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NRI: FND: Smart Material Composites and Design of Internal Structural Geometry for Tunably-Compliant Soft Robots

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Award ID # 1734117

Compliance matching in soft robotics

To prevent the robot from penetrating into the surface and causing damage or mechanical immobilization, the forces transferred between the robot and surface must be evenly distributed over a large contact area. This requires ***compliance matching — that is, the principle that contacting materials should share similar mechanical rigidity in order to evenly distribute internal load and minimize interfacial stress concentrations****.*

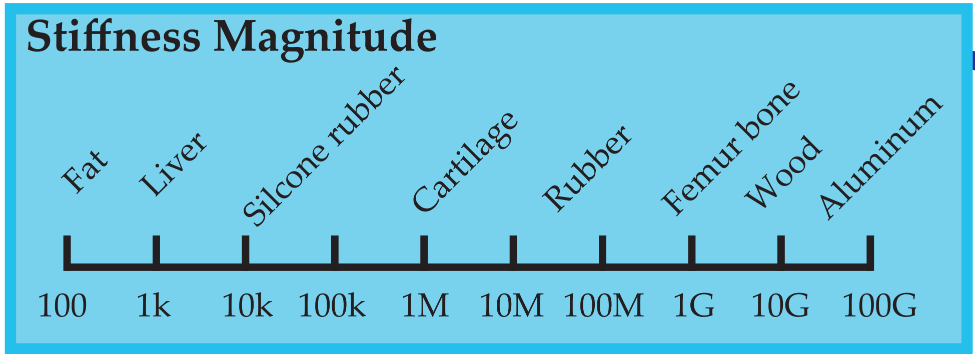
C. Majidi. Soft robotics: a perspective–current trends and prospects for the future. *Soft Robotics*, 1(1):5– 11, 2014 (**emphasis added**)

The problems

Task-specific compliance matching is not always possible when using traditional soft-robotic components and traditional variable-impedance mechanism. Some of the problems encountered are:

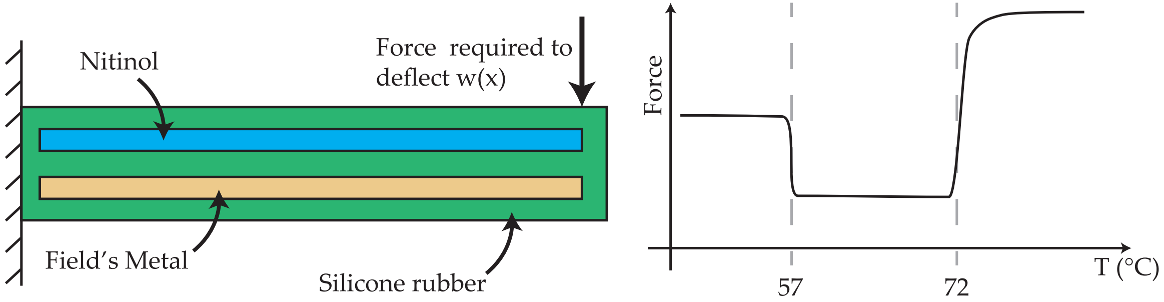
- Desired stiffness above an upper bound on the stiffness of a soft material
- Insufficient change or insufficient granularity in stiffness magnitude
- Tradeoffs between stroke length and stiffness variability
- Inability to control the axes of stiffness variability

Desired stiffness above an upper bound on the stiffness of a soft material or insufficient stiffness variability

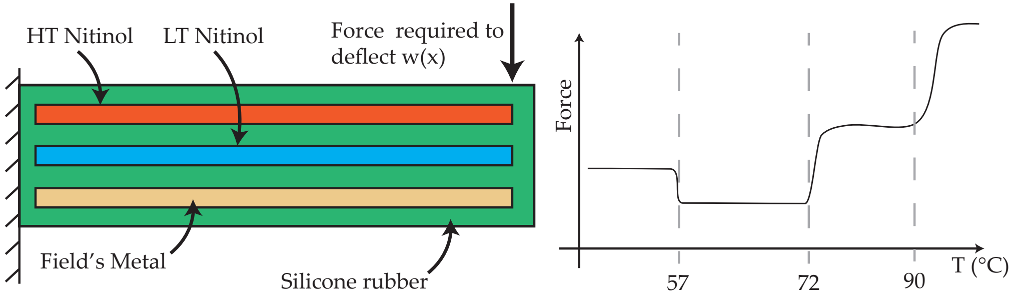


Desired stiffness above an upper bound on the stiffness of a soft material or insufficient stiffness variability

