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
Steering Assembly

Mechanical Feedback

Spool

Kingpins
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
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

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
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

Aidro Hydraulics, 3D Printed Hydraulic Manifold for Agricultural Machinery

https://www.aidro.it/3d-metal-printing.html
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
- Lulzbot Taz 5
  - 28 x 28 x 25 cm
  - 100 micron layer resolution

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

Digital Light Projecting (DLP)
- Projector flashes individual layers
- Rigid and flexible materials available
- Autodesk Ember
  - 6 x 4 x 16 cm
  - 50 micron resolution (nominal), 1 micron resolution (maximum)

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

Filament is heated and extruded
- Makerbot Replicator 2x
  - 25 x 16 x 16 cm
  - 100 micron layer resolution
- Lulzbot Taz 5
  - 28 x 28 x 25 cm
  - 100 micron layer resolution

https://shop3d.ca/products/form2

https://ember.autodesk.com/
3D Printing Materials

Fused Deposition Modeling (FDM)
- PLA and ABS
  - Filaments for rigid parts

High Impact Polystyrene
- D-limonene soluble filament

Polyvinyl 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 parts

Digital Light Projecting (DLP)
- CPS PR48
  - Clear, higher resolution than Formlabs clear but lower Young’s modulus resin
  - Other resins in Form 2 catalog

Polyjet Printing
- RGD 720
  - Clear resin
- SUP 705
  - Additional support material

Silicone Printing
- Alginate
- CELLINK & Fibrinogen
- CELLINK® PCL
- CELLINK & Tricalcium phosphate

https://ember.autodesk.com/
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
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

<table>
<thead>
<tr>
<th>Designs</th>
<th>Dsgn. 1</th>
<th>Dsgn. 2</th>
<th>Dsgn. 3</th>
<th>Dsgn. 4</th>
<th>Dsgn. 5</th>
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<tbody>
<tr>
<td>Model</td>
<td>Form Labs Form 2 Printer</td>
<td>Form Labs Form 2 Printer</td>
<td>Form Labs Form 2 Printer</td>
<td>Form Labs Form 2 Printer</td>
<td>Autodesk Ember</td>
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<td>Printer</td>
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<td>Support Point Size</td>
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<td>Wall Thickness</td>
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<td>1 mm</td>
<td>1 mm</td>
<td>0.7 mm</td>
<td>1.2 mm</td>
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<td>Number of Bellows</td>
<td>12</td>
<td>12</td>
<td>8</td>
<td>2</td>
<td>7</td>
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<td>Bellows Diameter</td>
<td>24 mm</td>
<td>24 mm</td>
<td>20 mm</td>
<td>24 mm</td>
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<td>Bellows Height</td>
<td>1.6 mm</td>
<td>1.6 mm</td>
<td>3 mm</td>
<td>1.6 mm</td>
<td>1.6 mm</td>
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<td>Results</td>
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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


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

Inflatable Compression Sleeve
**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**
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

**Test Set Up:**
- Manual Air Regulator
- Electronic pressure regulator
- Pressure Transmitter
- Position Sensor
- Load
- Actuator

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<table>
<thead>
<tr>
<th>Device</th>
<th>Model</th>
<th>Range</th>
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<tr>
<td>Pressure Transducer</td>
<td>Honeywell LM/2345-08</td>
<td>0-15 psig</td>
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<tr>
<td>Position Sensor</td>
<td>SHARP GP2Y</td>
<td>20-150 cm</td>
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<tr>
<td>Electronic Pressure Control Valve</td>
<td>Proportionair FQPV2</td>
<td>2-20 SCFH</td>
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</table>
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
Results

Pressure vs. Displacement

<table>
<thead>
<tr>
<th>Load</th>
<th>Pressure Threshold (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No load</td>
<td>0.47</td>
</tr>
<tr>
<td>200 g</td>
<td>0.75</td>
</tr>
<tr>
<td>500 g</td>
<td>1</td>
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</tbody>
</table>
Step Response for Expanding Actuator at $\Delta P = 1.20$ psi

Step Response for Expanding Actuator at $\Delta P = 1.60$ psi

Step Response for Retracting Actuator at $\Delta P = 1.20$ psi

Step Response for Retracting Actuator at $\Delta P = 1.60$ psi

Position (cm) vs. Time (s) for different loads and input pressures.


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
Manufacturing deficiencies and weak points

Fully 3D printed actuator
Fully 3D printed actuator

Experimental characterization
Fully 3D printed actuator

Characterization results

- **Pressure vs. Time**
- **Displacement vs. Time**
- **Displacement vs. Pressure**

Constant pressure @ 1 psi (6.9 kPa)
• **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

http://support.recurdyn.com/difference-hyperelastic-material-elastic-material-recurdyn/?ckattempt=1
• 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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https://www.purdue.edu/aatl/