Semi-physical Modeling of Soft Pneumatic Actuators with Stiffness Tuning

MECC/ALDSC 2023 10/04/23

Lake Tahoe, Nevada

Preston Fairchild[1], Noah Shephard[1], Yu Mei[1], Xiaobo Tan[1]

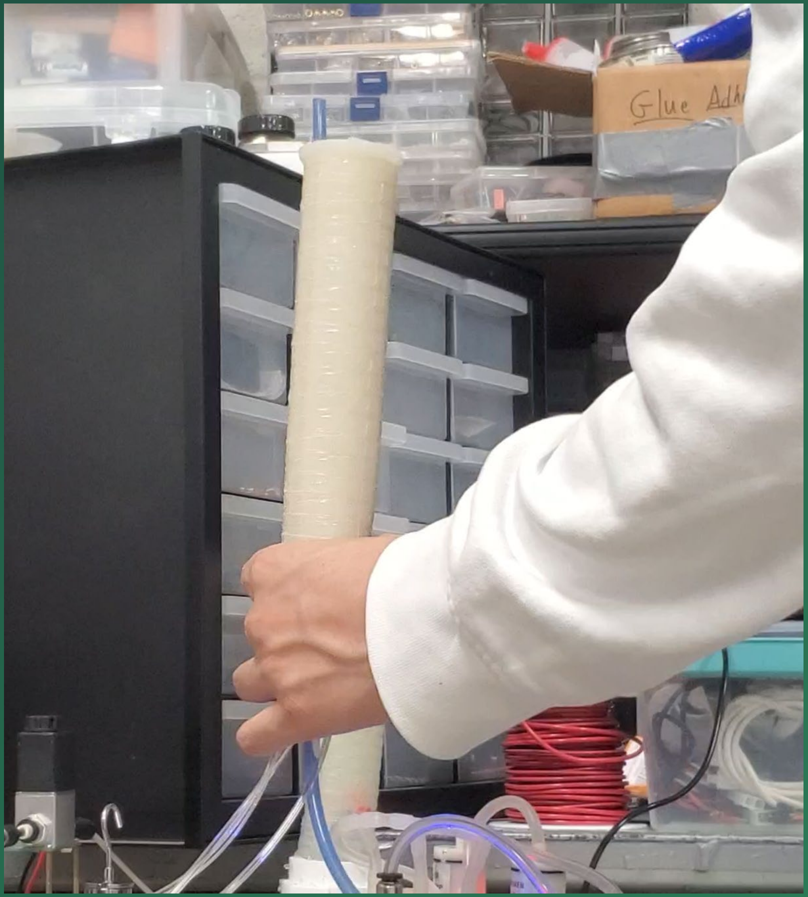
[1] Department of Electrical and Computer Engineering

Michigan State University

Soft Robotics

Why use soft robots?

- Flexible soft material
  - Safety around humans
  - Human Robot interaction
  - Handling of delicate materials (fruit, vegetables, baked goods)
- Continuum nature and high degrees of freedom
  - Versatile trajectories

