Fully 3D Printed Soft Actuator Characterization

Adaptive Additive Technologies Laboratory

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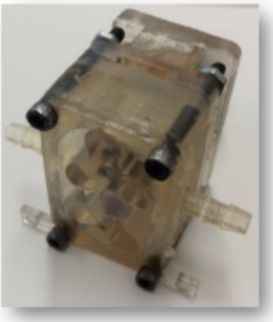
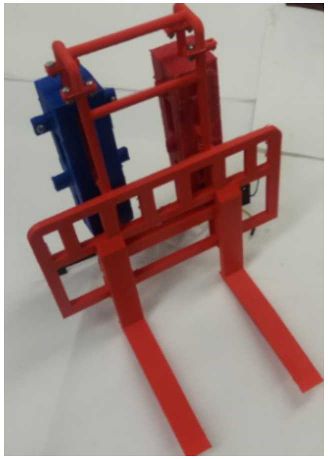
3D Printed Fluid Power Components

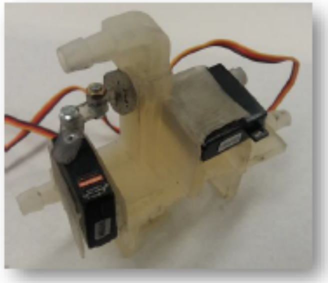


Lobe Pump

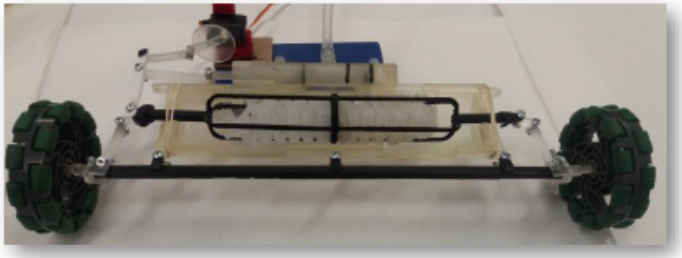
Soft Actuators



Lift



Gate Valve Assembly



Hydrostatic Steering

Final Forklift

The steering system for controlling forklift model needed a small actuator

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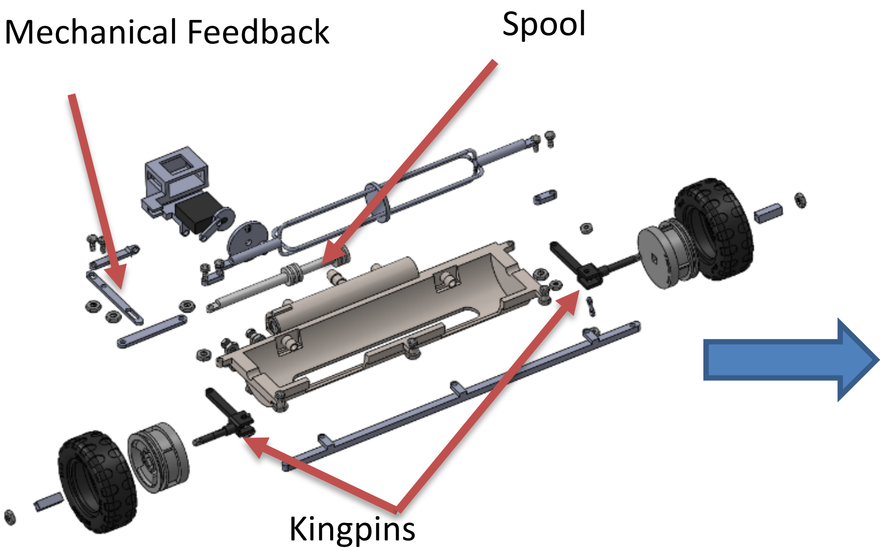
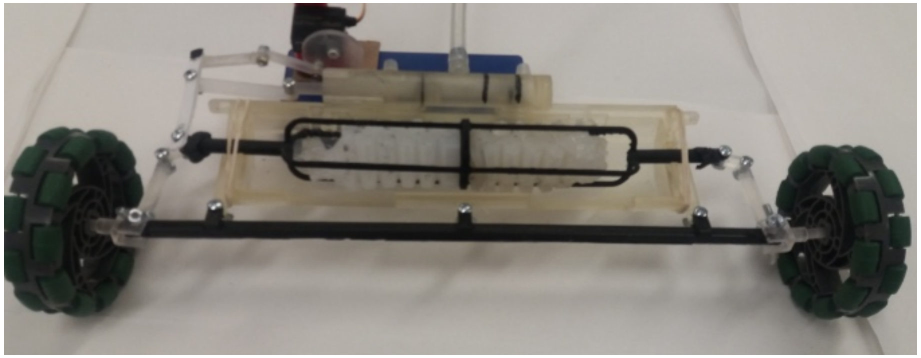
Steering Assembly





Literature Review

Oak Ridge National Lab:

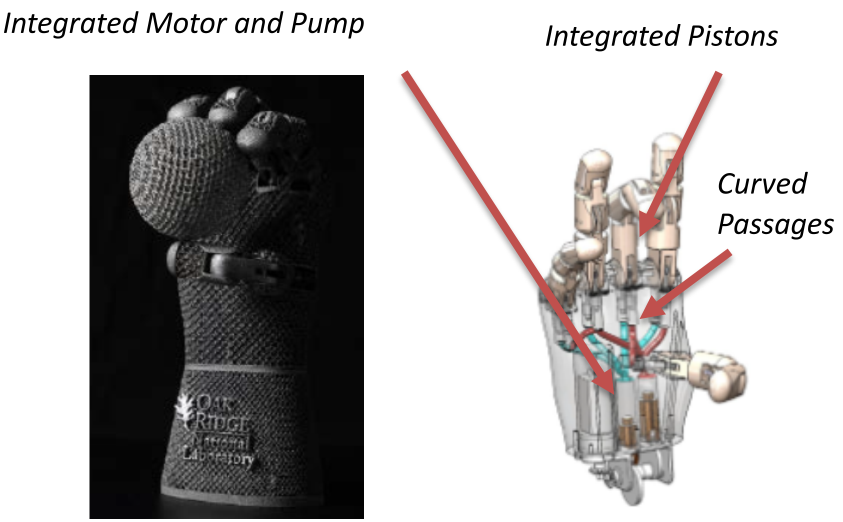
E-beam printing using Titanium

3D Printed Hand

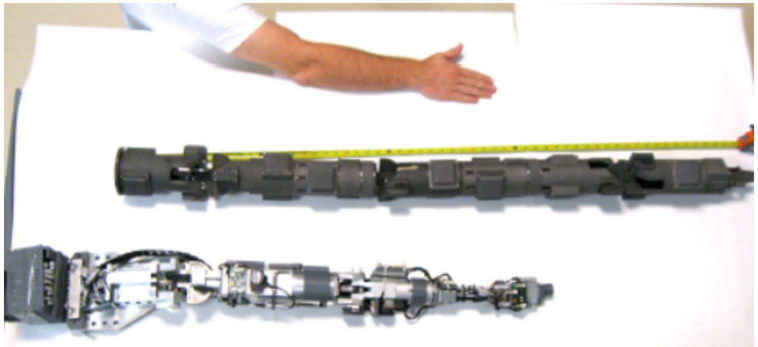
- Integrated pump, fluid passages and piston into a single structure
- Operating pressure: 3000 psi
- Meshed palm reduced weight by 80%
    - Less material and energy
    - Less build time
    - Lower cost

3D Printed Arm:

- Completely printed arm
- Avoided need for hoses
- Blended hydraulics and electronics
- Custom thermal valves for higher efficiency



Lonnie J. Love, Emerging Manufacturing Technologies and their Impact on Fluid Power



