PneuSlinky: An Alternative Approach to Optimize Inch-Worm-Inspired Locomotion

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***Abstract*—The "PneuSlinky" project introduces a novel soft robotic system employing fluidically-actuated, inch-worm-inspired locomotion and a pneunet-based two-finger gripper. Made from the elastic silicones DragonSkin 10 and EcoFlex 30, this robot operates safely and effectively across varied terrains and can grasp objects up to 10 cm in diameter. Innovative inflatable anchors enhance its mobility on flat and inclined surfaces. Rigorous testing and Abaqus simulations have optimized its design. This research advances soft robotics by merging bio-inspired mechanisms with practical applications, offering significant improvements in safety, adaptability, and operational efficiency in unstructured environments.**

I. Introduction

The "PneuSlinky" project introduces a groundbreaking soft robotic system designed to fundamentally improve upon the concepts of fluidic actuation and bio-inspired locomotion. This novel robot leverages inch-worm-inspired movement mechanisms and advanced pneumatic grippers to navigate diverse terrains and manipulate objects significantly larger than those handled by conventional soft robots.

The construction of the robot utilizes DragonSkin 10 and EcoFlex 30, silicone-based polymers known for their exceptional elasticity and resilience. These materials ensure the robot's durability and flexibility, enabling it to withstand environmental stresses while maintaining safety for human interaction. The absence of rigid components in the robot's design not only enhances its adaptability but also ensures complete biocompatibility, making it suitable for a wide range of applications including those in medical and educational settings.

At its core, "PneuSlinky" employs an inch-worm locomotion strategy that is enhanced by inflatable anchors along the robot's body. These anchors engage and disengage with the ground, allowing the robot to propel itself forward efficiently on both flat and inclined surfaces. This method of movement is energy-efficient and maximizes the robot's adaptability, enabling it to navigate over obstacles and through uneven terrain effectively.

The robot's gripping mechanism features a two-finger pneunet-based gripper designed to inflate and conform to the shapes of various objects, securing them firmly without causing damage. This adaptability in the gripper's design allows it to handle objects up to 10 cm in diameter—far exceeding the capability of traditional soft grippers.

One of the unique advantages of soft robotic technologies that "PneuSlinky" exploits is the inherent safety and compliance of soft materials, which prevent harm to human operators and delicate objects. This makes the robot ideal for interactive applications where traditional rigid robots might pose risks. Additionally, the bio-inspired design principles allow the robot to perform efficiently in unstructured environments, navigating complex spaces that rigid robots cannot.

The robot's capabilities and performance have been rigorously tested through various experimental setups, including bending angle measurements and cantilever-beam deflection experiments, to assess its functionality under different operational conditions. Computational simulations in Abaqus software have been crucial in refining the robot's design, allowing for iterative enhancements based on simulated performance metrics.

II. Related Works

Previous work in soft robotics experimented with different actuation and grasping methods. PneuNet designs incorporate a network of small bladders to distribute the strain of a device; their architecture has been explored as an actuator and end-effector [1] [2] [3]. Pneu-net characteristics such as actuation speed and bending angles can be adjusted by changing the spacing geometry of the bladders [4]. However, these adjustments can be relatively complex, making the mold designs more complicated. The large bending angles capable of pneu-net make it desirable for grippers. Recent advances in pneu-net end-effectors include making grippers with modular attachments and altering the geometry of the bladders to facilitate simultaneous bending in longitudinal and transverse directions [5] [6].

Soft robots have sought bio-inspiration to create systems that work effectively in unstructured environments. One source of inspiration is the inchworm location. Previous research in soft robotics has successfully emulated an inch-worm motion with either traditional wire-based actuation or shape memory alloy (SMA) wires [7] [8] [9]. Moreira et al. explore a rigid inch-worm-inspired robot with friction pads to allow for a two-anchor gait [10]. Although this robot is primarily made out of PLA via FDM, friction anchors on both sides allowed the robot to traverse inclined planes.

