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3D PRINTED SEGMENTED FLEXIBLE PNEUMATIC ACTUATOR

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ABSTRACT

Soft actuators have been studied and analyzed as a new solution for soft robotic technologies. These types of actuators have many advantages due to their predictable deformations and their ease of control, enabling them to hold and move delicate objects performing complex movements in confined spaces. Soft actuators can be made using different manufacturing processes, but the most common is mold casting. However, this manufacturing process involves several steps, increasing the manufacturing time and hindering changes in the design. This paper presents a novel design of a 3D printed soft pneumatic actuator based on additive manufacturing, achieving design versatility and performance. The produced actuator has seven segments that can be individually controlled. The actuators were made using fused deposition modeling (FDM) technology in one continuous process and without support material. The mechanical performance of the soft actuators was demonstrated, analyzing the deformation in the z-axis based on input pressure.

Keywords – Soft Actuator, Additive Manufacturing, FDM, Support Material.

INTRODUCTION

During the past few decades, robots have become widespread in industrial applications; mainly being used in the manufacturing sector for the automotive industry. However, in the last decade, research and industry have started to explore and develop robots for new applications areas. Robots are now being used in predominantly human domains and are gaining acceptance for use in close proximity interactions with humans to either assist human operators or work collaboratively with them. This conceptual change in the use of a robot has resulted in developments in materials and manufacturing processes, trying to get closer to biologically inspired designs and creating a new subfield in robotics called "soft robotics". The soft robotics field has increased in the past few years, providing new types of structures that can produce intricate controlled movements to accomplish specific tasks. These types of structures are more suited to direct human interaction due to the use of soft actuators and soft materials. Soft actuators are flexible and adaptable structures that are commonly made of flexible elastomeric materials. Often to provide stiffness to the actuator, an internal rigid structure is used. [1].

One of the most common actuator designs that researchers have tried to study and copy, through the use of soft actuators, is human-like organic muscles. The drive to create an organic-like actuator comes from the ability of the human muscle to perform accurate positional movements and support external loads through contraction and expansion of highly flexible structures [2].

Soft actuations have several advantages over traditional actuators. Traditional actuators are generally confined to a specific range of motion, such as a linear or rotational trajectory. However, soft actuators which are typically controlled through pneumatic, hydraulic, or electrical systems can provide varying actuation distances and trajectories based on their design [2]. Soft actuators are able to deform and adapt to objects in their environments with theoretically infinite degrees of freedom, depending on the geometry, material, and design configuration [3].

Soft pneumatic actuators mechanically deform through application of pressure to a sealed structure. The most commonly used working fluid in pneumatic actuators is compressed air. Using air as the working fluid has pros and cons. Air is inexpensive, biocompatible, environmentally, safe, and has relatively no adverse effects on structures. However, it is also compressible. Therefore, it is more difficult to apply accurate finite control using air in pneumatic circuits [4].

Numerous types of soft pneumatic actuators exist in research and application. However, these actuators most commonly fall into three categories: McKibben actuators or Pneumatic Artificial Muscles (PAMs), fiber-reinforced actuators, and pneumatic networks. McKibben actuators or PAMS are composed of a bladder surrounded by a mesh sleeve. The McKibben muscles have been the subject of a significant amount of research, particularly as agonist and antagonist muscle pairs, and their effectiveness has been demonstrated in a broad range of applications [5]. Fiber-reinforced soft actuators incorporate supporting fibers surround an elastomeric air bladder structure. The fibers help to control the motion by limiting radial expansion [6]. The pneumatic networks actuator uses a network of internal channels to control expansion of specific sections of the actuator design [7].

3D PRINTING

Previous research in this area has identified limits and challenges in the manufacturing and performance of this type of actuator. There are different types of manufacturing processes to produce soft actuators, but the most common is mold casting. This manufacturing process involves several steps increasing the cost, time, and labor. In addition, the production of molds is time-consuming and limits design creativity. Molding processes restrict design complexity and hinder design changes.

Recent advances in 3D printing technology have improved the manufacturing process in terms of resolution, speed, cost, and materials. This has enabled the rapid fabrication of highly customizable soft flexible actuators. 3D printing has become an important technology for advancing the emerging field of soft robotics. The research community has used 3D printing technology to fabricate new custom designs for soft actuators and sensors, even incorporating smart materials such as dielectric electroactive structures [8].

