CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

Engineering Research Center for Compact and Efficient Fluid Power

Strategic Research Plan

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Executive Summary

The Center for Compact and Efficient Fluid Power (aka CCEFP or "the Center") is a network of fluid power research laboratories, academic faculty, graduate and undergraduate students at seven universities. The Center's vision is make fluid power the technology of choice for power generation, transmission, storage, and motion control applications. It pursues this vision by focusing on two key objectives:

- Driving a pre-competitive research strategy focused on industry needs that leverages fluid power's inherent strengths and eliminates or substantially reduces its key technical barriers. The CCEFP seeks to transfer its research discoveries to industry so that they can be commercialized and bring transformational changes in fluid power's current and future markets.
- Educating a growing pipeline of university students in fluid power, connecting many to positions in industry where their knowledge can be used to create new and better products, and connecting others to academia where they can educate the next generation of fluid power engineers.

To accomplish the first objective, the Center maintains a wide-ranging research strategy, based on input from multiple sources including the fluid power industry's needs as expressed in the NFPA Technology Roadmap. In seeking to address fluid power's key technical barriers, this research strategy calls for the CCEFP to support and coordinate pre-competitive research in three thrust areas:

- *Efficiency* – addressing the technical barriers associated with increasing the energy efficiency of fluid power components and systems, as well as efficient control and energy management through fluid power.
- *Compactness* – addressing the technical barriers associated with compacting or integrating power supplies, energy storage devices, and other components.
- *Effectiveness* – addressing the technical barriers associated with making fluid power safer, easier-to-use, leak-free and quiet.

In order to encourage a systems-based approach to addressing these technical barriers, the CCEFP has historically supported a number of test beds, on which the results of its individual research projects can be validated in a systems environment, and where its student researchers can develop their skills using a systems-level approach to solving technical challenges.

As the Center transitions from a National Science Foundation-funded Engineering Research Center to a sustaining research center it will seek, through its partnerships with industry and mission-centric government agencies, to support three existing and two envisioned fluid power research Centers of Excellence:

- Hydraulics Research Center of Excellence at Purdue University (existing)
- Hydraulics Testing and Evaluation Center of Excellence at the Milwaukee School of Engineering (existing)
- Fluid Power Manufacturing Research Center of Excellence at Georgia Tech (existing)
- Hydraulics/Powertrain Research Center of Excellence at the University of Minnesota (envisioned)

- Pneumatics/Human Scale Research Center of Excellence at Vanderbilt University (envisioned)

Why Fluid Power?

Fluid power is the use of fluids to generate, transmit and control power. Fluid power is sub-divided into *hydraulics*, which uses a liquid (typically mineral oil or water) as the working medium, and *pneumatics*, which uses a gas (typically air) as the working medium. Fluid power is used in a wide range of industries, including manufacturing, transportation, aerospace, agricultural, construction, mining and forestry. Nearly all U.S. manufacturing plants rely on fluid power in their production of goods; and over half of all U.S. industrial products have fluid power critical components.[1] Fluid power has the advantages of flexibility and high power density that can be more widely exploited. Based on magnetic material properties, an electric motor can develop the same torque as a hydraulic motor of the same size operating at a pressure of 250 psi.[2] Since hydraulic systems routinely operate at pressures of 3000 psi, such a hydraulic motor will have twelve times the torque of the same sized electric motor. If the shaft speeds are the same, the power ratio will also be twelve, which is why fluid power systems can have a much higher power density than electric systems. In a comparison of rotary and linear actuators for robots, it is found that hydraulic actuators have a power density that is up to one hundred times greater than for electric motors based on volume and five hundred times greater based on weight.[3] Fluid power systems also have one to two orders of magnitude greater bandwidth than electromechanical systems with similar power ratings.[4] Fluid power is essential for large equipment which require high-power and high- force. The use of fluid power is so prevalent that any improvement in efficiency will have an important impact on energy consumption. Further, the intrinsic bandwidth and power density advantages of fluid power has not been exploited on smaller scale, portable and self-powered systems.

Based on 2013 U.S. Census Bureau data, sales of fluid power components exceeded $22 billion and employed 71,000 people. Fluid power also has a significant downstream economic impact. Ten key industries that depend on fluid power are estimated to represent more than 23,900 companies in the United States, employing more than 874,000 people with an annual payroll of more than $54.4 billion. The substantial size of the market in terms of dollars and jobs indicates the potential for new and expanded businesses. However, more than corporate profits and jobs are at stake. Reducing energy consumption is directly related to reducing carbon dioxide emissions, the major cause of global warming. There are literally millions of devices in use around the world today ranging from industrial air compressors to large agricultural, mining and construction vehicles. As will be discussed in the next paragraph, reductions in the fuel consumption in current applications of fluid power can have a significant impact on U.S. energy use. These efficiency improvements will also facilitate the expansion of fluid power into adjacent market segments. Further, new compact fluid power systems will increase our quality of life by enabling human-scale, untethered systems such as the patient transfer device and the orthosis.