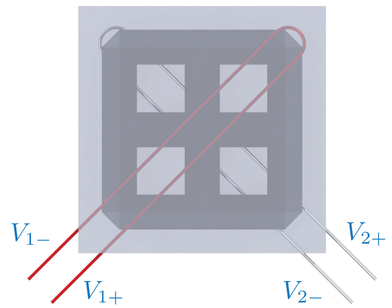
Material	Critical temperature	Stiffness variability
Nitinol	72° C Martensite to Austenite	34 GPa to 83 GPa
Field's metal	57° C melting point	9.25 GPa to 0 GPa
Silicone rubber	500° C maximum	0.05 GPa

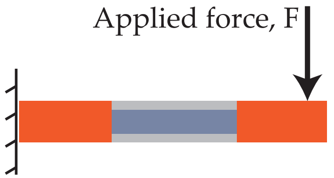


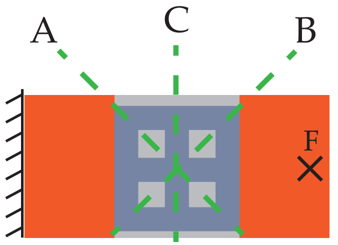
Material	Critical temperature	Stiffness variability
Low-Temp Nitinol	70° C Martensite to Austenite	34 GPa to 83 GPa
Hi-Temp Nitinol	90° C Martensite to Austenite	34 GPa to 83 GPa
Field's metal	57° C melting point	9.25 GPa to 0 GPa
Silicone rubber	500° C maximum	0.05 GPa

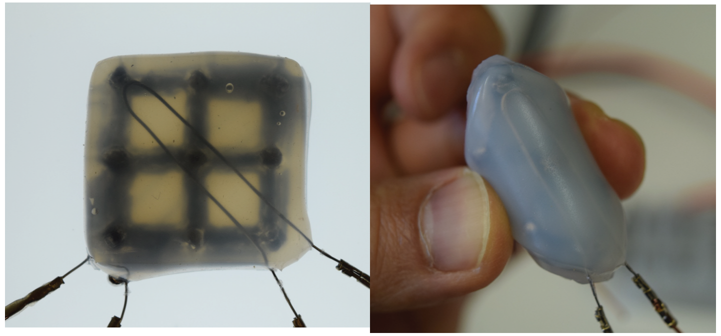


Controlling axes of compliance through selective activation of the composited smart material

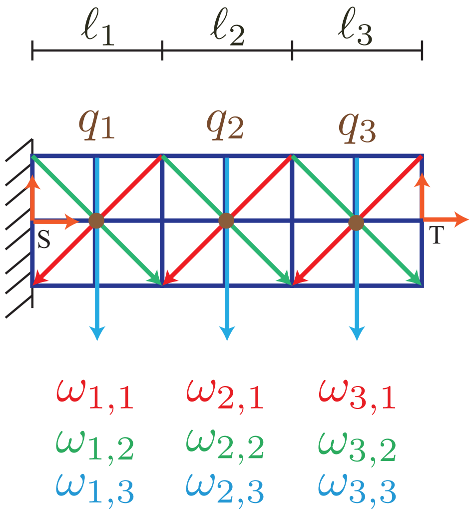








Simplified kinematics through update of nominal configuration and twists associated with the compliant axis.



$$g_{ST}(0) = \begin{bmatrix} 1 & 0 & 0 & \ell_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$q_1 = \begin{bmatrix} \ell_1/2 \\ 0 \\ 0 \end{bmatrix} \quad q_2 = \begin{bmatrix} \ell_1 + \ell_2/2 \\ 0 \\ 0 \end{bmatrix}$$

$$q_3 = \begin{bmatrix} \ell_1 + \ell_2 + \ell_3/2 \\ 0 \\ 0 \end{bmatrix}$$

$$\xi_{1,p} = \begin{bmatrix} -\omega_{1,p} \times q_1 \\ \omega_{1,p} \end{bmatrix} \quad \xi_{2,p} = \begin{bmatrix} -\omega_{2,p} \times q_2 \\ \omega_{2,p} \end{bmatrix}$$

$$\xi_{3,p} = \begin{bmatrix} -\omega_{3,p} \times q_3 \\ \omega_{3,p} \end{bmatrix}$$

