Project 16MA1: Efficient, Integrated, Freeform Flexible Hydraulic Actuators

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Outline of Project

- Research Motivation
- Research Targets
- Improved modeling for hydraulic artificial muscles.
- Model Validation of hydraulic artificial muscles.
- Control design and experiments.
- Current work: Application of hydraulic artificial muscles in additively manufactured systems.

Research Motivation

- Decrease the overall energy consumption in fluid power industry.
  - 2-3 Quads consumed by fluid power in U.S.
    - 1 Quad = 1 Quadrillion BTUs.
  - Total energy consumption in U.S. is 100 Quads per year.
  - 310-380 MMT CO_2 produced by fluid power in U.S.
  - Fluid power is 2-3% of U.S. energy demands.
  - System efficiencies ranging from 9% to 60%.
- Reducing energy consumption in fluid power is critical to CCEFP’s strategic plan.

Research Targets

- Increase specific power of hydraulic actuators.
- Utilize AM technologies to reduce energy consumption in hydraulic machinery.
- Reduce energy consumption by optimal control.

Applications:

(Hydraulic Hand Tool)

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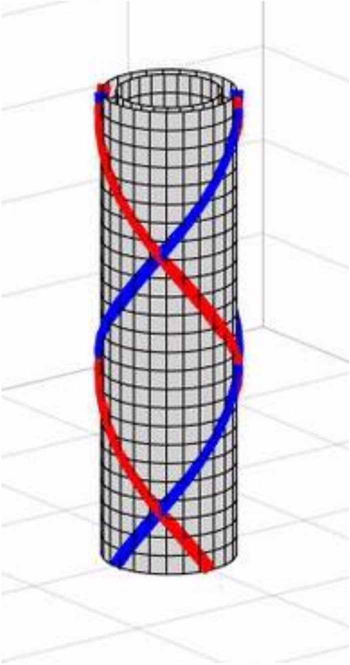
(Robot Arm/Leg)

* E. Ackerman, 2015, "What is Boston Dynamics Working on Next," *IEEE Spectrum*, August 17th, 2015. Available from: http://spectrum.ieee.org/automaton/robotics/humanoids/what-boston-dynamics-is-working-on-next

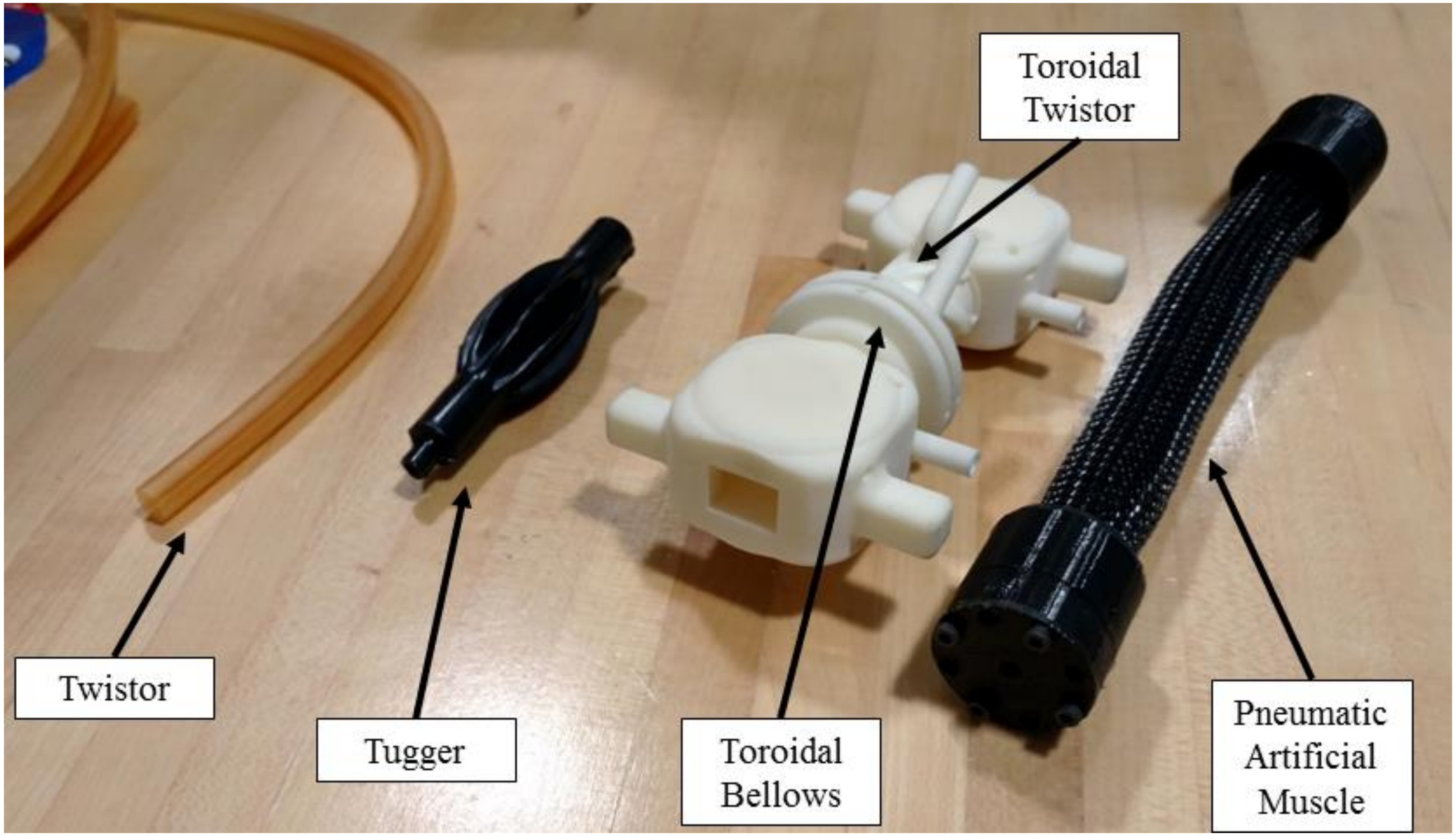
Increasing the Specific Power of Hydraulic Actuators

- HAM = Hydraulic artificial muscle
  - Powered by hydraulics.
  - Contracts when pressurized; acts like a human muscle.
  - Highest power-to-weight ratio in class of flexible actuators.



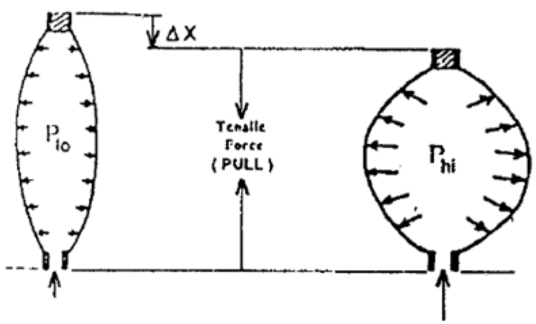
Background

- HAMs are a type of flexible fluidic actuator

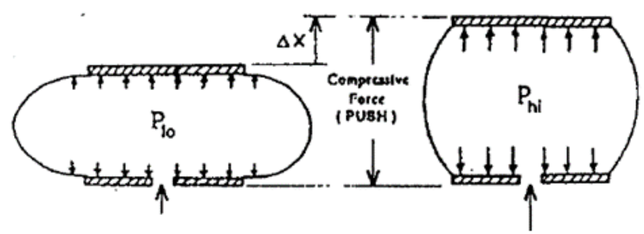


Flexible Fluidic Actuators

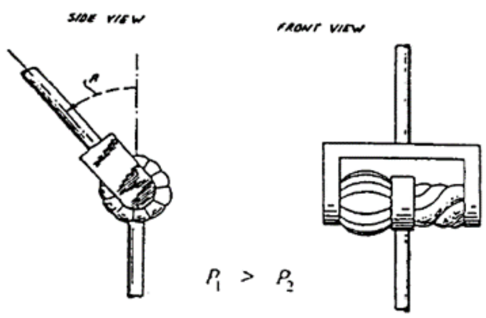
Flexible fluidic actuators transmit mechanical power through large deformations of elastic or hyperelastic membranes by an energized fluid.