DeHoff et al. Freeform Fluidics, International Journal for Fluid Power, 2013

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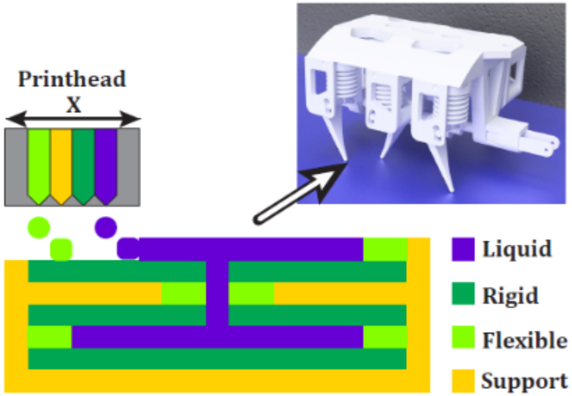
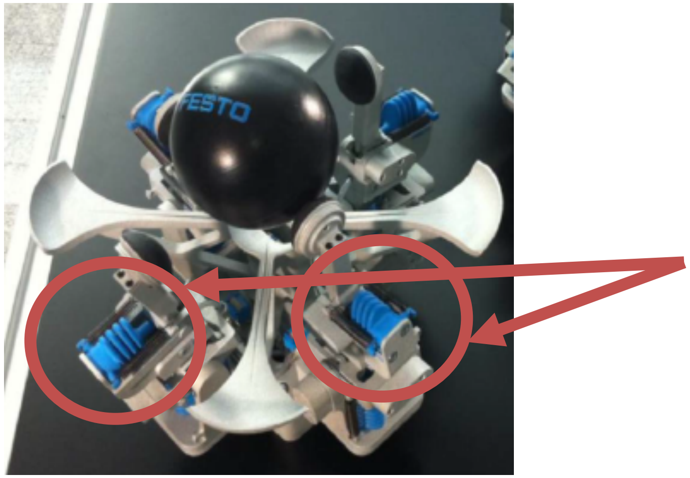
Literature Review (CONT'D)

Fully 3D Printed Robot by MacCurdy et al.:

- Co-printed solids and liquids to make robot in one print
- Printed bellows actuators and gear pump
- Used polyjet printing



MacCurdy et al. 2016 IEEE International Conference on Robotics and Automation



Rost and Schdle, 2013 12th International Conference on Machine Learning and Applications

Festo's Robotic Hand with 3D Printed Actuators:

- Printed bellows actuators directly
- Used SLS printing in Formiga P 110
- Integrated bellows actuators in robotic hand

Literature Review (CONT'D)

Aidro Hydraulics

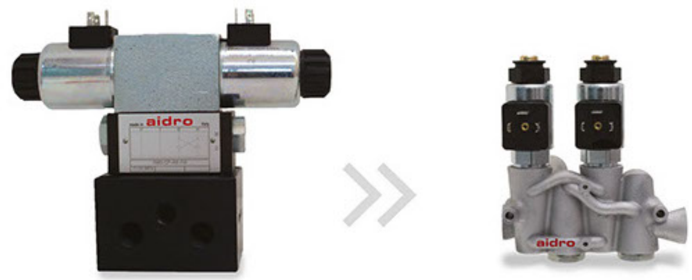
Metal 3D printing machine (DMLS technology)

Manifold:

- 75% weight reduction and reduced dimensions to half the original size
- Better mechanical properties
- Improved system performance

Spool Valve:

- New orifice shapes
- Lower pressure drop
- Fabricate spool in one single part



https://www.aidro.it/3d-metal-printing.html

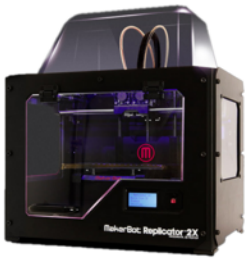
Aidro Hydraulics, 3D Printed Hydraulic Manifold for Agricultural Machinery

3D Printing Methods

Fused Deposition Modeling (FDM)

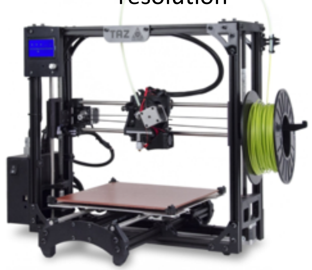
Filament is heated and extruded

- Makerbot Replicator 2x
  - 25 x 16 x 16 cm
  - 100 micron layer resolution



3dhubs.com/3d-printers/makerbot-2x

- Lulzbot Taz 5
  - 28 x 28 x 25 cm
  - 100 micron layer resolution

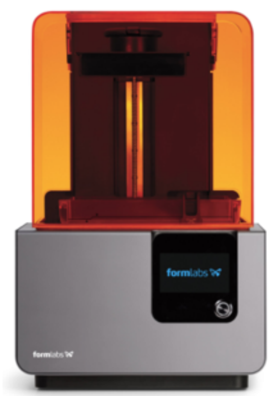


3dhubs.com/3d-printers/lulzbot_taz5

Stereolithography (STL)

Selective Laser Sintering (SLS)

- Laser reflects a beam of light in a mirror to cure resin
- Rigid and flexible materials available
- Formlabs Form 2
  - 15 x 15 x 18 cm
  - 140 micron laser point size resolution



https://shop3d.ca/products/form2

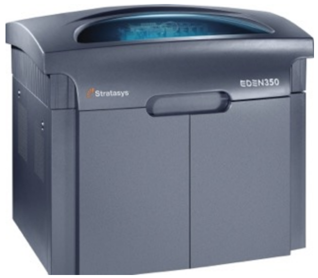
Digital Light Projecting (DLP)

- Projector flashes individual layers
- Highest resolution
- Autodesk Ember
  - 6 x 4 x 16 cm
  - 50 micron resolution (nominal), 1 micron resolution (maximum)

https://ember.autodesk.com/

Polyjet Printing

- Resin is deposited by the build head and a light source cures the resin
- Objet Eden 360 V
  - 35 x 35 x 20 cm
  - 20-85 microns for features below 50 mm; up to 200 microns for full model size



http://www.goengineer.com/products/objet-eden-350350v/

Silicone Printing

Pneumatic-based extrusion for 3D bioprinting living tissues and silicone substrates

- Dual printheads
- UV-crosslinking system

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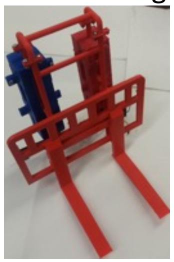
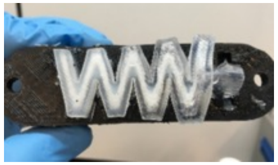
3D Printing Materials

Fused Deposition Modeling (FDM)

PLA and ABS
- Filaments for rigid parts



High Impact Polystyrene
- D-limonene soluble filament



Polyvinil Alcohol
- Water soluble filament

Stereolithography (STL)

Selective Laser Sintering (SLS)

Formlabs Clear
- Clear resin

Formlabs Tough
- Designed to simulate ABS plastic

Formlabs Durable
- Designed to simulate Polypropylene
- Resistant to friction and wear

Formlabs Flexible
- Ideal for seals and other flexible partts

Digital Light Projecting (DLP)

CPS PR48
- Clear, higher resolution than Formlabs clear but lower Young's modulus resin

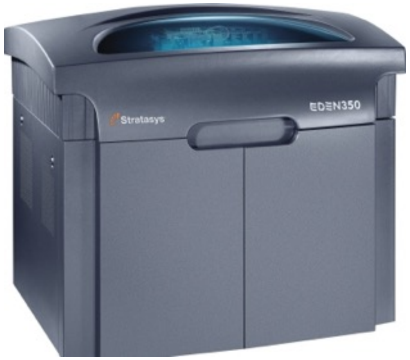
Other resins in Form 2 catalog

https://ember.autodesk.com/

Polyjet Printing

RGD 720
- Clear resin

SUP 705
- Additional support material



Silicone Printing

Alginate

CELLINK & Fibrinogen

CELLINK® PCL

CELLINK & Tricalcium phosphate

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Obtaining a Working Actuator

First Attempt: Piston-Cylinder Assembly

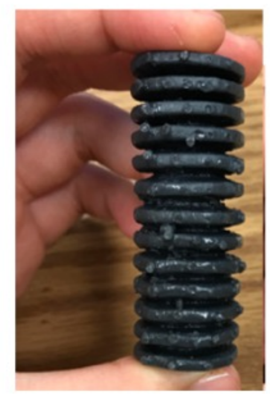
Printed piston, cylinder, and seal via STL

Advantages: Resembles real world application, simple design

Disadvantages: Poor tolerances cause excessive friction and/or leakage

Second Attempt: Resin-based Bellows Actuator

- Printed bellows directly using DLP
- Advantages: Encloses fluid, avoiding friction and leakage issues
- Disadvantages : Poor material properties (Formlabs' flexible resin)
- Attempted many material and shape configurations