Compliant Axis-Dependent Forward Kinematics

$$g_{ST}(\theta) = e^{\widehat{\xi_{1,p}}\theta_1} e^{\widehat{\xi_{2,p}}\theta_2} e^{\widehat{\xi_{3,p}}\theta_3} g_{ST}(0)$$

Metrics for Rating Stiffness Variability

Scoring for global change in magnitude and/or achievable workspace

Scoring minimum and maximum achievable stiffness

Material	Critical temperature	Stiffness variability
Low-Temp Nitinol	70° C Martensite to Austenite	34 GPa to 83 GPa
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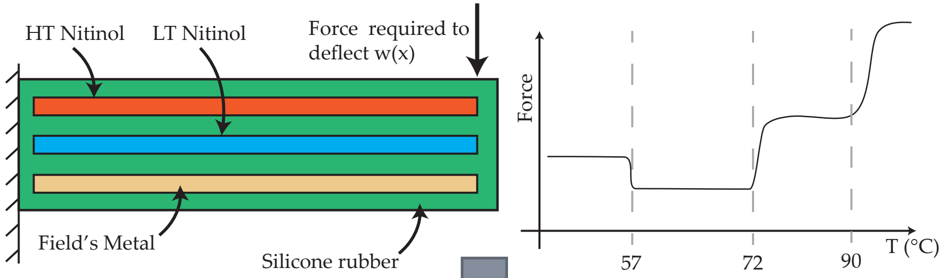
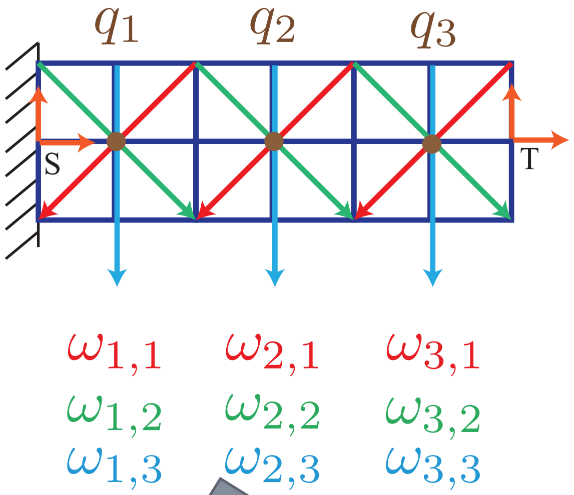
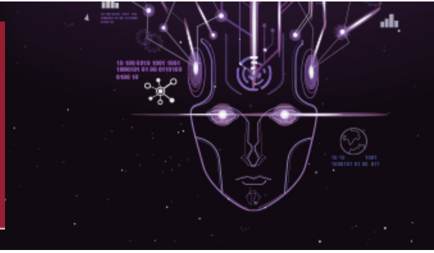


Score spatially distributed change in magnitude and directionality of stiffness



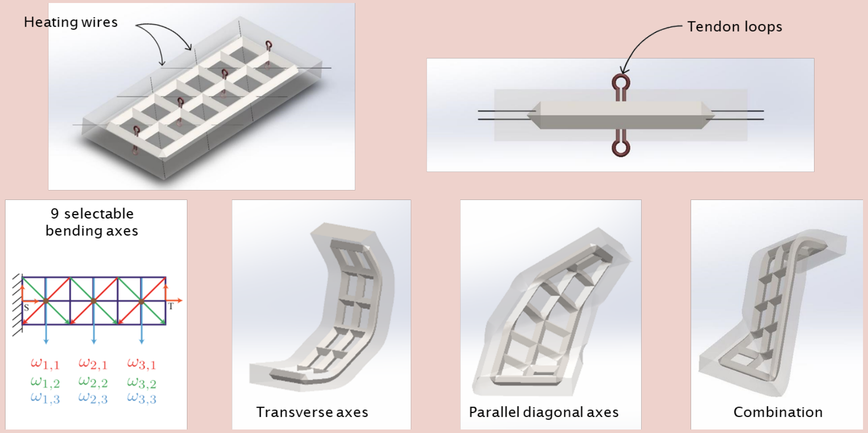
broadly applicable metric(s) across soft robotics, compliant mechanisms, and tunably-compliant robotics.