Prolate (contract/pull)

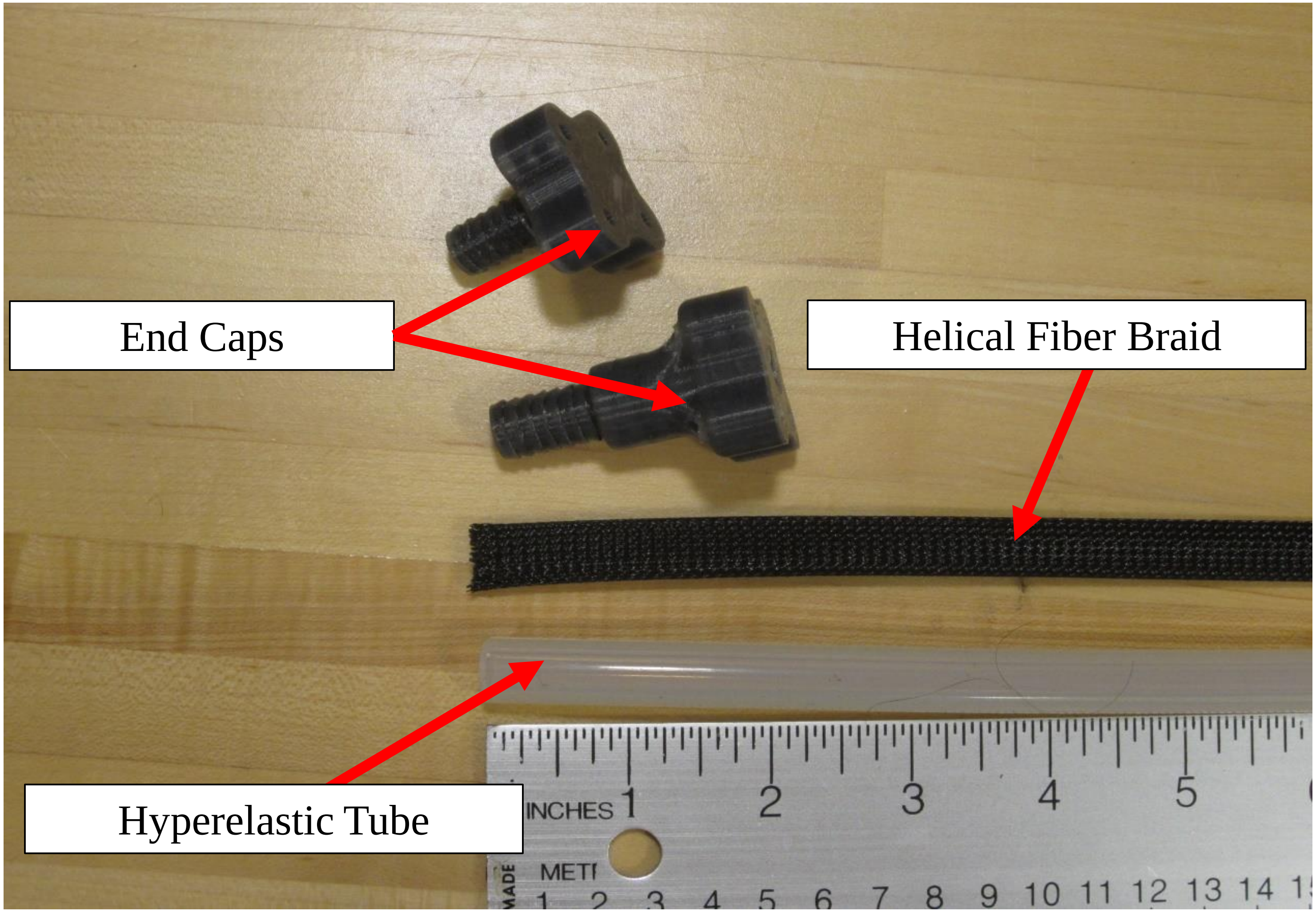


Oblate (expand/push)

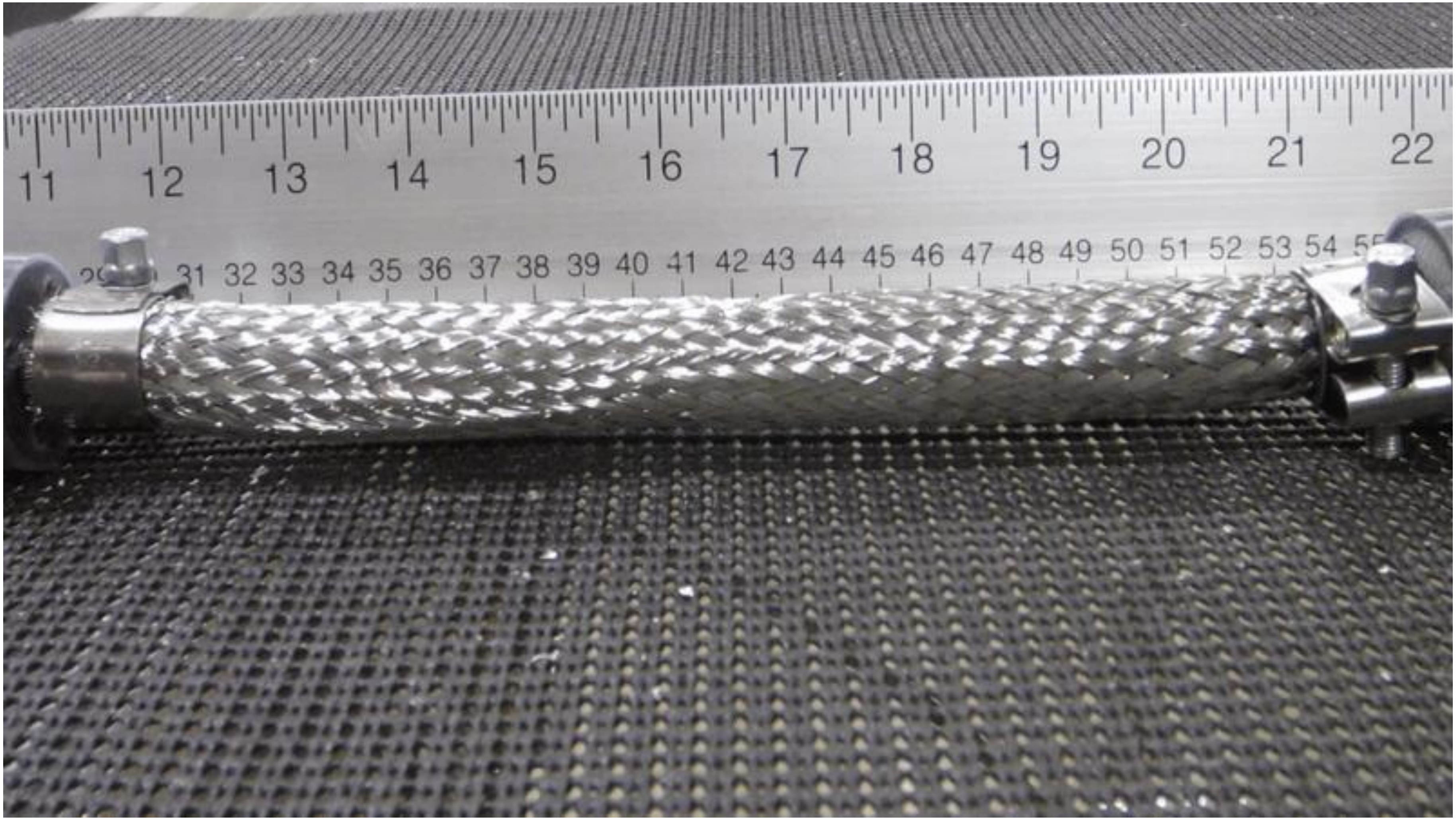


Helical (Twist)

