Bioinspired Design and Fabrication Principles of Reliable Fluidic Soft Actuation Modules

Weijia Tao, Erik H. Skorina, Fuchen Chen, Jennifer McInnis, Ming Luo, and Cagdas D. Onal

***Abstract*— A large percentage of the field of robotics is devoted to catching up to what nature can already do. Taking inspiration from the snake and the jumping spider, we describe advances towards standardized modular multi-material composite soft pneumatic actuator design and fabrication. Previous pneumatic bi-directional bending actuators used in our soft robotic snake suffered from repeatability challenges and were prone to bursting in the seams. Here, we present a standardized fabrication method of soft pneumatic actuators to reduce the seams and incorporate a more reliable port for the input pressure. In addition, we explore the integration of our flexible curvature sensor, allowing for less invasive proprioceptive sensing of the actuator state. Finally, taking inspiration from jumping spider legs we also propose a plastic exoskeleton system, which can guide soft actuators to form complex shapes when pressurized. We show that all of these actuators were consistent and reliable over numerous trials. The next step is to combine these individual actuators into their respective bioinspired robotic systems: a soft modular snake and a soft jumping spider.**

I. Introduction

Much of what is done in the field of robotics is in an effort to replicate what nature can already accomplish on a regular basis. One aspect that animals exploit to navigate their environments is soft structures. Soft structures and actuators allow for safe, flexible, and adaptive interactions with unpredictable environments. In particular we are inspired by snakes and jumping spiders. Snakes [1] are capable traversing complex, cluttered environments and squeeze through narrow spaces relative to their volume with ease. Jumping spiders [2] are capable of fast locomotion and prodigious jumps using pressurized liquid for actuation. To replicate the abilities of these animals, we use soft pneumatic actuators [3]–[8]. However, the soft structures of these actuators fragile and prone to breaks when under consistent use. In addition, because of lack of standardization in fabrication, the entire body will often have to be replaced when such a break happens. In this paper we seek expand the capabilities of soft actuators by developing reliable, standardized multi-material fluidic soft actuation systems.

In our previous work [9]–[15], we designed two different types of the soft actuators. The first was a soft bi-directional bending actuator that was inspired by the biological snake. This actuator contains of two separate chambers on either side of a inextensible constraint layer. When one pocket is pressurized it extends, but is prevented by the constraint layer, causing the entire actuator to bend. These actuators could be mounted in series to form the body of a snake. The most advanced version of this soft robotic snake (SRS) was presented in [13], which is entirely self-contained and included magnetic curvature sensors [16] embedded in the constraint layer.

Although this generation's actuators performed better than the old ones and represented a significant advance in multi-material composite fabrication with the integration of the curvature sensors, they had major reliability problems. The first cause of this is the connection between the external pressure lines and the soft actuators. This was done by piercing each of the chambers with a sharpened tube after fabrication without any additional seal. The other point of failure is the interface between the constraint layer and the soft actuators on either side. The chambers were fabricated separately, and then glued to the constraint layer. The bonded surfaces of the two parts are often not perfectly flat, and imperfections in the adhesion process create weak points in the actuator chamber.

An additional problem faced in maintaining the soft robotic snake that used this type of actuator was that all the actuators were molded together. Thus, if one actuator within the snake developed a leak or other failure, the entire body would need to be replaced. As the molding process was relatively time consuming, this made troubleshooting difficult and considerably slowed the speed of experiments. Also problematic is fluidic connections/ports, mechanical attachments, and electrical connectivity issues.

The second type of soft actuator we study is a soft linear muscle which was originally used to drive a rigid kinematic module, similar to muscles driving a skeleton. This consisted of a modified version of a single chamber of the soft bending actuator without the embedded constraint layer. We faced similar problems in developing these actuators to the soft bending actuator [14], [15], but with input pressures in excess of 3 times higher. To solve this problem for the linear actuators we initially designed a special connector which consisted of a standard push-in fitting mounted in a wooden plate bonded to the silicone. However, leaking could still occur when excess pressure causes the silicone to detach from the wooden plate. In addition, the use of these actuators, lacking any inherent structure, was limited to driving external linkages.

