1, Paper ID JAI101628, (2009)

Significant Products

Michael, P. and Wanke, T. ”Hydraulic Fluid and System Standards,” Handbook of Hydraulic Fluid Technology, 2nd Edition, G.E. Totten and V.J. De Negri Ed., CRC Press, Boca Raton, (2012)

Michael, P. Khalid, H. and Wanke, T. “An Investigation of External Gear Pump Efficiency and Stribeck Numbers,” SAE Commercial Vehicle Conference, Paper 2012-01-2041, Chicago, IL (2012)

Michael, P. Blazel, B. Reuchel, R. and Harville, X. “Hydraulic Fluid Compatibility and Filterability,” Proceedings of the 52nd National Conference on Fluid Power – National Fluid Power Association, Paper NCFP I11-35.2, Las Vegas, NV (2011)

Synergistic Activities

Chairman, Hydraulic Fluid Compatibility Section D02.N0.09, ASTM International
Chairman, Fluids Committee, National Fluid Power Association
REU Advisor in 2013, 2012, 2011, 2010, 2009, 2008 & 2007 (5 of the 6 students were from underrepresented groups)
RET Advisor in 2009 & 2008
Member Society of Tribologists and Lubrication Engineers
Technical Editor, "Tribology and Lubrication Technology" (TLT)

Collaborators And Other Affiliations

Collaborators Over The Last 48 Months:

- Ashlie Martini, University of California, Merced – Static Friction Studies
- Bill King, University of Illinois, Champaign, Urbana – Surface Texturing of Geroler Motors
- Eric Dorn, Sauer Danfoss – Hydraulic Motor Research
- Gilles LeMaire, Poclain Hydraulics – Hydraulic Motor Research
- Jeffery Mordas, MP Filtri – Filtration Research
- Jill Tebbe, US Army – Hydraulic Fluid Research
- Jose Garcia, Illinois Institute of Technology – Static Friction Studies
- Mark Devlin, Afton Chemical – Boundary Lubrication Research
- Matt Simon, Parker Hannifin – Geroler Motor Research
- Patrick Henning, Spectro Inc – Oil Analysis Instrumentation
- Scott Bair, Georgia Tech – High Pressure Rheology
- Steve Herzog, Rohmax USA – Hydraulic Fluid Research
- David Holt, Exxon-Mobil – Hydraulic Fluid Research

Thesis Advisor and Postgraduate Scholar Sponsors over the Last Five Years:
Graduate Students:

- Kelly Heathcote, General Dynamics
- Hassan Khalid, Pentair
- Aaron Kimball, Cobham Mission Systems
- Meghan Miller, ExxonMobil
- Corey Reynolds, Poclain Hydraulics
- Total Number of Graduate Students advised: 5

Undergraduate Research Assistants that have advanced to graduate school: 5

- Chelsey Ericson, University of Wisconsin
- Dan Schick, University of Wisconsin
- Kelsey Whittaker, University of California, Riverside
- Michael McCambridge, Arizona State University
- Ricardo Rivera Lopez, University of Pittsburgh

J. Shipley Newlin, Jr
Science Museum of Minnesota
St Paul, MN

Professional Preparation

1963 - 1966 1970 - 1971	St. John's College, Annapolis, Maryland – Liberal Arts and Sciences (Great Books Program)
1973 - 1974	Drexel University, Philadelphia, Pennsylvania – courses in Physics, Chemistry, and Mathematics
1975 - 1976	Temple University, Philadelphia, Pennsylvania – Graduate courses in Communications

Appointments

1986 – present	Science Program Director, Physical Sciences, Engineering, & Mathematics
2000 - 2006	Minneapolis College of Art & Design, Minneapolis, Minnesota Adjunct Professor
1984 - 1986	New York Hall of Science, Corona, Queens, New York Exhibits Director
1973 - 1983	The Franklin Institute, Philadelphia, Pennsylvania Director of Exhibits; Senior Instructor; Lecturer & Technician
1966 - 1969	U.S. Peace Corps Volunteer, Somalia School Construction Program Secondary School Teacher (English & Mathematics)

Closely Related Projects

1. 1994 "Experiment Gallery" (project director)
A permanent, developing hall devoted to visitor experiment in physics, chemistry, and engineering.