Fused deposition modeling (FDM) is an innovative 3D printing technique based on the additive manufacturing process, that allows for the production of parts by extrusion and deposition of material in a controlled way layer by layer. The heated extruder uses a simple feeding mechanism based on the friction of small gears, which can be modified to facilitate the printing of flexible materials. In this research a Lulzbot Taz 6 was used to manufacture 3D printed segmented flexible pneumatic actuators, using a flexible filament and a modified extruder head to support higher frictional forces and extrusion temperatures.

THERMOPLASTIC POLYURETHANE (TPU)

The most common flexible materials available for FDM 3D printing are thermoplastic polyurethanes (TPUs). These materials present an elastic behavior under traction and contractile forces [9]. This type of polymer can be produced with varying elastic properties, which means that is possible to find the same class of materials with different stiffness values. The dielectric films used in this research were made using a soft TPU with a Shore A hardness of 60 (Diabase X60 Ultra Flexible Filament). This is currently the softest, most flexible elastic filament available on the market. Printing with this filament can produce finished parts that are highly functional for applications that require stretch and flexibility. In addition, this material is resistant to oil, grease and abrasion, making this material ideal for industrial applications [10].

METHODOLOGY

Design

The soft actuator designed here is a structure composed of seven segmented channels, with independent air inputs for each channel. This design represents a seven-segment numeric display with independent segment actuation. Each channel has a width of 2 mm and a length of 25 mm. Figure 1 shows the CAD model for the designed soft pneumatic actuator.

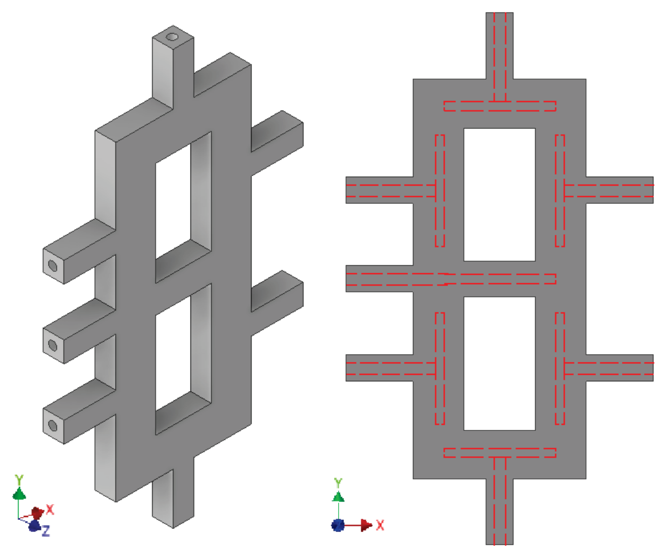

Figure 1. Soft pneumatic actuator CAD model.

The entire structure is composed of three regions. The first region is a single layer with a thickness of 0.2 mm. This layer works as a membrane for each segmented pneumatic actuator, which means this component will deform under pressure.

The second region is a multi-layer zone with a thickness of 4 mm. These layers form the walls of the actuator, and also provide internal support to the rest of the structure restricting the actuation in the x and y axes.

Finally, the third region is a multi-layer zone with a thickness of 2 mm. These layers form the base of the actuators and provide support in this area to restrict the actuation in the negative z-direction and force the actuator to be expanded only at the membrane. Figure 2 shows the actuator composition describing the locations of the different regions.

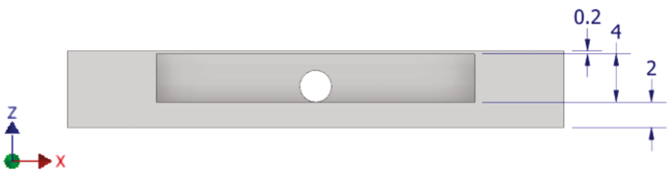

Figure 2. Actuator composition (dimensions in mm)

Each channel has an independent circular input channel to provide pressure to each actuator segment using compressed air. The input channel has a diameter of 2 mm, making this connection sufficiently tight to have a fully sealed actuator with no air leakage. A sketch of the entire structure can be seen in Figure 3.