This paper discusses our advancements in soft actuator design and fabrication principles, which will increase their reliability and standardization. The largest advance was in our connector design, which was inspired by [17] and relies

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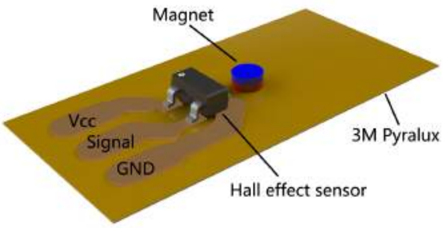

Fig. 1. Circuit design of the curvature sensor

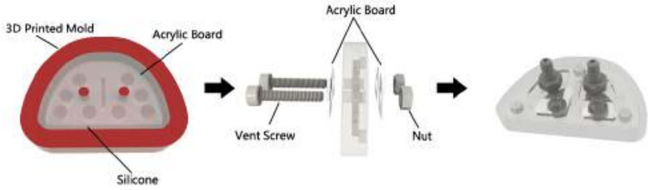

Fig. 2. Cover Fabrication Process

on the benefits of vent screws. This design is used for both our bidirectional bending and linear actuators. Additionally, we describe the instructions of how to mount the soft flexible sensor in to the constraint layer of the soft bending actuator. This is done in such a way that it allows each actuator to be self-contained and distinct, allowing for modularity in future robot design. Finally, we incorporate foldable plastic exoskeletons [18], [19] into the soft linear actuator to increase the breadth of its performance. This would allow them to function similarly to the legs of a jumping spider, where pressurization can result in significant external forces.

The contributions of this work include:

- Strong fluid connector design and fabrication for modular soft snake actuator
- The fabrication of the new soft actuator with the embedded flexible curvature sensor.
- The foldable plastic exoskeleton could give the soft actuator different locomotion when pressurized

II. Bidirectional Bending Actuation

The soft bidirectional bending actuator consists of two chambers each wrapped in a double-helix of thread mounted on either side of an inextensible constraint layer. Each chamber is connected to an external air supply, and when pressurized causes the segment to curve in the opposite direction. The central constraint layer contains a flexible curvature sensor which measures the kinematic state of the actuator.

A. *Flexible Curvature Sensor*

In order to sense the kinematic state of our soft snake robot, we have developed a flexible curvature sensor. This consists of a magnet and a Hall Effect sensor mounted on the constraint layer of the snake robot. When the actuator bends, the change in the magnetic field density are sensed by the hall effect sensor can be converted into the curvature of the actuator. We introduced this unique approach to curvature sensing in [16], For integration into soft bending modules, our curvature sensors required a few modifications. First, the magnet used is a 0.125 inch cube which forces the entire actuator to be too thick to use as the snake's constraint layer, requiring a reduction in thickness and circuit board stiffness as well as an increase in reliability.

In [13], we proposed the second version of the flexible sensor. A smaller magnet cube (1/16 inch) was used to reduce the thickness. The sensitivity was also increased to be able to sense the full range of the actuator motion. In addition, the PCB was fabricated out of a Laminate sheet combined with copper foil which greatly reduces the stiffness of the sensor and also provides protection for the traces. However, the laminate sheet could not bear high temperature, resulting in difficulty soldering. Furthermore, in both versions, the circuit still had a large chance to fail because of embedding and bending the complicated circuit traces.

To solve the above issues, we improve our design and produce the third version of the flexible sensor. To further reduce the thickness, we changed to a smaller Hall effect IC (the AH49E) and the cube magnet to a 1/32 inch high cylinder. The new hall effect sensor also allowed us to move the amplification circuit out of the soft actuator which greatly simplifies the design of the circuit and improves the reliability. The PCB material is now Pyralux (3M) which is softer and can tolerate higher temperatures. Figure 1 shows the circuit design of the new flexible curvature sensor. The entire fabrication process consists of three steps as below.

Step 1 : Circuit traces are designed and printed on a copper-clad flexible substrate (Pyralux, 3M) using a solid ink printer (Xerox Color 8570).