III. Intellectual Merits

The objective of this project is to minimize the limitations of inch-worm locomotion and pneu-nets through the use of anchors and steering, and granular jamming, respectively. Although inchworms are seen both in nature and academia, such invertebrates are typically supported by their environment and, occasionally, their momentum. Additionally, most inchworms in academia have only a single direction of movement. Having multiple actuation chambers off-centered can remedy this. A rigid skeletal structure can allow a soft robot to achieve more dexterity and manipulation limited by soft materials. Therefore, a jamming-based structure rigid on command but compliant at a neutral state is sought after. Furthermore, inflatable anchors with friction pads can significantly improve the speed at which an inch-worm robot can traverse. Incorporating a compliant-turned-rigid exoskeleton can improve the grasping capability of a pneu-net grasper, and inflatable anchors can significantly improve inch-worm locomotion. Finally, we created a soft robot assembly that utilizes molds entirely from PLA. Although most soft robot molds use SLA, FDM 3D printing with PLA is more common and affordable. Therefore, a soft robot capable of being fabricated with PLA molds allows for increased accessibility to those who might not have the proper resources and equipment.

Our design can be implemented in a number of different applications. The most notable is in the education field. Due to the techniques utilized for manufacturing including FDM printing the molds, and low pressure actuation, our design proves to be accessible to manufacture, and safe for students to operate without risk of injury in the case of failure. Additionally our robot can be used for pick and place applications, if scaled up in size, it can be used in warehouses to relocate items, and if scaled down can be used in smaller environments that could pose risk to a rigid robot, or is not electronic friendly such as under water.

IV. Methodology

A. Design and manufacturing

Prototyping for the proposed system was a three-step process, with each iteration coming closer to a fully functioning example. Before any official CAD designs of the first assembly could be made, the group collectively met and proposed various ideas on a whiteboard; this step was crucial to the ideation process as the best ideas would eventually be filtered through. After brainstorming, the team decided to adopt an axis-symmetric design for the locomotion component of the robot; this would allow the system to function correctly regardless of unexpected tipping or rocking. To achieve this feature, the body would need to be composed of multiple simple actuators (in this case, the team chose an array of 3 bodies), each offset in such a way that both horizontal and vertical actuation could be achieved by varying the applied pressure of each component. To complement the design of the body, the initial idea for the gripper was to continue with the theme of the axis-symmetric design, meaning that it would consist of three individual fingers that would actuate simultaneously. After the prototyping phase, the project's third and final prototype was designed:

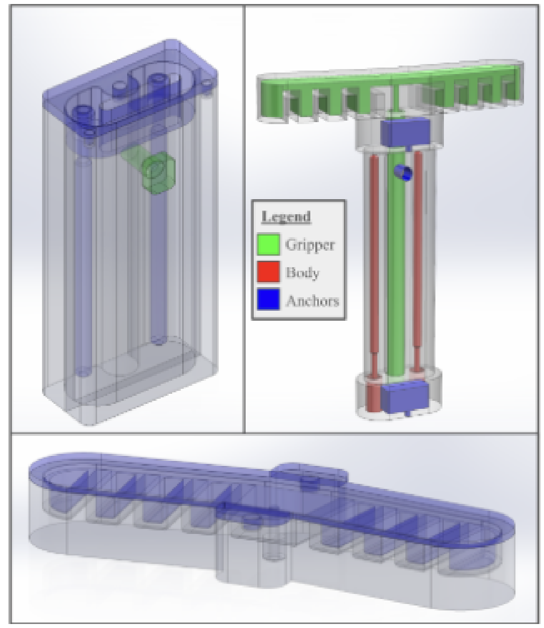

Fig. 1. Final Prototype CAD Assembly and Mold Examples

Fig 1 depicts the new assembly of the system, which features several key changes compared to previous versions. The most notable update is that of the gripper, which now features a pneu-net-inspired design; these actuators are known for being versatile and capable of bending to large angles, making them ideal for this situation. This change from the initial gripper design was because the first version was not able to achieve the range of grasping needed for the applications. Additionally, having a two-prong grasper rather than three helped alleviate the friction on the ground while locomoting. To further help reduce friction, the molds were intentionally designed so that the gripper arms are offset from the ground at a slight angle (in this instance, about 7°); this ultimately reduces the drag caused by the gripper while the remainder of the robot actuates for locomotion. Each gripper arm was also extended from 20 mm to 50 mm, allowing the system to grasp larger objects. The body channels elongated by 50 mm (now 100 mm long) and reduced from three pieces to a single piece, now featuring two channels over the previous total of three. By removing the robot's axis-symmetric layout, it can now be designed in a more rectangular fashion to alleviate the risk of flipping over. In addition to these tweaks to the body and gripper, the anchors were increased in height, meaning that the body no longer rests on the ground. The air pockets on the anchors were also doubled in size with hopes of further decreasing slippage. Although the overall premise of each of the recurring mold designs was kept mostly the same, the gripper and body molds were given a feature that would provide the final parts a collar around where the tubing would be inserted; this allows members to simply use a zip tie to seal the actuators rather than having to wait for silicone epoxy sealant to cure. Combining these changes, the system can actuate correctly, locomoting and grasping effectively.

B. Modeling component

Finite element (FE) simulations of the soft robot are conducted using commercial software Abaqus/standard. The PneuSlinky soft robot parts are imported into abaqus as STEP. Files after being designed in SOLIDWORKS software. 3rd order Ogden hyperelastic material model is used to model the base material properties of the silicon-based actuator. The hyperelastic coefficients based on DragonSkin 10 (calculated in Lab1) are used to define the hyperelastic properties of the actuator. Four sets of FE simulations are carried out for this project: 1. Bending of soft robot's body; 2. Steering the soft robot; 3. Actuation of soft robot's gripper; 4. Crawling of the robot. The boundary conditions and mesh view of FE simulation of the robot's body bending, steering, and gripper's actuation are presented in Fig 2(a-d), respectively. For bending and steering simulations, the back end of the robot's body is encased (all displacements and rotations are prescribed to zero), while two (bending) or just one (steering) of the air channels are pressurized with a constant pressure of 100 kPa. The parts are meshed with C3D10H (10-node hybrid quadratic tetrahedron) elements with an average seed size of 1 mm.

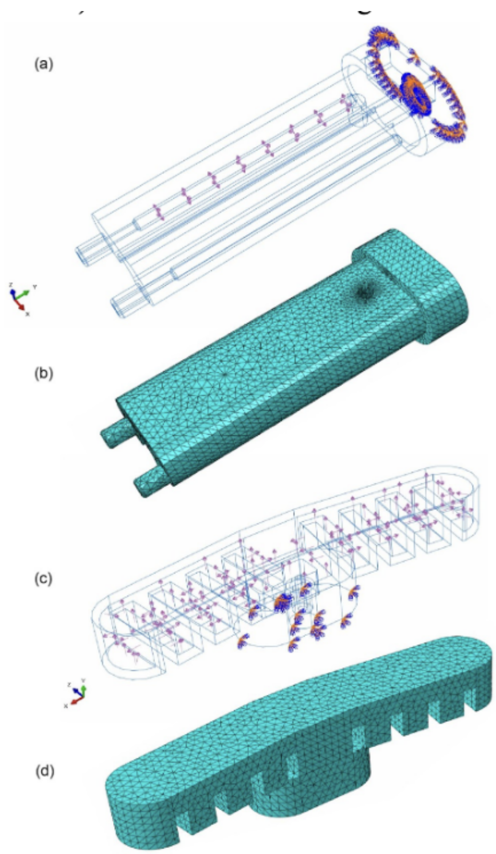

Fig. 2. Mesh and boundary conditions of robot bending and steering (a,b) and gripper's actuation (c-d).

The results of the bending, steering, and gripper actuation simulations are presented in Fig 3. The results of simulation help better predict the motion of the robot and thus contribute to controlling the robot and the actuation of different parts of the robot.