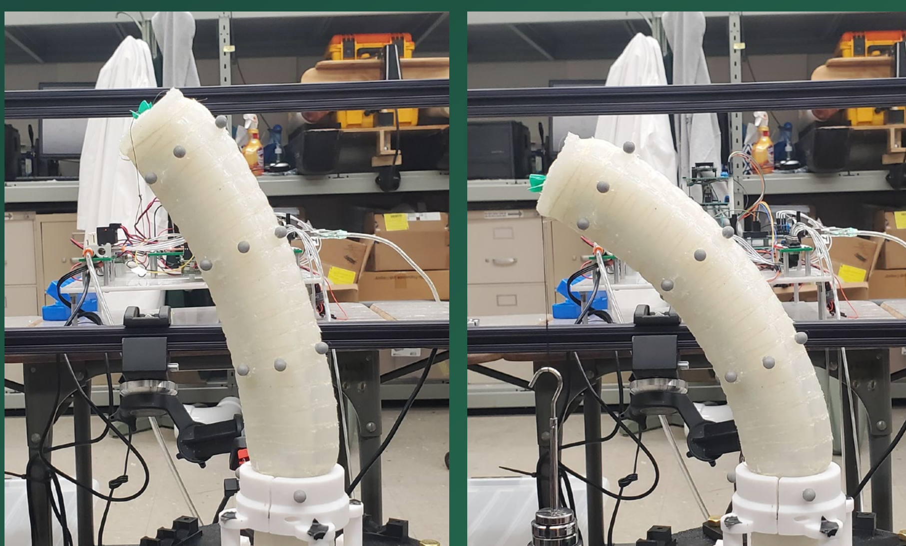


Safe handling of soft robot under actuation

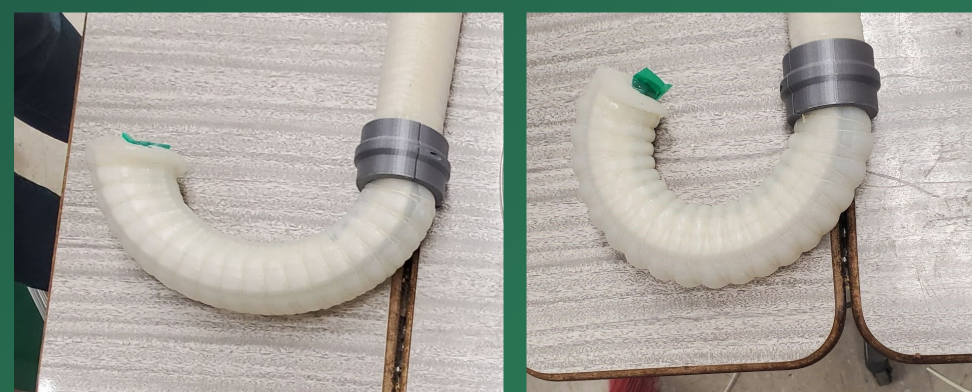
Challenges of Soft Robotics

- Difficult to control with high degree of freedom and nonlinearities
- High deformity under external forces and payload
- Variations in fabrication process produces nonuniform operation

How can a model account for these?



Soft manipulator before and after 100g payload was applied



Different shape when actuated with same control input on different chambers

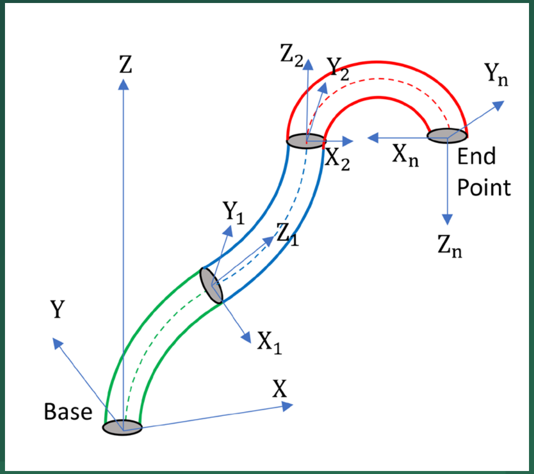
Piecewise Constant Curvature Model

Individual segments of the manipulator are represented through arcs with a constant curvature

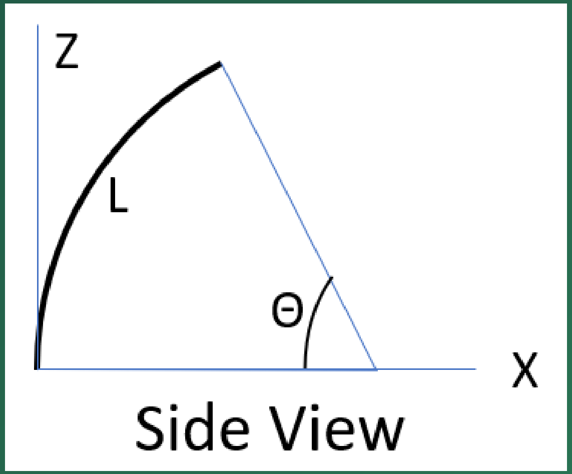
A single segment is described with three configurable variables:

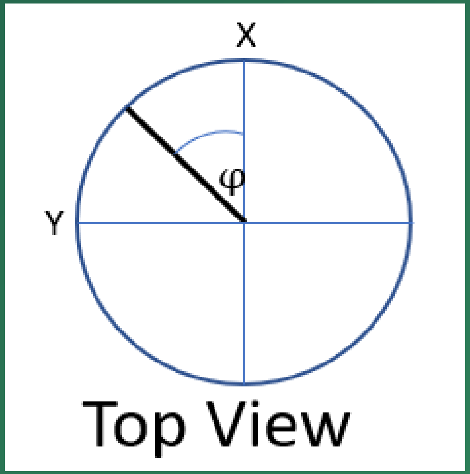
[L,ϴ, φ]

1. L is the overall length of the arc at the center
2. ϴ is the magnitude of bending.
3. φ is the direction of bending



Piecewise Constant Curvature Representation





Variable Curvature

With no external forces considered, soft robots can closely follow the PCC model. With external forces considered, a variable curvature can be utilized

$$k = \frac{d^2 w}{dx^2} = \frac{1}{r} = \frac{\theta}{L}$$

$$k(s) = \frac{M(s)}{EI}, s \in [0, L]$$

k is the curvature
s is a parametric variable along the arc length of the manipulator
M is the moment experienced at *s* on the manipulator
EI is the bending stiffness of the arm as a function of young's modulus and the second moment of inertia

Shape Reconstruction

With known curvature, the shape can be reconstructed as functions of the bending curvature and bending direction. With the shape, two types of external forces are considered