Artificial muscle components



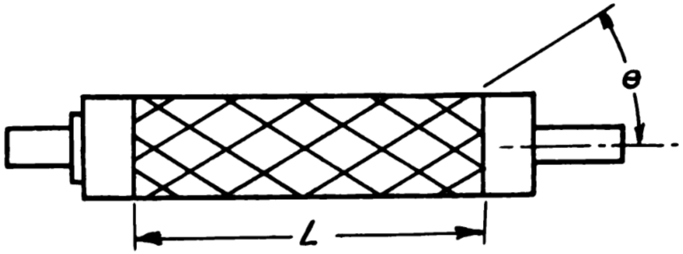
How it works

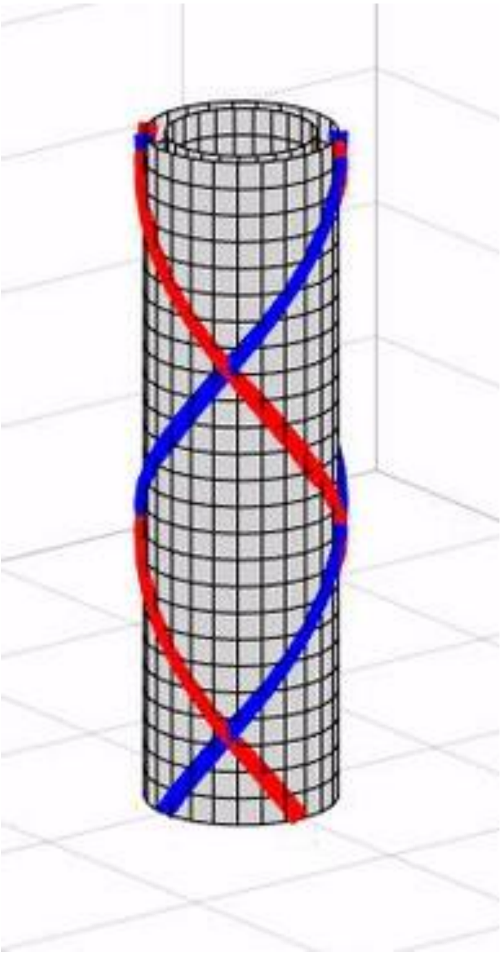

11 12 13 14 15 16 17 18 19 20 21 22
31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54

Background: Modeling

- First modeled by Gaylord using principle of virtual work

$$F = \frac{P(3L^2 - b^2)}{4\pi n^2}$$

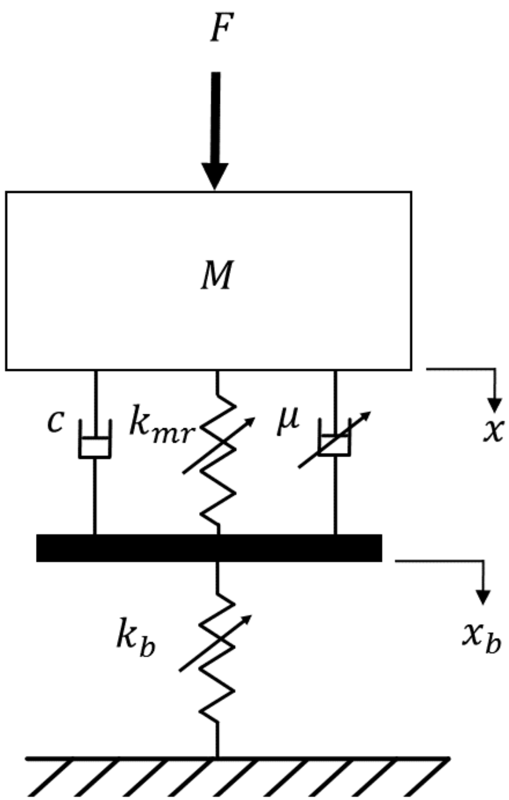




R.H. Gaylord. Fluid actuated motor system and stroking device. *US Patent 2844126*, 1957.

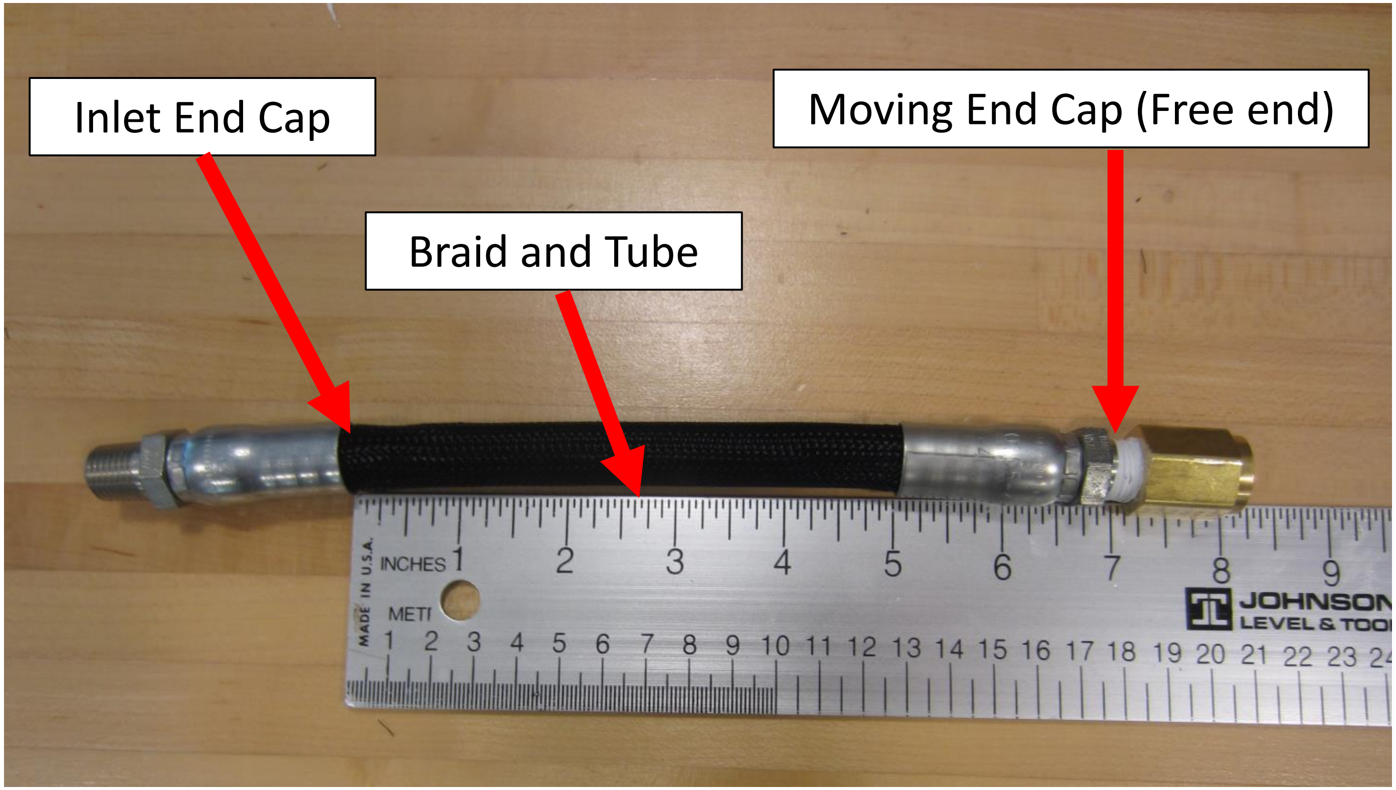
Modeling: Actuator Dynamics

- Nonlinear lumped parameter spring-mass-damper model; Based on Gaylord model



- Hyperelasticity of rubber tube.
- Internal damping.
- Nonlinear kinetic friction.
- Inertia.
- Braid stiffness.

