2017 NFPA TECHNOLOGY ROADMAP

# IMPROVING THE DESIGN AND FUNCTION OF FLUID POWER COMPONENTS AND SYSTEMS

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## BACKGROUND AND INTRODUCTION

### Technology Roadmap for the Fluid Power Industry

In August 2009, the National Fluid Power Association (NFPA) published the *Technology Roadmap for the Fluid Power Industry.* The purpose of the Roadmap was to provide NFPA member companies and their research partners with an industry-wide consensus regarding the research and development needs of the fluid power industry.

The Roadmap was the result of a facilitated process among representatives from 20 organizations in the fluid power industry, and it charted a ten-year research and technology development agenda to realize industry-elevating advancements in mobile hydraulics, industrial hydraulics, and pneumatics. In creating the Roadmap, the representatives specifically focused on advancements they thought would help the industry meet the future needs of its customers, expand fluid power into new customer markets, and attract the best and brightest students to field.

Since its publication, the Roadmap has been used by the NFPA Education and Technology Foundation and the Center for Compact and Efficient Fluid Power (CCEFP) to guide their respective research efforts, and by numerous NFPA members and other industry partners to inform decisions about research partnerships and product development.

### A Pre-Competitive Research Agenda for the Fluid Power Industry

In 2012, NFPA convened a task force of industry representatives to review and update the *Technology Roadmap for the Fluid Power Industry*. Their report, *A Pre-Competitive Research Agenda for the Fluid Power Industry*, was published in January 2013, and addressed several shortcomings of the original Roadmap. The updated report:

- Expanded the use of end market customer perspectives and drivers in determining the fluid power research challenges to be met and objectives to be achieved.

- Defined “pre-competitive” for the purposes of the report and NFPA’s future use. The report’s research agenda is targeted in areas that are broad enough that they are unlikely to be pursued by individual companies for competitive advantage, but targeted enough that they are likely to result in technological advancements that can assist wide industry sectors.

- Reviewed and incorporated the research successes and progress of the CCEFP in the identification of future research objectives.

- Made specific recommendations for supporting market education and standardization efforts that will complement and help advance the research agenda.

The 2012 report has again been used by the NFPA Education and Technology Foundation and the CCEFP to guide their respective research efforts, and again by numerous NFPA members and other industry partners to inform decisions about research partnerships and product development. It has also been used by NFPA to guide its market education and standards development work.

**NFPA Roadmap Committee**

In 2014, NFPA launched the NFPA Roadmap Committee, a volunteer structure tasked with developing, maintaining, and supplementing the NFPA Technology Roadmap, the industry consensus-based document which identifies the areas of pre-competitive research needed to increase fluid power's competitive position in the marketplace, open up new markets for fluid power, and attract the best and brightest students to the field.

The Committee published its first report in August 2015. It was an update to the task force report published in January 2013, reviewing and updating a pre-competitive research agenda for the fluid power industry. Because many of the challenges to be addressed in this agenda deal with the design and function of fluid power components and systems, the report was titled the *2015 NFPA Technology Roadmap: Improving the Design and Function of Fluid Power Components and Systems.*

In completing that work, the Committee utilized many of the same processes and objectives identified by the 2012 task force, including the use of end market customer perspectives and drivers, the definition of pre-competitive research, the incorporation of CCEFP research successes and progress, and the inclusion of market education and standardization recommendations.

At the time of this publication, it was expected that the Committee would repeat this function on a biennial basis, and that the committee will publish updated reports on that schedule. It is also expected that the committee would participate in the organization and publication of other roadmap documents, each focused on more specific aspects of fluid power technology.

**2017 NFPA Technology Roadmap**

This is the second publication of the NFPA Roadmap Committee – an update to the 2015 report titled the *2017 NFPA Technology Roadmap: Improving the Design and Function of Fluid Power Components and Systems.* The Committee worked via email, conference call, and in-person communications from January to July 2017 to complete the report. Although the report contains information regarding the consensus and individual opinions of the committee members, and represents their most up-to-date thinking on the state-of-the-art, the report should not be interpreted as the single or wholly comprehensive agenda for the fluid power industry.



The 2017 NFPA Technology Roadmap is a tool that can be used, with permission obtained from NFPA, by organizations that wish to pursue projects of importance to the fluid power industry. These organizations include both research institutions and companies across the fluid power supply chain. By aligning their activities with the challenges, objectives, and proposed projects described in the Roadmap, they will all play a role in positively shaping the future of fluid power technology.