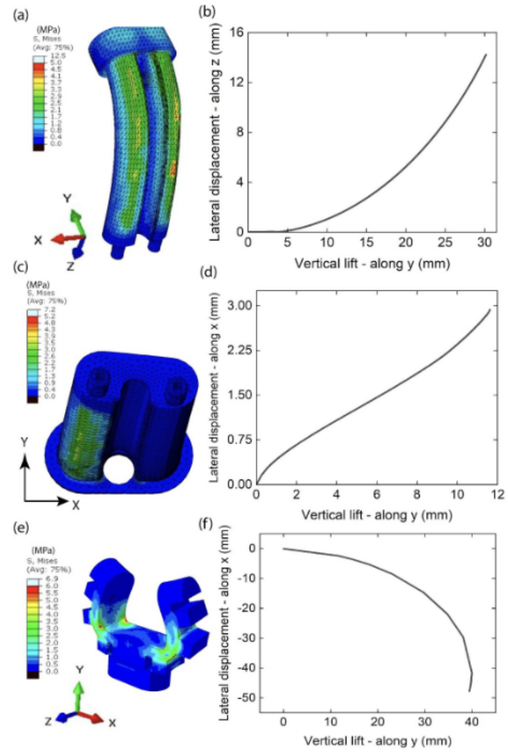

Fig. 3. (a) Robot's body bending; (b) Displacement curve of out-of-plane bending of robot's body; (c) Robot's body steering; (d) Displacement curve of robot body steering; (e) Robot's gripper actuation ; (f) Displacement curve of gripper movement.

The soft robot's crawling motion simulation setup and results are shown in Fig 4(a). The simulation is composed of two three steps: in step 1 the front anchor's friction coefficient is 0.6 (gripping), whereas frictionless contact is considered between the back anchor and rigid flat part (ground), while the body's air channels are pressurized. In the simulation's second step, friction-less contact is considered for the front anchor, and grippy friction coefficient is modeled for the back anchor, while the body's air channel's air pressure is set to zero. Fig 4(b) shows the simulation sequence.

C. Testing/validation

Validation of the system's functional capabilities could only be done when a final prototype was completed. Unfortunately, the adjustments to the gripper in the sections above did not entirely solve the aforementioned dragging issue; even with the 7° upward angle of the grasper, the base was still dragging and significantly affecting the robot's locomotion. However, if the grasping and locomotive components were separated, each actuator functioned as intended. Therefore, to ensure that the collected data reflected the capabilities of the team's final design, the gripper was tested separately from the rest of the design. Although it is difficult to characterize the sequence

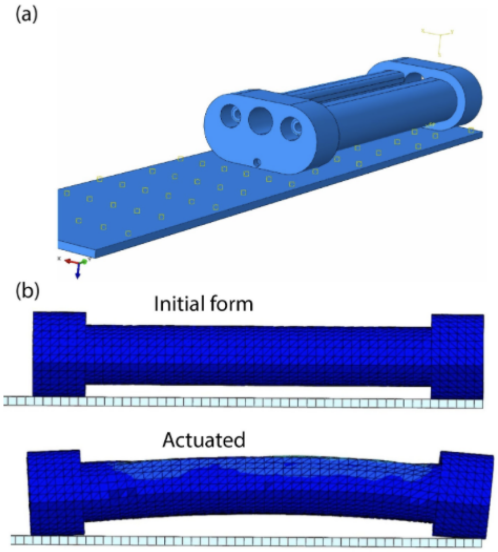

Fig. 4. (a) Crawling simulation FE model; (b) Crawling simulation results.

required for the system to crawl properly, below is a flow diagram(Fig 5) depicting the process of getting PneuSlinky to crawl:

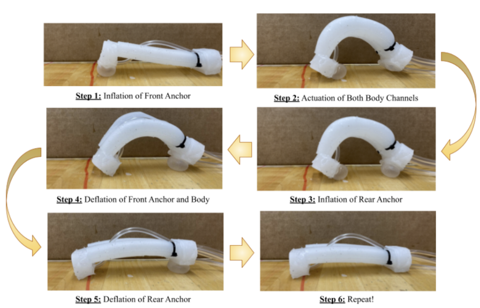

Fig. 5. Body & Anchor Locomotion Actuation Sequence

Based on the performance of the final robot in the competition, PneuSlinky has a crawling speed of 3.33 mm/s (crawling 200 mm in 60 seconds).