Experimental Setup: HAM



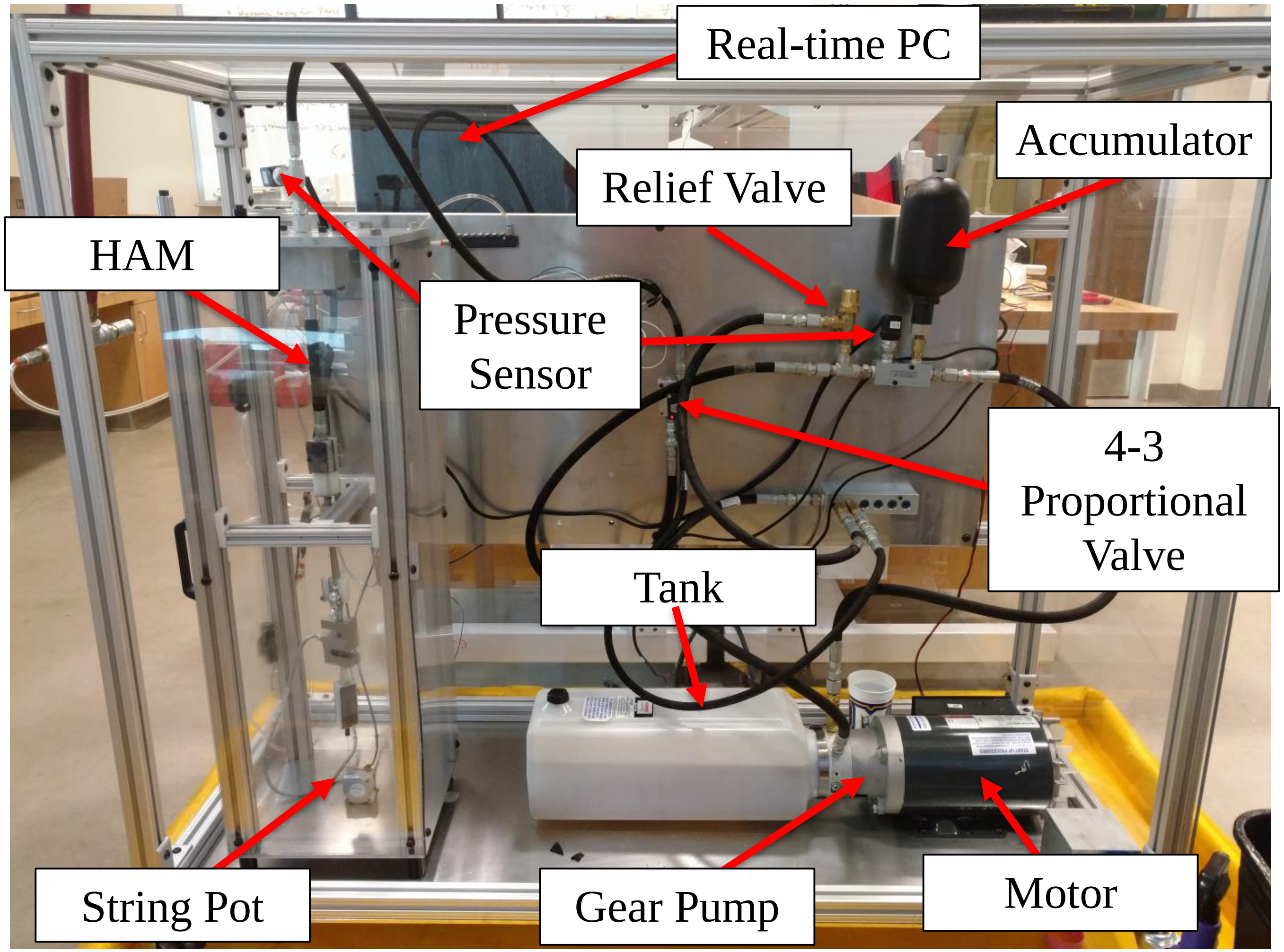
Failures Modes

End Cap Failure

Blow By

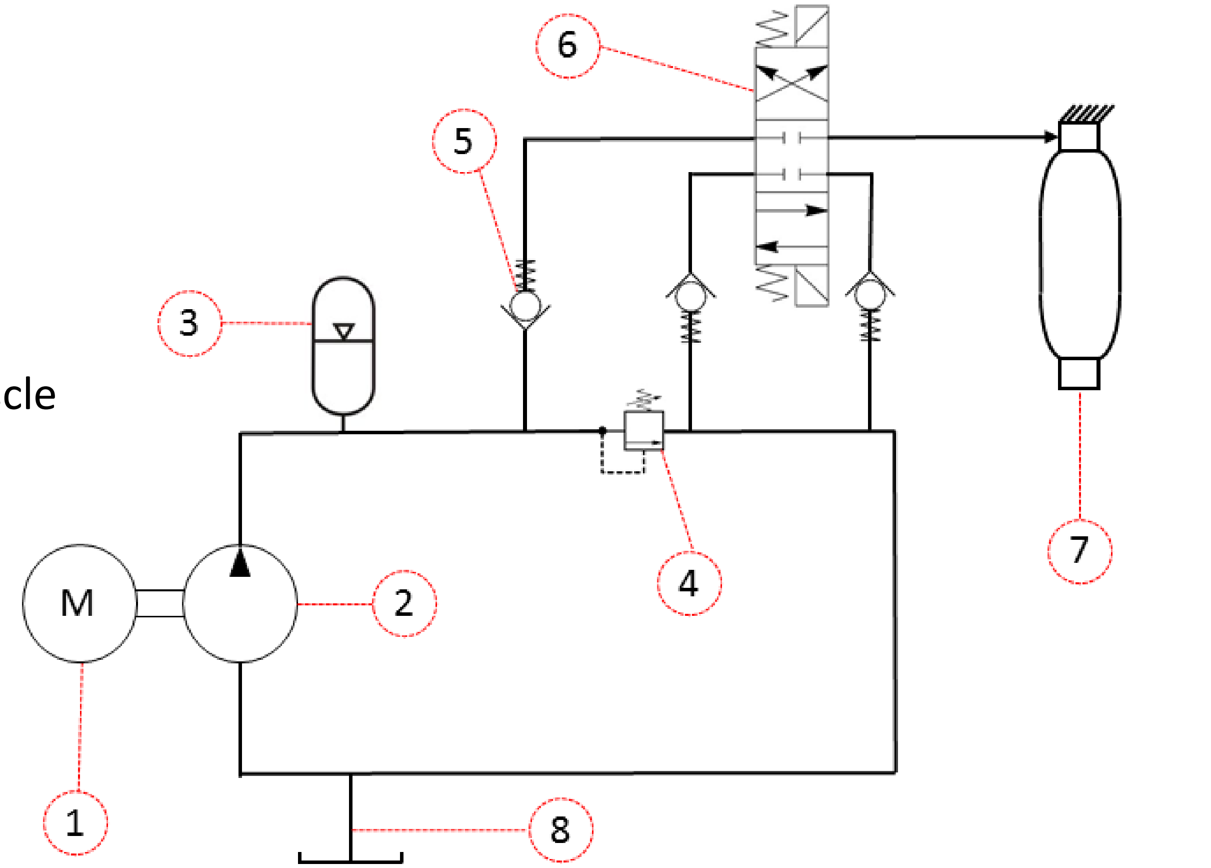
Braid Failure

Experimental Setup: Test Stand



Experimental Setup: Test Stand

1. Motor
2. Pump
3. Accumulator
4. Relief Valve
5. Check Valve
6. Proportional Flow CV
7. Hydraulic artificial muscle
8. Tank