NFPA will continue to use the Roadmap to shape and direct the research efforts of the NFPA Education & Technology Foundation and the CCEFP. It will also use the Roadmap as a vehicle by which to attract and organize additional funding for the projects and initiatives it describes.

Unlike previous reports, the 2017 NFPA Technology Roadmap focuses solely on the areas of pre-competitive research needed to increase fluid power's competitive position in the marketplace, and does not propose a specific agenda for fluid power standards development or market education.

The 2017 Roadmap also references a published report by the Fluid Power Advanced Manufacturing Consortium (FPAMC). That report, and the FPAMC, represents a roadmapping effort, led by the CCEFP and funded by a federal grant from the National Institute of Standards and Technology (NIST), to define a set of enabling manufacturing technologies and the research necessary to better apply those technologies to the manufacture of fluid power components. Although the 2017 Roadmap incorporates some of the elements of this "Manufacturing Roadmap," the two reports should be viewed as separate documents with distinct purposes.

By putting forth this Roadmap, representing a broad consensus of industry players, and focused on pre-competitive initiatives that will help develop new technologies to benefit the industries, markets, and people served by fluid power, NFPA demonstrates a commitment both to collaboration and to long-term growth and sustainability.

## ROADMAP ELEMENTS

The 2017 NFPA Technology Roadmap is comprised is of three primary elements, each connected to the next in an interdependent chain.


**Customer Drivers** are the business or technology objectives of fluid power customers. They help them serve the needs of their own customers, and are not necessarily connected to their use of fluid power.

**Research Challenges** are the broad areas of attention that must be addressed if fluid power is to meet or better meet the customer needs described by the drivers.

**Research Targets** are the objectives that quantify or otherwise describe successful strategies for pursuing the Research Challenges.

## ROADMAP UPDATE PROCESS AND TIMELINE

The following process and timeline was used to update the NFPA Technology Roadmap and produce this report.

Jan 23, 2017 Introductory conference call to present update process and timeline

**Phase 1 – Customer Drivers/Research Challenges**

Feb 21, 2017 Customer Driver briefing materials sent to Roadmap Committee, including:
- NFPA Customer Market Survey
- Executive summaries of NFPA Customer Technology Trends reports
- Customer Drivers identified in 2015 NFPA Technology Roadmap

Mar 9, 2017 Presentation of draft Fluid Power Manufacturing Roadmap

Mar 16, 2017 Research Challenge briefing materials sent to Roadmap Committee, including:
- Summary of CCEFP Research Strategy
- Summary of Fluid Power Manufacturing Roadmap
- Research Challenges identified in 2015 NFPA Technology Roadmap

Apr 6, 2017 In-person meeting of Roadmap Committee to:
- Identify and rank Customer Drivers
- Identify, rank, and connect Research Challenges to Customer Drivers
- Discuss possible Research Targets

**Phase 2 – Customer Drivers/Research Challenges**

Apr 24, 2017 Working Groups for each Research Challenge identified

May 16, 2017 Research Target briefing materials sent to Working Groups, including:
- Summary of work performed at April 6 in-person meeting
- Summary of CCEFP Research Project Accomplishments
- Research Targets identified in 2015 NFPA Technology Roadmap

May/Jun 2017 Working Group conference calls to identify and rank Research Targets

**Phase 3 – Final Roadmap Document**

Jun 30, 2017 Draft Roadmap sent to Roadmap Committee for review and comment

Aug 15, 2017 Final Roadmap presented at in-person meeting



## CUSTOMER DRIVERS

Fluid power technology is used in hundreds of applications in dozens of specific customer markets. Generally speaking, all of fluid power's customer markets can be grouped into three general areas—those that are served by hydraulics in mobile applications, by hydraulics in industrial applications, and by pneumatics.

### Trends in Customer Markets

As part of an open discussion at the April 6, 2017 Committee meeting, the following trends in these general fluid power customer markets were identified. Discussion was focused on changes that may have occurred within the last two years, or since the time of the last refresh of the NFPA Technology Roadmap.

- Oil prices have changed, making energy savings less of a customer driver than it was two years ago. The availability of natural gas may have tempered this trend somewhat, but that impacts on-highway more than off-highway vehicles.
- Emission regulations have tightened and are expected to get even tighter, but the current political climate makes that a wild card.
- FDA regulations on food processing and food handling have changed, requiring changes in the materials being used on these machines.
- Industry 4.0 (the widespread use of sensors, connected systems and products, and big data analytics) has arrived.
- There is an increased drive for the electrification of drive systems, control systems, and actuation technologies. This is partially driven by the rise of machines with remote, automated, and/or driverless functionality.
- There is a greater emphasis on worker safety.

