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VERSATILE LAYERING APPROACH TO PNEUMATIC SOFT ACTUATOR MANUFACTURING

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ABSTRACT

This paper presents a layering approach for the manufacturing of pneumatic soft actuators as a coalesced solution to the diverse array of existing fabrication methods. While most research groups have developed their own (often tedious) fabrication strategies for soft actuators, these methods are usually based on available equipment and project-specific design requirements, making them impractical for use in other laboratories. In contrast, the layered substrate approach enables repeatable production of highly-capable pneumatic actuators that can be easily customized to suit a variety of applications. Here we propose layering fiber-reinforced silicone on both sides of a thin pneumatic chamber to directionally constrain expansion. Similar in concept to the Venus flytrap, pressurization of the chamber causes the module to deform and expand where unrestrained. Strategic orientation and patterning of the fiber reinforcement layers results in multiple unique shear and bending capabilities upon pressurization. Combinations of multiple reinforced pneumatic units in series or parallel could match the capabilities of most soft pneumatic actuators, while requiring only simple, universal fabrication methods that may be replicated by other research groups.

INTRODUCTION

The recent explosion of research on soft robotics has taken several different pathways, all with the overarching aim of developing capable robots with soft materials that render the robots safe for interaction with humans. The vast array of recent research presents various approaches to stiffness variability, biomimicry, material optimization, actuation mechanisms, modeling strategies, and more [1, 2, 3, 4, 5, 6]. In this work, we focus on the specific field of pneumatic soft actuators.

Pneumatic soft actuators offer several advantages over their rigid counterparts as reviewed by Polygerinos et al. [7], namely their ability to deal with uncertainty in their environment. Pneumatic actuators possess the ability to grasp diverse objects with minimal complexity [8]. Because they do not contain any sharp, heavy, or rigid components, they lend themselves well to co-robotics environments where safety is a high priority [9, 10, 11, 12].

The fundamental concept behind the design of pneumatic actuators is inspired by examples seen in nature such as the Venus flytrap plant and muscular hydrostats such as the human tongue, where the combination of hydrostatic pressure and constraints imposed by muscles or leaf geometry creates unique bending behavior [13, 14, 15, 16].

Many examples from the literature utilize fiber reinforcement as a means of geometrically constraining expansion so as to direct expansion in a particular desired direction or induce bending [8, 17, 18, 19, 20, 21, 22]. This is often the case for long, narrow

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silicone actuators where a helical fiber wrapping prevents radial expansion, thereby increasing elongation in the longitudinal direction. When one side of the actuator is made inextensible, this longitudinal expansion results in a bending motion.

In order to conduct experiments on this topic, members in each lab are required to develop skills in elastomer casting and design for manufacturing to create functional robotic units for research purposes. The fabrication of pneumatic actuators is accomplished through a variety of methods that depend on the available equipment, the area of expertise of the designer, and the project-specific design requirements at hand. Unfortunately, the uniqueness of these methods makes them difficult to replicate in other laboratories, so the tedious development of lab-specific fabrication methods is usually required.

Here we propose a universal layering fabrication strategy that requires only basic equipment so that the technique may be used in a variety of lab facilities. This method involves layering thin sheets of fiber-reinforced silicone with hollow chambers inside for inflation. Strategic orientation of the fiber reinforcement can be used to customize the deformation type. For example, Figure 1 shows a fiber layout that enables bending upon pressurization of the pneumatic chamber. These units could then be stacked or combined in intentional grid patterns that could enable complicated morphing behavior by means of a simple geometry at the unit level. Varying the fiber arrangement within the units could result in a shear-type deformation of the unit and would thus allow further morphing capabilities in a larger combination of units.

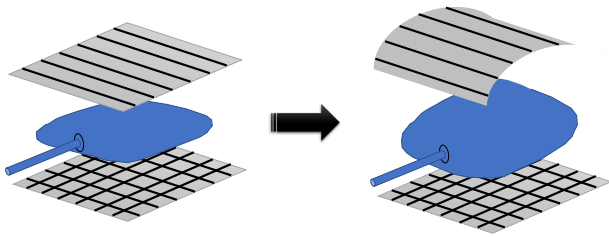


FIGURE 1. Exploded view of layered pneumatic actuator with strategically-oriented fiber reinforcement to induce bending upon pressurization.