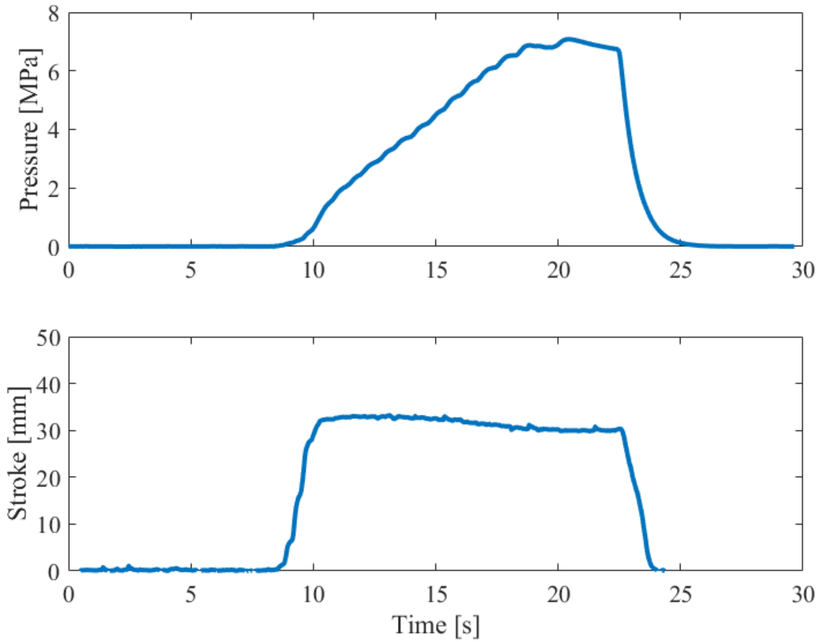


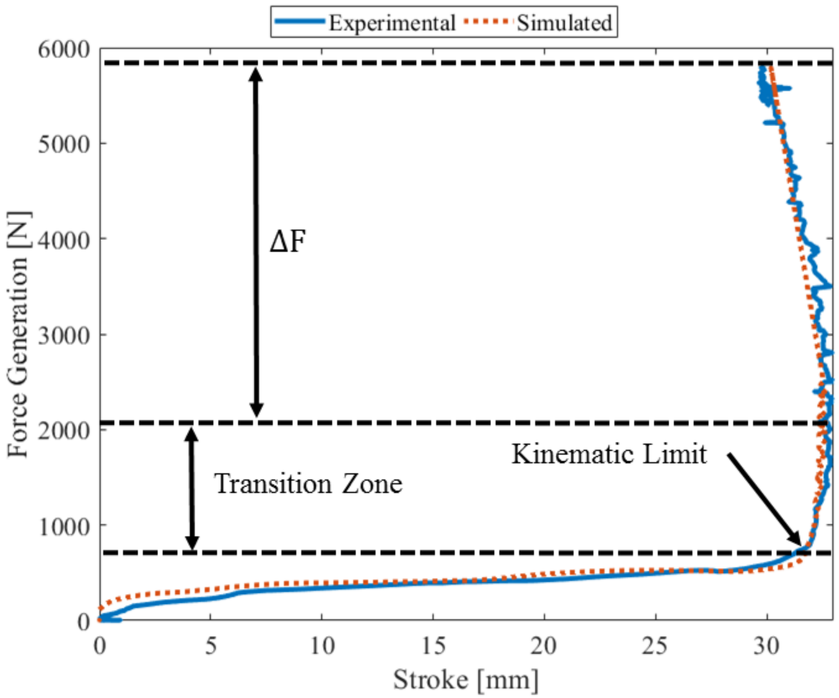
Not shown: Pressure transducers

Experimental Results

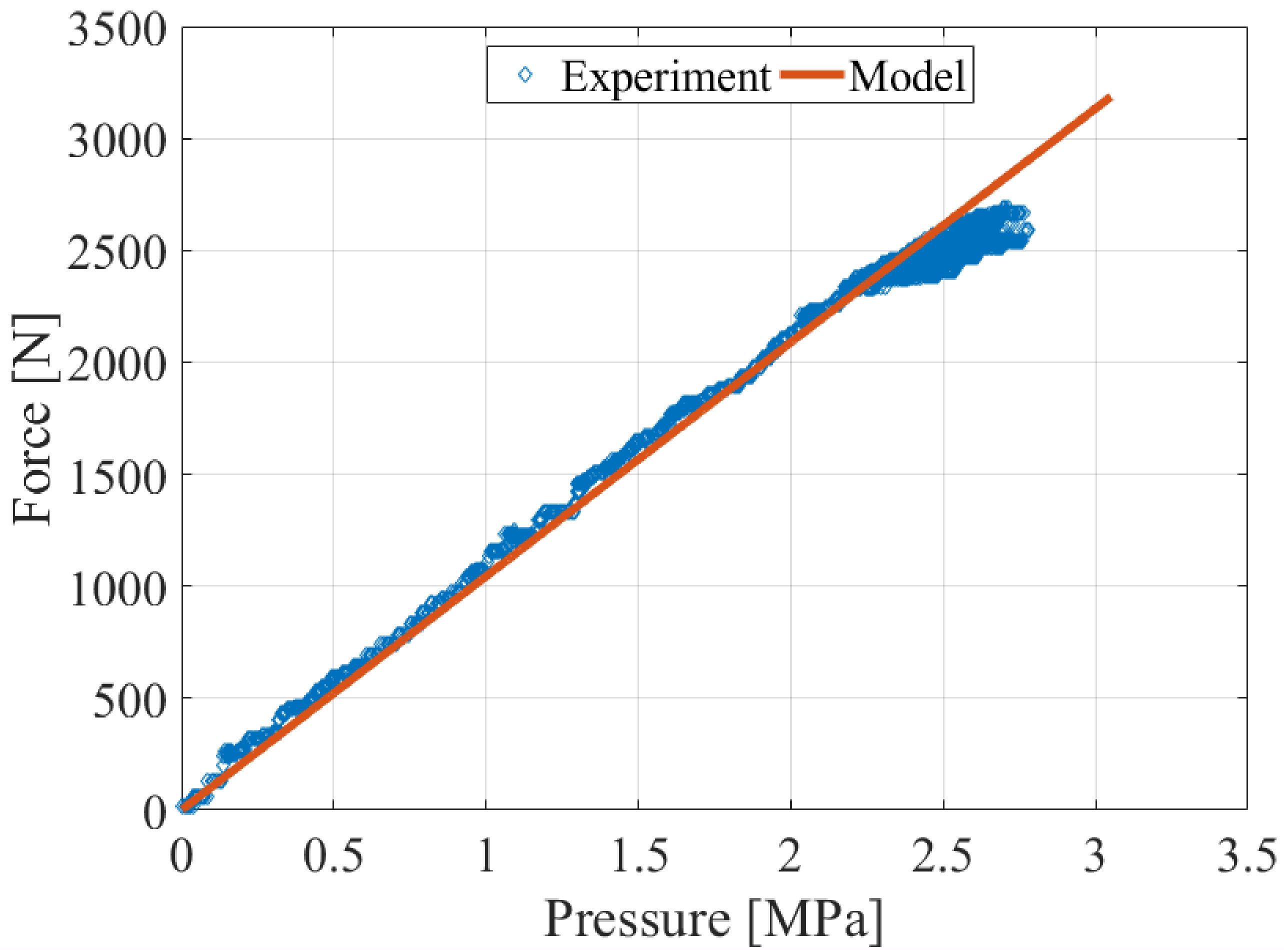
- Quasi-static tests:
  - Free contraction - Pressure = 7 MPa ~ 1000 psi
  - Isometric – Pressure 3.5 MPa ~ 500 psi
- Dynamic tests: 3.25 MPa ~ 475 psi
  - Square wave input response @ 0.25
- Control Experiments
    - Sine wave tracking
    - Square-like wave trajectory tracking