### Customer Drivers

As previously stated, Customer Drivers are the business or technology objectives of fluid power customers. They help them serve the needs of their own customers, or end-users, and are not necessarily connected to their use of fluid power. In reviewing the identified trends in fluid power's customer markets, and in discussing what end-user needs they might reflect, the following six drivers were identified as universal among fluid power's general customer markets.

Fluid power's customers want to provide their customers with:

- Increased productivity and performance
- Increased availability/up-time
- Lower total and life cycle costs
- Increased ease/predictability of maintenance
- Quieter machines
- Machines that are compliant with safety regulations

It was decided that the 2017 NFPA Technology Roadmap would be built on the foundation of these six customer drivers.

**Trends in Fluid Power Capabilities**

After self-selecting into working groups representing the three general categories of fluid power customer markets, participants in the April 6 meeting ranked how well mobile hydraulics, industrial hydraulics and pneumatics were currently meeting these customer drivers.

| How well does fluid power currently meet each customer driver? | | | | |
|---|---|---|---|---|
| **Customer Driver** | **Hydraulic Mobile Markets** | **Hydraulic Industrial Markets** | **Pneumatic Markets** | **Weighted Averages** |
| Increased productivity and performance | **1** | **2.5** | **2** | **1.625** |
| Increased availability/up-time | **2** | **2** | **1** | **1.750** |
| Lower total and life cycle costs | **2** | **3** | **1** | **2.000** |
| Increased ease/predictability of maintenance | **3** | **1** | **2** | **2.250** |
| Quieter machines | **3** | **3** | **3** | **3.000** |
| Machines that are compliant with safety regulations | **2** | **3** | **1** | **2.000** |
| **1 = Fluid power is the technology of choice for meeting this customer driver**<br>**2 = Fluid power holds its own among viable competing technologies in meeting this customer driver**<br>**3 = Fluid power is seldom chosen over competing technologies for meeting this customer driver** | | | | |

The weighted averages reflect the relative fluid power product sales volumes in each market segment (50% mobile hydraulics, 25% industrial hydraulics, and 25% pneumatics). Based on those averages, fluid power's strongest advantage is in helping customers deliver increased productivity, performance, availability and up-time to the end-user. Its strongest disadvantage is in delivering machines that are quiet and which have easy or predictable maintenance.

## DEFINITION OF PRE-COMPETITIVE RESEARCH

Pre-competitive research is performed at the time in the technology development cycle when interested, but potentially competitive parties agree that there is value to be gained from a collaborative rather than a competitive approach. It generally resides in the middle ground between fundamental basic research conducted mainly in universities and proprietary research performed or directed mainly by companies. It can be performed to develop new technologies or to determine market readiness of new technologies.

Many organizations use a hierarchy of Technology Readiness Levels (TRLs) to describe a series of discreet steps along a technology development timeline. For the purposes of developing the Research Challenges and Targets included in this report, Roadmap Committee members focused on **TRL 1-4** on the following scale:

**TRL 1 Scientific research begins translation to applied R&D.**
**TRL 2 Invention begins.**
**TRL 3 Active R&D is initiated.**
**TRL 4 Basic technological components are integrated.**
TRL 5 Fidelity of breadboard technology improves significantly.
TRL 6 Model/prototype is tested in relevant environment.
TRL 7 Prototype near or at planned operational system.
TRL 8 Technology is proven to work.
TRL 9 Actual application of technology is in its final form.

## RESEARCH CHALLEGES

The 2017 NFPA Technology Roadmap identifies the following seven broad areas of research challenge for the fluid power industry to tackle in order to meet the future needs of its customers, expand fluid power into new customer markets, and attract the best and brightest students to field.

- Increasing the energy efficiency of fluid power components and systems.
- Improving the reliability of fluid power components and systems (e.g., increasing up-time, reducing maintenance requirements, making fuid power safe and easy to use).
- Reducing the size and weight of fluid power components and systems while maintaining or increasing their power output.
- Building "smart" fluid power components and systems (i.e., ones that perform self-diagnostics and troubleshooting and that integrate easily with "plug and play" functionality).
- Reducing the environmental impact of fluid power components and systems (e.g., lowering noise, eliminating leaks).
- Improving and applying the energy storage capabilities of fluid power components and systems.
- Improving and widening the scope of application for fast, accurate, and cost-effective fluid power control.

Organizations that wish to pursue projects of importance to the fluid power industry should seek alignment with these Research Challenges.