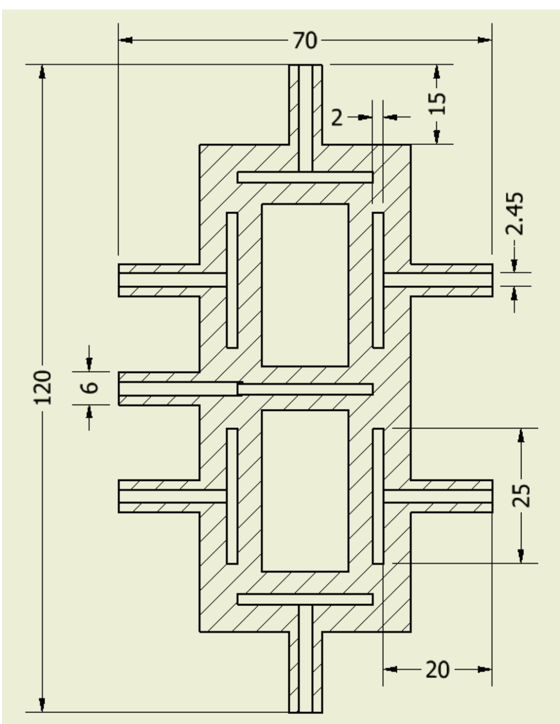

Figure 3. Flexible actuator structure (dimensions in mm)

This structure was designed to prove the conceptual idea of manufacturing multiple pneumatic actuators embedded in a flexible matrix, with the potential ability to produce a structure for conveying numeric information through the seven-segment display. In addition, this design demonstrated that is possible to manufacture flexible pneumatic actuators in one continuous process, with a flexible material, and without support material. Solving some restrictions of other 3D printed pneumatic actuators that need a second material to produce support in the inside of the channel. The idea of this design is to produce an informative structure that can be controlled with an electronic and pneumatic feedback system.

It is expected that the pneumatic actuators deform in all free, non-constrained directions, creating an expanded surface with a shape similar to a semi-ellipse as seen in Figure 4. In addition, the deformation of this type of actuator is not uniform in the entire active region. When the actuator is pressurized, the mechanical response will correspond to the different restrictions in the active area based on material thickness, type, and boundary constraints. For example, it is expected that the areas that are close to the edges present less deformation than the areas that are located in the center of the membrane, because in this location the material can move and expand more freely. The center of the membrane will have the largest deformations because it has the smallest number of boundary constraints. On the other hand, the t-shaped component of the actuator will have an air input at the center of the channel. Therefore, maximum deformation will occur close to the input source. Figures 4 and 5 show a sketch of the deformation based in the x and y axis accordingly.

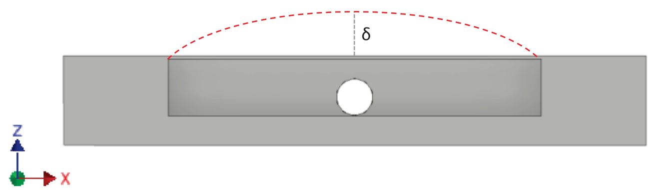

Figure 4. Deformation in the x axis. δ represents the displacement measured.

Figure 5. Deformation in the y axis.

<u>Manufacturing process</u>

All flexible structures were manufactured using the same 3D printer machine, material, and printing settings (layer height: 0.2 mm, infill density: 100%, printing temperature: 205°C, build plate temperature: 60°C, print speed: 10 mm/s). The CAD model was processed using the software Cura-Luzbot 3.2.32. This is a free software program that prepares the files for printing by converting the model into GCODE which controls printer operation. The printing process can be seen in Figure 6 and depicts the method for production of the structure without support material.

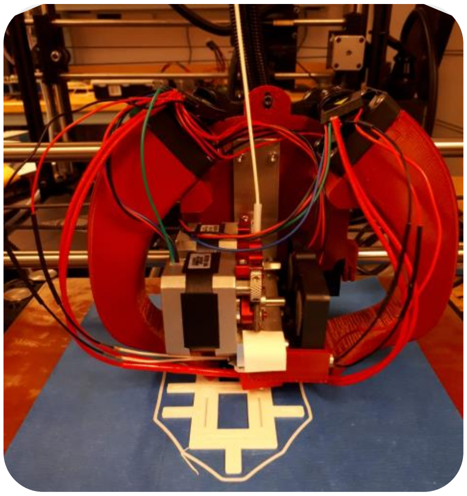

Figure 6. 3D printing manufacturing process of pneumatic actuators.

