# Soft Snake Robot

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## I. Introduction

Soft robotics is a rapidly expanding field with diverse applications across healthcare, wearable technologies, industrial processes, exploration, research, and entertainment [1]. Innovations in soft robotics in one sector often precipitate adaptations and technological progress across others [2]. This paper introduces the 'Soft Snake Robot' project, which aims to develop one of the leg segments of the 'Soft Snake Robot', employing soft pneumatic actuators. This segment represents a critical component of our broader effort to engineer a fully functional soft robotic snake. We provide a comprehensive overview of the design, manufacturing, testing, and validation phases of the snake robot, including the simulation of its leg functionality. Additionally, we discuss the development of an integrated gripper designed to enhance the robot's capability by enabling the precise manipulation of small objects.

## II. Relevant Studies

Soft snake-like robots have gained interest due to their potential for navigating complex, constrained environments while being inherently compliant and safe compared to rigid designs [3]. Several approaches have been explored, including modular designs with simplified pneumatic systems to reduce control complexity.Studies focusing on the unique properties of snake scales reveal that their structure, consisting of a hard layer over a softer one, reduces friction while maintaining flexibility [4]. Researches shows that this dual-layer approach facilitates the snake's ability to move swiftly and adapt to various surfaces [5]. These findings have spurred efforts to create synthetic materials that emulate these frictional and flexible characteristics, offering valuable insights for designing robots that can replicate similar movements efficiently. Futhermore, Lipsett et al. who introduced a soft snake robot utilizing just four air channels to generate traveling body waves for propulsion across any number of actuator modules, facilitating low-cost fabrication and reliable motion in pipelines [6]. Hubbard et al. demonstrated the first 3D soft sidewinding snake robot capable of lifting its body by combining lateral undulation and vertical bending in 3-DOF actuator modules [7]. Experiments revealed this design's advantage on surfaces like carpet, with sidewinding speeds up to 0.12 BL/s, enabling more reliable terrain traversal compared to lateral undulation alone despite slower maximum speed [7]. These soft snake robots leverage the inherent compliance and adaptability of soft robotics for enhanced mobility in the sorts of unstructured, constricted environments where rigid designs struggle [8].

**State of the art:** Drawing inspiration from biological models, specifically the locomotion of snakes, our team developed innovative materials and structures that replicate the efficiency of these creatures. We leveraged pneu-net actuators to optimize rapid, forceful, and large-displacement extensions and bending in three dimensions. This design approach could be incredibly beneficial for developing compact, tentacle-like robots or appendages that are ideal for navigating through tight spaces, such as pipes, or operating within containers with narrow openings. Additionally, the integration of 'ski skin' materials allows for the replication of the directional friction properties of snake scales, providing precise and adaptable control over the robot's movement. This ongoing synthesis of biology and robotics continues to push the boundaries of what soft robotic systems can achieve, emphasizing a biomimetic approach in robotic design [8]

## III. Intellectual Merit

The intellectual merit of this robotic project is encapsulated in its design and material choice. The design is sleek and snake-like form which excels in navigating unstructured environments. The use of Dragon Skin 10, enables the robot to deform, inflate, and move swiftly through tight spaces. This design enhances the robot's adaptability and functionality, allowing it to perform in areas inaccessible to rigid robots. The simple yet effective structure supports quick, precise movements, critical for complex tasks in exploration, search and rescue, and medical fields.

## IV. Design and Manufacturing

### A. CAD Design

The design process began by creating the CAD Designs of snake leg actuators and the connector in SolidWorks. Each robot segment includes actuators constructed from two trapezoidal components, which together form a triangular outer profile upon assembly. Consequently, the design incorporates trapezoidal shapes for the individual actuator parts and a triangular configuration for the collective assembly of these segments. Originally, the design utilized a circular pneunet structure which led to stability challenges. Adopting a trapezoidal pneunet design significantly improved the robustness of the model. Lastly, we fabricated the molds in PLA printer.