### Interplay of Research Challenges

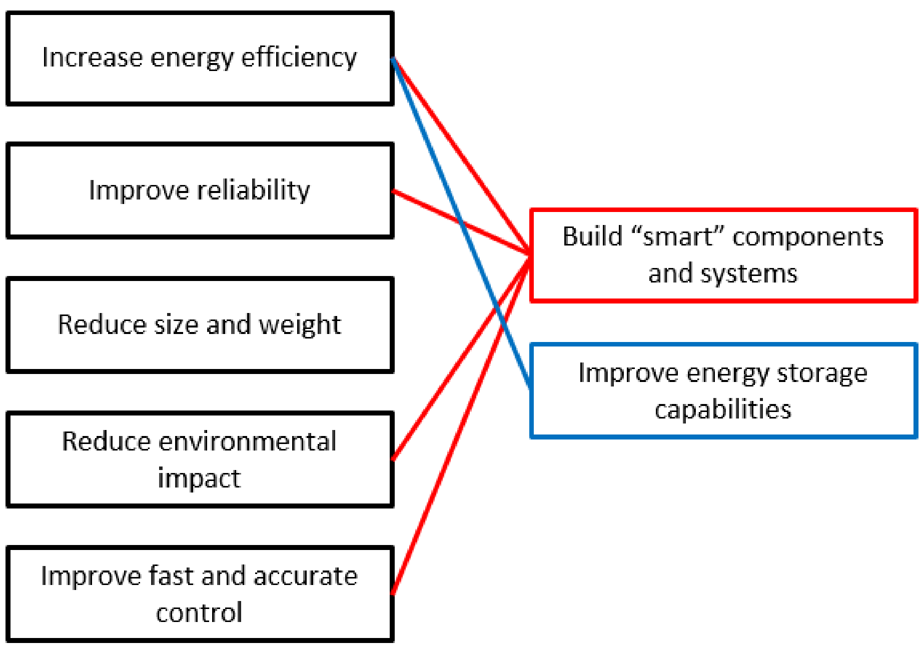
While the Roadmap Committee attempted to identify a set of Research Challenges where the scope of each individual Challenge was clear and distinct from the others, it was recognized that envisioned work within one area of Challenge could effectively serve as a mechanism for achieving other Research Challenges. In that vein, several observations were made, including:

- Successful creation of "smart" fluid power components and systems would likely enable advances in several other areas of Research Challenge, including improvements in the energy efficiency, reliability, environmental impact, and control of fluid power systems.

- Improvements in the energy storage capabilities of fluid power systems would likely enable advances in the energy efficiency of fluid power systems.

- An eighth area of Research Challenge, "Apply new materials or new production methods to fluid power components that improve their performance characteristics (ideally, without increasing their cost)," was discussed and considered. In the end, it was determined that the use of new materials or new production methods to improve the performance of fluid power components would be better positioned as a Research Target within each area of Research Challenge.

A map, illustrating the possible connections between the Research Challenges, is included below.



