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# Innovative Design and Fabrication of a 3D-printed Soft Pneumatic Actuator with Enhanced Bending Capacity and Better Controllability

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**Abstract**
This paper presents a comprehensive investigation into the design and performance analysis of a novel 3D-printed soft actuator, emphasizing its structural integrity and functional capabilities. The actuator is fabricated using material extrusion (MEX) 3D printing process. The study employs different testing methodologies to assess the actuator's performance under various pressure loading conditions, simulating real-world operational scenarios. Comprehensive finite element analysis (FEA) is conducted using Ansys (2023 R2), providing detailed insights into stress distribution, deformation patterns, and potential failure modes. The model is successfully validated by measurements of bending angle at different pressure levels. The model is used for further optimization of the actuator and bending angle of 209 degrees was achieved.

Keywords: additive manufacturing, soft actuators, pneumatic actuation, structural design, finite element analysis (FEA)

## 1. Introduction

The advancement of soft robotics has introduced flexible, adaptable mechanisms that excel in safely interacting with delicate objects, a challenge often unmet by rigid robotic systems due to the risk of damage [1]. This paper proposes an innovative 3D-printed soft rotary Actuator that combines flexibility, precision, and efficiency, addressing gaps in current soft robotics applications.

Soft actuators have gained significant attraction for applications in medicine, rehabilitation, and automation [2]. Traditional pneumatic soft actuators (PNSAs) generally produce rotation over a curve[3]. However, for certain applications, such as hybrid robotics that blend soft and rigid components, there is a need for actuators with isolated movement capabilities, specifically for tasks requiring exclusive rotation or elongation[4]. Such selective movement would enable precise control, expanding potential uses [5], such as in robotics systems where constrained spaces and defined trajectories are critical [6].

Recent years have seen efforts to develop soft actuators optimized for diverse, specialized applications. For example, gesture-controlled soft rotary actuators can achieve angular movements[7], while spider-inspired pneumatic actuators leverage hyperelastic sidewall compression to allow enhanced motion flexibility[8]. Other designs include three-chamber actuators mimicking human finger movements, permitting independent control for dexterous handling[9]. Bionic pneumatic grippers, featuring symmetrical, independently actuated fingers, increase grip adaptability and strength, making them effective in variable task conditions[10].

Despite these advancements, controlling soft actuators remains complex due to their deformable structure[11], necessitating sophisticated control strategies for accurate motion[12]. Additionally, many existing designs are limited by multi-directional bending, which complicates integration into systems requiring isolated bending axes[13]. To address these issues, this work introduces a novel actuator with single-axis bending achieved through strategically designed chambers. This configuration allows significant bending with maintained structural integrity, opening possibilities for applications in advanced robotic grippers, adaptive medical tools, and more.

## 2. Design and Fabrication

The proposed soft joint features a multi-chamber design that allows for up to 209 degree bending. The integration of an internal support structure enhances the joint's stiffness while maintaining flexibility.

### *2.1. Structural Design*

The pneumatic soft actuator was designed using SolidWorks 2023 software. The process began by creating a 3D model of the actuator's overall structure, focusing on the arrangement of the chambers to ensure desired expansion under pneumatic pressure.

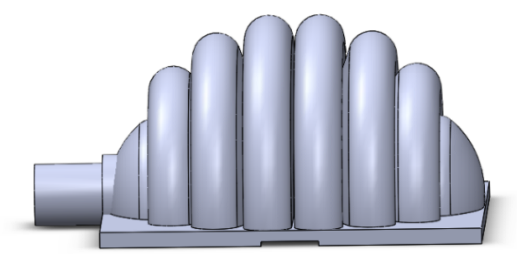

**Figure 1** The side view of the soft actuator designed in SolidWorks

The chambers were modeled with semi-cylindrical geometries, featuring internal cavities and reinforcement ribs to control the direction of deformation. The design made by considering that

the chamber walls would be thin enough for flexibility but strong enough to maintain structural integrity. The base was designed with more thickness and less flexibility, providing stability and housing for the pneumatic inlet.
To ensure that the model exhibits bending along a single axis, the chambers were designed with a radial configuration relative to that axis. As the volume within the chambers increases, they expand outward; this design permits expansion along the outer periphery, resulting in a circular bending motion at the axis. The curvature of the chambers facilitates further expansion due to the additional surface area provided by the curled structure, in comparison to a flat surface as shown in Figure 1.

### *2.2. Production Process*

The soft actuator was fabricated using 3D printing technology with TPU 87A material. The actuator's design was created using SolidWorks software. The 3D printing process was performed on an Ultimaker 3 3D printer (Ultimaker BV, Netherlands). To achieve optimal material properties, the printing parameters were carefully selected based on the manufacturer's recommendations and validated through experimental trials. This selection process was informed by a comprehensive review of relevant literature and practical testing, ensuring enhanced performance and reliability of the actuator for its intended applications as shown in Table 1.

**Table 1** Main 3D Printing Parameters

| **Main 3D Printing Parameters** | |
|---|---|
| Material | TPU 87A |
| 3D Printer | Ultimaker 3 |
| Layer height | 0.15 mm |
| Nozzle diameter | 0.4 mm |
| Infill density | 100% |
| Support | Only touching build plate |
| Extrusion temperature | 240 °C |
| Print speed | 20 mm/s |
| Material flow | 105% |

## 3. Finite Element Analysis

The designed model in Solidworks was exported to Ansys 2023 R2 software. A finite element model was developed to simulate the bending behavior of the soft actuator under various pressure loading conditions. The model incorporates boundary conditions that reflect real-world applications, allowing for accurate predictions of stress distribution and deformation patterns.