A groundbreaking report titled "Estimating the Impact (Energy, Emissions and Economics) of the U.S. Fluid Power Industry" was published by Oak Ridge National Laboratory (ORNL) in December 2012.[5] The report was a DOE-funded study to estimate the energy-specific footprint (consumption, emissions, efficiency) of currently deployed fluid power systems in the U.S.. The authors were Dr. Lonnie Love of ORNL and Eric Lanke and Pete Alles of the National Fluid Power Association. Thirty-one industrial partners provided input to the study. The report provides information that will have an impact on fluid power research for years to come. Some of the key findings include:

- Fluid power systems consume between 2.0 and 2.9 Quadrillion Btus (Quads) of energy per year and produce 310-380 million metric tons of CO_2. The energy to operate fluid power systems is 2-3% of all of the energy consumed in the U.S..

- Mobile hydraulics consumes 0.4-1.3 Quads/year
- Industrial hydraulic equipment consumes approximately 1.1 Quads/year
- Pneumatic equipment consumes approximately 0.5 Quads/year

- Across all industries, fluid power efficiencies range from 9% to 60% with an average of 22%. The specific application of the fluid power system impacts its efficiency.
- The study provides an overview of the aggregate, sector and market energy usage for fluid power systems. It also offers suggestions for some potential areas of improvement.

The DOE study provides insights on the impact of fluid power on energy consumption in the U.S. For the first time, fluid power practitioners have an understanding of energy use and efficiency in aggregate and by sector.

CCEFP Mission and Vision

CCEFP's mission is to change the way that fluid power is researched, applied and taught. To achieve this mission, the Center focuses its research in areas that will solve existing industry challenges or create new opportunities for fluid power or both. Using the NSF three-plane model for research strategy (Figure 1, page 15), the Center uses a systems approach to assure that its research is properly aligned with and applied to the end use of the technology. The Center is developing new approaches to teach the next generation of fluid power engineers and academics. In addition, CCEFP's education and outreach program is designed to transfer this knowledge to diverse audiences including students of all ages, users of fluid power and the general public.

CCEFP's original vision was to "make fluid power compact, efficient and effective". Although these remain important research goals and have been the Center's three research thrusts since its inception, the vision statement has recently changed. In 2014, the Center's vision became "make fluid power the technology of choice for power generation, transmission, storage, and motion control". We believe that the new vision better describes the compelling future state desired while the original vision statement describes means for achieving the future state. Improvements in manufacturing processes affect all three thrusts and are critical to achieving our vision. Focusing the Center's research on the desired compelling future state forms the basis for transformational change in the fluid power industry.

The Center has established a number of goals to help realize its vision:

1. Double fluid power efficiency in current applications and in new transportation applications.
2. Increase fluid power energy storage density by an order of magnitude.
3. Develop new miniature fluid power components and systems including power supplies that are one to two orders of magnitude smaller than anything currently available.
4. Make fluid power ubiquitous - meaning broadly used in many applications and environments. This requires fluid power that is clean, quiet, safe and easy to use.
5. Improve the manufacturing (quality, cost and delivery) of fluid power components and systems so that they become the technology of choice for both existing and new markets.

State of the Art for Fluid Power

In spite of its advantages, fluid power has largely been confined to applications where the required power density precludes other solutions. The likely cause of this is that fluid power has shortcomings that are barriers to more widespread use. These barriers include:

1. Inefficient components and systems;
2. Excessive weight and size for portable applications; and
3. Noise, leakage, contamination and awkward operator interfaces.

Inefficient components and systems waste energy and cause excessive heating of working fluids which decreases their lives. Current bearing technology has energy losses that limit efficiency of pumps, motors and actuators. Current fluid power control relies on the throttling action of metering valves, causing large amounts of energy to be wasted. Excessive weight and bulkiness also lead to increased energy consumption and prevent applications where smaller, untethered or portable devices are required. Despite the high power density of fluid power actuators, pneumatic and hydraulic power units are bulky. The needed compact energy sources and compact energy storages are not available. Noise and vibration are annoying and have adverse effects on human health and machine reliability, and awkward user interfaces require increased training and task completion time, prevent convenient use and compromise safety. Awkward machine interfaces that slow operations also result in increased energy consumption. The most common hydraulic fluids are toxic and benign fluids compromise performance and cause corrosion of components. For this reason, fluid power components must be leak-free to prevent environmental damage. Contamination is another barrier to reliable and trouble-free operation, and new approaches are needed to minimize its impact.

The manufacturing of fluid power components and systems has remained relatively unchanged for decades. It is characterized by small to mid-sized production volumes of components with tight manufacturing tolerances. Batch processing is common for many operations. Long lead times and high inventory counts are commonplace. A final “break-in” test operation is typically performed after final assembly. These practices result in substandard quality and reliability rates and unnecessarily high production costs.