Three different types of structures were printed and measured, varying the printing path of the first region of the structure in order to determine the influence of the filament orientation on actuation. The actuators were printed using an orientation of 90°, 45° and 0° based on the width of each actuator. Figure 7 shows the three different printing paths for the actuation membrane.

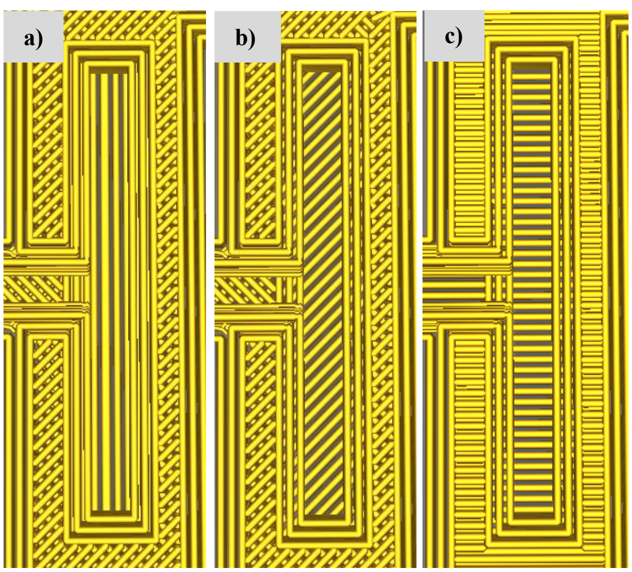

Figure 7. Printing paths for the actuation membrane. a) 90°; b) 45°, c) 0°.

Experimental setup

The experimental setup used a line of compressed air with a pressure of 60 psi. This line was connected to a manual pressure regulator valve, which reduced and controlled the pressure. The manual pressure regulator valve was connected in series to an electronic pressure regulator. This instrument controlled the pressure through the actuator and provided relief when it was needed to maintain a desired pressure amount. The flow from the regulator was controlled by a solid state relay (YXQ – SSR-80DA) and a signal generator, being able to control the amount of time of each actuation cycle. After that, a pressure transmitter (Wika A -10) was connected in order to measure the real pressure delivery to the actuator. Finally, the actuator was connected to the pressure transmitter closing the air flow line.

The manufactured pneumatic actuators were characterized measuring the displacement in z-axis based on the input pressure. The displacement was measured using a laser displacement sensor (Keyence LK-82) with a resolution of 0.01 mm. The laser was placed in a support structure, ensuring that the laser was located in a horizontal position above the actuator. On the other hand, the pressure was measured using a pressure transmitter with a range of 0 to 25 psi and a resolution of 0.01 psi. Both instruments were connected to a National Instruments USB data acquisition system (NI DAQ 6212) which measured the electrical signal provided for these sensors. The data acquisition system was controlled with the software LabVIEW which also managed recording of the data for post process analysis. The system also monitored the signal in real time to adjust and verify the conditions of the experiment. Figure 8 shows a diagram of the experimental setup.

All the experiments were made by pressurizing one t-shaped channel at a time. The structure has six T-shaped channels and one straight channel. All experiments and analysis addressed in this paper are based on the t-shaped actuators. The actuator with one straight channel was less challenging to produce and power and was included for the purpose of including all 0-9 digits in the numeric display.

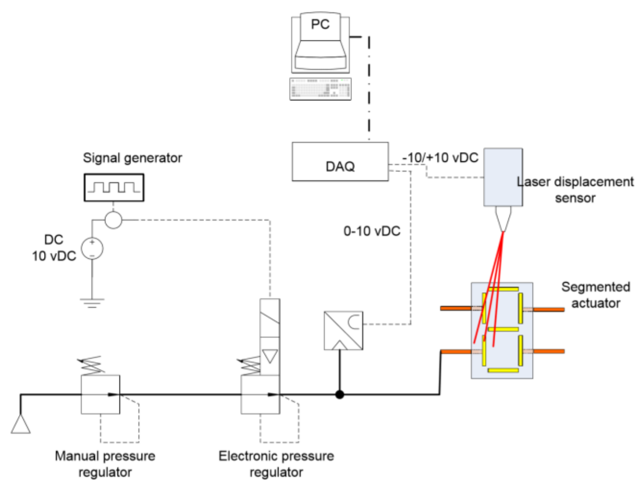

Figure 8. Experimental setup diagram [11].