Step 2 : The patterned copper-clad substrate is placed in a ferric chloride etching tank that remove all exposed copper, leaving the electrical traces intact.

Step 3 : Discrete circuit components are soldered and the miniature magnet is mounted on its precise position using a microscope.

B. *Soft Bending Actuator*

We introduced a completely new connection method for the input tubing which eliminates it as a point of failure. In addition, a better fabrication procedure is also introduced to improve reliability and reduce the possibility of fabrication error.

Our new soft actuator consists of two parts, the body and cover, which are made separately and then glued together. The cover serves as the connection between the chamber and tubing that provides pressure source. The cover is made of silicone and acrylic with a vent screw. The fabrication process is listed below and shown in Figure 2.

Step 1 : Ecoflex 0030 silicone is poured into a 3D printed mold and a laser cut acrylic board is slotted horizontally in the middle.

Step 2 : After the silicone cures, two additional acrylic boards are added to both sides of the cover with vent screws going through all three layers of acrylic board. The vent screws are fastened using a nut.

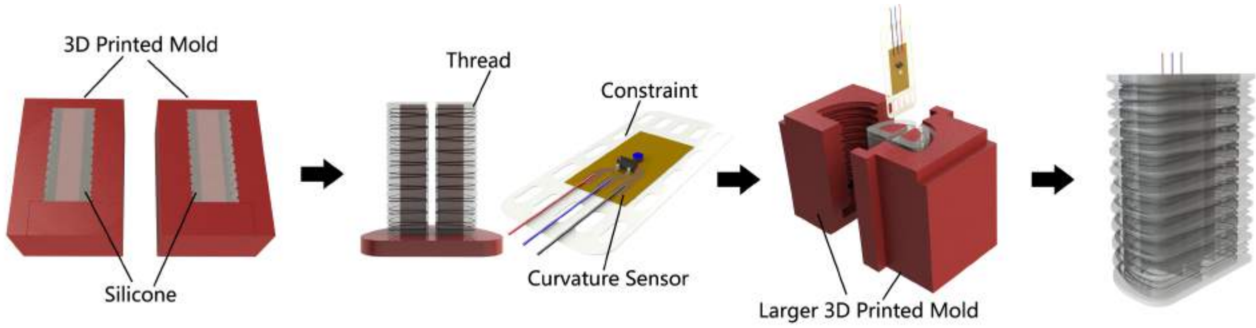

Fig. 3. Body Fabrication Process

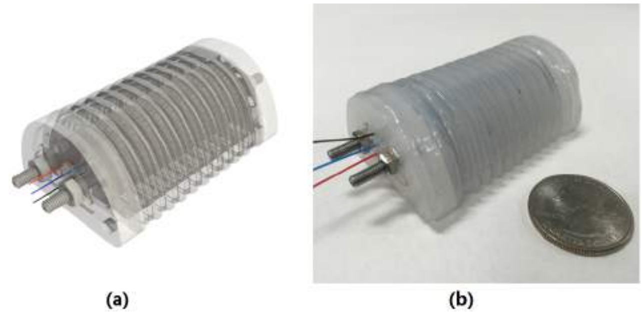

Fig. 4. Figures (a) and (b) shows the CAD and experimental prototype of the soft bending actuator.

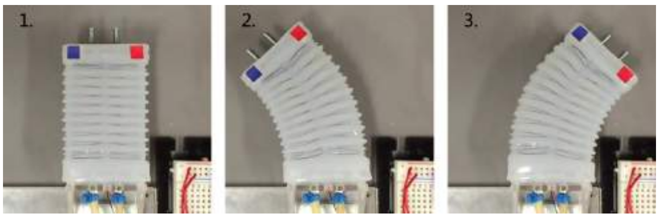

Fig. 5. The movement of the bending actuator in one whole period.