2. 1993 Experiment Bench Project (project director)
NSF-supported project to develop ten multiple-outcome exhibits to promote experimenting in a museum setting.

3. 2012 "Engineering Studio" (project director)
Permanent exhibits that involve visitors in engineering design, problem-solving, prototyping, and testing.

4. 1976 "Benjamin Franklin: Scientist and Inventor" (project director)
The Franklin Institute's special lecture-demonstration for the US Bicentennial

5. 1980 "Physics: Movement, Matter, and Energy" (project director)
An exhibition on mechanics that contains more than 40 interactive devices and computer activities at three levels of sophistication.

Significant Products

6. 1982 "Shipbuilding on the Delaware" (project director)
A major, permanent exhibition on the history, science, technology, and economics of the shipbuilding industry that flourished along the Delaware River from 1700 to 1960.

7. 1997 "Atmospheric Explorations" (co-principal investigator)
NSF-supported project (with Atmospheric Sciences Group at Augsburg College) to develop three computerized exhibit models of atmospheric phenomena.

8. 2002 "Playing with Time" (principal investigator)
A major traveling exhibition about change over a range of time scales from billions of years to femtoseconds

9. 2002 “Investigations in Cell Biology” (co-principle investigator)
A set of six wet-biology exhibits at which visitors can pursue computer-guided experiments on cells, bacteria, and DNA.

10. 2007 “Wild Music” (principle investigator)
A traveling exhibition on the biological origins of music and how we share music with other animals.

Synergistic Activities

Organizing and leading a long series of annual seminars on the relationship of the humanities to science held at meetings of the Association of Science-Technology Centers

Museum staff liaison with the Minnesota Astronomical Society

Presentations on science learning and exhibits at annual meetings of the Association of Science-Technology Centers

Collaborators & Other Affiliations

Collaborators within the last 48 months

William K Durfee, Professor and Director of Design Education, University of Minnesota Molly Kelton, doctoral student in mathematics education at San Diego State University Troy Livingston, VP for Innovation and Learning, Museum of Life + Science, Durham, NC Ricardo Nemirovsky, Professor of Mathematics Education, San Diego State University Alana Parkes, Exhibit Planner, Museum of Science, Boston, MA

Glenn M Schmieg, Professor of Physics (ret), University of Wisconsin, Milwaukee

Paul Tatter, former Executive Director, Explora, Albuquerque, NM Tracey Wright, Education Researcher, TERC, Cambridge, MA

Eui H. Park
Department of Industrial and Systems Engineering
North Carolina Agriculture and Technical State University

Professional Preparation

Yonsei University, Korea	Physics	B.S. 1972
Mississippi State University	Industrial Engineering	M.S. 1978
City University	Business Administration	M.B.A. 1980
Mississippi State University	Industrial Engineering	Ph.D. 1983

Appointments

1983 – present	Assistant/Associate/Full Professor, Department of Industrial and Systems Engineering, North Carolina A&T State University
1990 – 2005	Chairperson, Department of Industrial and Systems Engineering, North Carolina A&T State University
1978 – 1982	Senior Engineer, Division of Engineering Computing Systems, Boeing Commercial Airplane Company, Seattle, Washington
1985	Summer Faculty, Information Productions Division, IBM - Charlotte, NC
1983 – present	Consulted with ConVatec, Kaplan, Panel Concepts, Brayton International, Longwood, Guilford County Public Health, Korean Institute of Metals and Machinery, Hyundai, and Korean Management Association.

Closely Related Products

1. X. Jiang, B. Osafo-Yeboah, and E. Park, "Using the Callsign Acquisition Test (CAT) to Investigate the Impact of Background Noise, Gender, and Bone vibrator Location on the Intelligibility of Bone-Conducted Speech," International Journal of Industrial Ergonomics, International Journal of Industrial Ergonomics 39, pp. 246-254, (2009).

2. Park, E., J. Park, Celestine Ntuen, Daebum Kim, and Jendall Johnson, "Forecast Driven Simulation Model for Service Quality Improvement of the Emergency Department in the Moses H. Cone Memorial Hospital," The Asian Journal on Quality, Vol 9, No 3.

3. Kim, D. E. Park, Celestine Ntuen, and Younho Seong, "An AGV Dispatching Algorithm with Look-ahead Procedure for a Tandem Multiple-load AGV System," The Journal of Management and Engineering Integration, Winter 2009.