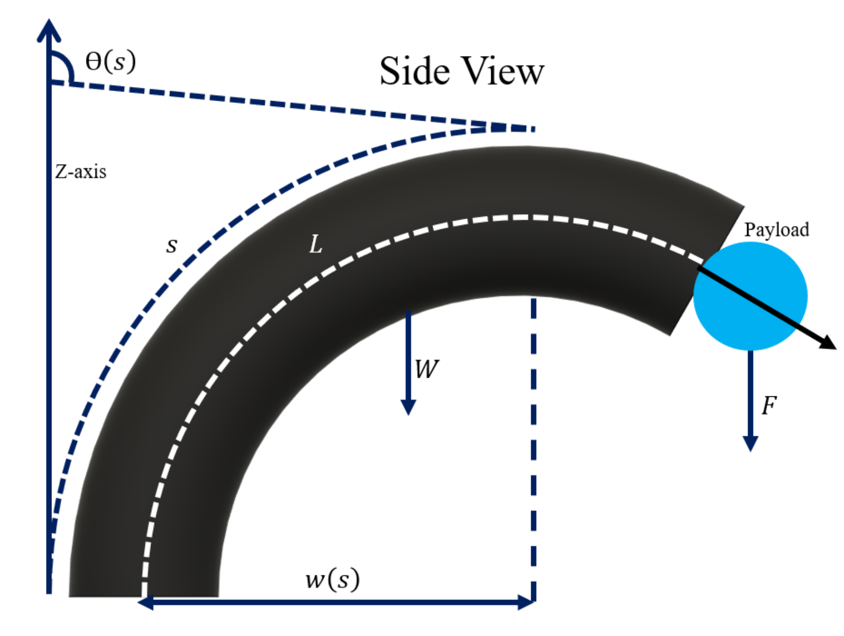
1. The weight of the manipulator

$$M(s) = \int_{s}^{L_c} \frac{W}{L_c} * \sin(\Theta(s))[w(L_c) - w(s)]\ ds,$$

$$w(s) = \int_{0}^{s} \sin(\Theta(s))\, ds,\ \Theta(s) = \int_{0}^{s} k(s) ds$$

2. A payload on the manipulator

$$M(s) = F * \sin(\Theta(s)) * [w(L_c) - w(s)]$$

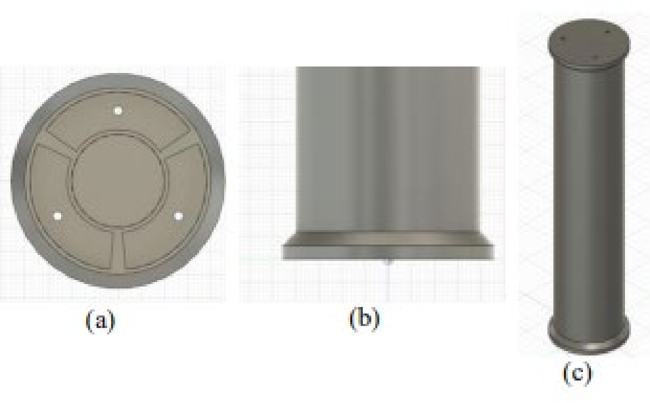


Design of Soft Robot

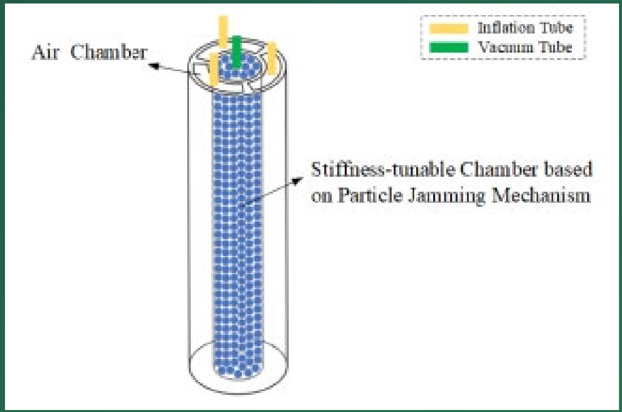
Robot used in this work is a silicone body, pneumatically actuated soft robot.

- Three air chambers evenly separated for bending actuation
- Central chamber filled with granular material to act as a stiffness tuning device

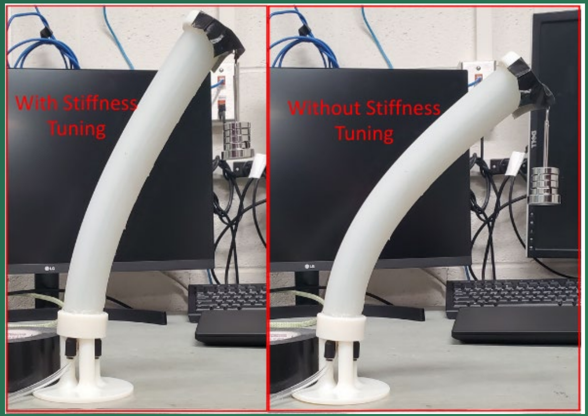
Based on this design a model for the length, moment, and stiffness is needed.