RESULTS

3D printed segmented flexible pneumatic actuator

All 3D printed flexible structures were successfully printed. Preliminary actuation testing was performed on each pneumatic actuator to verify that each actuator was completely sealed.

Figure 9 shows a 3D printed flexible structure and a 3D printed flexible structure with a cut in the second region to visualize the internal voids

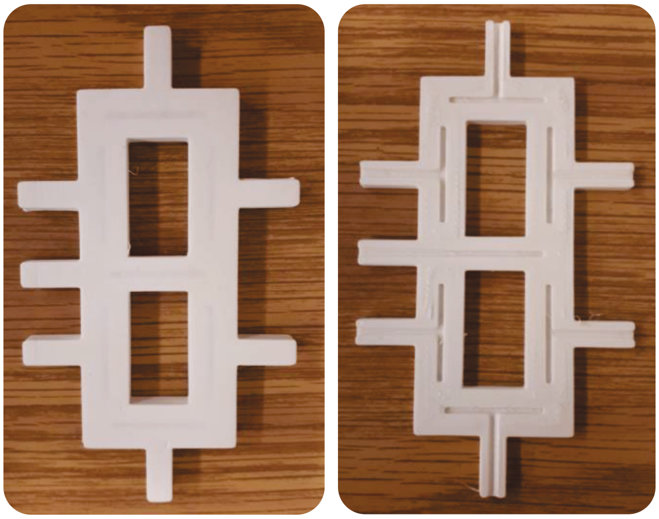

Figure 9. a). Complete 3D printed flexible structure. b). 3D printed flexible structure with a cut in the second region.

Pressure measurement

The actuation test was completed at four different pressures: 10, 15, 20, and 25 psi. Each type of actuator was tested under these four pressure conditions. Preliminary testing demonstrated that the best frequency to produce an actuation cycle for these pneumatic actuators is 0.25 Hz. This frequency allows the pneumatic actuator to experience an increase in pressure in the initial stage until achieving stabilization for a prolonged time and to finally relieve the pressure without affecting the structural integrity of the membrane. Figure 10 depicts the pressure cycle for all the pressure values.

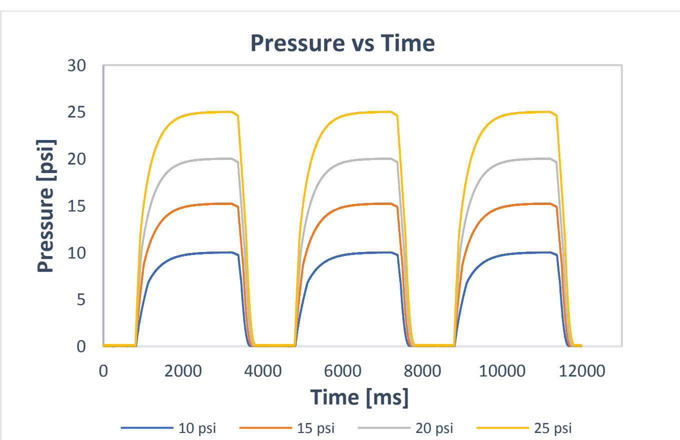

Figure 10. Pressure cycle

Based on the previous figure, is possible to see that the pressure cycle is consistent for all pressures and has a characteristic behavior that corresponds to a pneumatic actuator. In addition, the results demonstrated that the testbench works properly, without leaking in the connections or pneumatic actuators.

Displacement measurement

Each actuator of each structure was divided into four parts in the length dimension, in order to have different displacement measurements along the length of the actuator. These multiple measurements allow for characterization of the displacement profile along the length of the actuator. Figure 11 shows a diagram of the divisions made for the displacement measurements.

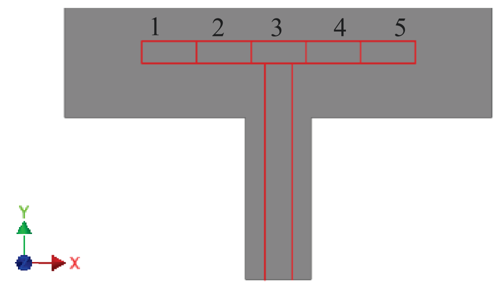

Figure 11. Division to discretize the pneumatic actuator and stablish the regions to measure the displacement.