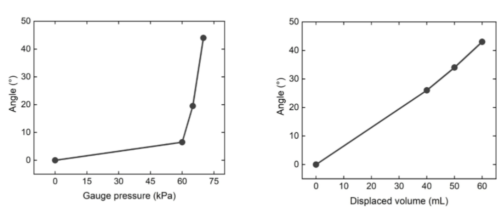

Fig. 6. (left) Angle vs Gauge pressure for robot's body; (right) Bending angle vs displaced volume for the gripper.

The collected data for the grasper and body of the robot are simple angle vs. pressure plots as shown in Fig 6(left). However, they provide a solid understanding of the low-pressure requirements for the system to function properly. The figure shows the collected results for both the gripper and main body of the final prototype iteration:

As shown in Fig 6(left), the body does not bend significantly until a certain threshold pressure has been attained (6̃0kPa); however, once given this sufficient pressure, the body acts relatively linearly, ensuring predictable behavior from the robot body. The primary reason for this initial required pressure is likely due to the quantity of silicone surrounding the body's air channels. Previous iterations suffered from too little surrounding material, causing actuators to pop if put under excessive stress. Thankfully, the final version of the body does not suffer from this critical failure, though at the cost of a higher pressure requirement. All tested parts were pre-stretched before testing to ensure that the Mullins effect could be overcome. Due to its wall thickness of 2 mm throughout, the gripper did not feature an initial pressure requirement, bending linearly with respect to the volume of air provided to the actuator. However, it is important to indicate that the gripper is capable of more motion beyond what is depicted in Figure 6(right); the syringes available for testing did not store enough air to achieve full actuation, though it has been tested that it is capable of grasping to the extent that the two gripper ends meet (creating a circle). Overall, though several additional changes are required for the system to function properly while fully assembled, the locomotion and grasping components of the design function as intended.

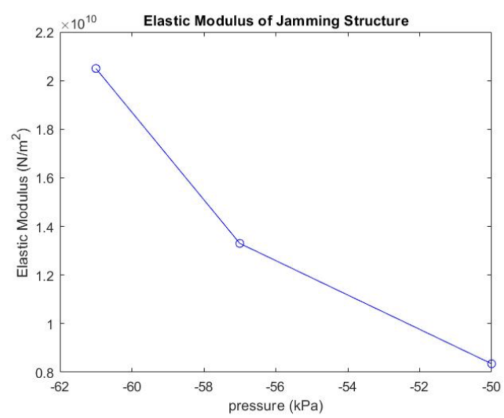

Fig. 7. Characterization of Granular Jamming Stiffening Element on pneu-net Gripper

Stiffening elements were explored to help improve the effectiveness of the gripper. Fig 5e highlights high concentrated regions of stress the pneu-net gripper experiences when actuated. It is beneficial to strengthen this region as this is a source of critical failure when picking up larger or heavier objects. Fig 7 shows the elastic modulus of a coffee ground based jamming element based on the internal negative pressure inside the system. With the fluid-like behavior granular jamming structures exhibit at a neutral state, external jamming pouches were attached towards the back of the pneu-net. Although characterization of the system highlights a significant change of stiffness from a neutral (0kPa) to an actuated strength, there was no significant change in the grasping ability of the gripper with the stiffening elements.

V. Conclusion

The team successfully created a robotic system capable of traversing wooden surfaces and grasping objects larger than 10cm in diameter. From this design, we show it can enhance inch-worm locomotion with the assistance of soft-material attachments.

Future work and improvements for this project primarily focus on increasing the efficiency of the inch-worm actuation. The current design of the body is a dual channel with an air channel passing through each channel. Assuming that granular-based exoskeletons can help support the weight of the robot body, implementing a Pneu-net architecture in the actuator can drastically improve bending results. Further, soft force-sensitive resistor sensors can be implemented both along the robot and on the bottoms of the anchors to allow for the robot to approximate xfriction force and bending angle.

The architecture of this design proves that it is possible to create complex, Pneu-net-based soft robots using commercially available 3D printers and PLA plastic. Further improvements in the manufacturing procedure can result in PLA-based molds capable of multiple cycles before failure.

VI. Link to Video

Link to the lab results demonstration **CLICK HERE TO ACCESS THE VIDEO**

Acknowledgment

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