4. Seong, Y., E. Park and H. Lee, "Sensemaking and Human Judgment Under Dynamic Environment," Journal of the Ergonomics Society of Korea, Vol. 25, No.3, pp. 1-12, August 2006.

Significant Products

5. Park, E. & C. Ntuen," A Model for Predicting Human Reliability under Workload and Skill Performance," 2006 INFORMS International Conference, Hong Kong, China, June 2006.

6. Ntuen, C. & E. Park, "Human Performance in Monitoring Linear Automation Behavior," Proceedings of 15th Triennial Congress of the International Ergonomics Association, Seoul, Korea, August 2003.

7. Ntuen, C. & E. Park "Supporting Courses of Action Planning with Intelligent Management of Battle Assets,", Proceedings of Command & Control Symposium, National Defense University, July 2003.

8. Ntuen, C., S. Eastman & E. Park, "CAAD: The Commander's Battle Plan Assistance, Handbook of Human-Computer Interface for Military Application (M. Vassillious & T. Huang), Computer Society Press , Chapter 21, pp.237-257, 2001.

9. Park, E., Q. Jenkins, and X. Jiang, “ Measuring Trust of Human Operators in New Generation Rescue Robots,” Proceedings of 2008 JFPC International Symposium on Fluid Power, Toyama, Japan, September 2008.

10. Ntuen, C. and E. Park, “ Predicting Human Reliability under Workload and Skill,” Proceedings of the 10th IFAC Symposium on Information Control Problems in Manufacturing, Seoul, Korea, Aug. 2007

Synergistic Activities

Fellow, Institute of Industrial Engineers, since 2000, Board of Directors, Member, Piedmont Triad Center for Advanced Manufacturing, 1997 – 2005, Director, Manufacturing Initiatives, North Carolina A&T State University, 1989 – 1995, Co-Program Chair, Symposium on Human Interactions with Complex Systems, five times since 1991., Principle Investigator in 22 awarded funded research projects totaling over $7 million in the past eleven years.

Collaborators

Dr. Earl Barnes – School of Industrial & Systems Engineering, Georgia Institute of Technology, Dr. Wayne Book – School of Mechanical Engineering, Georgia Institute of Technology, Dr. Daebuem Kim and Young Park – Kangnam University, Korea, Dr. Xiaochun Jinag, Dr. Celestine Ntuen, Dr. Bala Ram, Dr. Sanjiv Sarin, and Dr. Younho Seong – Industrial & Systems Engineering, North Carolina A&T State University, Dr. Gary Rubloff – Institute of Systems Research, University of Maryland

Graduate Advisors: Drs. Larry Brown and Fazli Rabbi (Mississippi State University); Dr. Joe Tanchoco (Purdue University)

Richard F. Salant
Georgia Institute of Technology

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
1994-present	Professor, Dept. of Mechanical Engineering, Univ. of Minnesota
2001-2002	Visiting Professor, Univ. of Bath, United Kingdom
1996	Visiting Associate Professor, Univ. of Auckland, New Zealand
1987-1994	Associate Professor, Dept. of Mechanical Engineering, Univ. of Minnesota
1992-1993	Visiting Senior Lecturer, Hong Kong Univ. of Science and Technology
1981-1987	Assistant Professor, Department of Mechanical Engineering, Univ. of Minnesota

Publications

Dutta, R., F. Wang, B. F. Bohlmann and K. A. Stelson, "Analysis of Short-Term Energy Storage for Mid-Sized Hydrostatic Wind Turbine," *Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control*, Vol. 136, No. 1, 2014.

Wang, F., M. Bissen, W. Ward and K. A. Stelson, "Modeling and Design of a Hybrid Bicycle with Hydraulic Transmission," *The Ninth JFPS International Symposium on Fluid Power,* Matsue, Japan, 28-31 October 2014.

Wang, F. and K. A. Stelson, "A Novel Pressure-Controlled Hydro-Mechanical Transmission," *Bath/ASME Symposium on Fluid Power & Motion Control (FPMC 2014),* 10-12 September 2014, Bath, UK.

Wang, F., M. A. M. Zulkefli, Z. Sun and K. A. Stelson, "Investigation of Energy Management for Hydraulic Hybrid Wheel Loaders," *Proceedings of the 2013 ASME Dynamic Systems and Control Conference,* 21-23 October 2013, Palo Alto, CA.