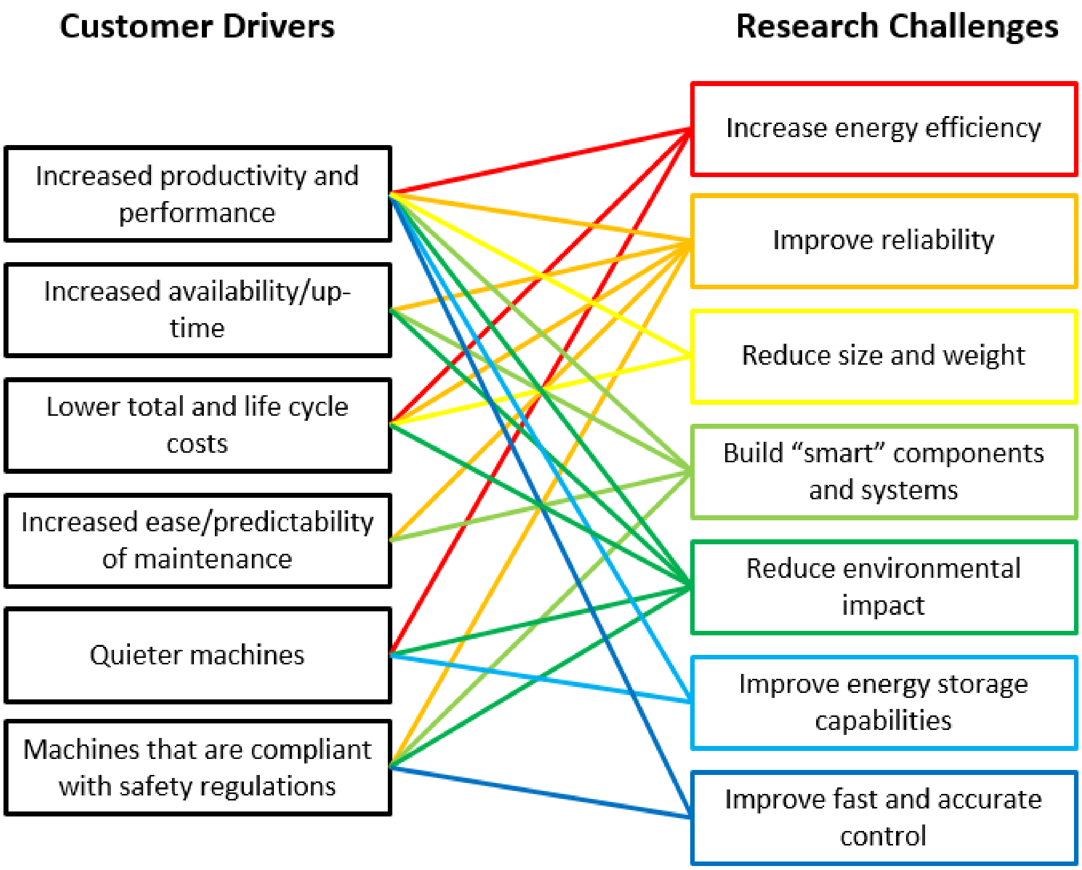

**Connections to Customer Drivers**

Advances in all the areas of Research Challenge are needed for fluid power to meet or continue to meet the needs described by the Customer Drivers. In addition to this general statement, the Roadmap Committee examined each Research Challenge in detail, and identified for each the Customer Drivers with the most significant alignment. In other words, advances in each area of Research Challenge was seen as resulting in fluid power's ability to meet a different set of Customer Drivers. The strongest of these connections are described below.

| RESEARCH CHALLENGE | | CUSTOMER DRIVERS |
|---|---|---|
| Increasing the energy efficiency of fluid power components and systems… | …will help fluid power customers provide their customers with… | • Increased productivity and performance<br>• Lower total and life cycle costs<br>• Quieter machines |

| | | |
|---|---|---|
| Improving the reliability of fluid power components and systems (e.g., increasing up-time, reducing maintenance requirements, making fuid power safe and easy to use)… | …will help fluid power customers provide their customers with… | • Increased productivity and performance<br>• Increased availability/up-time<br>• Lower total and life cycle costs<br>• Increased ease/predictability of maintenance<br>• Machines that are compliant with safety regulations |
| Reducing the size and weight of fluid power components and systems while maintaining or increasing their power output… | …will help fluid power customers provide their customers with… | • Increased productivity and performance<br>• Lower total and life cycle costs |
| Building "smart" fluid power components and systems (i.e., ones that perform self-diagnostics and troubleshooting and that integrate easily with "plug and play" functionality)… | …will help fluid power customers provide their customers with… | • Increased productivity and performance<br>• Increased availability/up-time<br>• Increased ease/predictability of maintenance<br>• Machines that are compliant with safety regulations |
| Reducing the environmental impact of fluid power components and systems (e.g., lowering noise, eliminating leaks)… | …will help fluid power customers provide their customers with… | • Increased productivity and performance<br>• Increased availability/up-time<br>• Lower total and life cycle costs<br>• Quieter machines<br>• Machines that are compliant with safety regulations |
| Improving and applying the energy storage capabilities of fluid power components and systems… | …will help fluid power customers provide their customers with… | • Increased productivity and performance<br>• Quieter machines |
| Improving and widening the scope of application for fast, accurate, and cost-effective fluid power control… | …will help fluid power customers provide their customers with… | • Increased productivity and performance<br>• Machines that are compliant with safety regulations |

A map, illustrating these strong connections between Research Challenges and Customer Drivers, is included below.




It was suggested that future Roadmaps prioritize the Customer Drivers for each Research Challenge to better show the perceived impact of fluid power improvements in our customer markets.

## RESEARCH ADVANCES

Before identifying specific Research Targets for each area of Research Challenge, the Roadmap Committee reviewed related areas of recent research advancement, especially within the universities that make up the Center for Compact and Efficient Fluid Power (CCEFP). Those advances included:

Increasing the energy efficiency of fluid power components and systems.

