Efficient, Integrated, Freeform Flexible Hydraulic Actuators

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Marquette’s Research Team

- Dr. Mark L. Nagurka.
  - Graduated from MIT, taught at CMU and now MU for 20 years.
  - Worked with Hank Paynter.

- Jonathon E. Slightam
  - PhD. Student and research assistant at MU.
  - Worked on CCEFP projects for B.S. and M.Sc. at MSOE.
  - Currently working on hydraulic controls for aerial buckets in electric power industry.
Project Overview / Efficient, Integrated, Freeform Flexible Hydraulic Actuators

Research Goals:
• Advance the state-of-the-art in hydraulic actuator technology.
  • Flexible Fluidic Actuators (FFAs)
  • Additive Manufacturing
  • Efficient control.

Role in the CCEFP’s overall research strategy:
• Increases specific power.
• Reduce energy consumption through:
  • Reduced weight by additive manufacturing.
  • Optimal trajectory plans and robust model-based control.

Original contribution:
• New hydraulic actuation technology.
  • Broad applications.

Prior work and research:
• Project 2G.
• What’s been done with hydraulic FFAs?
• Why this work will be better & successful.

Major Objectives/Deliverables

Expected major objectives and deliverables:
• Benchtop Freeform FFA prototype.
• Crimping Tool Prototype.
• Optimal energy trajectory planner.
• 6 degree-of-freedom robotic arm testbed.

Next Steps

Plan for this upcoming year:
• Tasks and milestones.

Areas for Industry help / contributions:
• Collaboration.
• Testing components.
• Pumps, valves, instrumentation, etc.
Research Goals

• The goal of this research is to advance the state-of-the-art in hydraulic actuator technology using flexible fluidic actuators and additive manufacturing.
  – Increase actuation specific power.
  – Decrease system weight using AM.
  – Improve efficiency through optimal control.
Research Motivation

• Decrease the overall energy consumption in the fluid power industry.
  – 2-2.9 quads consumed by fluid power in U.S [1].
    • 1 Quad = 1 Quadrillion BTUs.
  – Total energy consumption in U.S. is 100 Quads per year [1].
  – 310-380 MMT CO₂ produced by fluid power in U.S [1].
  – Fluid power is 2-3% of U.S. energy demands [1].
  – System efficiencies ranging from 9% to 60% [1].

• Reducing energy consumption in fluid power is critical to the CCEFPs strategic plan [2], [3].
Research Objectives

• *Increase power density of hydraulic actuators to 25kW/kg or greater.*
• *Utilize AM technologies to reduce energy consumption in hydraulic machinery by 30%.*
• *Reduce energy consumption up to 5% using optimal control techniques.*
Research Objectives
**Definition:** Flexible fluidic actuators are devices that transmit mechanical power through large deformations of elastic or hyperelastic membranes by an energized fluid.

- **Prolate (contract/pull)**
- **Oblate (expand/push)**
- **Helical (Twist)**
Flexible Fluidic Actuators

Oblate (expand/push)
Flexible Fluidic Actuators

Oblate (expand/push)
Flexible Fluidic Actuators

Helical (Twist/Rotate)
Flexible Fluidic Actuators

Prolate (contract/pull)
Flexible Fluidic Actuators

Flexible Fluidic Actuator Performance (Prolate Pneumatic):

• Specific power as 1.5 – 10 kW/kg.
• Efficiency ranging from 32 to 49%.
  – Efficiencies can be improved with unfolding geometries.
• Power Transmission is unidirectional.
  – Behavior of a nonlinear spring.
Flexible Fluidic Actuators

Flexible Fluidic Actuator Performance (Prolate Hydraulic):

- Use of hydraulic for energization is relatively new.
- Specific power as high as 5.6 kW/kg.
- Efficiencies near 80%.
- Performance limitations unknown.
  - Devices reported operate at low pressure (<4MPa or <580psi).
Freeform fabrication allows for integrated components, fluidic conduits, actuators, and optimal layouts and topologies.
FFAs + Additive Manufacturing

What are the benefits?

• Can reduce weight as high as 80% [43].
  – Commercial optimization software:
    – Altair Hyperworks, Peretoworks, Abequs, Comsol.
  – Case studies:
    – Airbus, MSOE, ORNL, Boston Dynamics, others.
• Can reduce energy consumption by as high as 42% [46].
• Can increase compactness as high as 90% [42]
• More efficient fluid flow paths in manifolds and conduits.
• Consistent trend will emerge with more case studies.
Design for AM

Structural Topology Optimization
Design for AM

Fluid Flow Topology Optimization (Manifold Flow Optimization)
Additive Manufacturing

Large array of different AM technologies:

• Fused deposition modeling.
  • Composites (strength-to-weight ratio similar to Aluminum alloys).
  • Big area additive manufacturing (BAAM).
• Power bed fusion.
• Stereolithography.
• Hybrid processes (additive + subtractive).
• Project will likely use multiple technologies (composite, polymer, hybrid–metal).
• Proposed collaboration with ORNL, Milwaukee Tool, possibly others.
Shortcomings with AM + FFAs

• Limited knowledge on hydraulic FFAs.
  – Large potential to increase the specific power.
  – Little work done with hydraulic fluids.

• Hypothesize that 25kW/kg is obtainable.
  – Specific power is dictated by the weight of the actuator, the rate of fluid energy into the actuator, and the weight of the fluid.

• Limited design for additive manufacturing knowledge in fluid power industry.
Improving Efficiency by Control

Optimal control: Control methods optimize the control signal based on a cost function.

• Optimal energy control systems determine the optimal system trajectory to minimize the energy consumption based on kinetic and potential energy.
Optimal Control

Successes with energy optimal control methods:

• Optimized trajectory planning can improve energy efficiency in motion control applications by 2-10%.

• Power regeneration by control can regenerate as high as 55% of the initial power expended.

• Energy savings of 12% were reported using optimal control methods for an industrial manipulator.
Major Project Outcomes

• Design and fabricate a hydraulic actuator with a specific power of 25 kW/kg.

• System weights reduced by 30% using optimization design tools and AM of efficient, integrated, light-weight, compact, freeform structures.

• Design energy optimal trajectory planners and robust controllers that improve energy efficiency by at least 5%.
Milestones

• Flexible hydraulic actuating system benchtop prototype.
• Hydraulic crimping tool prototype.
• Optimal energy controller/trajectory planner.
• 6 degree-of-freedom robotic arm.

Many opportunities for integration into center testbeds.
Significant Impact

• Reductions in system weight by 30% result in a similar reduction in energy consumption. If adopted by entire industry, energy consumption could be cut by 0.85 quads.

• Model-based energy optimal trajectory planners could reduce energy consumption by as much as 0.3 Quads and $5.6 billion/year.
Questions and Comments

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Citations