Ramdan, M. I. and K. A. Stelson, "Optimized Single-Stage Power-Split Hydraulic Hybrid City Bus," *ASME/BATH 2013 Symposium on Fluid Power and Motion Control (FPMC 2013),* 6-9 October 2013, Sarasota, FL.

Whitten, M. and K. A. Stelson, "Determining Water Content at Saturation for Three Common Wind Turbine Gearbox Oils: Mobilgear SHC XMP 320, AMSOIL EP Gear Lube ISO-320 and Castrol Optigear A320," *ASME/BATH 2013 Symposium on Fluid Power and Motion Control (FPMC 2013),* 6-9 October 2013, Sarasota, FL.

Wang, F. and K. A. Stelson, "Model Predictive Control for Power Optimization in a Hydrostatic Wind Turbine," *The 13th Scandinavian International Conference on Fluid Power, SICFP2013,* 3-5 June 2013, Linköping, Sweden, pp. 155-160.

Deppen, T. O., A. G. Alleyne, J. J. Meyer and K. A. Stelson, "An Energy Management Strategy for Hydraulic Hybrid Vehicles," *Proceedings of the 2012 American Control Conference,* June 27-29, 2012, Montréal, Canada.

Deppen, T. O., A. G. Alleyne, J. J. Meyer and K. A. Stelson, "Optimal Energy Use in a Light Weight Hydraulic Hybrid Passenger Vehicle," *Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control*, Vol. 134, no. 4, July 2012.

Wang, F. and K. A. Stelson, "Minimizing the Power Dissipation in the Piston-Cylinder Gap Using a Barrel-Shaped Piston," *Bath/ASME Symposium on Fluid Power & Motion Control (FPMC 2012),* 12-14 September 2012, Bath, UK, pp. 123-133.

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; and *ASME Journal of Dynamic Systems, Measurement and Control,* 2003-present.

Editorial Board, *Transaction on Control, Automation and Systems Engineering,* 2000-present; *IMechE Journal of Engineering Manufacture,* 2000-present; and *Technical Transactions – Mechanics* (Poland), (2014-present).

Collaborators & Other Affiliations

Graduate and Postdoctoral Advisors: Massachusetts Institute of Technology S.M. thesis advisor, Shawn Buckley; Massachusetts Institute of Technology Sc.D. thesis advisor, David Gossard.

Collaborators: A. G. Alleyne (Univ. of Illinois, Urbana-Champaign), B. F. Bohlmann (Univ. of Minnesota), D. Buono (Univ. of Naples Federico II), T. Cui (Univ. of Minnesota), T. O. Deppen (Univ. of Illinois, Urbana-Champaign), R. Dutta (Case New Holland), R. Ertel (MTS Systems), E. Frosina (University of Naples Federico II), C. Groepper (MTS Systems), M. J. Gust (Univ. of Minnesota), B. Hencey (Cornell), P. Y. Li (Univ. of Minnesota), S. C. Mantell (Univ. of Minnesota), J. J. Meyer (Bosch Rexroth), B. Mohanty (Univ. of Minnesota), M. Pavanetto (Duplomatic Oleodinamica), R. Rajamani (Univ. of Minnesota), M. I. Ramdan (Univ. Sains Malaysia), T. W. Secord (Medtronic), A. D. Senatore (Univ. of Naples Federico II), Z. X. Sun (Univ. of Minnesota), B. R. Thul (Donaldson), B. Trietch (Rhode Island Office of Energy Resources), F. Wang (Zhejiang Univ.), Y. Wang (Seagate), M. Whitten (Donaldson), X. Yu (Univ. of N. Texas), H. Zhu (Baxter Medical), A. M. Zukefli (Univ. of Minnesota).