The commercial success of a technology is strongly influenced by its value proposition. When multiple technology options are available for a specific function in an application, such as power transmission in mobile off-road equipment, the technology that most effectively addresses the critical attributes of the function is likely to be selected. An analysis of the state of the art of the four most common power transmission technologies (hydraulic, pneumatic, mechanical and electrical) assessing important attributes of power transmission technologies for each can provide insights into the challenges and opportunities for their widespread adoption. This process was completed for key fluid power markets and applications and some potential future markets and the results are detailed in the following pages.

Mobile Off-Road Equipment

Hydraulics is the dominant power transmission choice for mobile off-road equipment. These machines are heavy (1-100+ tons), require actuation for propulsion, steering and multiple work circuits and have varying power requirements including very low speed and high torque for some functions. Because of the characteristics of the equipment and their duty cycles, mobile off-road equipment users place a premium on certain attributes. These high priority attributes for mobile off-road equipment are highlighted in purple in Table 1.

Table 1: Power transmission attributes and priorities for mobile off-road equipment

	Power Transmission Technology			
Attribute	**Hydraulics**	**Pneumatics**	**Mechanical**	**Electrical**
Power to weight ratio (prime mover)	++	– –	+	–
Energy to weight ratio (prime mover)	++	– –	+	–
Power to weight ratio (storage)	++	–	++	–
Energy to weight ratio (storage)	– –	–	– –	++
Power to weight ratio (actuation)	++	–	++	–
High torque and force	+	– –	–	– –
High power bi-directional transients	+	– –	++	–
Bandwidth	++	–	– –	+
Load holding without energy	++	+	+	–
Flexible routing	++	++	– –	++
Power transmission loss	– –	–	++	++
Infinitely variable transmission of power	++	+	– –	++
Efficiency	– –	– –	++	+
Noise	– –	–	+	++
Cleanliness	– –	++	+	++
Design tools	– –	– –	+	++
Educated workforce	– –	– –	+	++

Excellent	**Good**	**Poor**	**Deficient**

The relatively low efficiency of hydraulics has not deterred its use in mobile off-road equipment because other advantages outweighed the poor efficiency. Recent increases in fuel prices and the more demanding Tier IV non-road emissions standards have caused mobile off-road equipment users to demand increased efficiency from their new equipment to lower operating costs. This requirement can be met by increasing the overall system efficiency by lowering component losses, and improving control and energy management. Hybridization can further improve efficiency. At present, these technologies provide a differentiation for equipment OEMs, but the trend is that high efficiency machines will become the norm. Thus, an important need to maintain fluid power's dominance in mobile off-road equipment is to significantly improve its efficiency.

Industrial Equipment

Industrial equipment uses power transmission systems similar to those in mobile hydraulics. A major difference is that industrial equipment is stationary so that power or energy to weight ratios are less important. The critical attributes for industrial hydraulics are highlighted in purple in Table 2.

Table 2: Power transmission attributes and priorities for industrial hydraulics

	Power Transmission Technology			
Attribute	**Hydraulics**	**Pneumatics**	**Mechanical**	**Electrical**
Power to weight ratio (prime mover)	++	−−	+	−
Energy to weight ratio (prime mover)	++	−−	+	−
Power to weight ratio (storage)	++	−	++	−
Energy to weight ratio (storage)	−−	−	−−	++
Power to weight ratio (actuation)	++	−	++	−
High torque and force	+	−−	−	−−
High power bi-directional transients	+	−−	++	−
Bandwidth	++	−	−−	+
Load holding without energy	++	+	+	−
Flexible routing	++	++	−−	++
Power transmission loss	−−	−	++	++
Infinitely variable transmission of power	++	+	−−	++
Efficiency	−−	−−	++	+
Noise	−−	−	+	++
Cleanliness	−−	++	+	++
Design tools	−−	−−	+	++
Educated workforce	−−	−−	+	++

Excellent	Good	Poor	Deficient

Fluid power has been losing market share to electrical systems in industrial hydraulics applications and markets for more than 20 years. By comparing the performance of hydraulic and electric power transmission systems in the attributes that are critical for industrial hydraulics, one can identify the attributes that must be improved for fluid power to be competitive. Noise and cleanliness are high priorities in factories for worker comfort and safety reasons. Efficiency is another critical attribute in industrial equipment because energy consumption is an important component operating costs. Thus, the technical barriers that must be overcome for industrial hydraulics are efficiency, noise and cleanliness (no leaks).

Factory Automation

For factory automation, pneumatics is often the technology of choice due to its simplicity, flexibility and low cost. Requirements include cleaning a work area (e.g., blowing chips off of a machine tool or work piece), motion control and power transmission. The attributes of different power transmission methods that are important for factory automation are highlighted in purple in Table 3. As was the case with industrial equipment, noise and cleanliness are high priorities.