CAD of soft robot



Stiffness tuning diagram

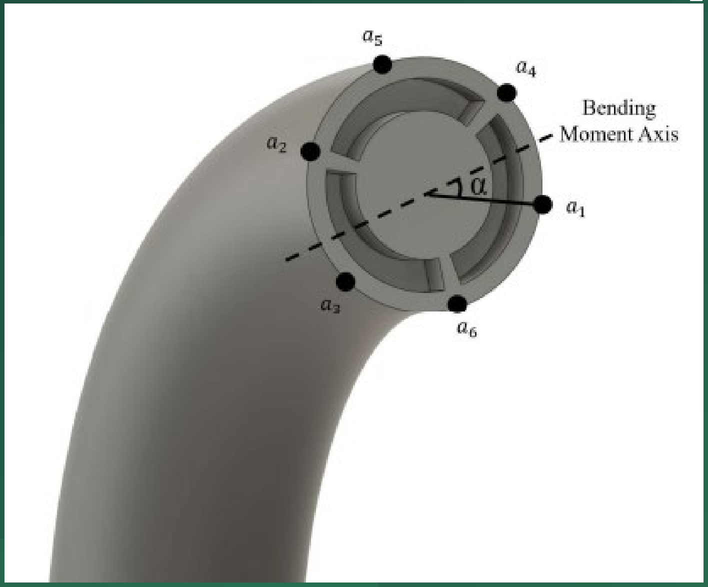


Stiffness tuning effect

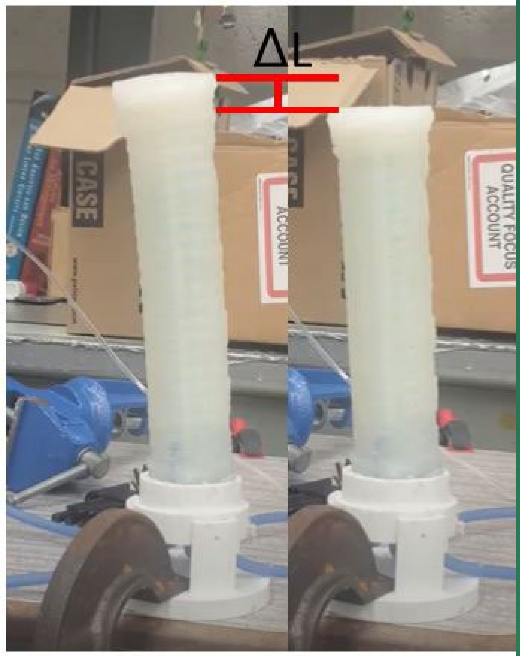
Length Modeling

Length of the manipulator changes under actuation. Under pressure inputs $P = [P_1,\ P_2,\ P_3]$, the robot increases in length enough to significantly alter the tip position.

$$\Delta L(\alpha) = P_1[a_1 + a_2 + (a_1 - a_2)\cos(\alpha)] + P_2\left[a_3 + a_4 + (a_3 - a_4)\cos(\alpha + \frac{2\pi}{3})\right] + P_3\left[a_5 + a_6 + (a_5 - a_6)\cos(\alpha - \frac{2\pi}{3})\right]$$



Length around circumference



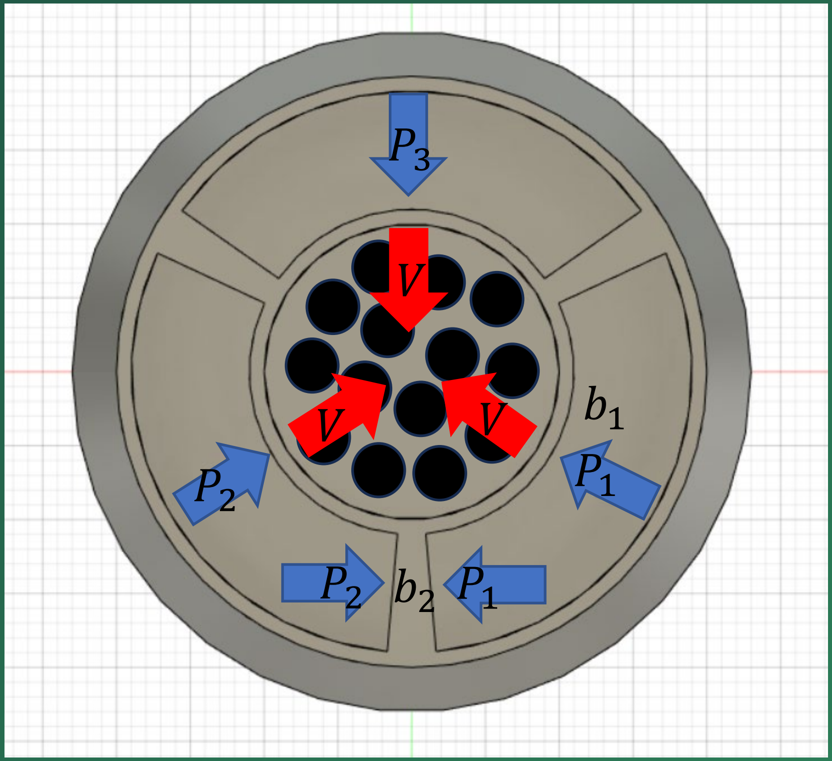
Change in Length

Stiffness Modeling

Pressure between the air chambers and stiffness tuning device can create a variable stiffness

$$EI = b_1 + b_2 \min(P) + b_3[V + \frac{1}{3} sum(P)]$$

- b_1 is the base stiffness
- b_2 is the stiffness generated by the antagonistic pressure
- b_3 is the stiffness generated by the stiffness tuning device
- V is the vacuum pressure on the stiffness tuning chamber