Zongxuan Sun
Department of Mechanical Engineering
University of Minnesota, Twin Cities Campus

Professional Preparation

Southeast University, China	Automatic Control	B.S. 1995
University of Illinois at Urbana-Champaign	Mechanical Engineering	M.S. 1998
University of Illinois at Urbana-Champaign	Mechanical Engineering	Ph.D. 2000

Appointments

1/2014 – present	Co-Deputy Director, NSF Engineering Center for Compact and Efficient Fluid Power
8/2012 - present	Associate Professor, Department of Mechanical Engineering, University of Minnesota
8/2007 - 8/2012	Assistant Professor, Department of Mechanical Engineering, University of Minnesota
11/2006 – 8/2007	Staff Researcher, Research and Development Center, General Motors Corp.
9/2000-10/2006	Senior Researcher, Research and Development Center, General Motors Corp.
7/1999 – 9/2000	Senior Engineer, Western Digital Corp.
8/1996-5/2000	Research Assistant, University of Illinois at Urbana-Champaign

Products

1. Li, K., Sadighi, A. and Sun, Z., "Active Motion Control of a Hydraulic Free Piston Engine", IEEE/ASME Transactions on Mechatronics, 2013, DOI: 10.1109/TMECH.2013.2276102.
2. Li, K., Sadighi, A. and Sun, Z., "Motion Control of a Hydraulic Free-Piston Engine", Proceedings of the American Control Conference, Montreal, Canada, pp.2878-2883, June 2012.
3. Li, K. and Sun, Z., "Stability Analysis of a Hydraulic Free Piston Engine with HCCI Combustion", Proceedings of the 2011 Dynamic Systems and Control Conference, Arlington, VA, DSCC2011-5983, Nov., 2011.
4. Sadighi, A., Li, K. and Sun, Z., "A Comparative Study of Permanent Magnet Linear Alternator and Hydraulic Free Piston Engines", Proceedings of the 2011 Dynamic Systems and Control Conference, Arlington, VA, DSCC2011-6041, Nov., 2011.
5. Li, K. and Sun, Z., "Modeling and Control of a Hydraulic Free Piston Engine with HCCI Combustion", Proceedings of the 52^{nd} National Conference on Fluid Power, Las Vegas, NV, pp.567-576, March, 2011.
6. Li, K., Santiago, W. and Sun, Z., "Modeling of a Two-Stroke Free-Piston Engine with HCCI Combustion", Proceedings of the 2010 Dynamic Systems and Control Conference, Boston, MA, DSCC2010-4267, September, 2010.
7. Zhang Z. and Sun, Z., "A Novel Internal Model-Based Tracking Control for a Class of Linear Time-Varying Systems", ASME Transactions on Journal of Dynamic Systems, Measurement and Control, Vol. 132, 011004, January, 2010.
8. Sun, Z., Zhang, Z. and Tsao, T.-C., "Trajectory Tracking and Disturbance Rejection for Linear Time-Varying Systems: Input/Output Representation", Systems and Control Letters, 58, pp.452-460, 2009.
9. He, X., Durret, R. and Sun, Z., "Late Intake Valve Closing as an Emission Control Strategy at Tie 2 Bin 5 Engine-Out NO_x Level", SAE International Journal of Engines, 1(1), pp.427-443, 2008.
10. Kuo, T., Sun, Z., Kang, J., Eng, J., Chang, C., Brown, B., Najt P. and Chang, M., "Method for Transition Between Control Auto-Ignition and Spark Ignition Mode in Direct Fuel Injection Engines", US patent 7,370,616, 2008.

Synergistic Activities

- Organizer and panelist, Panel discussion "Engine and Combustion Modeling for Model-Based Control," The 2013 SAE World Congress, Detroit, MI.
- Guest editor, "Active Automotive Safety Systems", IEEE Control System Magazine, 2010.
- Session co-organizer, "HCCI Control", The 2010 SAE World Congress.
- Session co-organizer, "Engine Control", The 2009 SAE Powertrain and Fluid Systems Conference.
- Mentor, for minority summer students, GM Research and Development Center, 2002, 2003.

Collaborators & Other Affiliations

Collaborators and Co-Editors: Shih-Ken Chen, Burak Gecim, Kumar Hebbale, Chi-Kuan Kao, Hsu-Chiang Miao (GM), T.-C. Tsao (UCLA), G. Zhu (MSU), David Kittelson, Kim Stelson, Will Northrop, Michael Manser, Juergen Konczak, Henry Liu, David Du (UMN), Sonja Glavaski, Qinghui Yuan, Ben Morris (Eaton), John Brevick (Ford)

Graduate Advisors and Postgraduate Sponsors: T.-C. Tsao (UCLA)