Table 3: Power transmission attributes and priorities for industrial pneumatics

	Power Transmission Technology			
Attribute	**Hydraulics**	**Pneumatics**	**Mechanical**	**Electrical**
Power to weight ratio (prime mover)	++	– –	+	–
Energy to weight ratio (prime mover)	++	– –	+	–
Power to weight ratio (storage)	++	–	++	–
Energy to weight ratio (storage)	– –	–	– –	++
Power to weight ratio (actuation)	++	–	++	–
High torque and force	+	– –	–	– –
High power bi-directional transients	+	– –	++	–
Bandwidth	++	–	– –	+
Load holding without energy	++	+	+	–
Flexible routing	++	++	– –	++
Power transmission loss	– –	–	++	++
Infinitely variable transmission of power	++	+	– –	++
Efficiency	– –	– –	++	–
Noise	– –	–	+	–
Cleanliness	– –	++	+	++
Design tools	– –	– –	+	++
Educated workforce	– –	– –	+	++

Excellent	Good	Poor	Deficient

Factories using pneumatics typically store compressed air in a tank that is filled by an electrically powered compressor. Air lines are routed to the locations requiring pressurized air. Large plants may have multiple compressors serving specific segments of the building. A vast number of pneumatic hand tools have been developed. These tools are light, robust and inexpensive and are common in sites using pneumatics. In theory, a plant could use electric instead of air tools, but the electrical devices tend to be more expensive and more prone to being damaged by the processes being used in the plant. An "all electric" site would also not have shop air to use for cleaning and other non-power transmission needs. Neither hydraulic nor mechanical power transmission technologies offer the flexibility that pneumatics provides, so they are less often chosen.

Pneumatics in industrial equipment is at a significant disadvantage when compared to mechanical and electrical alternatives in part due to its poor ability to transmit high torque and force as well as transmit high power bi-directional transients and its low bandwidth. However, hydraulics provides the highest level of all of these attributes among current technology alternatives. Thus, the key technical barriers that must be overcome for industrial pneumatics are efficiency and noise.

Human-scale Powered Devices

The Center seeks to expand fluid power's use in human-scaled fluid power devices. Some examples of new market opportunities are medical applications, self-powered tools and self-powered exoskeletons. The attributes that are critical to growth in current human-scale applications and creating new market opportunities are highlighted in purple in Table 4.

Table 4: Power transmission attributes and priorities for human scale powered devices

	Power Transmission Technology			
Attribute	**Hydraulics**	**Pneumatics**	**Mechanical**	**Electrical**
Power to weight ratio (prime mover)	−	− −	+	−
Energy to weight ratio (prime mover)	−	− −	+	−
Power to weight ratio (storage)	−	−	+ +	−
Energy to weight ratio (storage)	− −	−	− −	+ +
Power to weight ratio (actuation)	−	−	+ +	−
High torque and force	+	− −	−	− −
High power bi-directional transients	+	− −	+ +	−
Bandwidth	+ +	−	− −	+
Load holding without energy	+ +	+	+	−
Flexible routing	+ +	+ +	− −	+ +
Power transmission loss	− −	−	+ +	+ +
Infinitely variable transmission of power	−	+	− −	+ +
Efficiency	− −	− −	+ +	+
Noise	− −	−	+	+ +
Cleanliness	− −	+ +	+	+ +
Design tools	− −	− −	+	+ +
Educated workforce	− −	− −	+	+ +

Excellent	Good	Poor	Deficient

Because the scale of these devices is so small, the assessments of a number of attributes in hydraulic power transmission have been changed. Current hydraulic solutions do not scale well into the low power range required for human-scale. The key challenges to realizing the Center's objective of expanding fluid power use in current human-scale powered devices is making the power supply smaller, developing more compact energy storage, increasing system efficiency, reducing noise and, in the case of hydraulics, making the system leak-free.

Hybrid Passenger Vehicles

Hydraulic hybrid systems are commercially available in medium and heavy duty commercial vehicle and in mobile off-road equipment. The Center seeks to do the research needed to allow the commercialization of hydraulic hybrid technologies in personal use vehicles, such as passenger cars. Hydraulics scales up easily, but scaling down is challenging. The attributes that are critical to the use of hydraulic hybrids in the passenger car market are highlighted in purple in Table 5.

Table 5: Power transmission attributes and priorities for hybrid passenger vehicles

	Power Transmission Technology			
Attribute	**Hydraulics**	**Pneumatics**	**Mechanical**	**Electrical**
Power to weight ratio (prime mover)	+ +	− −	+	−
Energy to weight ratio (prime mover)	+ +	− −	+	−
Power to weight ratio (storage)	+ +	−	+ +	−
Energy to weight ratio (storage)	− −	−	− −	+ +
Power to weight ratio (actuation)	+ +	−	+ +	−
High torque and force	+	− −	−	− −
High power bi-directional transients	+	− −	+ +	−
Bandwidth	+ +	−	− −	+
Load holding without energy	+ +	+	+	−
Flexible routing	+ +	+ +	− −	+ +
Power transmission loss	− −	−	+ +	+ +
Infinitely variable transmission of power	+ +	+	− −	+ +
Efficiency	− −	− −	+ +	+
Noise	− −	−	+	+ +
Cleanliness	− −	+ +	+	+ +
Design tools	− −	− −	+	+ +
Educated workforce	− −	− −	+	+ +