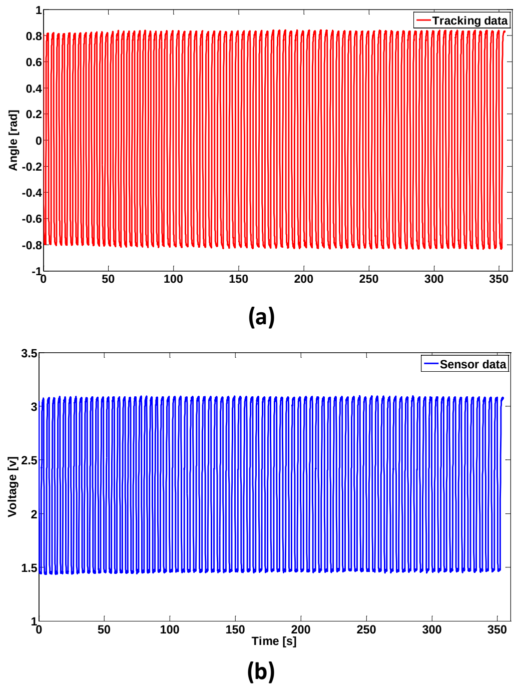

Fig. 6. Visual tracking data (a) and on-board curvature sensor measurements (b) of the soft bending actuator over 80 bidirectional bending cycles. The values can not be observed to drift over time, showing the repeatability and reliability of our actuators. Figure 7 shows zoomed-in examples of these cycles.

The acrylic board embedded in the end cap prevents it from deforming under pressure. In addition, the three layers of acrylic fit snuggly around the vent screw, and can be tightened against the two layers of silicone to provide a seal capable of withstanding pressures much higher then the rest of the system. Regular screws are used on the side where no pressure input is required. Both the vent and regular screws also serve as convenient attachment points to attach the actuator to other platforms.

The new fabrication process to make the soft bending actuator is simpler and more repeatable to embed curvature sensor and constraint. The procedures are listed as followed and in Figure 3.

Step 1 : Two inner bodies of the actuator are created first using 3D printed mold.

Step 2 : A second 3D printed mold is used to fix the inner bodies in position while the inextensible thread is tied around each of them in a double helix.

Step 3 : A constraint layer is laser cut from 177.8 μm PET plastic sheet. Flexible curvature sensor is fabricated and attached to the constraint layer.

Step 4 : The constraint layer, along with the sensor, is inserted in between the two inner bodies.

Step 5 : A final 3D printed mold is used to surround the above product and filled with silicone, forming the body of the actuator.

This method allows the entire actuator chambers to be made at one time without bonding two different, already cured, pieces of silicone together, which reduces the chance of any gaps around chamber. After the body and two end-caps are all fabricated, they are glued together to form the entire soft bending segment. The final segment is shown in Figure 4 (a), (b).