It is important to identify if the actuation is affected by the distance of the channel and/or the orientation of the printed filament. Table 1, 2 and 3 show the displacement results for each actuator under the different pressure conditions. The values of displacement were calculated as the average of all measurements realized under the same distance, pressure, and printing path orientation.

Table 1. Displacement of the pneumatic actuators with 90° printing orientation

	Displacement [mm]				
Pressure [psi]	Position 1	Position 2	Position 3	Position 4	Position 5
10	0.11	0.13	0.15	0.13	0.11
15	0.15	0.22	0.25	0.22	0.17
20	0.22	0.24	0.28	0.25	0.23
25	0.30	0.31	0.35	0.31	0.28

Table 2. Displacement of the pneumatic actuators with 45° printing orientation

	Displacement [mm]				
Pressure [psi]	Position 1	Position 2	Position 3	Position 4	Position 5
10	0.05	0.06	0.09	0.06	0.05
15	0.08	0.13	0.15	0.13	0.08
20	0.13	0.17	0.20	0.17	0.14

25	0.16	0.22	0.26	0.23	0.17

Table 3. Displacement of the pneumatic actuators with 0° printing orientation

Displacement [mm]					
Pressure [psi]	Position 1	Position 2	Position 3	Position 4	Position 5
10	0,04	0,05	0,06	0,05	0,05
15	0,07	0,08	0,09	0,08	0,06
20	0,10	0,10	0,11	0,10	0,09
25	0,11	0,13	0,14	0,14	0,13

Based on the previous results, it is possible to affirm that position 3 presents a greater displacement in comparison to the other positions. This is likely due to its proximity to the air inlet duct, and because of the duct and central location, this section of the actuator is only restricted on one side. Furthermore, these deformation differences along the length of the actuator are caused because measurement positions 1 and 5 have constraints on three of their sides, and the measurement positions 2 and 4 have movement constrained on only two sides.

Another parameter that may affect the deformation of the pneumatic actuators is the printing orientation. Figure 12 shows a comparison between the different types of printing orientation, taking into account only the results obtained in position 3.

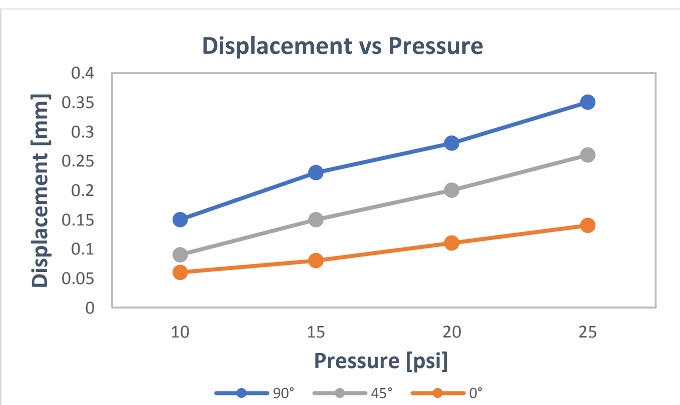

Figure 12. Comparison between the different types of printing orientations

As expected, the results of the previous figure show a clear influence of the printing orientation on the performance of the actuators. The actuators that were printed using a printing angle of 90° showing the highest deformations. Followed by the ones with a printing angle of 45°, and finally the actuators with a printing angle of 0°. This may occur because it is easier to deform three or four long rods of printed filament than more than 40 small rods of printed filament, as seen in the figure 6. In addition, the increased line paths of printing material cause an increase in the number of junctions between the material affecting the stiffness of the overall membrane.

CONCLUSIONS

This work demonstrates a novel design of a 3D printed soft pneumatic actuator based on additive manufacturing by fused deposition modeling. The designed and printed structure proved the conceptual idea of manufacturing multiple pneumatic actuators embedded in a flexible matrix, with the potential ability to relay numeric information in a seven-segment display. Moreover, the design demonstrated that is possible to manufacture flexible pneumatic actuators in one continuous process, with flexible material, and without support material.

The mechanical performance of soft actuators was demonstrated, analyzing deformation in the z-axis based on input pressure, and the influence of the filament printing orientation. The manufactured soft pneumatic actuators were capable of demonstrating displacements of up to 0.35 mm, having just an available initial volume of 0.2 mL.

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