- Research is underway at the Milwaukee School of Engineering (MSOE) on improving efficiency of fluid power systems through the use of polymer enhanced fluids.
- Researchers at the University of Illinois at Urbana-Champaign (UIUC) have demonstrated pneumatic energy recovery and redeployment to flexible actuators for wrist stabilization and strain reduction as applied to a human crutch.
- Four-quadrant pump-motor research within the CCEFP is investigating mechanical valve timing for optimized porting, reduced electrical energy consumption, and improved reliability.
- A Free Piston Engine Pump (FPEP) at the University of Minnesota (UMN) has demonstrated the ability to control firing under continued operation. Improved fuel and air management modifications are underway. This FPEP represents a radical improvement in overall fuel efficiency versus conventional engine-hydraulic pump systems.
- The compact portable Stirling power unit at Vanderbilt University represents a scalable heat recovery system for industrial waste heat recovery applications.
- A 3D printed excavator with integrated, weight reduced fluid power systems was demonstrated at the 2017 CONEXPO-CON/AGG Show to tremendous reviews and visibility. It included a 3D-printed cab, stick, and oil cooler.
- Digital valves demonstrated at CCEFP universities have been shown to reduce load losses.
- Engine and fluid power system optimization studies, including hybridized systems, have been conducted within the CCEFP.
- Piezo energy harvesting for self-powered sensors have been demonstrated within the CCEFP.
- Nano-texturing of hydraulic lines studied within the CCEFP. Not feasible for high pressure systems but could reduce pressure drop losses for low pressure lines such as inlet/suction lines.
- Exhaust air recovery system that using a novel strain energy storage device has been demonstrated within the CCEFP, with a 25% reduction in air consumption.
- Elastomeric strain energy storage device demonstrated within the CCEFP for pneumatic system (low pressure) while models for high pressure hydraulic versions predict up to 4X times the energy storage density over conventional compressed gas systems.
- Numerous hydraulic hybrid systems (hydraulic hybrid passenger car, excavator swing, etc.) have been demonstrated or modeled within the CCEFP that predict up to 75% energy recovery based on duty cycle.

Improving the reliability of fluid power components and systems (e.g., increasing up-time, reducing maintenance requirements, making fuid power safe and easy to use).

- Nano-texturing for friction reduction of hoses and bearing surfaces studied within the CCEFP.
- Piston bore shaping (tapering, barreling, etc.) has been studied at Purdue University to improve both efficiency and startup capability.
- Tribologist at Zhejiang University in China is studying the life improvement potential of additively manufactured surfaces from a friction and wear standpoint.
- Several OEM commercial solutions (remote monitoring, asset tracking, performance & productivity optimization, etc.) beginning to emerge on the marketplace.
- Research involving truck-mounted cranes at Purdue University is leveraging embedded sensors to address many reliability issues.
- Numerous Human/Machine Interface (HMI) research studies of an excavator simulator undertaken at the Georgia Institute of Technology.
- Intelligent systems that leverage the use of embedded sensors are common place within the CCEFP academic community, including co-bots at Vanderbilt and UMN, passive control at UMN and powertrain optimization controls without operator involvement at Purdue and UMN.

Reducing the size and weight of fluid power components and systems while maintaining or increasing their power output.

- Additive manufacturing of compact power supply (electric motor-pump-valve-reservoir) for hydraulic ankle at UMN increased power density through weight reduction.
- 3D printing and additive manufacturing concepts for fluid power systems (ankle-foot orthosis, steerable pneumatic surgical needle, and hydraulic ankle) designed and prototypes realized within the CCEFP. Up to 50% improvement in weight projected.
- 3D printed excavator boom study at Georgia Tech used a stress optimization technique to remove “unnecessary” load bearing material from conventionally manufactured boom. Up to 20% reduction possible. Integration of internal fluid passages into 3D printed boom demonstrated how system size can be reduced through integration enabled by additive manufacturing.
- Hybrid MEMS proportional valve at UMN combines desired flow rates and response times with smaller package size.
- Compact controlled Stirling power unit at Vanderbilt and free piston engine pump at UMN reduce overall system size and weight by integrating the pump and engine into a single assembly.
- Flexible hydraulic and pneumatic actuator research at UIUC and Marquette University dramatically reduce the weight of human scale systems.

# IMPROVING THE DESIGN AND FUNCTION OF FLUID POWER COMPONENTS AND SYSTEMS

Building "smart" fluid power components and systems (i.e., ones that perform self-diagnostics and troubleshooting and that integrate easily with "plug and play" functionality).