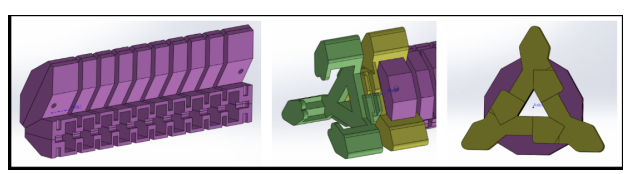

Fig. 1. CAD Design of the actuator

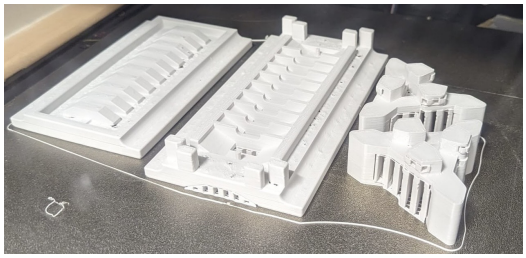

Fig. 2. Molds of the design

### B. Manufacturing

Manufacturing and assembly of the robot :

1. Mold Preparation: The top and bottom pieces of the molds, necessary for each of the two new simpler actuator halves, were 3D-printed from PLA filament. To ensure a smooth demolding process, we applied a coat of MINWAX Polycrylic brand acrylic spray to seal the PLA and then used a mold release spray on the inside surfaces.
2. Casting: With the molds prepared, we mixed Dragon Skin 10 silicone and carefully poured it into the molds through the designated filling holes. Any visible air bubbles were punctured with a needle to ensure a flawless finish. The molds were then placed in an oven to cure at 70°C for 30 minutes.
3. Demolding and Assembly: After the initial curing, the molds were gently separated and the half-actuators were removed. To assemble, we cleaned the flat mating surfaces of any debris using tape, applied a fresh batch of Dragon Skin 10 to these surfaces, and reassembled the halves in their respective top mold pieces. The molds were designed to interlock for precise alignment and sealing. A second curing session in the oven solidified the bond.
4.Integration of Connector and Final Assembly: For the final assembly of three actuators into a single functional unit, a connector was designed which interlocked seamlessly with the ends of each actuator.

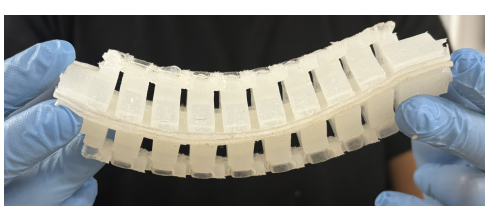

Fig. 3. One Leg of the snake

Connector Design:

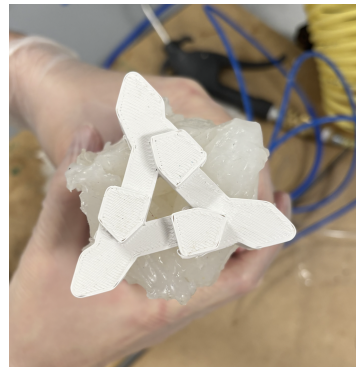

Fig. 4. Connector of the snake

We assembled all the three leg actuators and connector for the final robot.

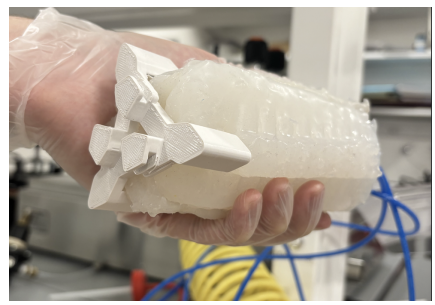

Fig. 5. Snake robot with all the three actuators

We also developed a gripper that uses granular jamming technology, employing a balloon filled with coffee grounds. This gripper was then connected to the front of the actuator via tubing.

Fig. 6. Final Design of Snake robot

## V. Modeling component

We used Finite Element Analysis to model the behaviour of the actuator. Initially, we designed the CAD model of the upper and lower part of the actuator. We used Abaqus to merge it together and apply pressure load conditions and observe the actuator's response, including the stress-strain relationships, deformation under load, and potential points of failure.
We used Yeoh model as it is a good fit for a wide range of strains and it can effectively simulate different deformation modes with minimal data [9]. It has simple mathematical formulation compared to other hyperelastic models [10].

$$W = \sum_{i=1}^{3} C_i (I_1 - 3)^i$$

We used Dragonskin 10 material for the actuator. The coefficients of the C1, C2 and C3 were found using SORO Database. We chose C1 = 0.0547, C2 = 0.0002 and C3 =0.