Thesis Advisor or Postgraduate-Scholar Sponsor: Dr. X. Song (GM), Dr. Z. Zhang (Tsinghua University, China), Dr. A. Sadighi (US Hybrid), Dr. P. Gillella (Parker), Dr. Y. Wang (Seagate), V. Gupta (Cummins), A. Heinzen (GM), M. McCuen (Chrysler), V. Mallela (Schlumberger), C. Wu, A. Zulkefli, K. Li, Y. Yoon, C. Zhang, Y. Wang, M. Yang (UMN)

Jun Ueda
School of Mechanical Engineering
Georgia Institute of Technology

Professional Preparation

Kyoto University, Japan	Mechanical Engineering	B.S.,	1994
Kyoto University, Japan	Mechanical Engineering	M.S.,	1996
Kyoto University, Japan	Mechanical Engineering	Ph.D.,	2002

Appointments

2008-Present Assistant Professor, Mechanical Engineering, Georgia Institute of Technology
2010-Present Adjunct Faculty, Applied Physiology, Georgia Institute of Technology
2006 Lecturer, Mechanical Engineering, Massachusetts Institute of Technology
2005-2008 Visiting Scholar, Mechanical Engineering, Massachusetts Institute of Technology
2002-2008 Assistant Professor, Information Science, Nara Institute of Science and Technology, Japan
1996-2000 Senior Research Scientist, Advanced Technology R&D Center, Mitsubishi Electric Corporation

Closely Related Products

1. Schultz, J. and Ueda, J., "Analysis of antagonist stiffness for nested compliant mechanisms in agonist-antagonist arrangements," *the 2011 ASME Dynamic Systems and Control Conference* (DSCC'11).
2. MacNair, D. and Ueda, J. David MacNair and Jun Ueda, “A Fingerprint Method for Variability and Robustness Analysis of Stochastically Controlled Cellular Actuator Arrays,” *The International Journal of Robotics Research*, Volume 30, Issue 5, pp. 536 - 555, April 2011.
3. Ueda, J.; Ming, D.; Krishnamoorthy, V.; Shinohara, M.; Ogasawara, T. "Individual Muscle Control Using an Exoskeleton Robot for Muscle Function Testing," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol.18, no.4, pp.339-350, Aug. 2010.
4. Ueda, J.,Secord,T., Asada,H. “Large Effective Strain Piezoelectric Actuators Using Nested Cellular Architecture with Exponential Strain Amplification Mechanisms”, *IEEE/ASME Transactions on Mechatronics,* Vol. 15, No. 5, pp. 770-782, 2010.
5. Ueda, J., Yoshikawa, T., “Force Reflecting Bilateral Teleoperation with Time Delay By Signal Filtering,” *IEEE Transactions on Robotics and Automation*, Vol. 20, No. 3, pp.613- 619, June, 2004.

Significant Products

1. Schultz J.and Ueda, J. “Experimental Verification of Discrete Switching Vibration Suppression,” *IEEE/ASME Transactions on Mechatronics*, *in Press*.
2. Ueda, J., Kondo, M., Ogasawara, T " The Multifingered NAIST-Hand System for Robot In-hand Manipulation," *Mechanism and Machine Theory*, Volume 45, Issue 2, Pages 224-238, February 2010.
3. Ueda, J., Odhner, Asada, L., H. Harry, "Broadcast Feedback of Stochastic Cellular Actuators Inspired by Biological Muscle Control," *The International Journal of Robotics Research*, Volume 26, Issue 11-12, pp. 1251--1265, November-December 2007.
4. Ueda, J.,, Ikeda, A., Ogasawara, T., "Grip-force Control of an Elastic Object by Vision-based Slip Margin Feedback during the Incipient Slip", *IEEE Transactions on Robotics*, Vol.21, Issue 6, pp.1139- 1147, December, 2005.
5. Ueda, J., Yoshikawa, T., "Mode Shape Compensator for Improving Robustness of Manipulator Mounted on Flexible Base", *IEEE Transactions on Robotics and Automation*, Vol. 20, No. 2, pp. 256- 268, April, 2004.