Low Melting Point Lattice Embedded in Elastomer [1]

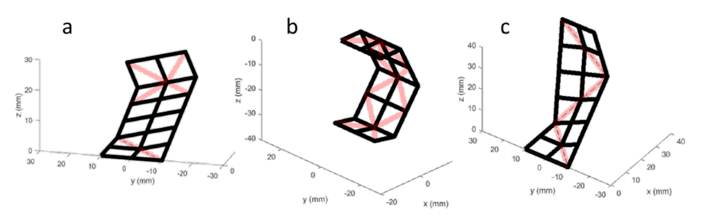
Device

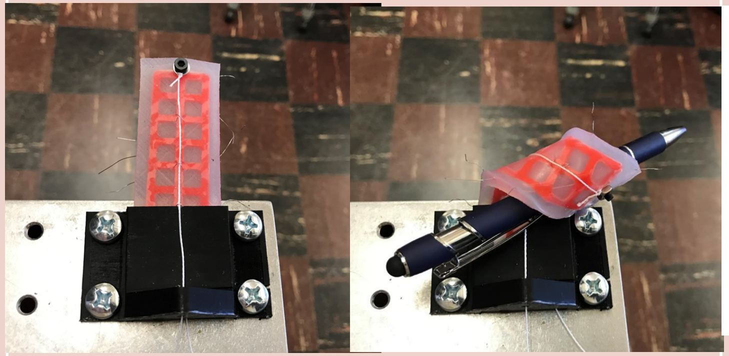
A low melting point metal or polymer lattice is encased in an elastomer with nichrome heating wires to enable selective melting of the lattice. Tendon loops route a tendon along each side of the element.



Stiffness Control Mechanism

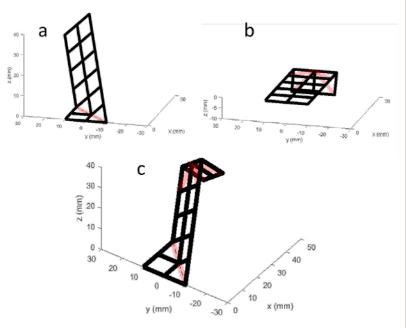
Selective melting of the embedded lattice “skeleton” lowers the stiffness of the structure in the selected direction. This axis selectivity enables directional control and unique morphing capabilities.





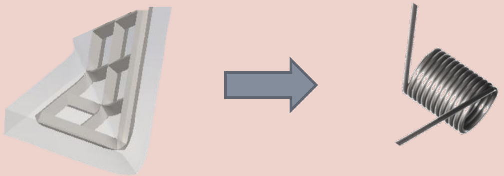
Mode of Actuation

With the axis Selectivity enabled by Localized Heating elements, a single tendon on each side of the element activates a variety of unique configurations, especially when axes are allowed to cool and re-solidify in a new configuration before activating the next axis.



Modeling

Here we relate the tendon forces to the resulting configuration of the element in static equilibrium for any set of axes selected (melted). In this relationship, we model the melted axes as torsional springs with constant stiffness to represent the elastomer’s resistance to bending.



This model allows us to determine what configurations are possible for any given axis selection and conversely what tendon forces are required to achieve a desired configuration.

[1] E. A. Allen, B. C. Townsend, and J. P. Swensen, “Configuration Modeling of a Soft Robotic Element with Selectable Bending Axes,” in Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2019), Macau, China, Nov. 2019.

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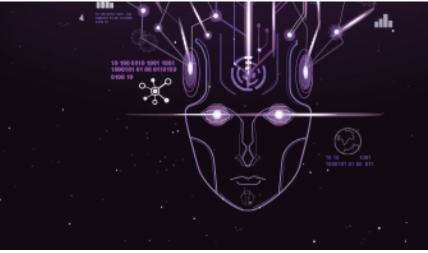
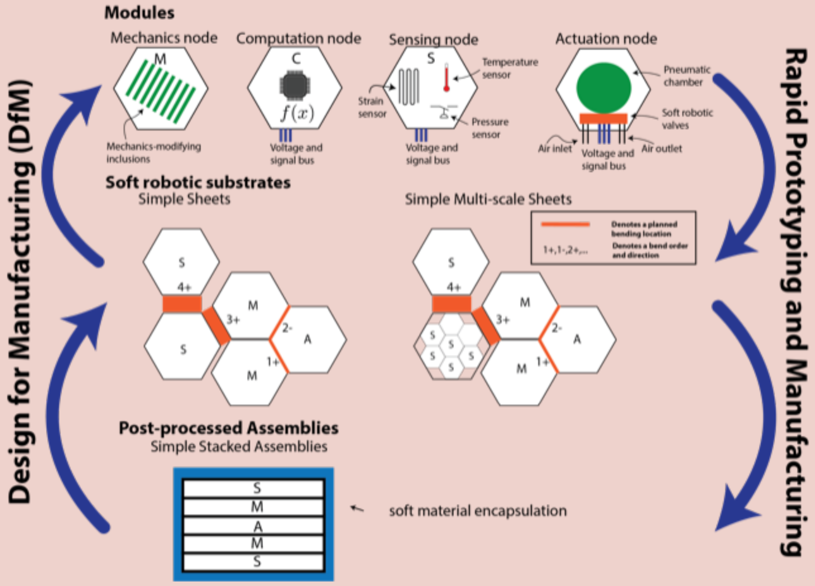