In this work we demonstrate the fabrication of a single unit and its ability to deform along the desired axis. A simple bending unit as shown in Figure 1 is constructed using the proposed fabrication method, and its bending behavior is characterized by observing the relationship between chamber pressure and the resulting bend radius of the unit. Although the long-term goal is to

fabricate the units in bulk quantities and then combine them, this work provides a mere proof-of-concept for the proposed fabrication strategy and bending capabilities.

MATERIALS AND METHODS

In the following, we present the proposed fabrication method, the materials used, and the method implemented for measuring the deformation of the soft actuators.

Materials

Most pneumatic actuators in the literature utilize silicone rubber as a matrix material. Its elastic nature, durability, and ability to withstand high temperatures make it well-suited to soft robotics applications. Some silicone mixtures closely match the non-linear characteristics of human skin, making them ideal for applications where biomimicry is a key objective [7, 5]. Others have used siloxane or urethane rubbers which behave similarly, but can release potentially-harmful gases during mixing. In this work, Dragon SkinTM 10 MEDIUM silicone is used for fabrication of the soft actuators. This particular Pt-cure silicone has a pot life of 20 minutes and a 5 hour cure time.

Several different fiber reinforcements are used in the literature to constrain expansion of pneumatic grippers. Among these materials, nylon thread, Kevlar fibers, and Nylon mesh are the most prevalent [22, 19, 20, 21]. While these materials offer excellent tensile strength, they are prone to slipping through the silicone unless wrapped in a continuous manner. To prevent this slipping, a fibrous twine is used as a fiber reinforcement in this work. The frayed strands along the twine grip the silicone, preventing the string from pulling out when under tensile loading.

In places where we wish to constrain the expansion in two directions, two sets of parallel fibers could be overlaid perpendicularly to create a grid that prevents stretching in both directions. Alternatively, we propose using a polyester mesh fabric to bi-directionally constrain expansion. The fabric works essentially the same as the perpendicular fibers, but it is thinner and easier to embed in the silicone in a single step. Both the twine and the polyester mesh fabric are essentially inextensible but flexible and do not inhibit bending.

Fabrication Method

As opposed to the numerous different mold geometries used in different laboratories, we propose a layering approach to the manufacturing of pneumatic soft actuators. By fabricating the actuators in sheets, the need for complicated mold designs and multi-step assembly is avoided. While this work provides a mere proof-of-concept with the fabrication of a single unit, large sheets with multiple units could be fabricated at once with little extra work.