Synergistic Activities

1. Early Academic Career Award in Robotics and Automation from IEEE Robotics and Automation Society, for fundamental contributions to robust control of robot dynamics including time-delayed telerobotics, flexible robots, cellular actuator devices, and rehabilitation robots May 2009
2. Associate Editor for *IEEE/ASME Transactions on Mechatronics* April 2008 –Present
3. Associate Editor and Committee Member for *2011 IEEE International Conference on Robotics and Automation* (ICRA 2011), *the 2010 IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics* (BioRob 2010), *2010 Robotics Science and Systems Conference* (RSS 2010), *2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics* (AIM 2009), and *ASME Dynamic Systems and Control Conference* (DSCC 2009, 2010, 2011, 2012).
    a. Organized a panel discussion session on Mechatronics for Biosystems and Healthcare at AIM 2009
    b. Organized a workshop on Biologically Inspired Actuation with Dr. Stefanini at ICRA 2011
    c. Organizes a workshop on Biosystems and Healthcare at DSCC 2011
    d. Serves as Students and Young Members Chair for DSCC 2012
4. Best Automation Paper Finalist *at the 2008 IEEE International Conference on Robotics and Automation* (ICRA 2008) May 2008
5. Training Faculty, National Institute of Child Health & Human Development, "Training Movement Scientists: Focus on Prosthetics and Orthotics" (1T32 HD055180-01A1) at the School of Applied Physiology, Georgia Institute of Technology Feb 2010-Present

Collaborators & Other Affiliations

(i) Collaborators and Co-Editors

Shinohara, M., (Applied Physiology, Georgia Institute of Technology), Kogler, G.(Applied Physiology, Georgia Institute of Technology), Stilman, M (Interactive Computing, Georgia Institute of Technology), Christensen, H. (Interactive Computing, Georgia Institute of Technology), Book, W. (Mechanical Engineering, Georgia Institute of Technology), Krishnamoorthy, V.(Emory University), Webster, R.(Vanderbilt University), Barth, E. (Vanderbilt University), Asada, H. (Massachusetts Institute of Technology), Ogasawara, T. (Nara Institute of Science and Technology, Japan), Takemura, H.(Tokyo University of Science, Japan), Kurita, Y.(Hiroshima University, Japan), Haga, N. (University of Tokyo Hospital, Japan), Burdet, E. (Imperial College, London, UK); Gennisson, J. (ESPCI ParisTech, France); Kaneko M (Osaka University, Japan); Mihailidis, A. (University of Toronto), Gao, D. (General Motors), Stefanini , C. (Biomedical Engineering, Scuola Superiore Sant'Anna, Italy).

(ii) Graduate and Postdoctoral Advisors

Graduate advisor: Yoshikawa, T., Ritsumeikan University, Japan (formally Kyoto University)
Postdoctoral Advisor: Asada, H. Mechanical Engineering, Massachusetts Institute of Technology

(iii) Thesis Advisor and Postgraduate-Scholar Sponsor

Graduate thesis advisor:
Joshua Schultz, Ph.D. Candidate, Mechanical Engineering, Georgia Institute of Technology
David MacNair, Ph.D. Candidate, Robotics Ph.D. Program, Georgia Institute of Technology
Billy Gallagher, Ph.D. Candidate, Robotics Ph.D. Program, Georgia Institute of Technology
Melih Turkseven, Ph.D. Student, Mechanical Engineering, Georgia Institute of Technology
Gregory Henderson, M.S. Student, Mechanical Engineering, Georgia Institute of Technology
Timothy McPherson, M.S. Student, Mechanical Engineering, Georgia Institute of Technology
Ellenor Brown, Ph.D. Student, Applied Physiology, Georgia Institute of Technology

Postdoctoral scholar:

Dr. Yuichi Kurita, Assistant Professor of Nara Institute of Science and Technology, Japan
Dr. Ding Ming, Postdoctoral Fellow, the Science University of Tokyo, Japan

Andrea Vacca
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*, Journal of Systems and Control Engineering, to be published (available online since Feb 2015).
2. 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.
3. Devendran, R., Vacca, A., 2014, *A novel design concept for variable delivery flow external gear pumps and motors*, International Journal of Fluid Power, 15:3, 121-137.
4. 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.
5. 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.