- Piezo energy harvesting for powering sensors demonstrated within the CCEFP and ready for commercialization.
- Emerging remote diagnostics and affiliated software services were commonplace at the recent 2017 CONEXPO-CON/AGG Show.
- Adaptive control techniques have been studied by UMN researchers for hybrid applications.
- Several industry component and systems providers have released configurable components such as programmable valves and pumps as well as control software to easily configure desired system characteristics.
- UMN startup, Innotronics, is developing a low cost, non-contacting magnetic field based position sensor for pneumatic and hydraulic actuators and other position sensing applications.

Reducing the environmental impact of fluid power components and systems (e.g., lowering noise, eliminating leaks).

- Multi-physics seal model for rod seals developed at Georgia Tech.
- CCEFP sound dampening acoustical material demonstrated and ready for commercialization.
- Noise transmission propagation through pump casing study underway at Purdue.
- Vitro-Acoustic Consortium at the University of Kentucky is researching fluid power noise and abatement techniques.
- Research is underway at the University of Northen Iowa on biodegradable and bio-based lubricants.

Improving and applying the energy storage capabilities of fluid power components and systems.

- Elastomeric strain energy storage device demonstrated with the CCEFP for pneumatic system (low pressure) while models for high pressure hydraulic versions predict up to 4X times the energy storage density over conventional compressed gas systems.
- Open air accumulator concept at UMN licensed for wind power energy storage systems. Concept scales up well so is best suited for large stationary systems.
- Concentric compressed air storage concept developed within the CCEFP but no research taken.
- Hydraulically driven flywheel energy storage concept system study underway at UMN.
- Early simulation studies of the fast response time and rapid on/off capability of a Free Piston Engine Pump (FPEP) system within the CCEFP suggest conventional storage of energy in the fuel is sufficient.
- Lightweight aluminum core with composite vessels for accumulators shown within the CCEFP to significantly increase kilowatt-hours per kg.
- Vanderbilt is studying the use of a Stirling power unit to recover waste heat as either fluid or electric power.



- Researchers at the University of Wisconsin are studying the use of foam inside an accunulator to retain energy that would otherwuse be lost when air is rapidly compressed.
- Researchers at the University of Minnesota are studying the use of heat pipes to remove heat quickly from the system and to use that heat as energy.

Improving and widening the scope of application for fast, accurate, and cost-effective fluid power control.

- This Challenge area has not been part of previous Roadmaps, so there has been no specific needs expressed around which the industry's research partners have pursued projects and initiatives. Many of the research projects described above, however, have utilized advanced control techniques, and the industry's base of research partners contains a high number of controls experts.

## RESEARCH TARGETS

For each of the Research Challenges described above, a specific set of Research Targets has also been defined. Research Targets are objectives that quantify or otherwise describe successful strategies for pursuing the Research Challenges. As pre-competitive challenges, it is often difficult to be precise, but these Targets are meant to provide direction for what industry views as fruitful areas of investigation.

The industry's research partners, especially those within the Center for Compact and Efficient Fluid Power (CCEFP), frequently design research projects related to these Targets that seek quantifiable improvements in the 30-50% range. That standard, endorsed by the Roadmap Committee, encourages the exploration of novel mechanisms and, when successful, produces breakthroughs that represent unequivocal improvements.

Organizations that wish to pursue projects aligned with a specific Research Challenge should focus their activities on the Targets described below.

<u>New Materials and Production Methods</u>

As previously noted, the use of new materials or new production methods to improve the performance of fluid power components should be positioned as a Research Target within each area of Research Challenge. The wording of this "universal" Research Target could be:

- Apply new materials or new production methods to fluid power components (ideally without increasing their cost), that either:
    - Increase their energy efficiency;
    - Improve their reliability;
    - Reduce their size and weight;
    - Provide "smart" functionality;
    - Reduce their environmental impact;
    - Improve their energy storage capability; or
    - Widen the scope of application for fast and accurate fluid power control.

<u>Increasing the energy efficiency of fluid power components and systems.</u>

- Reduce the energy consumption of fluid power systems, including, but not limited to, efforts to reduce the pressure loss between power source and actuation, efforts to reduce parasitic system losses, and through the use of energy efficient fluids.

- Improve the energy recovery methods of fluid power systems, specifically not their energy storage capabilities, but their ability to recover and immediately reuse energy.

- Reduce the power loss experienced by fluid power components.

No specific priority order was identified for these Research Targets.

Improving the reliability of fluid power components and systems (e.g., increasing up-time, reducing maintenance requirements, making fuid power safe and easy to use).