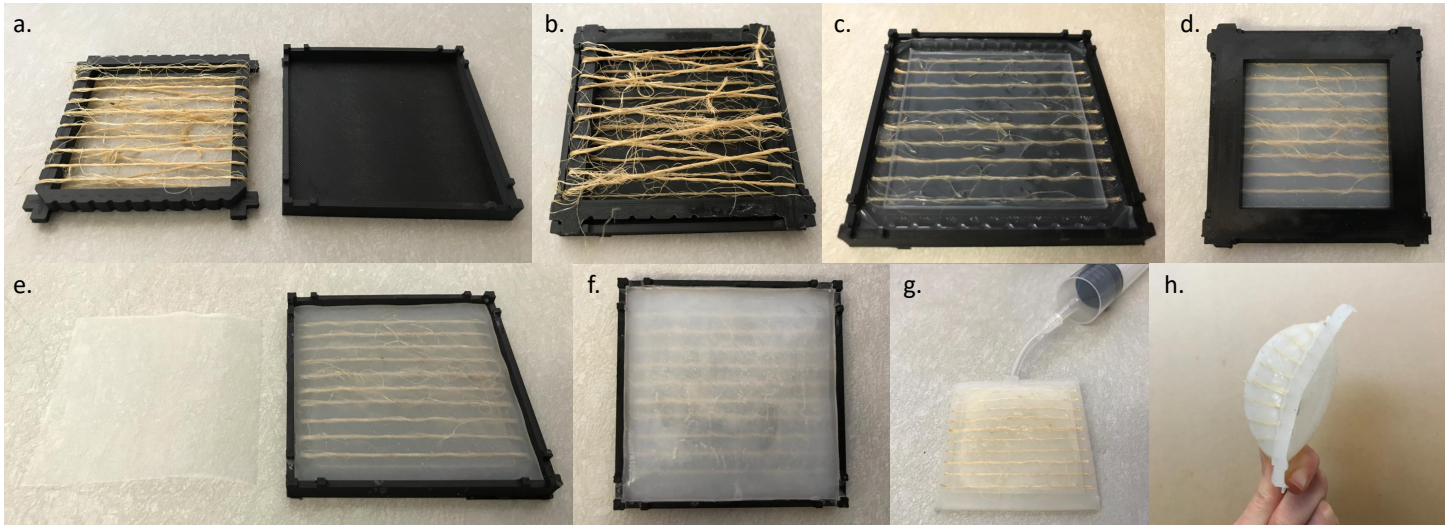


FIGURE 2. Diagram showing the fabrication process for a single bending actuator unit with (a) prepared fiber frame and mold, (b) twine helix frame inserted in mold, (c) first layer of actuator with trimmed fibers, (d) stencil placed in mold to shield edges from mold-release spray, (e) polyester mesh prepared for insertion in top layer, (f) polyester mesh embedded in second layer of silicone, (g) supply tube and syringe attachment, and (h) bending behavior upon pressurization of the unit.

For this work, a mold, fiber frame, and stencil part shown in Fig. 2 are 3D printed with ABS material. The twine is wrapped around the frame to form a snug, crisscross helix pattern with the fibers aligned parallel on the bottom side of the frame. The free ends are tied together to secure the twine. To prepare the silicone, equal parts of liquid silicone parts A and B are mixed and degassed. A thin layer (approximately 1-2 mm) of the liquid silicone is then poured into the mold. The frame with the twine is then inset such that the bottom half of the twine helix is in the silicone. Additional silicone is poured on top until the bottom layer of fibers are completely covered and a total thickness of 2.5 mm is reached. The first half of the actuator is allowed to cure for 3.5 hours. This incomplete curing improves the adhesion between the layers of silicone.

Next, the top of the fiber helix is cut open to allow the frame to be removed. The twine strands are trimmed flush with the edge of the mold, and the 3D printed stencil is placed in the mold. The partially cured silicone is sprayed liberally with mold release to prevent adhesion of the silicone layers at the center of the chamber. The stencil is removed, and another thin layer (approximately 1-2 mm) of prepared liquid silicone is poured on top. A square of polyester mesh cut to the size of the mold is placed on top and smoothed out before the final layer of silicone is added. The total thickness is now 5mm. The unit is allowed to cure for 5 hours, then removed from the mold. Finally, a blunt needle is used to puncture a hole at one edge of the chamber, and a thin supply tube is inserted in the hole. A thin layer of Sil-poxy seals the opening around the tubing.

Measuring Deformation

The deformation of the chamber is measured to show the ability of the constraints to direct expansion and induce desired bending. The edge of the chamber with the supply tube attachment is clamped in a vise, and a 150 mL syringe is attached to the supply tube as shown in Fig. 3 to apply pressure. The pressure within the chamber can be roughly calculated by measuring the force applied to the syringe and dividing by the area of the cylindrical syringe body, assuming pressure loss in the tubing to be negligible. The force is applied to the syringe via a Mark-10 Series 5 Digital Force Gauge. Meanwhile, side-view photos taken as the force is increased in 5N increments capture the bending profiles corresponding to each applied force.

The bending radius in each photo is then determined by overlaying a curve on the photo that matches the curvature of the actuator as shown in Fig. 3. The radius of the overlayed curve is normalized by using the length of an item in the photo with known dimensions.

RESULTS AND DISCUSSION

In the following we present the results of the deformation measurements and weigh the pros and cons of the universal fabrication method.

Controlled Deformation

The pneumatic bending unit achieved the desired bending behavior when pressurized with the syringe. The parallel fibers