Excellent	Good	Poor	Deficient

The hybrid vehicle market has enormous potential both commercially and environmentally. However, levels of noise, vibration and harshness and other characteristics that are acceptable in mobile off-road equipment are unacceptable in passenger cars. As can be seen in Table 5, hydraulic hybrids offer unique advantages over electric hybrids in attributes considered critical by vehicle manufacturers and car buyers. These include high power and energy to weight ratio, for the prime mover (e.g., pump), high power to weight ratio for energy storage, high bandwidth, flexible routing and infinitely variable transmission of power. On the other hand, a hydraulic hybrid solution is significantly worse than an electric hybrid in four categories. The goal of increasing hydraulics usage in transportation by making hydraulic hybrid passenger cars a commercial success can only be realized if the technical barriers of low energy to weight ratio for storage (i.e. compact energy storage), system efficiency, noise and cleanliness (no leaks) are overcome.

State of the Art of Fluid Power Manufacturing

The state of the art in low cost, precision machining is currently in the automotive market. Their manufacturing processes are characterized by high volumes that minimize changing setups which lead to higher productivity, less variation and better statistical process control resulting in lower cost components and systems. Fluid power components and systems, on the other hand, are typically manufactured in small to medium sized batches (e.g., dozens to a thousand). This means short production runs, much higher numbers of set up changes, increased variability and higher cost. In addition, fluid power components and systems have precise dimensional requirements and often function in highly loaded operating conditions. This places a premium on both material properties and manufacturing. This leads to the creation of stable, high paying, skilled, domestic manufacturing jobs capable of competing on a global basis.

To bring a focus on the area of advancing fluid power manufacturing capabilities, the CCEFP applied for and received a NIST grant in 2015 to create the Fluid Power Advanced Manufacturing Consortium (FPAMC) that will develop and provide leadership in advancing a national fluid power manufacturing roadmap. This nascent effort began with an advanced manufacturing workshop in July 2015 and the fluid power industry advanced manufacturing roadmap scheduled for release in 2016. This roadmap will be a tool to direct the Center's advanced manufacturing research and development efforts. It is expected to be a combination of processes and technologies currently in use in other market segments and new processes, technologies and materials such as 3D printing and composites.

Desired Future State

The desired future state for the fluid power industry is described by the Center's vision: "make fluid power the technology of choice for power generation, transmission, storage, and motion control".

The ultimate objective of the Center and the focus of its mission, vision and goals is to transform the fluid power industry. The definition of success in achieving this objective, which is the desired future state, has several aspects. Part of it is ongoing research that leverages fluid power's inherent strengths and eliminates or substantially reduces key technical barriers, to transfer the discoveries to industry and have industry commercialize them to make transformational changes that will create growth in current markets and expand the use and benefits of fluid power into new, high growth markets and provide benefits to the fluid power industry, its customers and society. A second aspect of the desired future state is the continuation of the pipeline of students trained in fluid power. Some of these students will go into fluid power companies to use their knowledge to create new and better products, some will remain in academia to train the next generation of engineers and some will go into non-fluid power companies where they may bring fluid power's benefits to other industries. In order to continue this pipeline of students the Center must have a critical mass of researchers (PIs and students) and industry partners to generate the resources required to continue its research, education and intellectual capital transfer on an ongoing basis. Intellectual capital includes assets that a research university can provide to industry such as access to qualified students (graduate and undergraduate) both as university researchers and company employees, as well as access to researchers and research facilities and the potential for licensing and/or creating intellectual property. A third aspect is advancing the manufacturing methods used to produce fluid power components and systems.

The desired future state is a Center that has a proven record of delivering these aspects of success and has implemented a strategy that makes it self-sustaining. We believe that CCEFP's sustainability plan provides a strategy that will bring about the desired future state and ensure that the Center continues to bring transformational changes to the fluid power industry for years to come.

Barriers to Achieving the Desired Future State

The technical barriers that the CCEFP strategic research plan addresses were derived from the weaknesses of fluid power identified in the state of the art analysis in the previous pages. The significant technical barriers facing fluid power are:

1. Efficient Components and Systems
2. Efficient Control
3. Efficient Energy Management
4. Compact Power Supplies
5. Compact Energy Storage
6. Compact Integration
7. Safe and Easy-to-Use
8. Leak-free
9. Quiet

Technical barriers 1, 2 and 3 stem from the low efficiency that hydraulics and pneumatics have when compared to mechanical and electrical alternatives (tables 1-3) and the Center's major goal of doubling fluid power efficiency. Technical barriers 4 and 6 come from the Center's major goal of developing new miniature fluid power components and systems. Technical barrier 5 also supports the miniature components and systems goal, but also addresses the disadvantage that fluid power has compared to alternative technologies in the energy to weight ratio of its energy storage devices (tables 1, 4 and 5). Technical barrier 7 is derived from, among other things, the lack of design tools and an educated workforce challenges for fluid power (tables 1-5). Technical barriers 8 and 9 address the cleanliness and noise attributes in the state of the art assessment, respectively (tables 2-5). Fluid power is at a competitive disadvantage in cleanliness and noise when compared to alternatives at a minimum. In some applications these may represent "show stoppers".