Significant Products

6. 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.
7. 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.
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, *A Novel Pressure-Feedback Based Adaptive Control Method to Damp Instabilities in Hydraulic Machines*, SAE Int. J. Commer. Veh. 5(2):2012.
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), Gulati N. (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), S. Dhar (Simerics), M. Greco (ZEC, Italy)

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, 16*th* Annual Conference of the International Soci- ety for Computer Aided Surgery (ISCAS) 2012; Best Oral Presentation Award, ASME Design of Medical Devices Conference 2012; Best Oral Presentation, Hamlyn Sym- posium on Medical Robotics 2011; Best Technology Presentation, 19*th* International Congress of the European Association of Endoscopic Surgery 2011; Best Paper Award, Eurosensors 2008. IEEE RAS, IEEE EMBS, EAES, ASEE member.

Contributing Associate Editors-in-Chief of World Journal of Gastroenterology, Baishi- deng Publishing Group Co., Limited. Associate Editor for IEEE ICRA 2013. Reviewer for IEEE Transactions on Robotics, IEEE/ASME Transactions on Mechatronics, IEEE Transactions on Biomedical Engineering, IEEE Transactions on Magnetics. Developed a new course *Miniaturized Wireless Mechatronic Systems* at Vanderbilt University. The class is a combination of lectures, literature readings, hands-on lab programming of wireless microcontrollers, modeling interactions between the mecha- tronic system and the surrounding environment, and a significant research project. Recent seminars given at: University of Illinois-UC, Tennessee State University, Univer- sity of Colorado - Boulder, Imperial College of London, EPFL, and Tianjin University.

Collaborators & Other Affiliations

Recent Collaborators. Akos Ledeczi (Vanderbilt University), Mark Rentschler (Uni- versity of Colorado - Boulder), Peter Volgyesi (Vanderbilt University).
Graduate Advisor. Paolo Dario (Scuola Superiore Sant'Anna).
Advisees – Ph.D. Primary Adviser (4): Trevor L. Bruns and Charreau S. Bell (Vanderbilt University, expected 2016), Christian Di Natali and Marco Beccani (Van- derbilt University, expected 2015).
Advisees – Ph.D. Co-Adviser (1): Massimiliano Simi (Scuola Superiore Sant'Anna, expected 2013).

James D. Van de Ven
Mechanical Engineering Department
University of Minnesota

Professional Preparation

South Dakota School of Mines and Technology	Mech. Engr.	B.S. 2001
University of Minnesota-Twin Cities	Mech. Engr.	Ph.D. 2006
ERC for Compact and Efficient Fluid Power, Univ. of MN	Mech. Engr.	Postdoctoral 2006-2007

Appointments

Assistant Professor, August 2011 – present, Mechanical Engineering Department, University of Minnesota-Twin Cities, Minneapolis, MN

Assistant Professor, August 2007 – 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

This page is intentionally left blank

Lisa J. Wissbaum
Department of Mechanical Engineering
University of Minnesota

Professional Preparation

University of Minnesota	College of Liberal Arts	B.I.S., 2001
University of Minnesota	Humphrey Institutute of Public Affairs	MPA, 2008

Appointments

2009-present	Administrative Director, NSF Engineering Research Center for Compact and Efficient Fluid Power
2008-2009	Executive Office and Administrative Specialist, IPrime - Chemical Engineering Department, Univ. of Minnesota
2006-2008	Administrative Fellow, NSF IGERT, Dept. of Mechanical Engineering, Univ. of Minnesota
1985-2006	Travel Manager, Account Manager, Travel Agent - TravelCorp, Minnesota

Closely Related Products

Anders, Deena, J. Burza, C. Coslin, P Kresser, E. Messiou, S. Nelson-Salcedo, A. Morris, M. Pidduck, K. Sharpe, K. Sowards, L. Wissbaum, "Immigration Policy and Law in the Post-9/11 Era: A study of Civil and Human Rights Concerns," published in *Law Enforcement Executive FORUM, 2007 7(7), p.33.*

Synergistic Activities

- Candidate for Department Administrator, University of Minnesota, Sponsored Projects Administration Spectrum Program. Completion expected in 2013
- Member of Project and Change Management Collaborators Group, University of Minnesota, since 2011.
- Certificate candidate for Project Management; University of Minnesota, College of Continuing Education (CCE), Completion expected in 2013.
- Supervisory training through University of Minnesota, Office of Human Resources (OHR) through the Office Organizational Effectiveness, completed November 2011
- Certificate in Travel management (CTC), 1998

Collaborators & Other Affiliations

Graduate Advisors: Hubert Humphrey Institute of Public, advisors, G. Edward Schuh, Gary DeCramer.

This page is intentionally left blank