Pressure Between Chambers

Moment Modeling

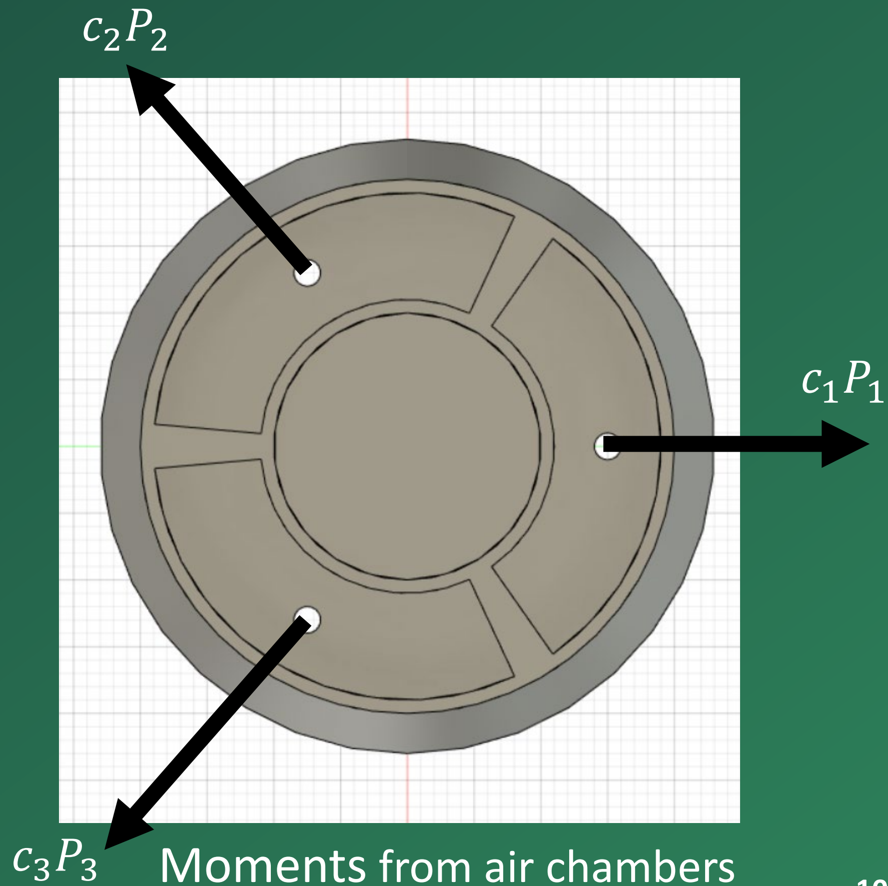
Each chamber generates a bending moment based on the pressure input. These values are unique enough to warrant individual parameters.

$$M_x = c_1 P_1 - \frac{1}{2} c_2 P_2 - \frac{1}{2} c_3 P_3$$

$$M_y = c_2 P_2 \frac{\sqrt{3}}{2} - c_3 P_3 \frac{\sqrt{3}}{2}$$

$$|M| = \sqrt{{M_x}^2 + {M_y}^2}$$

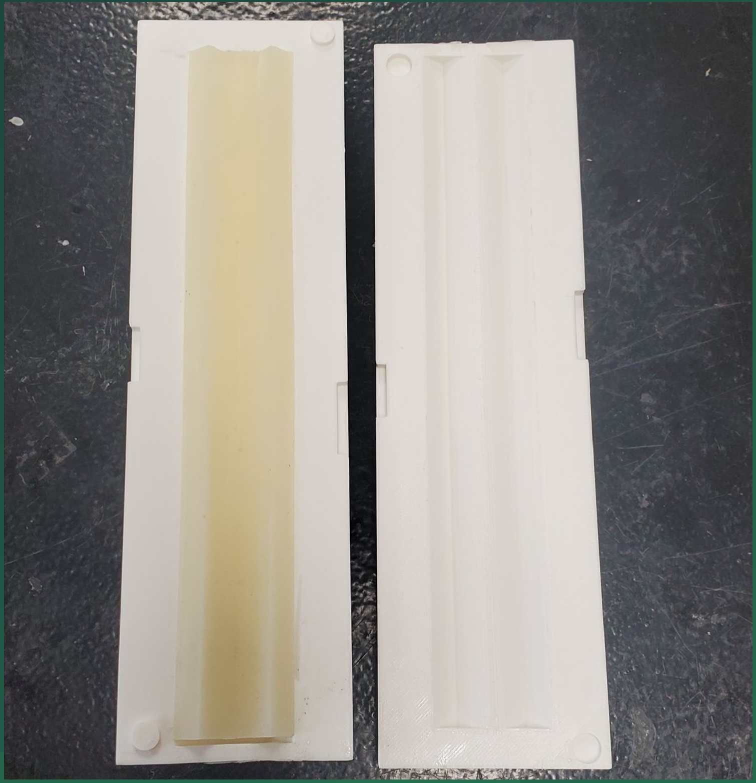
$$\angle M = \tan^{-1}(M_y / M_x) = \varphi$$



Moments from air chambers

Fabrication of Soft Robot

- 3D printed mold used for silicone casting with Dragon Skin™ 20
- Wax pieces used for internal air chambers for better sealing
- Fiber reinforcement with Kevlar thread to prevent bellowing