Three of these technical barriers are transformational: efficient components and systems, compact power supplies and compact energy storage. These transformational technical barriers in fluid power generally provide the largest benefits in mobile applications. As a result, mobile hydraulics has been the dominant research focus for Center since its inception. Prior to graduating from the NSF ERC program, three of the Center's four test beds focused on mobile hydraulics and the fourth, the ankle-foot orthosis, had researchers working on both hydraulic and pneumatic solutions.

The nine technical barriers can be grouped in three broad categories. Efficiency includes the barriers of efficient components and systems, efficient control and efficient energy management. Compactness includes the barriers of compact power supplies, compact energy storage and compact integration. Effectiveness includes the barriers of safe and easy-to-use, leak-free and quiet. Historically, these three broad categories – efficiency, compactness and effectiveness – were the Center's three research thrusts.

Achieving the desired future state involves more than inventing component, system and control design advancements that overcome the technical barriers. Another critical piece is bringing new manufacturing processes and technologies as well as new materials into the fluid power industry. Both design and manufacturing must be improved to bring about a transformational change in the industry.

Research Strategy Foundation

The CCEFP research strategy is industry-driven. Every three years, the National Fluid Power Association (NFPA) updates its fluid power technology roadmap through a series of conference calls between industry and staff from both NFPA and CCEFP. The roadmap is focused on aspects of design and performance of fluid power components and systems. The needs of the industry identified in the roadmap form the basis for the research topic areas requested in the biannual CCEFP call for research proposals. The use of industry needs to define the research direction assures that the Center's research addresses the significant and transformational technical barriers that must be overcome to achieve the desired future state for fluid power as well as the major goals of the Center.

Research Strategy Implementation

The primary motivation for and output of the Strategic Research Plan is guiding the research focus of the Center. It also helps to identify areas where stronger leadership or a significant change of focus is required. CCEFP has used an industry-led process to determine the desired research areas in its biannual call for research proposals since its inception. With its graduation as an NSF Engineering Research Center, the Center has developed a strong collaboration with the U.S. fluid power industry's trade organization, National Fluid Power Association (NFPA). CCEFP and NFPA have jointly developed a set of Center Operating Procedures (COPs) that cover a wide variety of topics including industry-led research project selection. The procedures are based on those used by the Center in the past and will replace the old processes staring with projects funded in CCEFP FY11-12. One important aspect of the post-ERC CCEFP is that it will consider research project submissions from universities beyond the original seven in the Center. There will be a requirement that all universities receiving funding from the CCEFP limit their indirect rate to 10% or less. All seven of the current CCEFP universities have agreed to this and any new schools must, as well.

The use of these procedures ensures that the selection of research topics in the call for proposals and the specific projects that are funded are in alignment with the industry's wants and needs. The process is CCEFP facilitated, but industry led. The new procedures for research project selection are described below.

Research Project Selection

The project selection process is done a two-year funding cycle. The Center originally did its project selection process on an annual basis, but the decision was made that starting in CCEFP FY5, the funding period would be extended to two years mainly to encourage proposals that pursue higher impact research. The longer funding cycle also provides more stability to plan graduate student funding.

Call for Proposals

The process for creating the call for proposals is as follows:[6]

1. The CCEFP Research Strategy is reviewed and updated per COP-003.
2. CCEFP Director or his designee works with the CCEFP Industry Engagement Committee to design and distribute a CCEFP Call for Project Proposals to the Participating and Newly-

Identified Universities that will result in project proposals aligned with the prioritized areas of research study.

3. PIs from participating and newly-identified universities respond to call for proposals by completing appropriate templates.

Project Selection

The process for selecting projects is as follows:[7]

1. Responses to the CCEFP strategic call for proposals will be posted on a secure website two weeks before the CCEFP Annual Meeting to allow sufficient time for the proposal review teams to familiarize themselves with the proposals. Access instructions to the website will be provided to each individual representative.
2. A ½ day session at the CCEFP Annual Meeting will be dedicated for PIs to present an overview of their project proposals to the CCEFP Industry Engagement Committee and proposal review team attendees along with Q & A.
3. Following the CCEFP Annual Meeting, each proposal review team representative will assess and rank order project proposals based on the selection criteria. Ranking results from multiple representatives will be combined and compared using appropriate statistical methods and forwarded to the CCEFP Director and CCEFP Industry Liaison Officer.
4. The CCEFP Director and CCEFP Industry Liaison Officer will review the project rankings to ensure proper distribution and strategic alignment, and prepare a final list of rank-ordered projects to be funded.
5. The final list of projects to be funded will be presented to the CCEFP Industry Engagement Committee. Any deviations from the received ranked order due to concerns about distribution or strategic alignment will be described and explained by the CCEFP Director.
6. Projects will be awarded in the final ranked order up to the available funding limit. Typically projects will be funded for two years unless otherwise specified.
7. PIs will be notified of the awards per the lead university SPA [Sponsored Projects Administration] organization.
8. Existing CCEFP projects that are discontinued qualify for bridge funding per CCEFP guidelines.