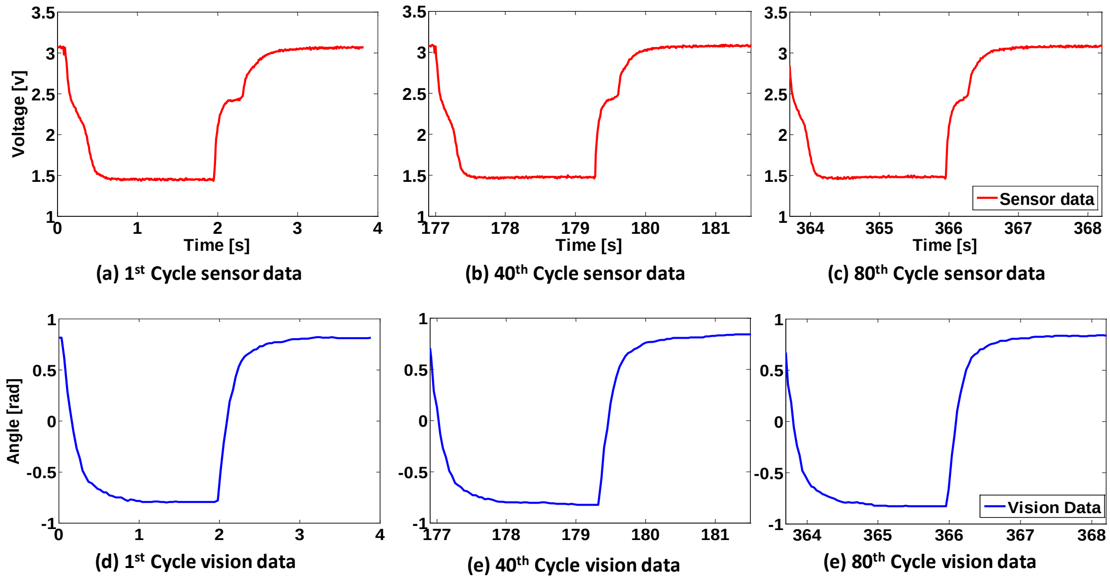

Fig. 7. The 80 times test for the actuator operation. (a), (b), (c) show the data from the on-board curvature sensor for the 1st, 40th and 80th cycles while (e), (f), and (g) show the visual tracking data at 1st, 40th and 80th cycles.

C. Analysis of Final Product

In order to test the reliability of the soft bending actuator, we drove it over 80 cycles of bidirectional bending (approximately 4 seconds per cycle) using an input pressure of 5 psi, and recorded data from the curvature sensors as well as an external camera system. Figure 5 shows one cycle of the bending actuator's movement as seen by the vision system.

Figure 6 shows representative data on embedded curvature sensor measurements and visual tracking over 80 bidirectional bending cycles. As both sets of data remain consistent with no observable drift, the performance of the actuator and the sensor is very stable. Zooming in, Fig. 7 displays a comparison of the vision and curvature sensor outputs for three separate cycles. The vision data shows that the segment has the same bending profile at the beginning of the test (Fig. 7 (d)) as at the end (Fig. 7 (e)). The curvature sensor data (Fig. 7 (a) and (c) respectively) is similarly consistent, but is not as smooth as the tracking data during the transitions between actuation states. This is likely the result of the structural properties of the curvature sensor, itself, which are different then the rest of the actuator. In particular, pressurization of a chamber may cause the curvature sensor to bow vertically before the entire actuator bends. The structural support from bowing would cause the sensor to resist bending until it buckles, resulting in the lagging phenomenon exhibited in Fig 7(a)-(c).

III. Exoskeleton-Enabled Soft Actuation System

The Soft Linear Actuator System is made primarily single chamber of the bidirectional bending actuator with a modified cross-section wrapped in the same double-helix of thread and with the same acrylic capping method. Without additional constraints, these actuators extend axially. Instead of a simple constraint layer used for the bidirectional bending actuator, we used a more complex hard exoskeleton

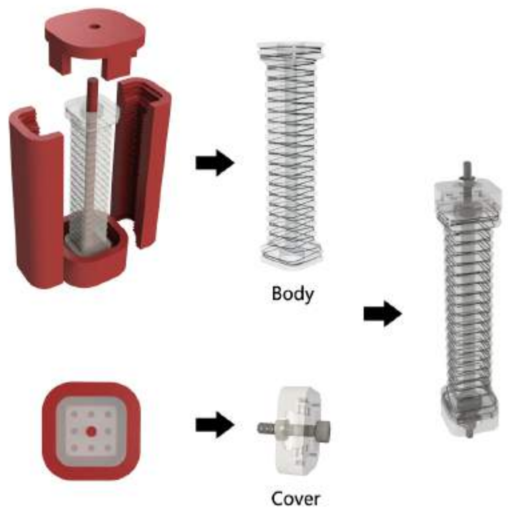

Fig. 8. Soft linear actuator fabrication process

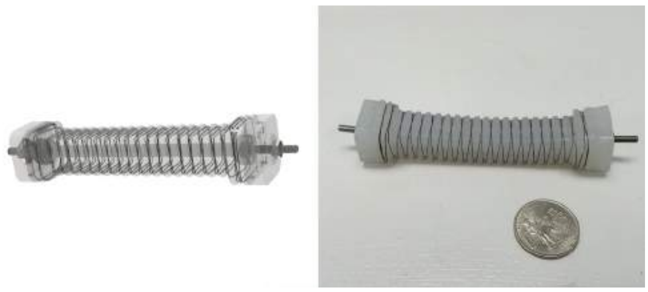

Fig. 9. Figures (a) and (b) shows the CAD and experimental prototype of the soft linear actuator.