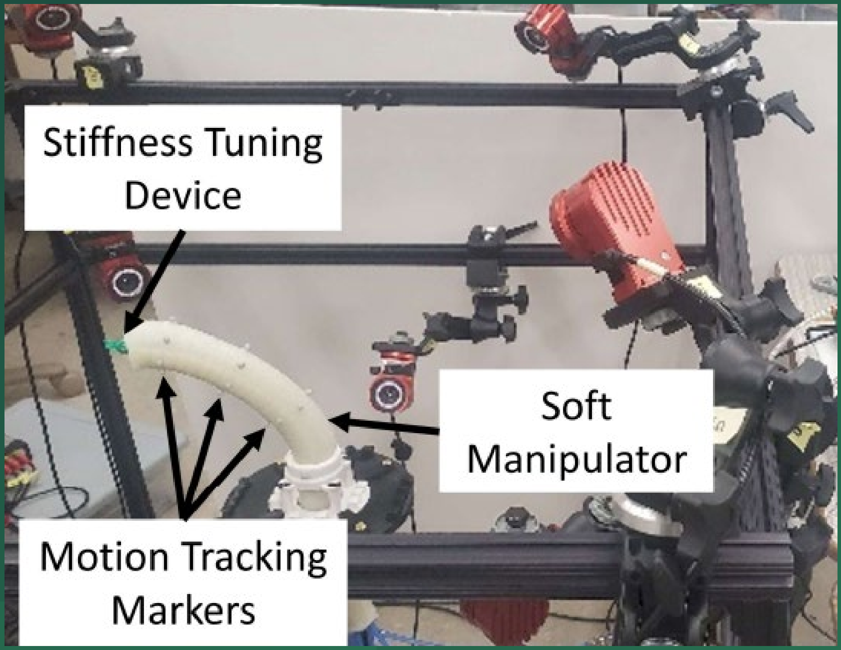
Wax Mold

Robot Mold

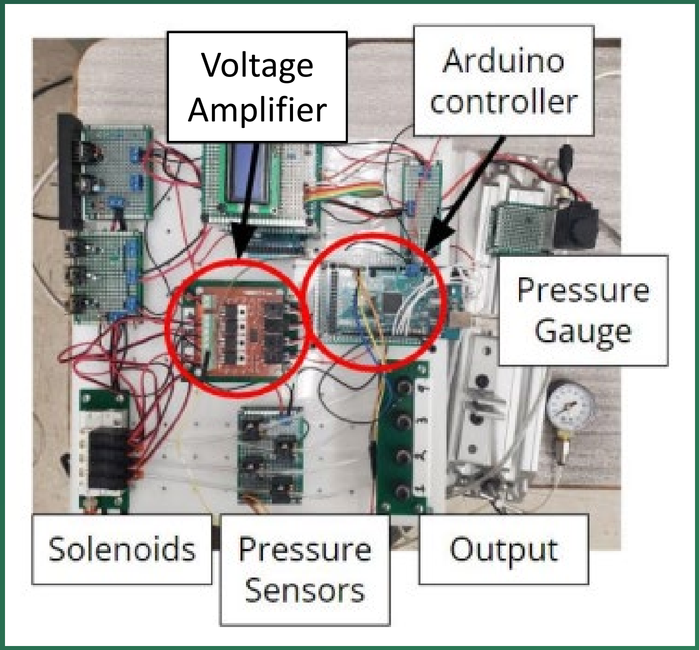
No Fiber reinforcement

Experimental Setup

- Motion capture system used to capture position of the manipulator for its length and bending angle
- Difference in bending from before and after a payload is added is used to estimate the true stiffness
- Model was trained on 20 randomly generated control inputs