The ranking of the project proposals by industry subject matter experts (step 3 above) is facilitated by the use of a rubric that provides a quantitative evaluation of various aspects of the proposal. The criteria for scoring the proposals are separated into three subgroups: project risk, project reward or strategic alignment.

FY11 & 12 CCEFP-funded Research Projects

In CCEFP's FY11-12 (June 1, 2016 – May 31, 2018), ten projects were funded.

Control and Prognostic of Electro-Hydraulic Machines
PI: Prof. Andrea Vacca, Purdue University

Hybrid MEMS Proportional Fluid Control Valve
PI: Prof. Tom Chase, University of Minnesota

Free Piston Engine Based Off-Road Vehicles
PI: Prof. Zongxuan Sun, University of Minnesota

Four-Quadrant Multi-Fluid Pump/Motor
PI: Prof. John Lumkes, Purdue University

Efficient, Integrated, Freeform Flexible Hydraulic Actuators
PI: Prof. Mark Nagurka, Marquette University

AC Hydraulic Pump/Motor
PI: Prof. Jim Van de Ven, University of Minnesota

Investigation of Noise Transmission through Pump Casing
PI: Prof. Monika Ivantysynova, Purdue University

Simulation, Rheology and Efficiency of Polymer Enhanced Fluids
PI: Prof. Paul Michael, Milwaukee School of Engineering

Controlled Stirling Power Unit
PI: Prof. Eric Barth,Vanderbilt University

Portable Pneumatically Powered Orthoses
PI: Prof. Elizabeth Hsiao-Wecksler, University of Illinois at Urbana-Champaign

Research Initiatives for Sustainability

The U.S. fluid power industry is fortunate to have a number of world class fluid power research and development facilities at American academic institutions. Some, such as the Maha Lab at Purdue, the Manufacturing Research Center at Georgia Tech and the Fluid Power Institute at Milwaukee School of Engineering, were in place at the inception of the Center in 2006 and some were created through the ERC funding provided by NSF. In addition, CCEFP researchers have identified two other areas where fluid power's benefits can be used to help sustain the Center. We currently envision a coalition of five research "centers of excellence" (COE) as detailed below. Other COEs may be added in the future as specific research areas and lead principal investigators are identified.

Hydraulics Research Center of Excellence

The Maha Fluid Power Research Center at Purdue University has a proven track record. The lab has 11 test rigs and four vehicles that support a very wide variety of research activities. It also has specialty measuring and computing tools that complement the test infrastructure. The Maha Lab supports more than 50 graduate students and visiting researchers and is a strong contributor to advancing the state of the art of hydraulics. The Center believes that Purdue's Maha Lab, and its principal investigators Prof. Monika Ivantysynova and Prof. Andrea Vacca, are a Research Center of Excellence that can be emulated by others working in hydraulics research and other fields.

Hydraulics Testing and Evaluation Center of Excellence

Serving industry since 1962, the Fluid Power Institute (FPI) at Milwaukee School of Engineering (MSOE) is one of the leading academic fluid power laboratories in the nation. FPI performs many types of tests including burst tests, impulse/fatigue tests, performance tests, environmental evaluations, troubleshooting & failure analysis and component manufacturing contamination. FPI's on-campus FPI laboratory occupies 2,400 square feet and features eight test cells. FPI's off campus laboratory facility is a reconfigurable 12,000 square foot workspace with drive-in access, a high-bay ceiling and major hydraulic power capabilities. Thomas Wanke is Director of the Fluid Power Institute.

Powertrain Research Center of Excellence

The primary use of fluid power is to transmit power. Transportation including light duty vehicles, heavy duty vehicles, and off road vehicles accounts for about 30% of the national energy consumption and 70% of petroleum use. The powertrain system for transportation vehicles (the prime mover, the power transfer, and system integration) is critical to realize energy efficiency and reduced emissions. Fluid power is a unique way for power transfer and can play a significant role in the powertrain system and help sustain the CCEFP.

Significant opportunities exist for mobile hydraulic systems in both on road and off road applications.
Hydraulics is currently the dominant power transmission technology in off road vehicles, so the initial focus of the Powertrain Research Center of Excellence will be in off road vehicles. This will allow use of the fluid power industry's existing manufacturing and distribution networks as well as leveraging the on-going research work at the CCEFP and its existing large industry base.