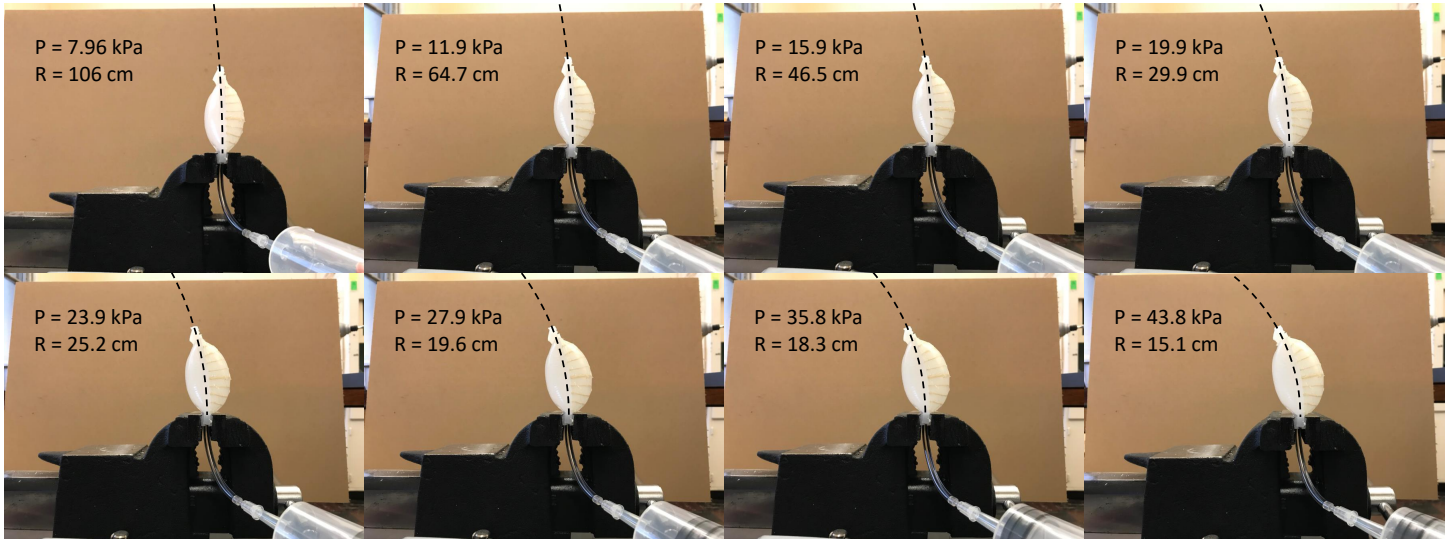


FIGURE 3. Side-view photos of bending unit deformation upon pressurization. The right-hand-side of the unit is reinforced with fibers in one direction; a polyester mesh fabric bi-directionally reinforces the left-hand-side of the unit.

reinforcing the right side of the chamber prevented expansion in the direction of the fibers but allowed the silicone to stretch perpendicular to the fibers. The polyester mesh embedded in the left side of the actuator prevented the silicone from stretching in both directions. Although both sides of the actuator are flexible and allowed to bulge out upon pressurization, only the right side is allowed to stretch substantially, so increased pressure causes the right layer of silicone to stretch, making the actuator bend to the left as evidenced by Fig. 3.

The measured actuator bend angles and the corresponding pressures are shown in Fig. 4. From this plot we can see the clearly non-linear relationship between the pressure and bend radius. It will be useful in the future to develop a model to describe/predict the deformation of these bending units, but this task is beyond the scope of this work. The measurements shown in Fig. 4 will be useful in the future for comparing with theoretical models for the bending behavior.

Pressurizing silicone channels to create a bending motion is not a new idea, so the bending behavior of the pneumatic unit is not surprising or novel. Many pneumatic bending actuators exist in the literature, but the present work demonstrates that the underlying fiber layout has the ability to direct expansion and control bending behavior. Modifying the fiber arrangements within a pneumatic unit would enable 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. These types of fiber layouts and the resulting motions have yet to be explored but will be the focus of future work.

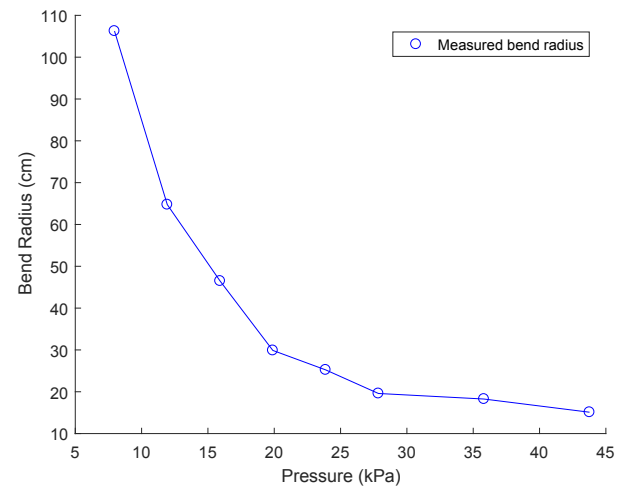


FIGURE 4. Measured bend radius a single pneumatic bending unit.