Static test – Free Contraction

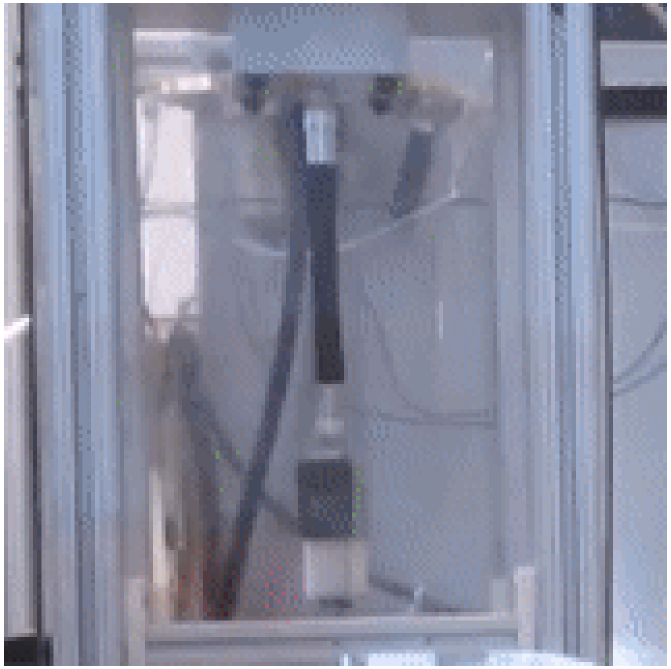


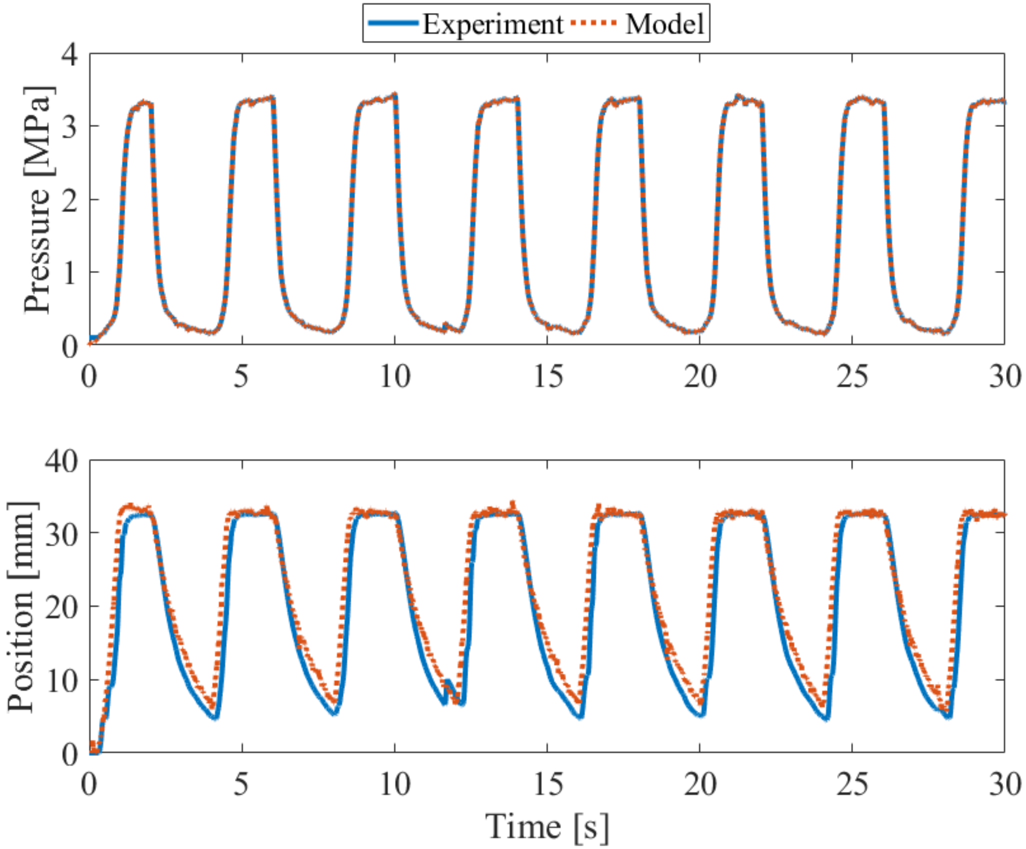


Static test – Isometric Results



Dynamic Results (0.25 Hz)