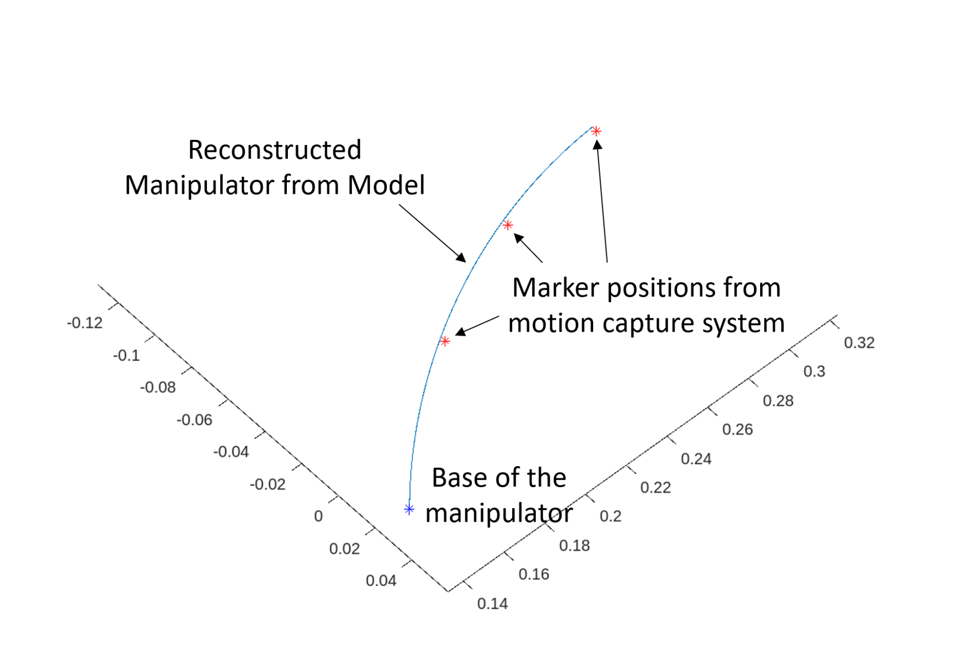
Motion Tracking System



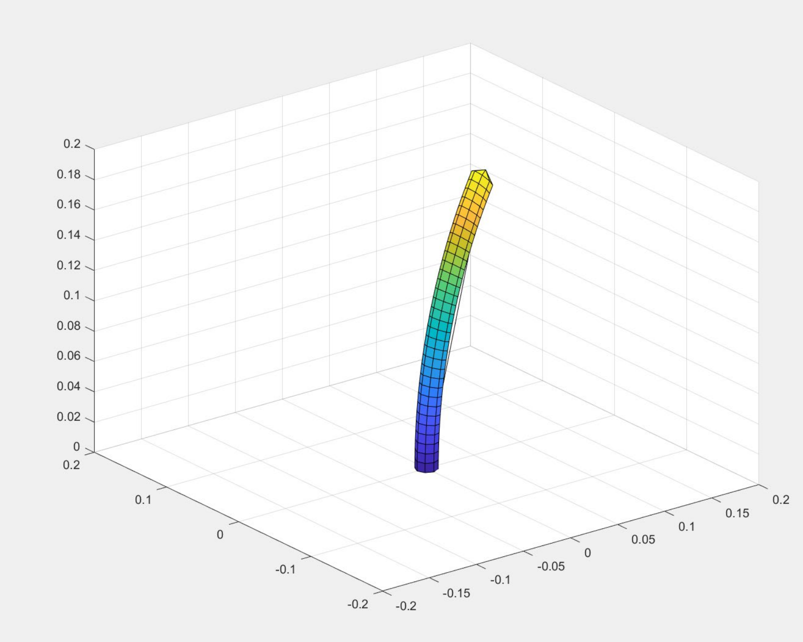
Pneumatic Control Board

Data interpretation

With the parameters calculated using model, the shape of the manipulator can be reconstructed.



