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 and industry partners. 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.

The Center transitioned from a National Science Foundation-funded Engineering Research Center to an industry-sustained research center in 2016. It was quickly recognized that in order to obtain a critical mass of research, new public funding would be necessary. A multi-year government advocacy effort led by CCEFP and supported by its industry partners and the National Fluid Power Association resulted in Department of Energy funding for off-highway vehicle research, of which fluid power is a major enabling technology. Forming project teams from its participating universities and industry partners to secure DOE funding for fluid power research in off-highway vehicles is the cornerstone of the revised CCEFP strategy. Presenting research results from these projects at CCEFP Summits ensures that knowledge gained is broadly disseminated to industry and the greater fluid power research community. These Summits are a key venue for establishing and maintaining a critical network between academia, researchers, students, industry, and national laboratories.

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. The Center encourages 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 changed. In 2014, the Center's vision became "make fluid power the technology of choice for power generation, transmission, storage, and motion control". This revision of the strategy recognizes the strong market trend toward electrification and autonomous vehicles. Research that blends the positive aspects of fluid power with electric power or leverages the benefit of fluid power components and systems for autonomous or semi-autonomous off-highway vehicles is also included in our vision. We believe this new vision better describes the compelling future state and the potential of fluid power. Improvements in manufacturing processes are critical to achieving our vision and associated research is also included 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 received a NIST grant in 2015 to create the Fluid Power Advanced Manufacturing Consortium (FPAMC) as well as a national fluid power manufacturing roadmap (link to manufacturing roadmap here). This roadmap is 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) as both 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.

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 center aligned with the fluid power industry's needs and to provide transformational research that can revolutionize the industry.

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