Fiber-Reinforced Pneumatic Actuators with Strategic Layering [2]

Device

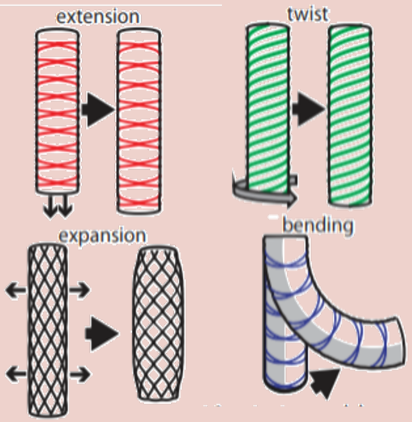
Fiber reinforcement is a common way of producing predictable motions in soft pneumatic actuators upon inflation. Here, the effects of different fiber arrangements and potential stacking/layering of multiple pneumatic units is explored. The combination of bending, twisting, and other pneumatic actuators within a bulk material may produce desirable morphing capabilities.



Stiffness Control Mechanism

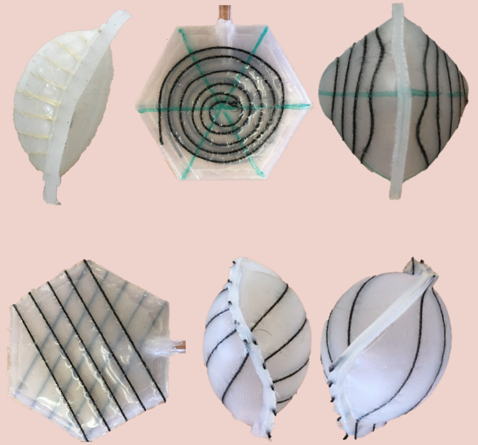
Many pneumatic bending actuators exist in the literature, but the present work demonstrates that the underlying fiber layout has the ability to modify the mechanics of the actuator, directing expansion and controlling bending behavior.

Modifying the fiber arrangements within a pneumatic unit enables different motions that may be desirable. For example, laying fibers across only one half of a layer or arranging fibers in concentric rings would alter the geometric constraints on the unit and produce different motions. Different fiber layouts and potential stacking schemes are explored in this work.



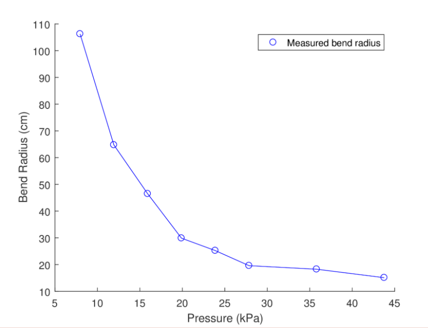
Mode of Actuation

Similar to examples seen in nature such as a Venus flytrap plant and the muscular hydrostats, here the combination of hydrostatic pressure and constraints imposed by inextensible fibers creates unique bending behavior.

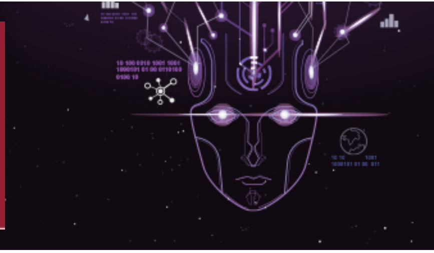


Modeling

Experimental measurements of a simple bending module are shown on the right. Developing a model to describe the bending and twisting behavior of the different modules and combinations of multiple units will be the focus of future work.



[2] E. A. Allen and J. P. Swensen, "Versatile Layering Approach to Pneumatic Soft Actuator Fabrication," in Proc. ASME 2019 Conference on Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS2019), Louisville, KY, 2019, p. V001T01A001.