First Priority
- Help fluid power systems better enable the machines of machine builders to meet increasing safety requirements.

Second Priority
- Increase the use of “smart tools” to increase the up-time and reduce the maintenance requirements of fluid power systems.

Reducing the size and weight of fluid power components and systems while maintaining or increasing their power output.

First Priority
- Reduce the weight of fluid power components without reducing their operating pressure.
- Produce smaller and/or more integrated fluid power systems without reducing their operating pressure.

Second Priority
- Produce fluid power systems that operate at a higher pressure, either continuously or intermittently, without increasing the size or weight of the system components.

Building “smart” fluid power components and systems (i.e., ones that perform self-diagnostics and troubleshooting and that integrate easily with “plug and play” functionality).

First Priority (developments here were seen as a necessary pre-cursor to developments in the other priority areas)
- Develop smaller, more cost-effective, more robust, and wireless pressure, temperature and position sensors.

Second Priority

- Use data analytics to drive and perform automatic and adaptive control functions (i.e., those that execute without active human direction).
- Allow human-directed electronic controls to actively and adaptively change fluid power system configurations and characteristics.
- Discover new diagnostic modalities that are more cost-effective that current modalities.

Third Priority

- Work with major OEMs to identify and promote standardized communication protocols for fluid power components and systems.

<u>Reducing the environmental impact of fluid power components and systems (e.g., lowering noise, eliminating leaks).</u>

First Priority

- Eliminate external leakage, either by:
    - Improving existing seal technologies (through material improvements and/or improvements in the design of interfaces); or
    - Creating effective testing and detection mechanisms that monitor and prevent leaks in working fluid power systems.

Second Priority

- Reduce the noise, vibration, and harshness (NVH) of fluid power systems to levels lower than that produced by the prime mover, either by:
    - Masking the NVH of fluid power systems; or
    - Eliminating the cause of NVH in fluid power systems.

Third Priority

- Lower the environmental impact of fluid power systems, either by:
    - Developing affordable, biodegradable, and non-hazardous fluids and lubricants; or
    - Developing recyclable fluid power systems or those made from recyclable materials.

<u>Improving and applying the energy storage capabilities of fluid power components and systems.</u>

First Priority

- Discover new, disruptive fluid power energy storage methods that meet or beat cost-per-kilowatt benchmarks of alternate energy storage technologies, that could be made widely available in the marketplace, and which retain or improve on fluid power's high re-charge speed.

Second Priority

- Improve existing fluid power energy storage methods, as measured by significant improvements in kilowatt hours per unit volume or in kilowatt hours per unit weight.

Improving and widening the scope of application for fast, accurate, and cost-effective fluid power control.

- Find more cost-effective solutions for the sensors and actuators that provide the control functions in fluid power systems.
- Identify and resolve the limitations inherent in mechanical systems that prevent the application of fast, accurate, and cost-effective fluid power control.
- Explore novel architectures and algorithms for the control of fluid power components and systems.
- Improve the speed, accuracy, and safety of human/machine control interfaces.
- Use imaging systems to improve the autonomous control functions in fluid power systems.

No specific priority order was identified for these Research Targets.

It was also recognized that the state-of-the-art in the fast and accurate fluid power control systems is generally more advanced in industrial than it is in mobile applications. Another possible Research Target in this Challenge area would therefore be the application of industrial fluid power control mechanisms and protocols in mobile applications.

## COMMITTEE AND WORKING GROUPS

The following individuals served on the NFPA Roadmap Committee and the various working groups it identified to help complete this report.

Chair
- Jim Kaas, Iowa Fluid Power

Vice Chair
- Mark Bokorney, Sun Hydraulics

Hydraulic Mobile Markets Working Group
- Gunter Matt, Bobcat
- Enrique Busquets, Bosch Rexroth
- Aleksander Egelja, Caterpillar
- Michael Freisleben, CNH Industrial
- Eric Bretey, Danfoss
- Kevin Lingenfelter, Danfoss
- Marty Barris, Donaldson Company
- Celine Cabana, FD Groups America
- Rick Hill, Gates
- Hudson Keyler, Gates
- Randy Van Dyken, Kawasaki
- Scott Lane, Linde Hydraulics
- Shubhamita Basu, Lubrizol
- Michael Crosby, Parker Hannifin
- Howard Zhang, Parker Hannifin
- Gilles Lemaire, Poclain Hydraulics
- Wiley Abner, Netshape Technologies
- Mark Bokorney, Sun Hydraulics

Hydraulic Industrial Markets Working Group
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