Evaluation of Fabrication Method

The universal fabrication method presented here proved effective for the fabrication of a single pneumatic unit. The 3D printed fiber frame piece successfully aligned the fibers with uniform spacing and submersion depth in the silicone. Fiber wrapping can be a tedious step in pneumatic actuator fabrication, where tiny threads must be aligned and wrapped with uniform tension to prevent buckling of the unit, but here the rigid frame with notches greatly simplifies the wrapping and securing of the fibers.

Minimizing wall thickness is another challenge where fiber

reinforcement is required. The silicone actuator walls must be thick enough to fully encase the fibers without room for air leaks. The twine used in this work was relatively thick (1.6mm), but the fiber frame allowed us to suspend the fibers at a precise depth in the mold so that a minimal amount of silicone was required to encase them. The resulting wall thickness was less than 3mm on each side of the chamber.

Two potential challenges are presented by the proposed fabrication method: first, it difficult to precisely control wall thickness as the depth of the silicone cannot be measured before it cures. This problem can be avoided by calculating the mass of silicone needed to achieve a desired thickness and pouring the silicone only until the desired mass is reached. The second challenge is the potential for poor adhesion at the edges between the two layers of the actuator which results in leakage. However, this issue only presents itself when an excessive amount of mold release is applied between the layers, which causes the spray to spread underneath the stencil.

An additional benefit of the universal fabrication method is the minimal time required to produce the units. This method is faster than many other methods as it only requires two casting/curing steps, the first of which is only a partial cure (3.5 hours); whereas most other methods require at least 3 casting/curing steps [22, 19].

The real efficacy of the universal fabrication method emerges from fabrication of multiple pneumatic units at a time. As shown in Fig. 5, the 3D printed parts used for fabrication of the single unit can be easily expanded to enable the creation of multiple units in a single broad sheet. The fiber reinforcement helix can be wrapped around a large frame that spans multiple units. The stencil is simply modified to encompass multiple windows where mold release should be applied to prevent adhesion in the center region of each unit. A large piece of polyester mesh fabric can be used across the entire sheet instead of small individual squares for each unit. The units can be assembled in a large sheet using the same method as used for a single unit. The units are then simply cut apart after the final curing step before insertion of the supply tubes.

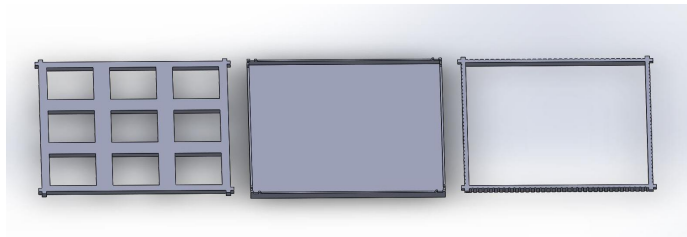


FIGURE 5. Stencil, mold, and fiber frame for bulk fabrication of multiple pneumatic units.

FUTURE WORK

The bending actuator unit is a mere building block for new geometries. Future work will explore the deformation behavior of pneumatic chambers with different fiber reinforcement layouts. These layouts may include patterns such as a spiral, concentric circles, isotoxal star, or lines radiating from a point. The resulting deformation of the units will be characterized for each fiber arrangement, in relation to the corresponding pressures. It may also be useful to implement different fiber layouts on the top and bottom layers of the actuator units to further optimize performance, depending on design goals.

After determining a few optimal fiber layouts that result in different deformations, we will begin fabricating the units in large quantities to explore different methods of combining multiple units. It may be possible to stack the actuators to increase stiffness. Combining the units in layered grids could result in a bulk material with desirable morphing capabilities.

Finally, in order to implement any sort of control algorithm, we must develop a model that accurately describes the bending or morphing of each unit type as a function of chamber pressure. Modeling will involve finite element modeling [23] and characterization using the left CauchyGreen deformation tensor [19]. The model will then be compared with physical measurements similar to those shown in Fig. 4 to verify model reliability.

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