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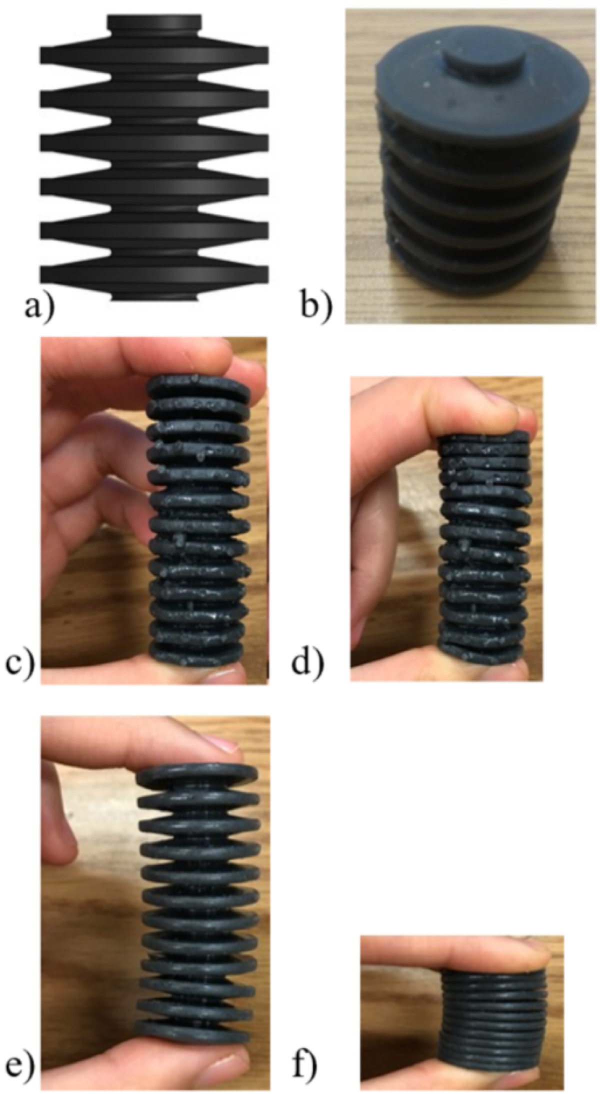
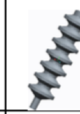
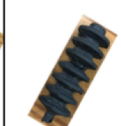
Fully printed SLA Bellows actuators



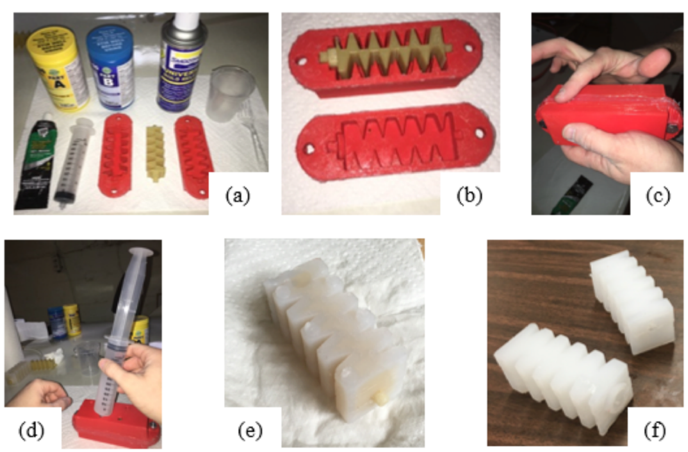
(a) Represents the CAD prototype
(b) 3D printed version of fully flexible resin.
(c) 50% Flexible 50% Clear 3D print prior to compression
(d) 50% Flexible 50% Clear 3-D Print under compression
(e) 75% Flexible 25% Clear 3-D print prior to compression
(f) 75% Flexible 25% Clear 3-D Print under compression

Designs	Dsgn. 1	Dsgn. 2	Dsgn. 3	Dsgn. 4	Dsgn. 5
Model					
Printer	Form Labs Form 2 Printer	Form Labs Form 2 Printer	Form Labs Form 2 Printer	Form Labs Form 2 Printer	Autodesk Ember
Support Point Size	0.3 mm	0.3 mm	0.3 mm	2.2 mm	Auto
Support Density	0.5	0.5	0.5	1.0	Auto
Internal Support	No support	No support	Yes	Yes	Yes
Print Location	Center	Center	Center	Center	Center
Print Orientation	Horz.	Horz.	Horz.	20° WRT Horz. plane	Vertical
Wall Thickness	0.4 mm	1 mm	1 mm	0.7 mm	1.2 mm
Number of Bellows	12	12	8	2	7
Bellows Diameter	24 mm	24 mm	20 mm	24 mm	24 mm
Bellows Height	1.6 mm	1.6 mm	3 mm	1.6 mm	1.6 mm
Results					

Soft actuators

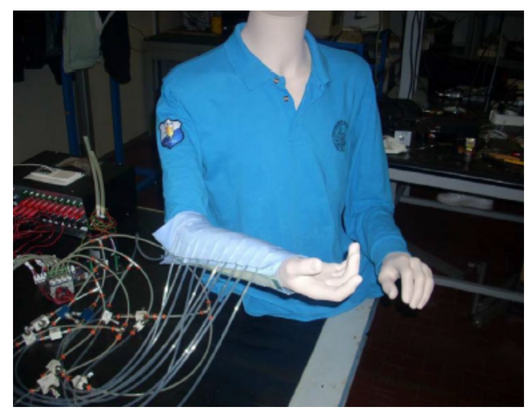
Third Attempt: Silicone-based Bellows Actuator

- 3D-printed mold via FDM
- Advantages: Better material properties, available literature
- Disadvantages : Actuators cannot be 3D printed directly
- Reasons for using soft actuators
  - Ease of fabrication
  - Safety of operation
  - High power-to-weight ratio
  - Low cost
- Material Choice: Ecoflex 00-30
  - Tensile Strength: 200 psi
  - Elongation at Break: 900%
  - Useful Temperature: -53 C to 232 C



Agarwal et al., Stretchable Materials for Robust Soft Actuators towards Assistive Wearable Devices, Scientific Reports, 2016

Inflatable Compression Sleeve

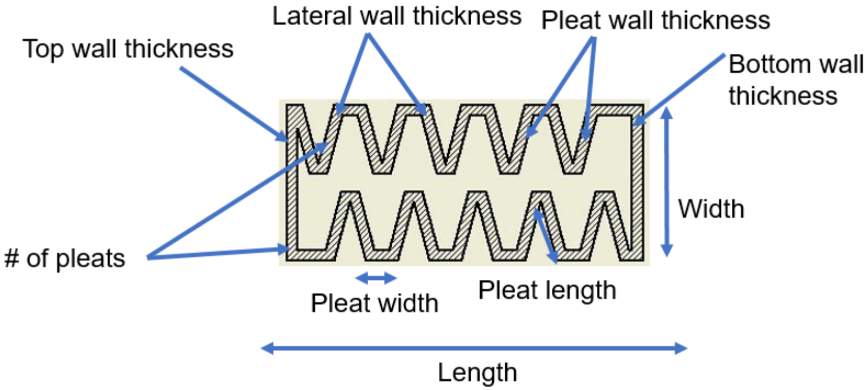


Belforte et al., Soft Pneumatic Actuators for Rehabilitation, Actuators, 2014

Silicone-based Bellows soft Actuator

Step 1: Define Geometry

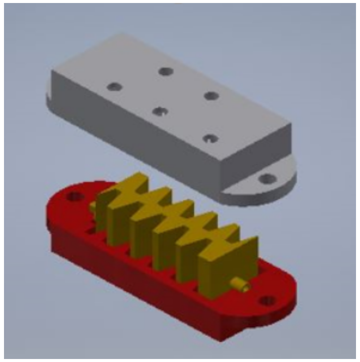
- Square cross-section to avoid radial expansion
- Geometry changes depending on the application
- Dimensional constraints:
  - Minimum wall thickness of 0.25 cm
  - Min./Max. length: 5-10 cm
  - Max. width/thickness: 5 cm
  - Min. Stroke: 0.14 cm