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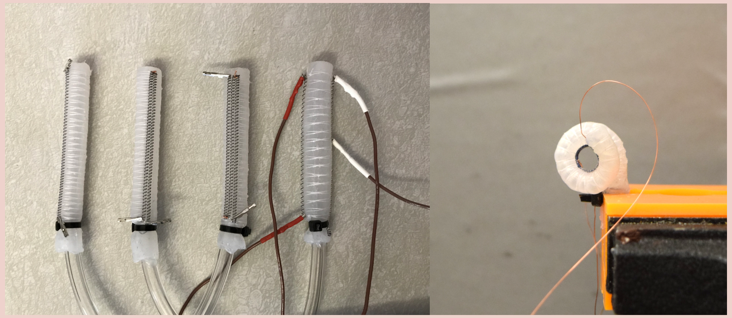
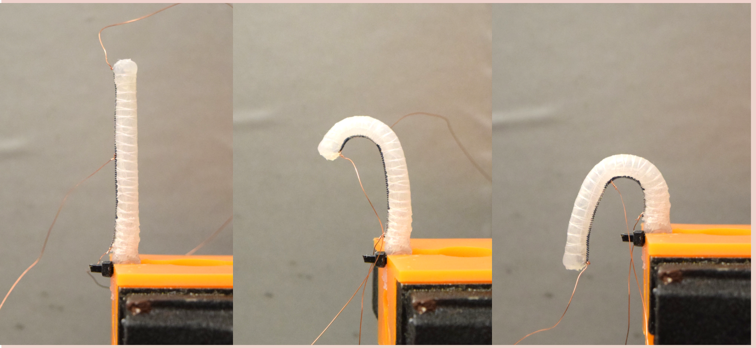
Pneumatic Actuator with Embedded Shape Memory Alloy “Muscles” (PneuSMA Actuator)

Device

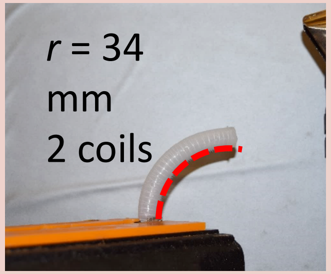
The PneuSMA actuator consists of shape memory alloy (SMA) springs attached along the side(s) of a silicone tube. The wrapped inextensible fibers prevent radial expansion and hold the SMA coils in place. Copper wires are attached at various locations along the coils to enable Joule heating of selected segments of the coils.

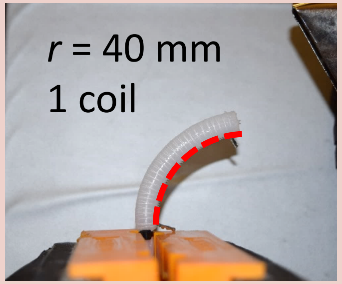


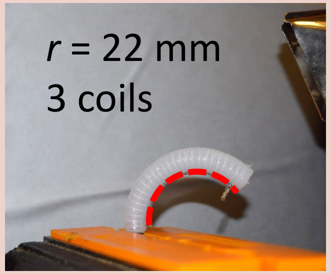


Stiffness Control Mechanism

Here, SMA springs are embedded in the walls of the actuator, serving as intrinsic muscles that may be selectively activated to constrain the device.



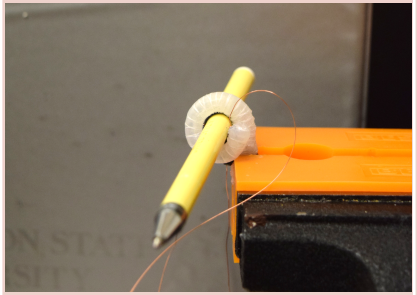




Combined pressurization of the cavity and contraction of the SMA coils results in an apparent increase in stiffness of the actuator.

Mode of Actuation

The PneuSMA actuator is controlled via activation of different SMA springs within the actuator, in conjunction with pneumatic actuation. The actuator demonstrates remarkable spatial controllability evidenced by testing under different pressures and SMA activation combinations.



Modeling

The bending of the PneuSMA actuator is described using a simplified modeling approached based on the linear stiffness of the silicone rubber and finite element analysis of parallel springs along the length of the actuator. This model accounts for the lengthening of the actuator due to the pressure on the inside walls of the actuator, the spring force from the SMA coils, and the effective spring forces from the silicone material.