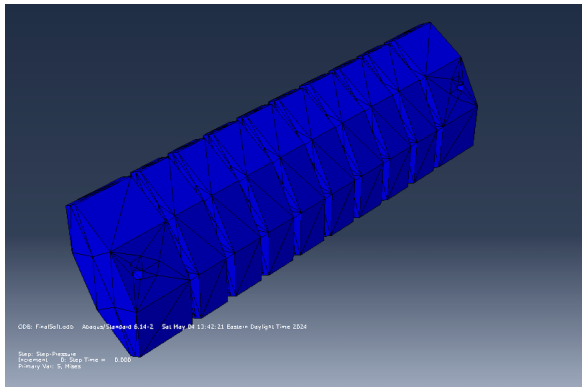

Fig. 7. Abaqus Simulation of one leg of the snake robot

The pressure load for this simulation was 0.055 MPa. The inner cavity inflates as the pressure load is applied.

## VI. Testing

### A. Pressure VS Elongation

For testing the change in length with respect to pressure, we assembled a testing setup that includes an MPRLS pressure sensor, an Arduino, and a syringe. As the syringe is creates pressure, we simultaneously measure and record the actuator's length corresponding to each pressure reading.

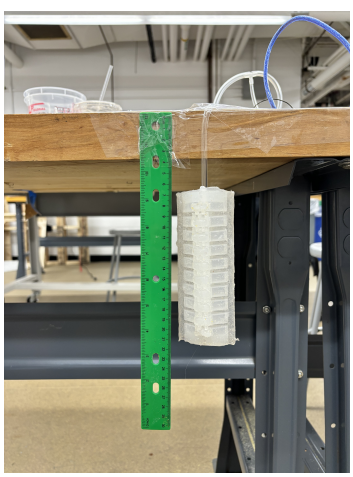

Fig. 8. Testing setup for pressure vs the elongation of the actuator

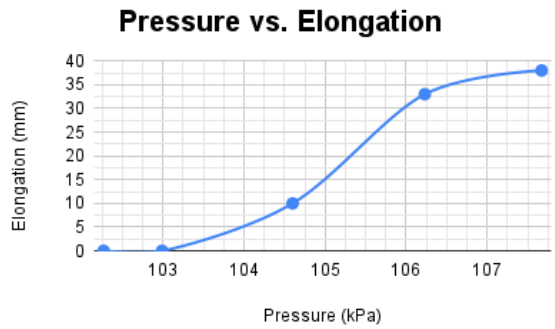


Fig. 9. Pressure vs Elongation

From the 9, we can observe that as pressure increases, the length of the actuator also increases.

### B. Volume of the syringe vs Force

For measuring the actuation force, the actuator was securely mounted over a scale in such a way that any extension would exert pressure directly onto the surface of the scale, rather than elongating the actuator.

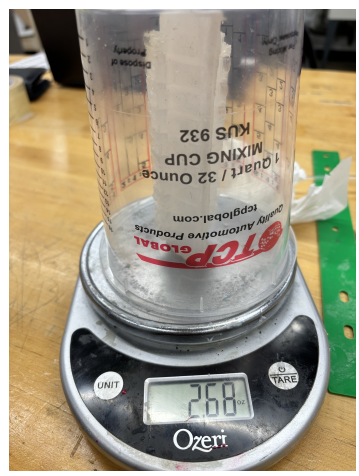


Fig. 10. Testing setup of Volume of the syringe vs Force

TABLE I
Pressure vs Length of the Actuator

| Volume of Syringe(cc) | Pressure (kPa) | Length (mm) |
|---|---|---|
| 0 | 102.27 | 147 |
| 50 | 102.99 | 147 |
| 100 | 104.6 | 157 |
| 150 | 106.23 | 180 |
| 200 | 107.67 | 185 |