Off-road vehicles are used in agriculture, construction, mining and quarrying, forestry and by the military, among other end uses. Off-road vehicles and equipment and the associated supply chains provide significant economic activities in the U.S. The manufacturing segment alone accounted for more than $100B in shipments and direct employment of more than 250,000 in the U.S. in 2011.[8] The efficiency and performance of the off-road vehicles are critical factors for domestic and global competition. The energy consumed in the U.S. by the agriculture, construction and mining industries totaled 4.8 quads in 2012.[9]

Given the need for significant improvement of fuel efficiency and performance, the off-road vehicles require pre-competitive research and training of future engineers. However, unlike on-road vehicles, currently there is no dedicated program/office in the federal government that funds the pre-competitive research and training in this area. CCEFP, NFPA and industry met with high level officials in the Department of Energy Transportation office to propose establishing an off-road vehicle program. The proposal was given positive feedback. The proposed program would help build strong partnerships between industry, academia and national labs to reduce the energy consumption and increase the productivity of off-road vehicles. CCEFP plans to engage a consulting company with expertise in procuring government funding to help garner the funding.

Prof. Zongxuan Sun of the University of Minnesota is leading efforts to establish a Powertrain Research Center of Excellence.

Pneumatics/Human Scale Research Center of Excellence

Unlike powertrain, human scale fluid power is largely focused on emerging markets. It is reasonable to predict that these markets will grow to billions of dollars over time. Examples include mobile robotics and biomedical applications such as surgery and rehabilitation. Significant progress has been made recently in the most notable barriers of compact power supplies and light weight integrated systems. The CCEFP currently lacks industry supporters who are focused in these areas. This is a major area of concern, a barrier to progress and a challenge to overcome.

Over $600 million in research funding is available from mission-centric government agencies such as NIH, NIDRR, DOD, CDC and NSF. Some potential applications of current and past CCEFP research that are aligned with these funding sources include robotics (prosthetics & orthotics, military robots and human augmentation, hazardous environments) and biomedical applications (MRI compatible surgery and rehabilitation, prosthetics & orthotics, patient handler). CCEFP funded research has helped to develop some of the key enabling technologies required for this COE including compact mobile power supplies (e.g., miniature HCCI piston engine compressor, Stirling thermocompressor), and MEMS pneumatic valves. One technology that appears to align particularly well with this COE is additive manufacturing facilitating design optimization, increased integration and lightweighting.

Prof. Eric J. Barth of Vanderbilt University is leading efforts to establish a Pneumatics/Human Scale Research Center of Excellence.

Fluid Power Manufacturing Research Center of Excellence

The Manufacturing Research Center at the Georgia Institute of Technology is world class. These facilities will be leveraged to help create the Fluid Power Manufacturing Research Center of Excellence. To that end, CCEFP was recently awarded a $413,269 NIST Advanced Manufacturing Technology Consortia (AMTech) planning grant. There are two main goals of the grant:

- Create an advanced manufacturing roadmap for the fluid power industry.
- Create a sustaining consortium to maintain and implement the roadmap.

The Fluid Power Advanced Manufacturing Consortium (FPAMC) has been established through the grant. FPAMC's initial advanced manufacturing roadmapping workshop was held July 28-29, 2015 at Georgia Tech. There were 39 participants in workshop including 23 from fluid power industry companies. Nine capability challenges facing the fluid power industry and 8 emerging technologies that should be leveraged by the industry were identified in the workshop. "Innovation scorecards" for these 17 items are being developed by subject matters experts. These scorecards will facilitate the creation of the first draft of the fluid power advanced manufacturing roadmap. A second FPAMC advanced manufacturing roadmapping workshop is planned for the first half 2016.

Prof. Tom Kurfess, HUSCO/Ramirez Distinguished Chair in Fluid Power and Motion Control at Georgia Tech, is leading efforts to establish a Fluid Power Manufacturing Research Center of Excellence.

Conclusion

The Engineering Research Center for Compact and Efficient Fluid Power (CCEFP) is the premier fluid power research collaborative in North America and is among the best in the world. The Center fills a void in U.S. fluid power research that existed for decades. Prior to the establishing of the CCEFP, the U.S. had no major fluid power research center (compared with thirty centers in Europe and many others in Asia). Fluid power researchers, who were previously disconnected, are now linked through the CCEFP.

CCEFP’s focus combines fluid power research and education with a strong industry partnership. From its inception in 2006, the Center’s mission has been to change the way fluid power is researched, applied and taught and its vision has been to make fluid power compact, efficient and effective. CCEFP’s mission and vision remain as vibrant and compelling today as they were in 2006. Said another way, while great progress has been made by CCEFP across a broad, yet targeted front, there is still work to do.

The relationships developed between the Center, its PIs and students, and industry during CCEFP’s ten years as a National Science Foundation Engineering Research Center provide solid footing on which to build a sustaining center. The current and envisioned centers of excellence are aligned with the fluid power industry’s needs and to provide transformational research that can revolutionize the industry. We believe that these COEs will have strong interaction and cross pollination in their research activities. Looking forward, CCEFP will remain a significant funding source for these COEs and will facilitate the interaction of the COEs with industry in order to assure the alignment of the research with their needs.

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