Step 2: Make Mold

- FDM 3D print mold with a PVA core

Step 3: Cast Mold



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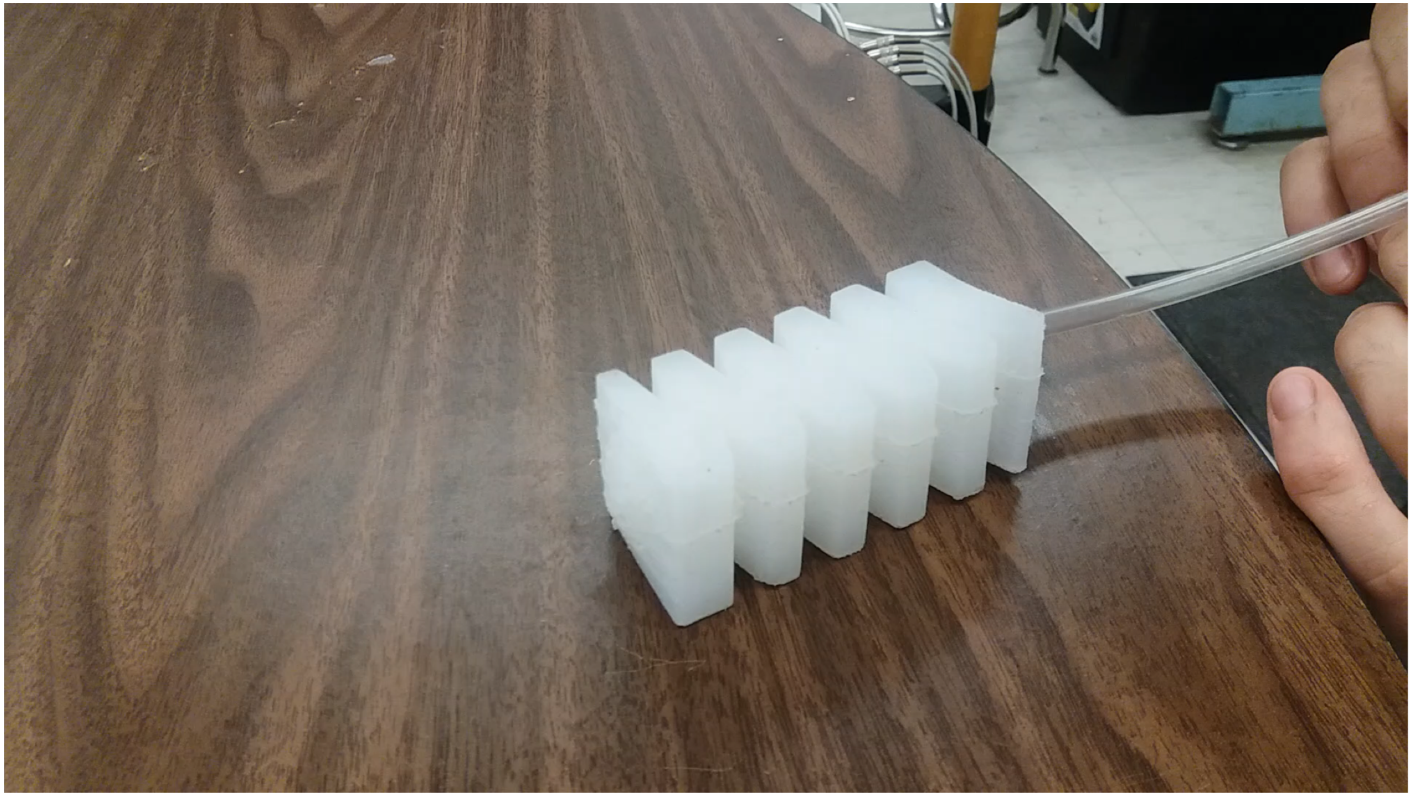
Silicone-based Bellows soft Actuator

Resulting actuator



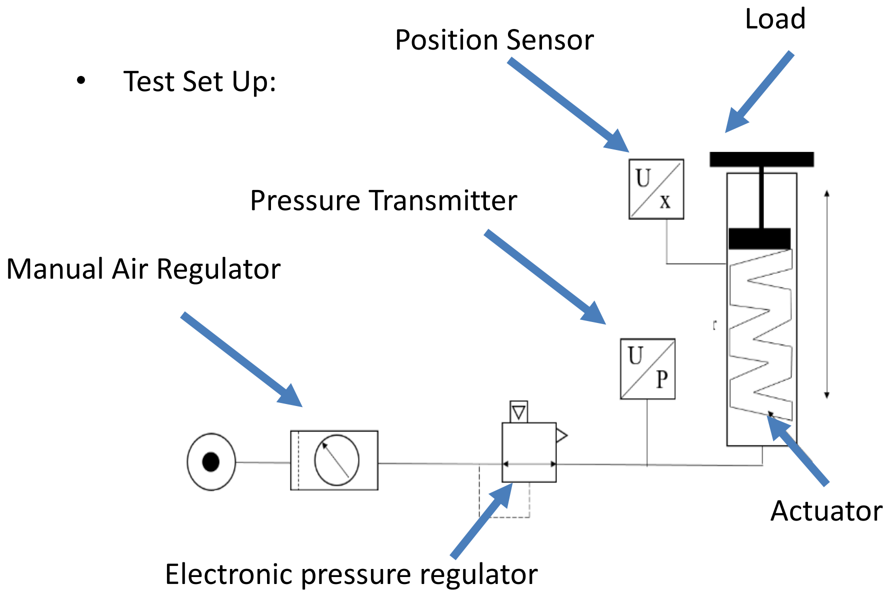
Soft Actuator Testing

Test Objectives:

- Effect on geometry on performance
- Pressure vs. stroke
- Velocity of actuation
- Response time, pressure threshold
- Max. Pressure, Max. Position
- Hysteresis, cyclic or constant loading

Device	Model	Range
Pressure Transducer	Honeywell LM/2345-08	0-15 psig
Position Sensor	SHARP GP2Y	20-150 cm
Electronic Pressure Control Valve	Proportionair FQPV2	2-20 SCFH

- Test Set Up:



Soft Actuator Testing

Testing procedure

- Maintain Load Constant: No load, 200 g, and 500 g
- Keep pressure constant for 60 seconds, time for the pressure and the position to settle.
- Increase – Decrease pressure values
- Measure Position

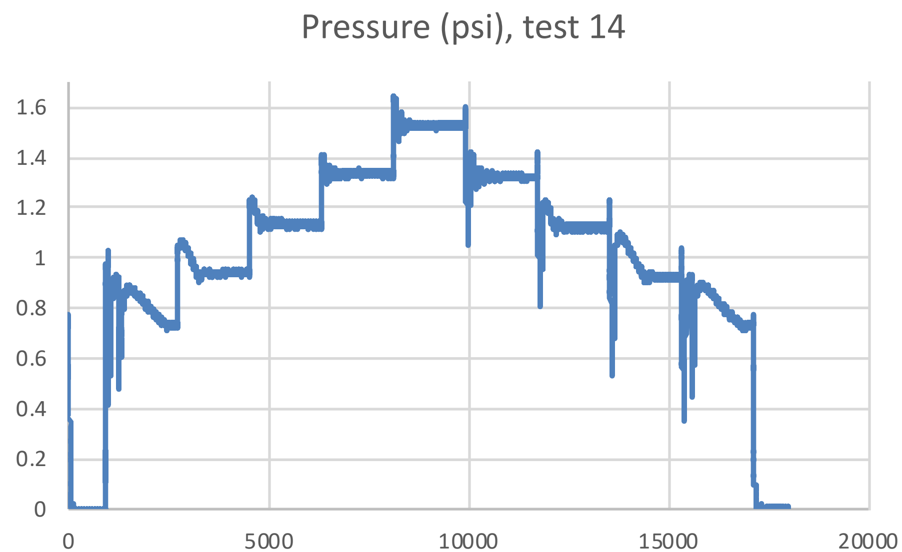
Steady-state:

- Length vs. Pressure
- Pressure Threshold
- No load, 200 g, 500 g

Dynamic:

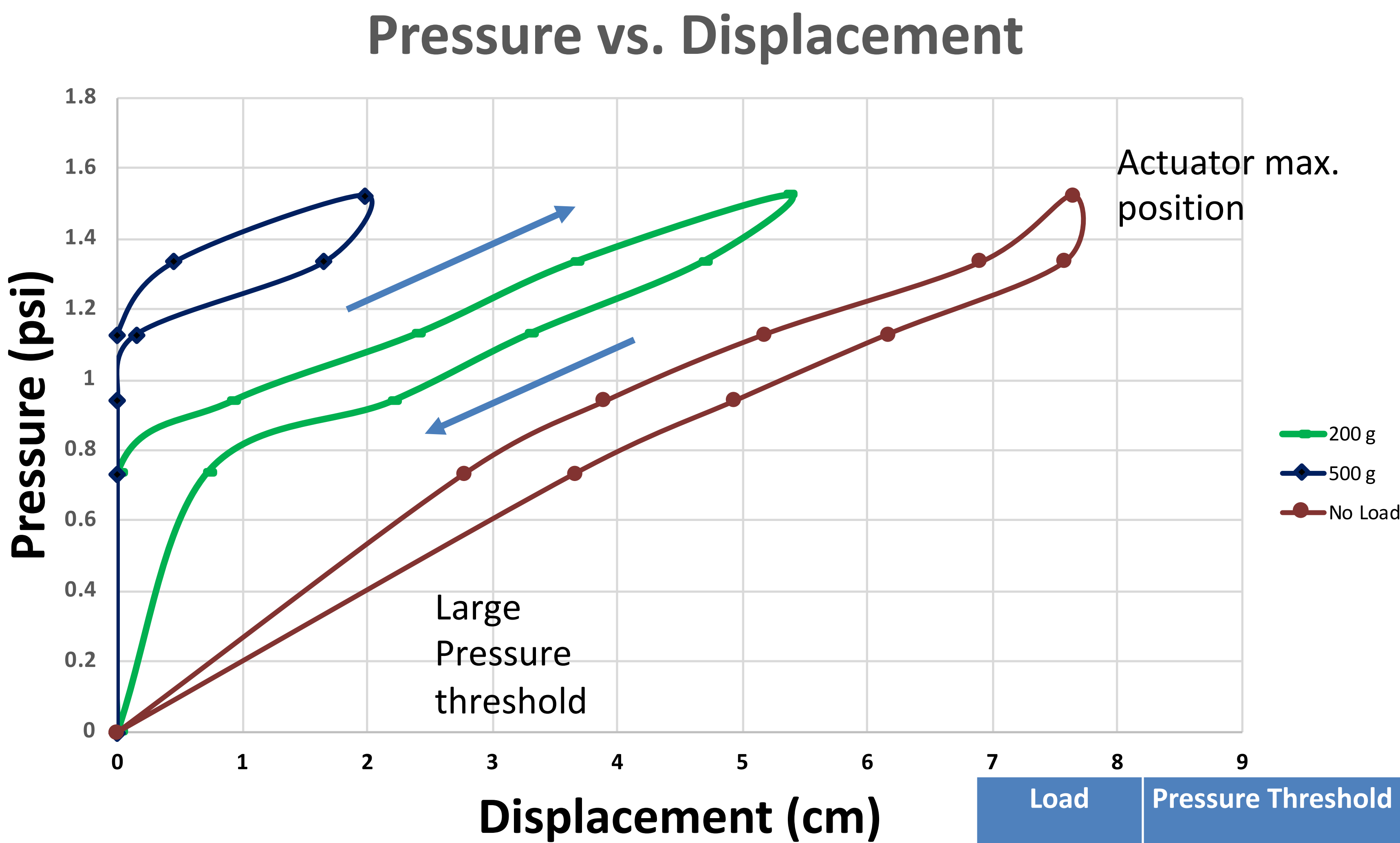
- Position vs. time
- Extension and De-pressurization
- Response time (to achieve constant position)
- No load, 200 g, 500 g

All tests performed in one single actuator



60 second (per constant segment)

Results



Load	Pressure Threshold (psi)
No load	0.47
200 g	0.75
500 g	1

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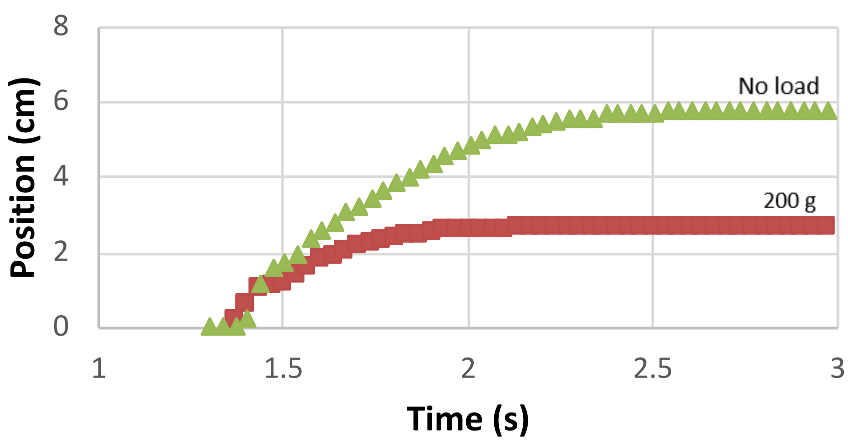
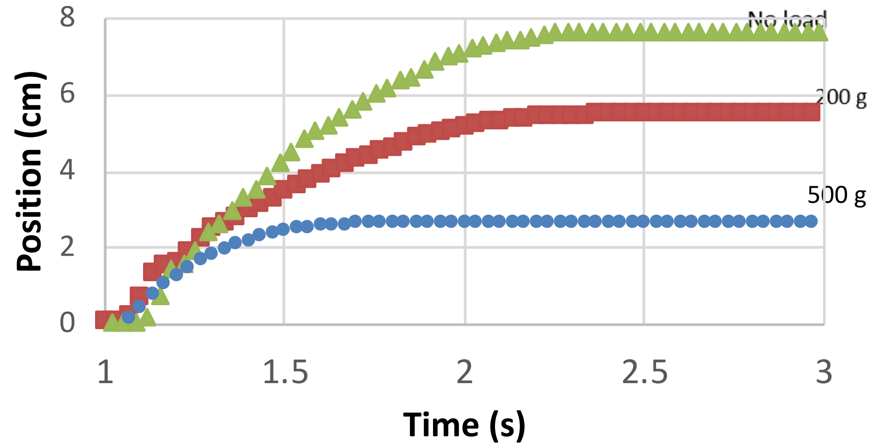
Dynamic Data: Input Pressure

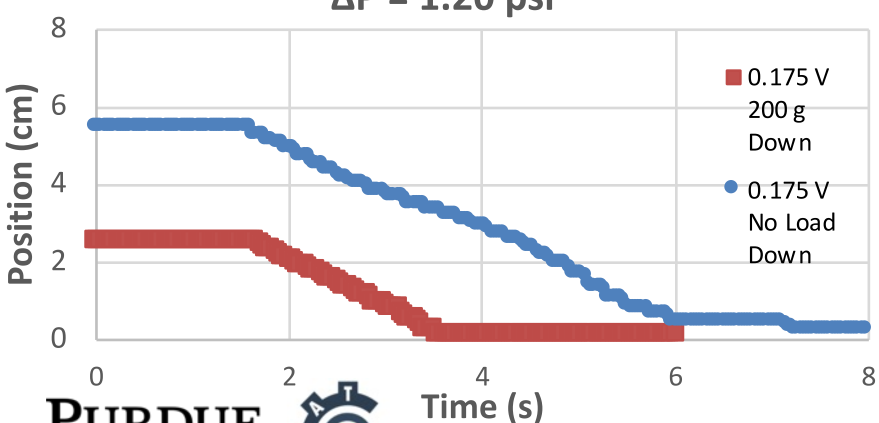
Step Response for Expanding Actuator at ΔP = 1.20 psi



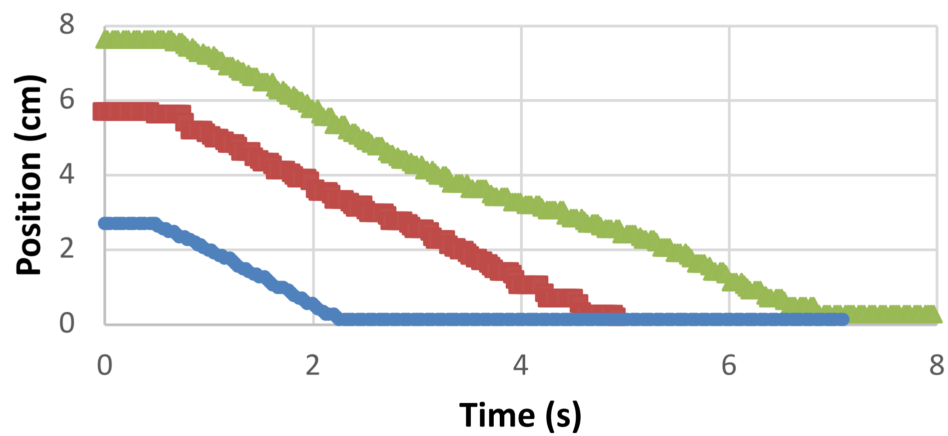
Step Response for Expanding Actuator at ΔP = 1.60 psi