TABLE II
Volume of the syringe vs Force

| Syringe Volume (cc) | Weight (g) | Force (N) |
|---|---|---|
| 0 | 0 | 0 |
| 50 | 48 | 0.47088 |
| 100 | 223 | 2.18763 |
| 150 | 289 | 2.83509 |
| 200 | 302 | 2.96262 |

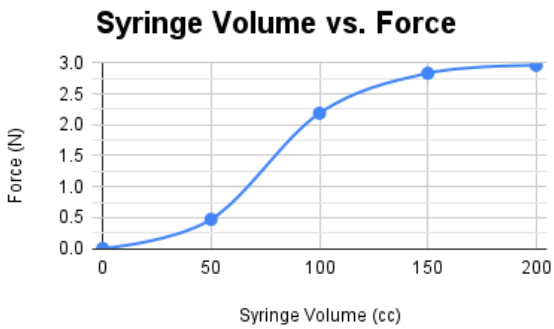


Fig. 11. Volume of the syringe vs Force

From the 11, we can see that as we increase the volume of the syringe, the weight of the actuator increases and therefore the force acting increases.

### C. Gripper Testing

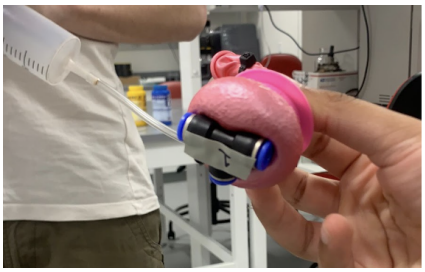

Fig. 12. Testing of Granular Gripper

When air was sucked out of the syringe we see that it granular jammer conforms to the shape.

### D. Control Strategy

For controlling the robot, we used four syringes. Ski-skin applied on the bottom merging two actuators. To enable the robot's movement, all three actuators are engaged, with two of them operating at maximum syringe volume, while the upper one operates at half the pressure. Additionally, for gripping objects, we have a separate syringe that activates to facilitate object manipulation.

## VII. Conclusion and Broader Impact

The Soft Snake Robot presents numerous potential applications that could significantly impact various industries and societal needs. Its unique design and capabilities make it ideal for tasks requiring maneuverability in constrained environments, such as maintenance, inspection, and rescue operations. The robot's ability to navigate through tight spaces and its robust construction allow for applications ranging from clearing blockages in pipes to performing search and rescue missions in hazardous or inaccessible areas. Moreover, the adaptability and effectiveness of the granular jamming mechanism and the innovative locomotion system offer substantial benefits for environmental monitoring, geological exploration, and even medical procedures like surgeries.

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## VIII. Appendix

Fig. 13. Fabricating the actuators

Fig. 14. Sticking of all three leg actuators

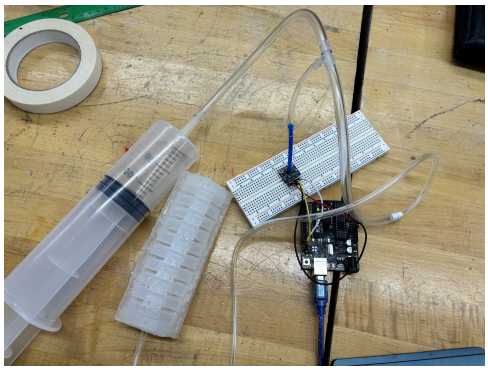

Fig. 15. Test setup of pressure vs elongation

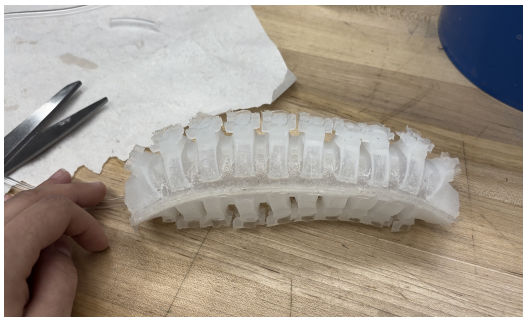

Fig. 16. 50 percent air inflated

Fig. 17. New Gripper Design