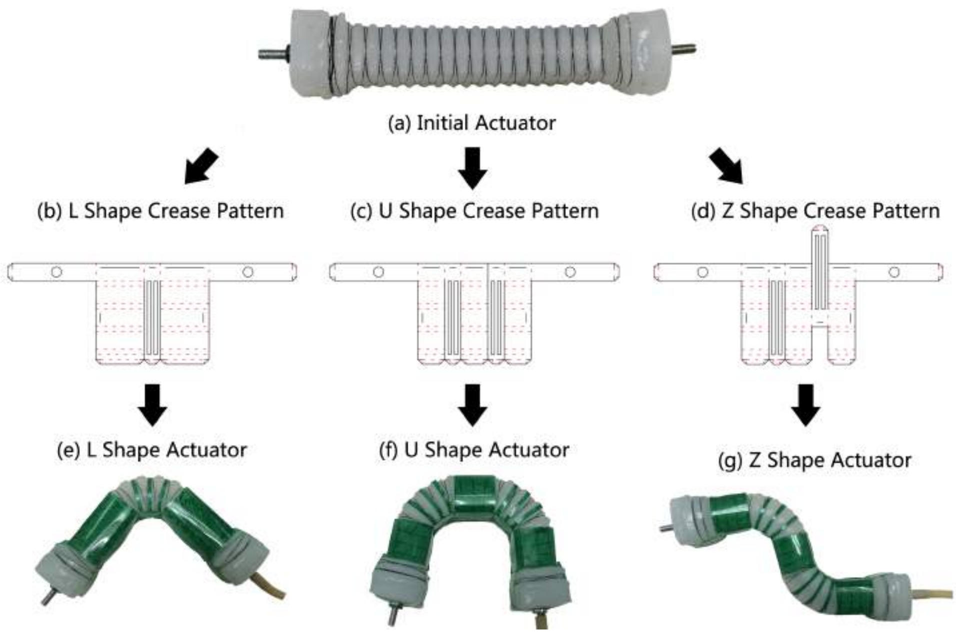

Fig. 10. The actuator's shape with foldable exoskeleton. (a) shows the initial state of the actuator before pressurization. (b), (c) and (d) show the cease pattern of the L,U,Z shape exoskeleton.(e), (f), and (g) show The final L,U,Z shape of the pressurized actuator

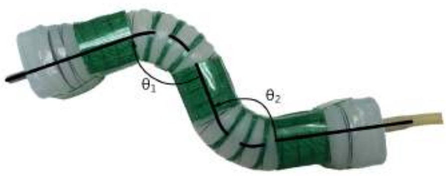

Fig. 11. A close-up of the Z-shaped soft linear actuator with an exoskeleton forcing it into a Z shape when under actuation. θ_1 and θ_2 are the angles used in Fig. 12.

constraint allowing for a range of motions. The fabrication process for the linear actuator actuator is similar to the soft bending actuator as shown in Figure 8. In this design, both ends of the chamber are enlarged to make the vent screw fit. Thread is also introduced to prevent lateral expansion. The final actuator is shown in Figure 9 (a), (b).

A. Complex Exoskeleton Constraints

Besides using plastic sheet as the constraint layer inside the soft bending actuator, it is also possible to use plastic sheet as external constraint or exoskeleton for a soft actuator. Without any constraint, the soft linear actuator is only able to extend along the axial direction. With the help of the foldable plastic exoskeleton, complicated motions can be achieved.