Step Response for Retracting Actuator at ΔP = 1.20 psi



Step Response for Retracting Actuator at ΔP = 1.60 psi



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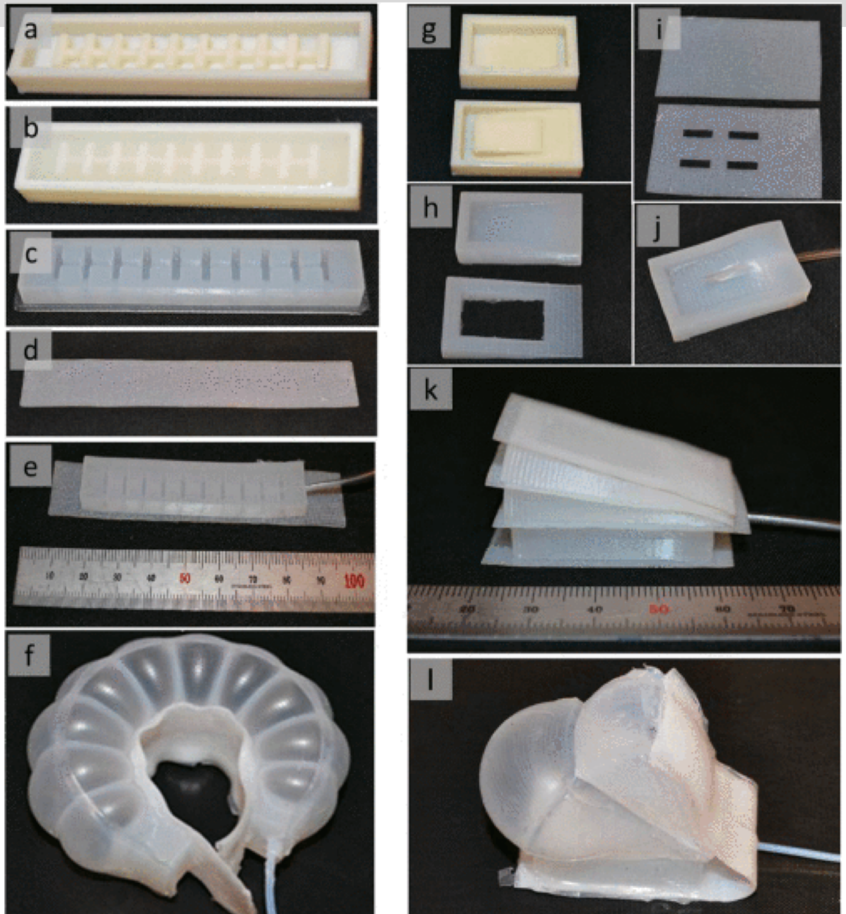
Soft actuators review of literature



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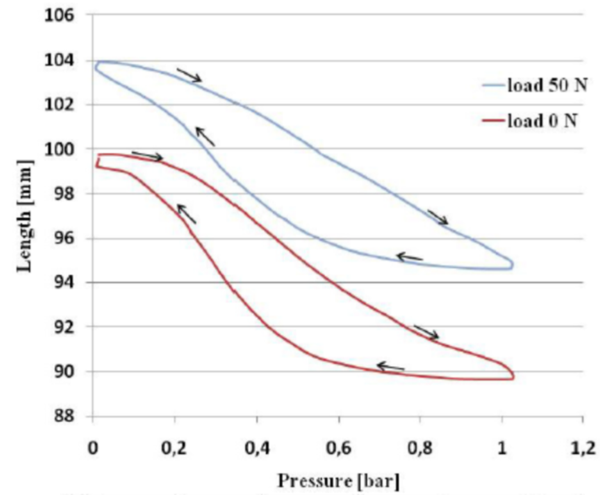

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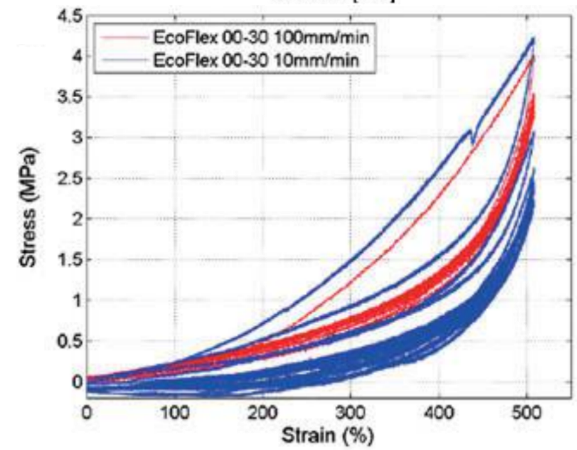

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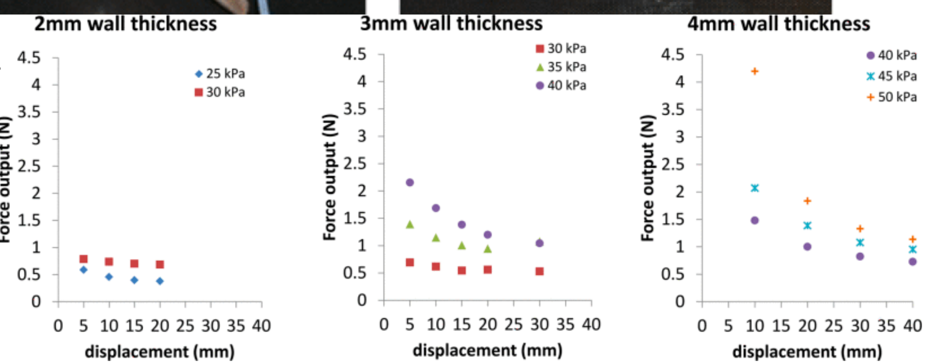


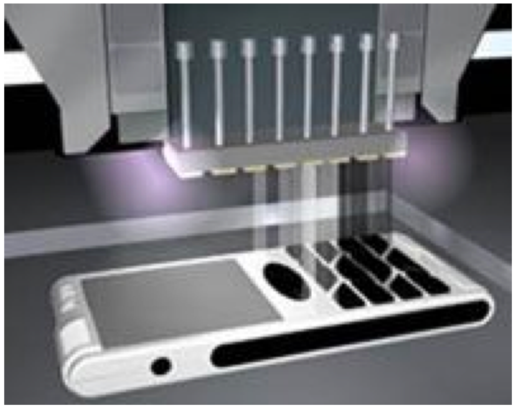
1. Sun, Y., Song, Y. S., & Paik, J. (2013, November). Characterization of silicone rubber based soft pneumatic actuators. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems* (pp. 4446-4453)

2. Guido Belforte, Gabriella Eula, Alexandre Ivanov and Silvia Sirolli Soft Pneumatic Actuators for Rehabilitation. Actuators May 26, 2014

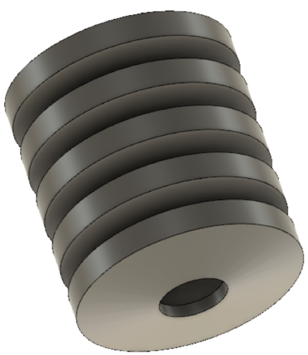
3. Case, J. C., White, E. L., & Kramer, R. K. (2015). Soft material characterization for robotic applications. *Soft Robotics*, *2*(2), 80-87.

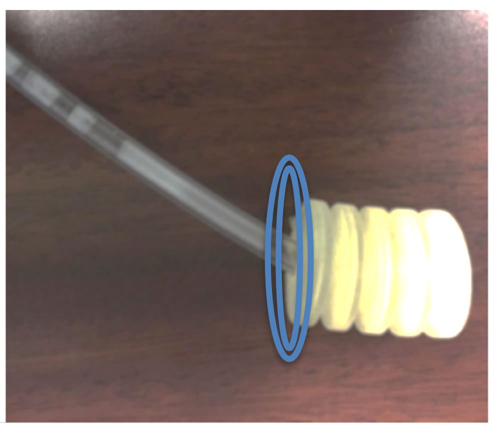
Fully 3-D printed actuator using Polyjet printing