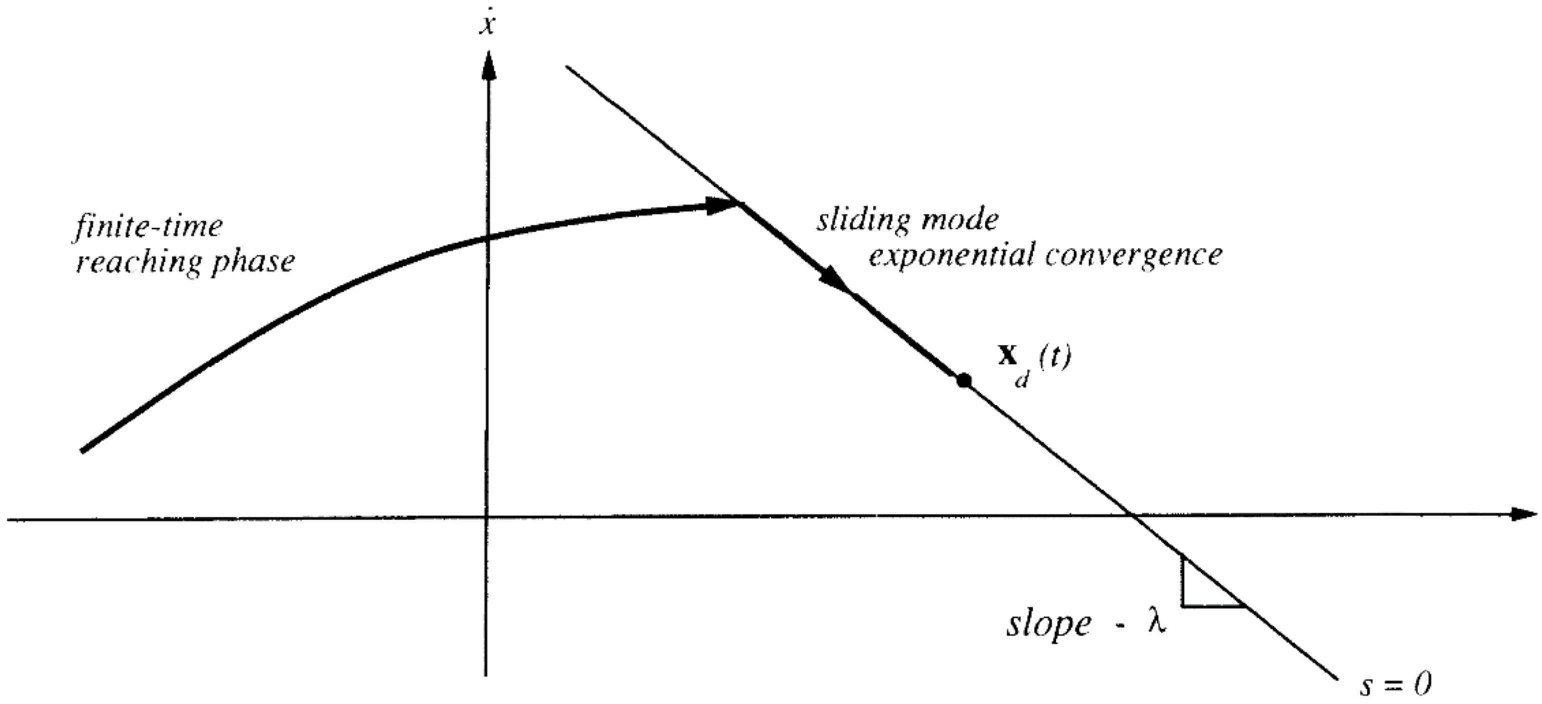




Model Based Control

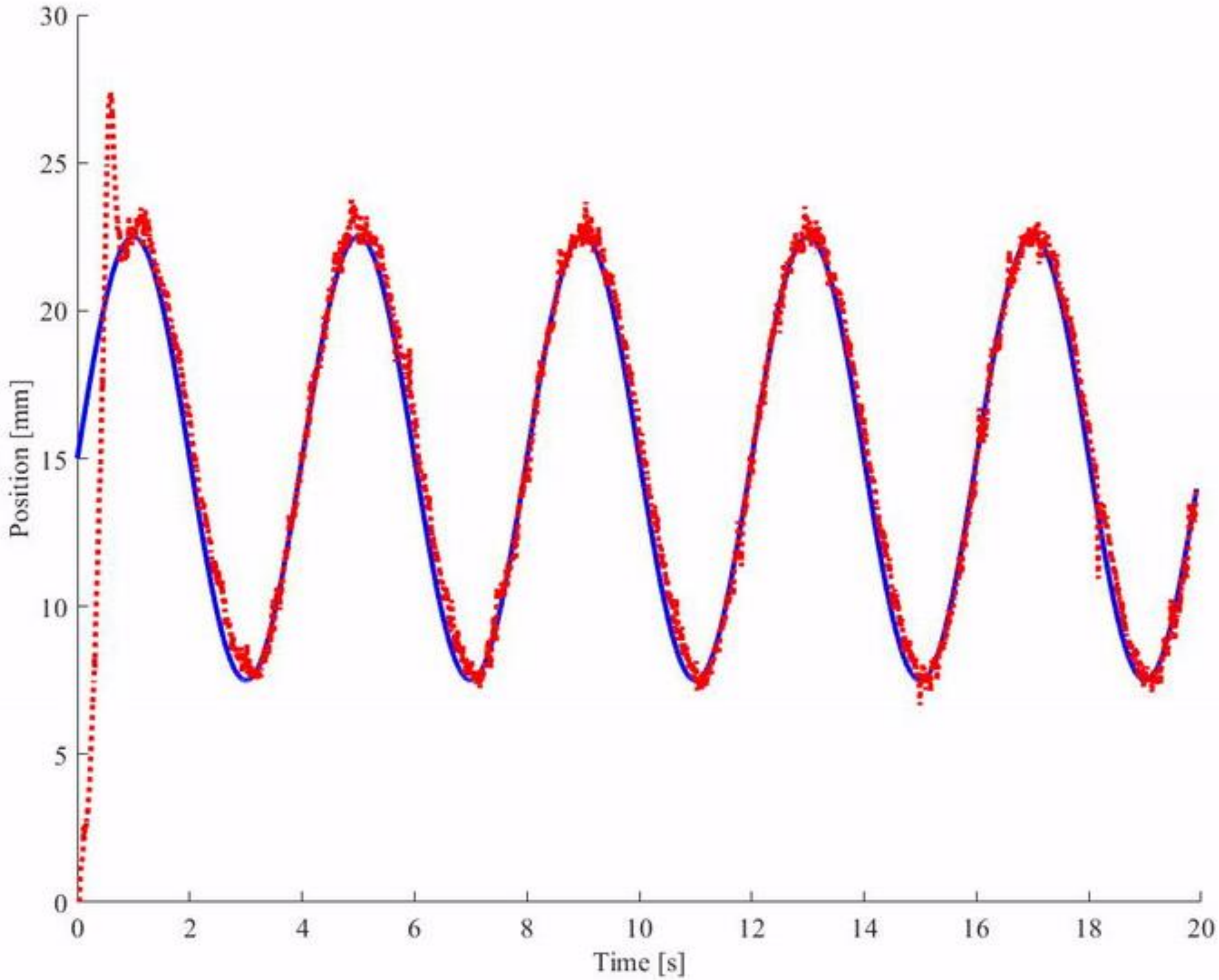
Used model to develop Sliding mode control law

$$u = u_{eq} + u_{rb}$$

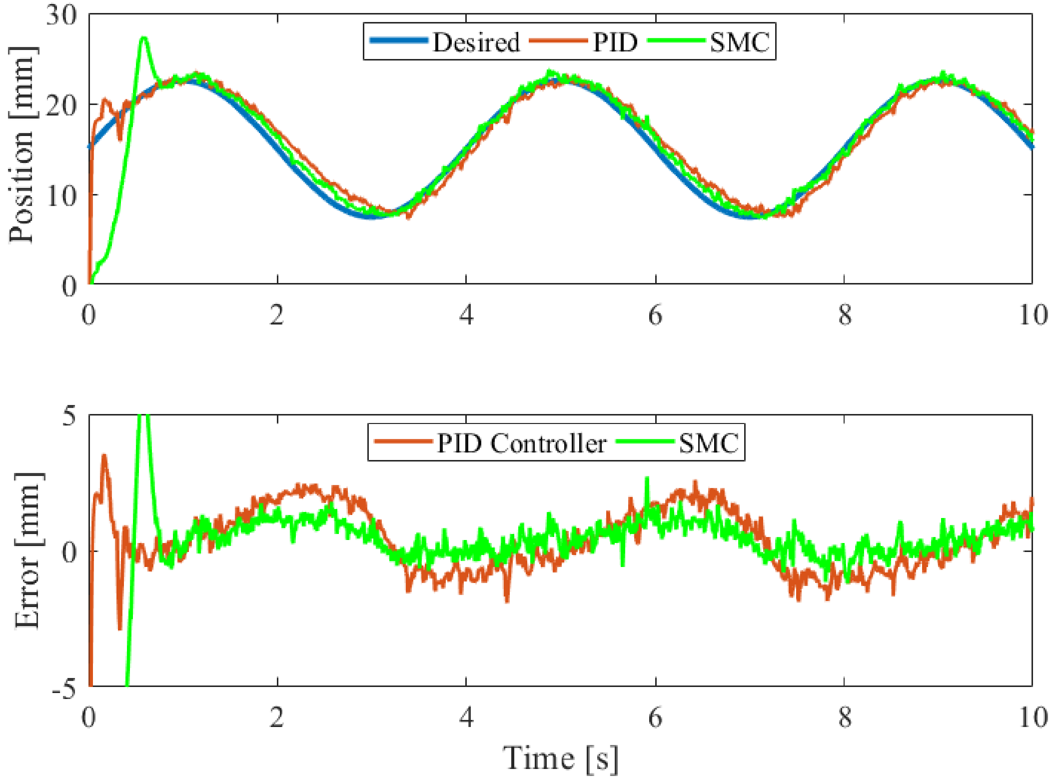


J.J. Slotine and W. Li. *Applied Nonlinear Control.* Prentice Hall. 1991.

Sine wave tracking (0.25 Hz)