The crease pattern is shown in Figure 10. The exoskeleton is folded from a laser cut 177.8 μm PET plastic sheet. In Figure 10, the red dashed lines are folding lines while the black lines are cut lines. After folded, the box shaped skeleton wraps around the actuator. At desired places, only one single surface of plastic sheet are kept connected, operating similarly to the constraint layer of the bending actuator and causing the single linear actuator to bend. Several strips are

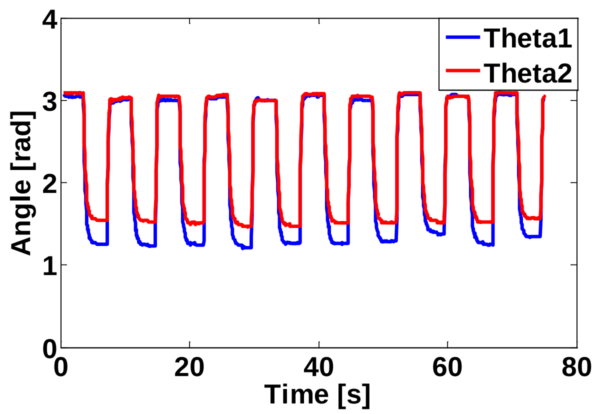

Fig. 12. The 10 cycle dynamic response of the two angles of the Z shape actuator. The input pressure is 7 psi and the frequency 0.125 Hz.

used to fix the relative position of the actuator and skeleton. Therefore, when the soft linear actuator is pressurized, the skeleton will force the actuator to covert its increase in length into the bending at specified locations.

B. Analysis of Final Product

Fig 10 shows the soft linear actuator' state before and after pressurized. This actuator could be generated the different shape based on the construction of the exoskeleton. In addition to demonstrating some of the possible shapes the plastic exoskeleton could produce, we used the motion capture system to observe the dynamic behavior of the Z-shaped module. Figure 11 shows the two angles θ_1, θ_2 of the Z shape actuator that were measured. Fig. 12 shows the two angle dynamic response. From the figure, the dynamic responses of the two angles are similar. In addition, we can see that the actuator behavior is consistent over a series of cycles. Joint 1 actuates more than Joint 2, while the dynamic effects of the pneumatic flow within the chamber are negligible so both joints actuate at approximately the same time, which provides us with a standard method to couple multiple degrees-of-freedom to generate desired complex motions.

IV. Conclusion and Future Work

This article presented a new fabrication method for a pair of standardized multi-material soft actuators. The first of which was a soft bending actuator with integrated curvature sensing. These actuators consist of two chambers of silicone each wrapped in a double helix of thread with a inextensible curvature sensor in between and all encased in silicone again. These actuators were found to be much more reliable than any previous ones and able to actuate repeatedly without hysteresis while still being able to sense their kinematic state.

The second was a coupled multi-angle bending actuation system combining a soft linear actuator with an external plastic exoskeleton. The exoskeleton serves as a complex constraint, allowing the single 1-input actuator to achieve a variety of poses, including u-shaped and zig-zag. We analyzed the motion of the zig-zag actuator and found that the dynamics of the pneumatic flow within the single chamber were negligible.

The next step of this project is to combine the actuators into useful configurations. In particular, we seek to these soft segments into fully independent modules. This will increase the segments usable in a snake, and allow for unique behaviors, such as the ability to grasp an object while moving. We are also interested in an underactuated soft snake robot, which would allow for new research directions such as optimizing the energy consumption of the soft robotic snake.

Work is also underway to eliminate the nonlinearities observed in the curvature sensor data. This could involve changing the backing film of the sensors to a more flexible material, adjusting the cross-section of the chambers to reduce bulging against the sensor, or moving the sensor to the outside of the actuator.

The benefits of the foldable plastic exoskeleton reduce the complexity of the soft actuator design for the same task. Fluidic soft actuation with a folded exoskeleton is currently being investigated to replicate the extension of a jumping spider leg. Jumping spiders, while small, can jump many times their own length using a unique actuation method involving pressurized fluid. The prototype will be tested to compare to a numerical simulation of the hydraulic extension of jumping spider legs, to verify if the mechanism and model can be scaled to larger actuators. Future work includes robotic design of a robot with multiple jumping legs and the control required for jumping and walking, as well as considering other applications of this actuation approach, including locomotion or gripping mechanisms.

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