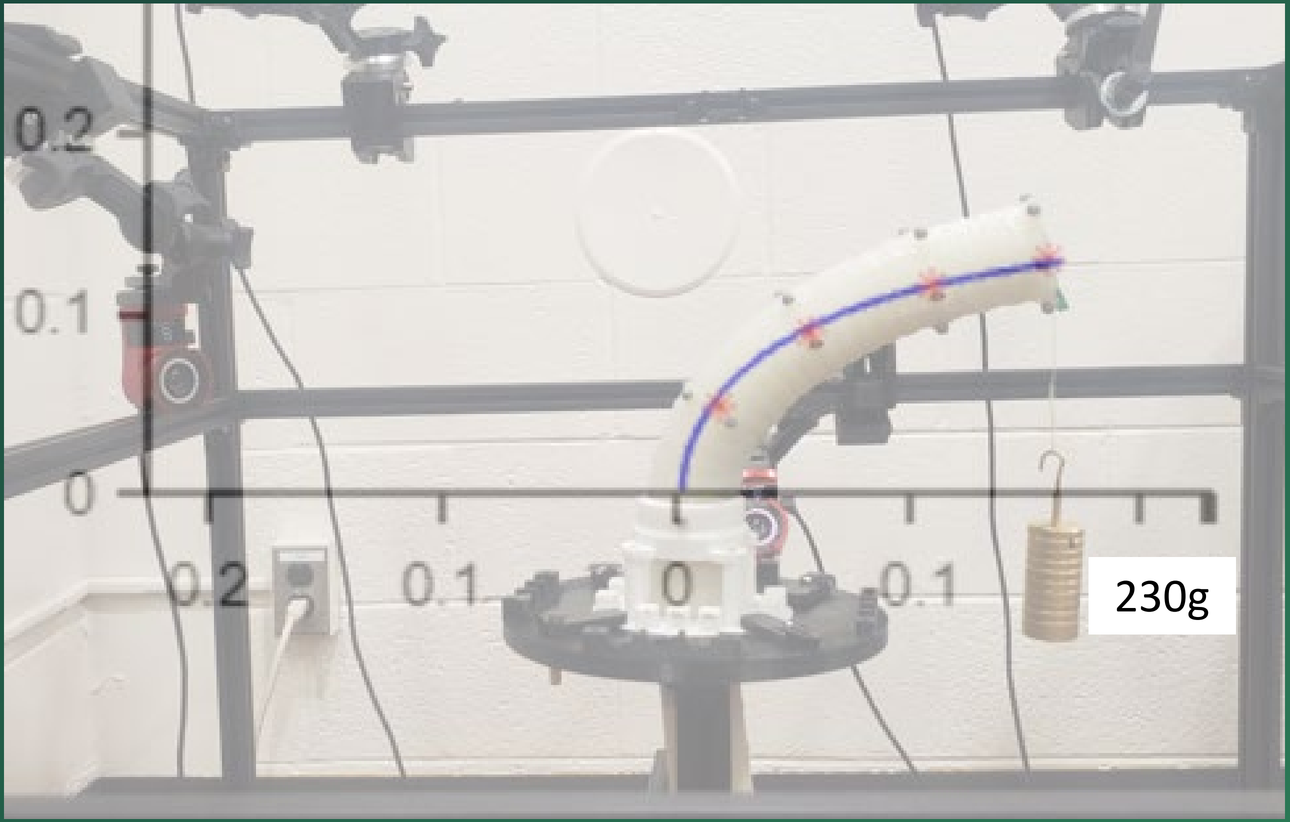
Marker Centroid vs Reconstructed shape



3D shape reconstruction

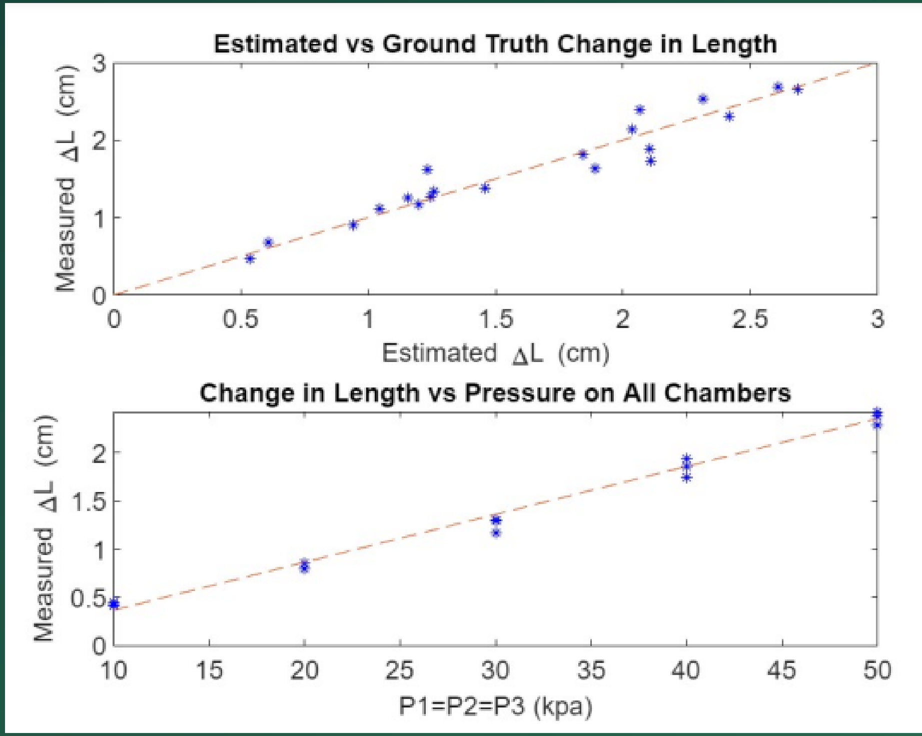
Payload Input

With a known payload value, the shape of the manipulator can still be reconstructed with the estimated stiffness value

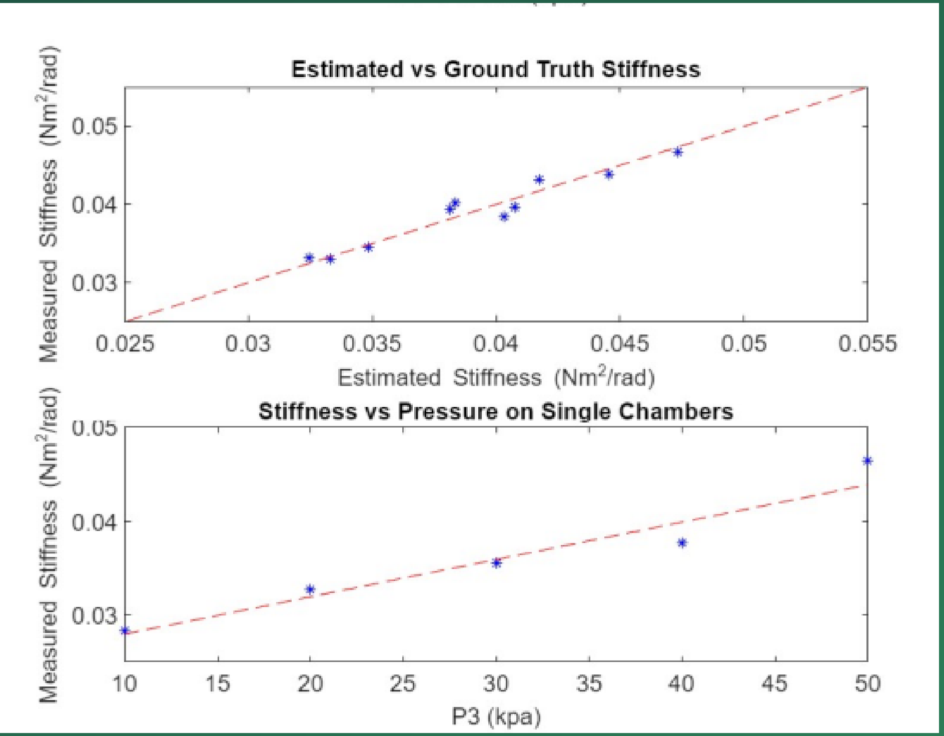


Overlay of reconstructed shape on actual robot

Parameter Estimation Results



Length Results



Stiffness Results

Shape reconstruction results

10 more random set of control inputs were generated and tested with the model that it was not trained on.

	Absolute (cm)	Percent
Mean Error	0.85	4.49%
Median Error	0.5	2.63%
Maximum Error	3.1	16.3%
Minimum Error	0.13	0.68%

Conclusions and Future Work

Conclusions

- Model able to accurately predict the length, moment, and stiffness of the manipulator
- Low error on predicting the shape of the manipulator

Future Work

- Extend modeling work to account for multiple segments and nonlinearities
- Utilize control methods to move robot on a given trajectory with the model

This work was supported by the National Science Foundation under grant ECC S 2024649

Questions?