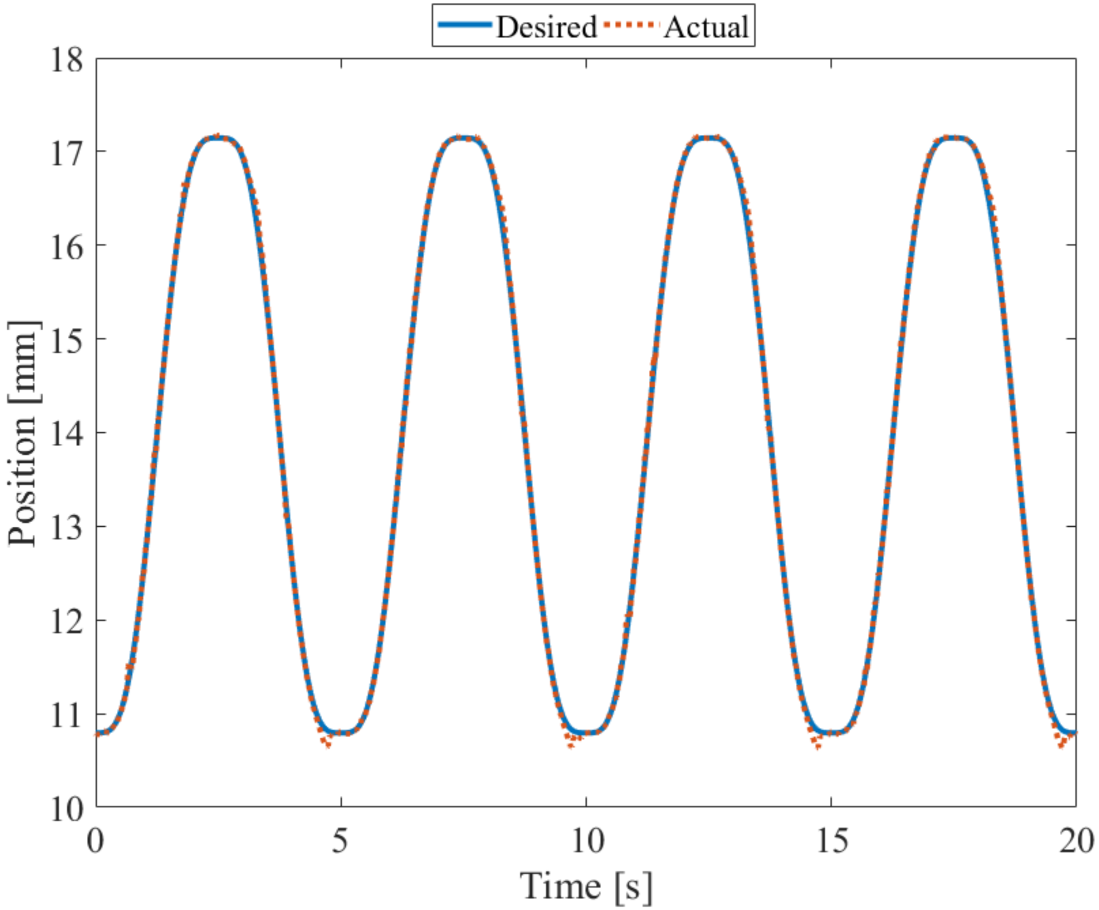


Sine wave tracking (0.25 Hz)



- Outperforms PID control

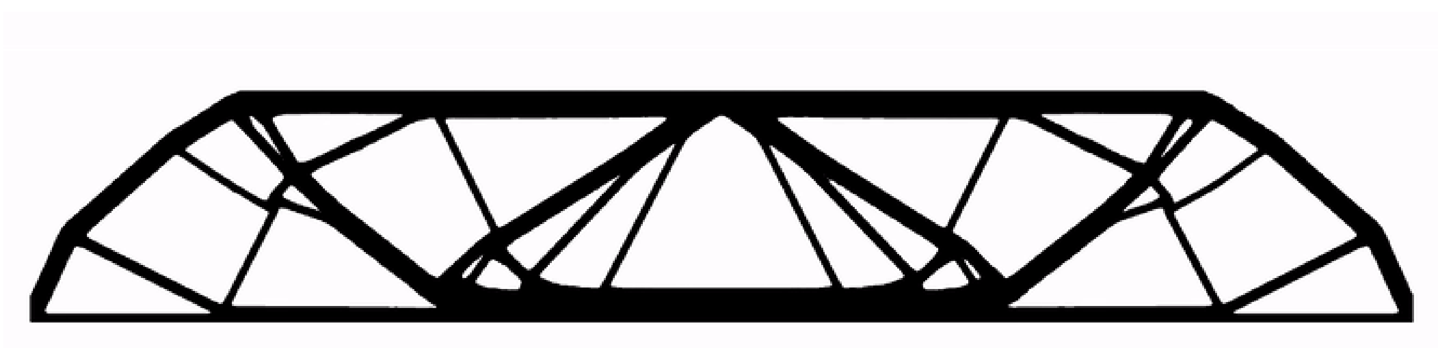
Trajectory Tracking



Maximum Error < 0.3 mm

Current work: Applications

- Topology optimization using Solidthinking Inspire and ParetoWorks



Current work: Applications

- System integration in hydraulic hand tool

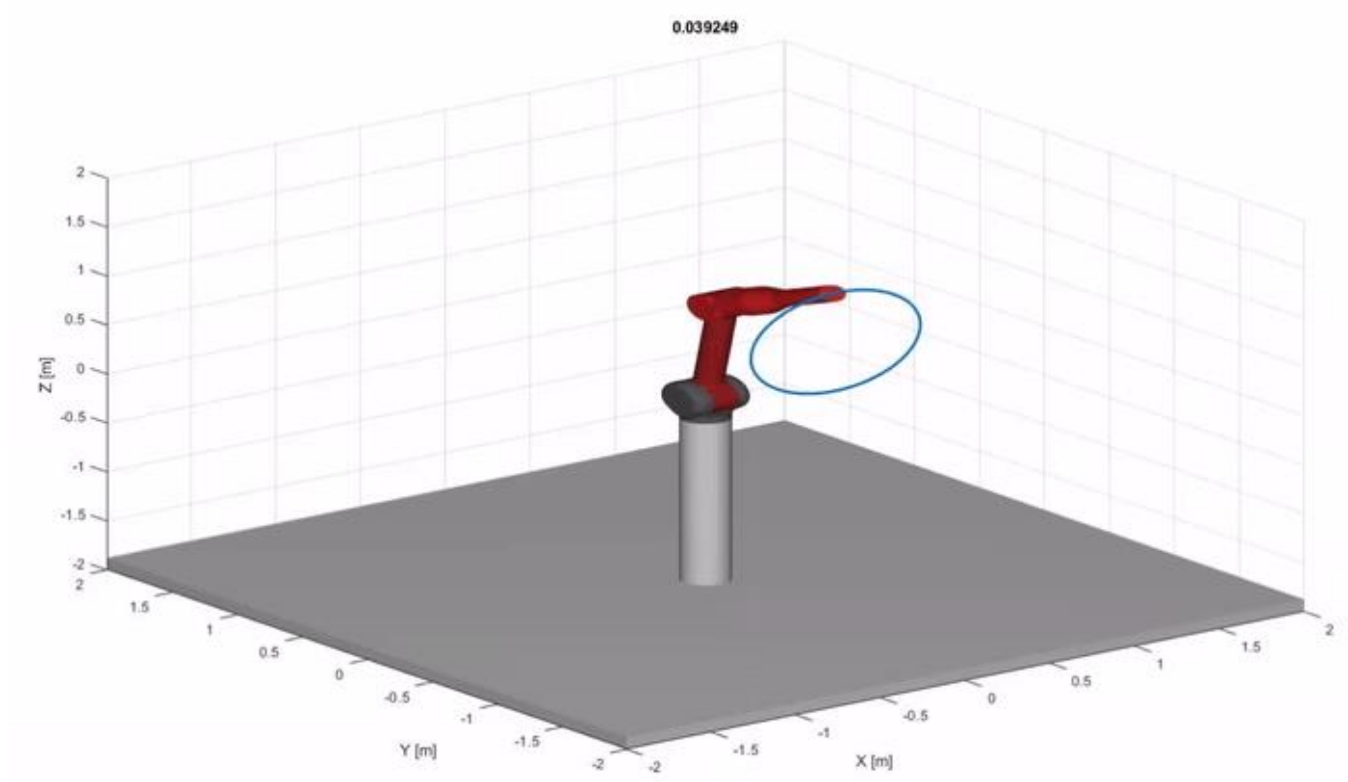
Current work: Applications

- Goal: Reduce weight
  - Integrate hydraulic artificial muscle
  - 3D print components

Redesign, Optimized, and 3D printed

Current work: Applications

- Multiple degree of freedom robot



Current work: Applications

- Multiple degree of freedom robot
  – How much energy can be saved using HAMs and Additive Manufacturing?

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* E. Ackerman, 2015, "What is Boston Dynamics Working on Next," *IEEE Spectrum*, August 17th, 2015. Available from: http://spectrum.ieee.org/automaton/robotics/humanoids/what-boston-dynamics-is-working-on-next

Conclusions

- Demonstrated lightweight, flexible hydraulic actuation.
- Developed and validated model.
- Improved control performance using model-based methods, e.g., SMC.
- Working on applications of HAMs and 3D printing technology to quantify benefits.
  - Call for participation.

Acknowledgements

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Q & A

Thank you for your attention and we welcome comments and questions.

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