Manufacture and testing



Polyjet Printing: Mix of Flexible and Hard Resin





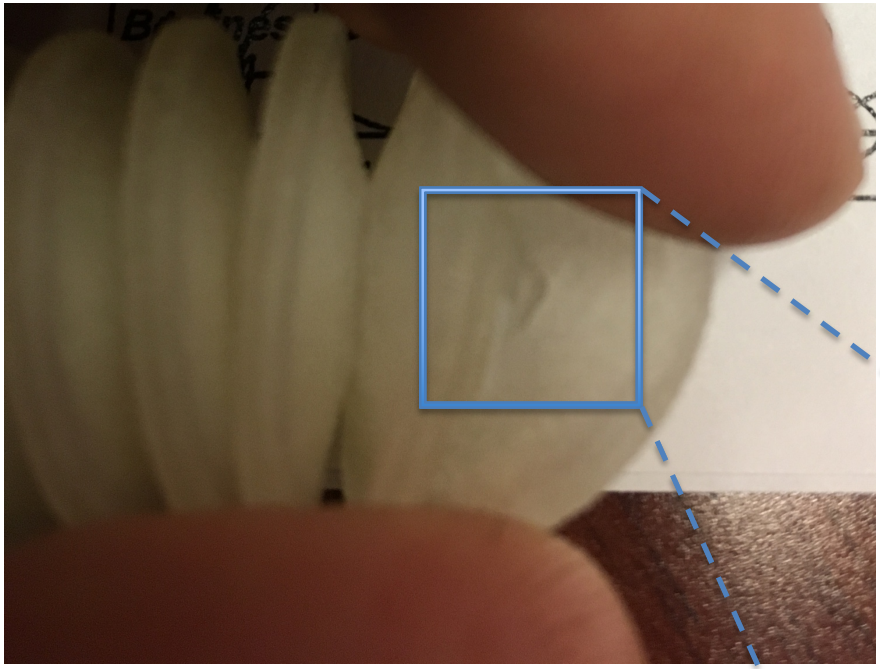
Tango Resin ®
Hardness: 26-28 Shore A

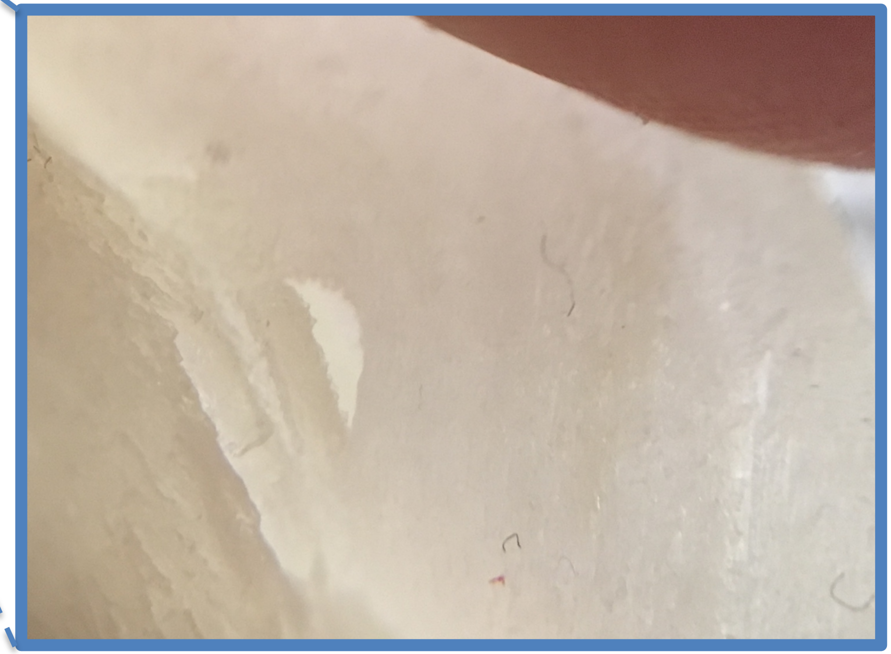
+

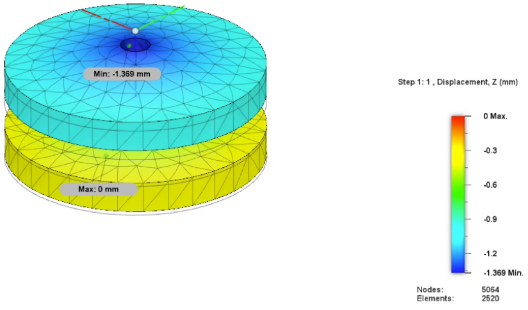
VeroClear ® Resin
Flexural Strength: 75-110 MPa

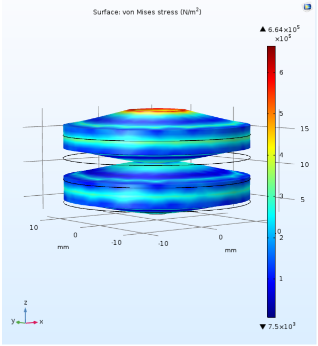
Fully 3D printed actuator

Manufacturing deficiencies and weak points





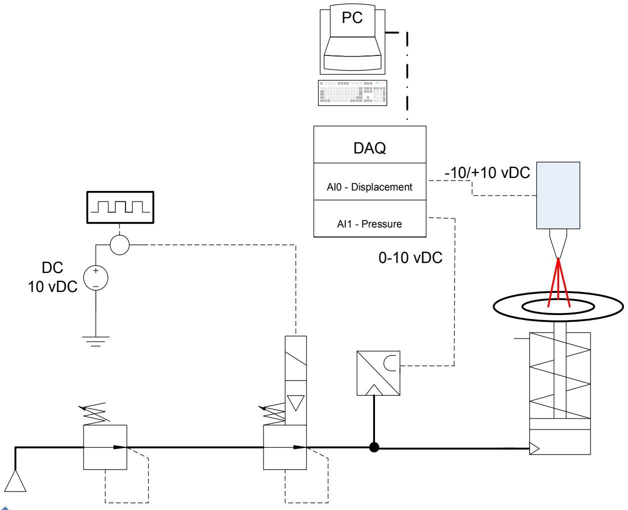


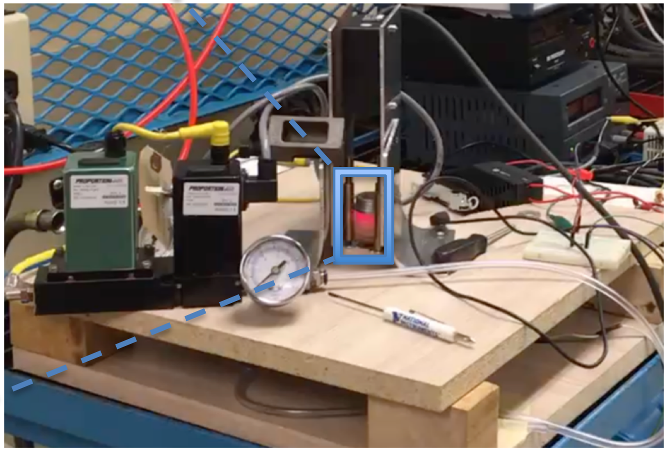


Fully 3D printed actuator

Fully 3-D printed actuator

Experimental characterization

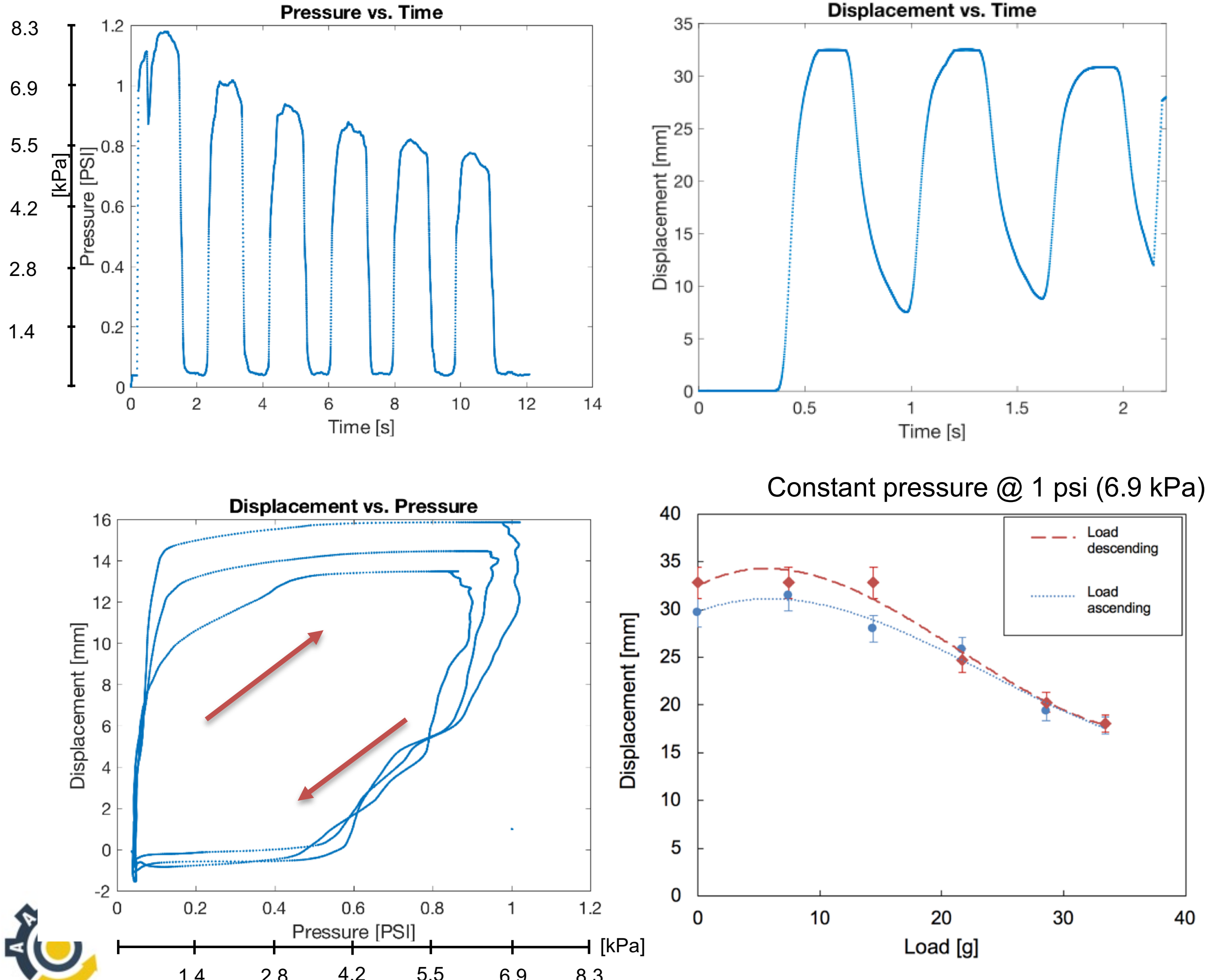




Fully 3D printed actuator

Fully 3-D printed actuator

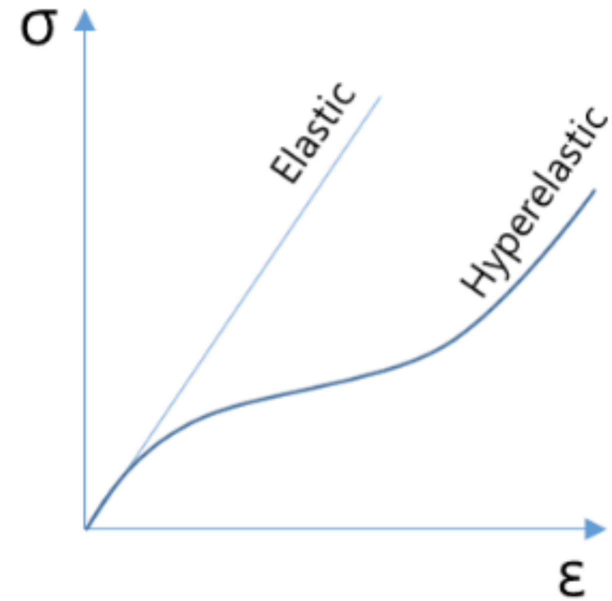
Characterization results

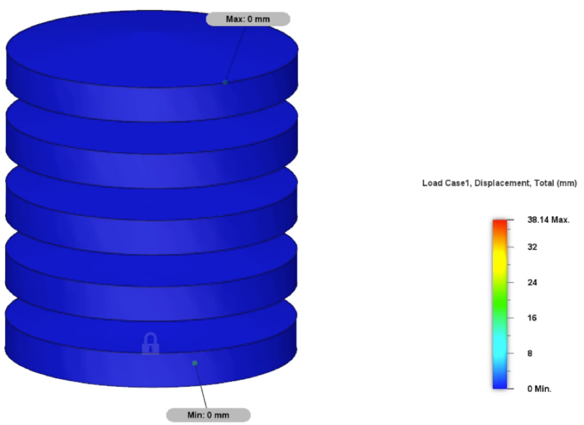


Soft actuator discussion and next steps

http://support.recurdyn.com/difference-hyperelastic-material-elastic-material-recurdyn/?ckattempt=1

- **Hyperelastic materials** are designed for modeling rubber or rubber-like materials in which the elastic deformation can be extremely large.
- Typical stress-strain capabilities of a hyper-elastic material
- Some of the Hysteresis is exhibited due to elasticity of the material and mostly the evacuation of the air
- Need to test with negative pressure to better characterize the actuator





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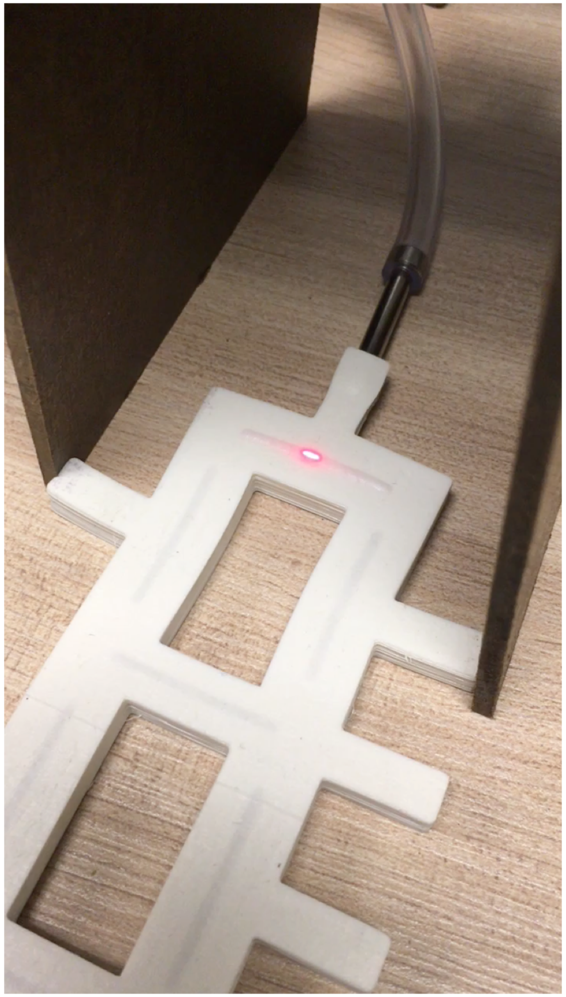
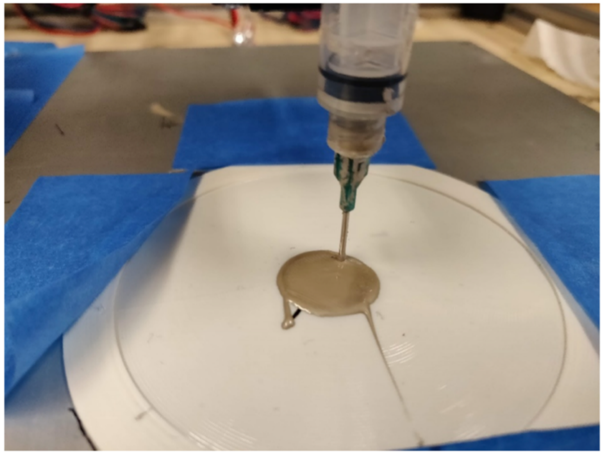
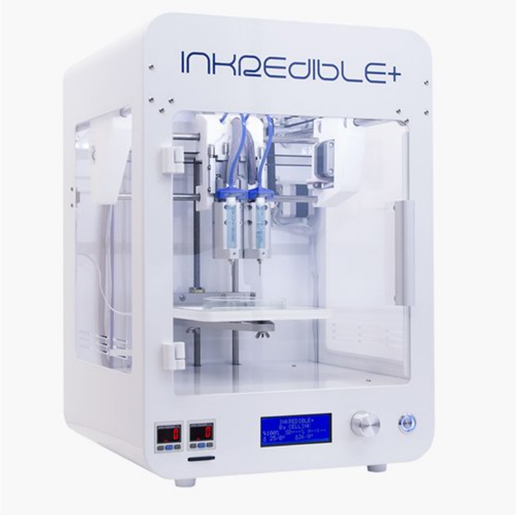
Soft actuator next steps



- Design and characterization of segmented and multiple actuators.
- FEA modeling of actuators
- Embedded sensing through the use of 3D printable electrically conductive polymers and layered structures





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