### *3.1. Material testing*

The mechanical properties of TPU 87A were characterized to ensure accurate modeling and simulation of the soft actuator's behavior under stress. To investigate the mechanical behavior of the TPU 87A material, a tensile stress-strain test was conducted in accordance with the ISO 37 standard using Multitest 2.5 (Mecmesin ,United Kingdom). The testing procedure involved preparing samples of TPU and subjecting them to uniaxial tension until failure, allowing for the measurement of key mechanical properties (Figure 2).


**Figure 2** tensile stress-strain test of TPU

The results of the test are shown in Figure 3.

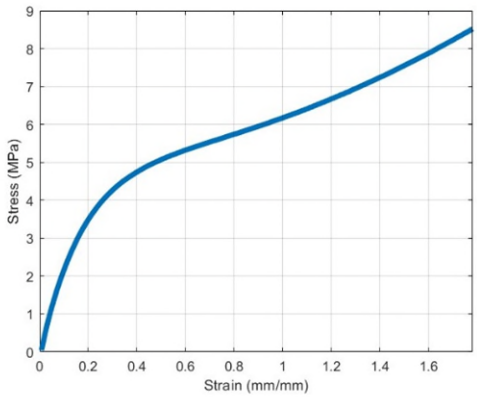


**Figure 3** Main Experimental stress-strain data of the TPU used to 3D print the soft pneumatic actuator.

### *3.2 Modeling of material behavior using Mooney Rivlin 5 parameters model*

The tensile stress-strain test conducted on TPU 87A revealed a nonlinear stress-strain relationship characteristic of hyperelastic materials (Figure 3). The Mooney-Rivlin 5 parameter model was selected because it effectively captures the complex stress-strain behavior of rubber-like materials, such as TPU, under large deformations. This model was chosen over simpler models like Neo-Hookean and Yeoh because it provided a better fit to our experimental data. The experimental stress-strain data were imported into the material model to determine the material constants C_10,C_01,C_20,C_11,C_02 that define the specific behavior of TPU 87A (Table 2).
The process of fitting the model involved optimizing these parameters to match the experimental stress-strain curve closely. This was achieved by using the uniaxial test data to define the hyperelastic material behavior in our simulations.The Mooney-Rivlin model can be expressed through a strain energy density function that relates the material's elastic response to its deformation(Equation 1). The five-parameter Mooney-Rivlin model is represented as follows:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{20}(I_1 - 3)^2 + C_{11}(I_1 - 3)(I_2 - 3) + C_{02}(I_2 - 3)^2 \quad (1)$$

Where ,$W$ is the strain energy density. $I_1$, First invariant of the deformation tensor, $I_2$, Second invariant of the deformation tensor and $C_{10}, C_{01}, C_{20}, C_{11}, C_{02}$ are the material constants that characterize the specific material behavior.

This formulation allows for a more accurate representation of the nonlinear elastic behavior of hyperelastic materials compared to the simpler two-parameter version, which only includes $C_{10}$ and $C_{01}$ [14].

Average experimental stress-strain data of the TPU were imported and used in a manually defined material (i.e., TPU) in the Engineering Data. The data were imported as Uniaxial Test Data for the Hyperelastic Experimental Data. The TPU was modeled using a five-parameter Mooney–Rivlin hyper-elastic material model that fitted its average stress-strain data. The parameters of the material model are listed in Table 2.

**Table 2** TPU hyper-elastic material model constants

| Hyper-Elastic Material Model | Material Constant | Value(Unit) |
|---|---|---|
| Five-parameter Mooney-Rivlin | $C_{10}$ | -3.339(MPa) |
| | $C_{01}$ | 8.028(MPa) |
| | $C_{20}$ | -2.159 (MPa) |
| | $C_{11}$ | 1.189 (MPa) |
| | $C_{02}$ | -0.581 (MPa) |
| | Incompressibility Parameter $D_1$ | 0.000 $MPa^{-1}$ |

### 3.3 Modeling in FEM Software

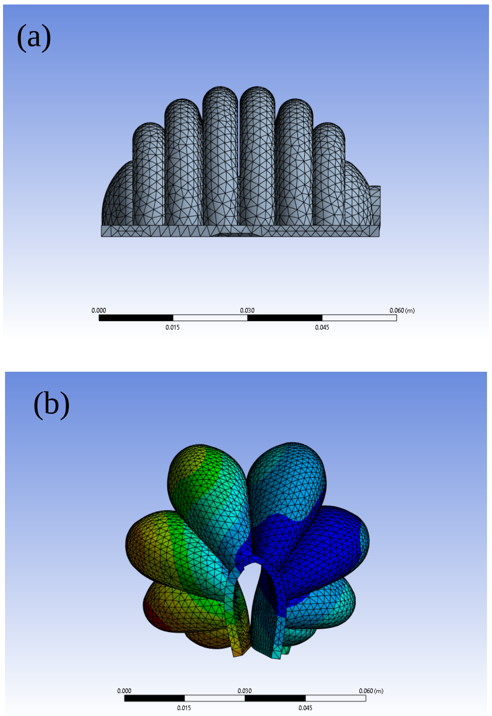


**Figure 4** a) Finite element simulations of the pneumatic soft actuator, b) The simulated deformation results of soft actuator

The FEM simulations were performed in ANSYS Workbench 2023 R2 (ANSYS Inc.) using a Static Structural Analysis. The 3D Solidworks model of the soft actuator (i.e., geometries) was directly imported to ANSYS Design Modeler. ANSYS was used to perform the FEM simulations of the soft actuator since it offers various hyper-elastic materials models and it is ideal for performing static structural simulations using hyper-elastic materials[14].

The model of the soft actuator was meshed using an adaptive technique with higher-order tetrahedral elements. A sizing function with a specified element size of 0.2 mm was applied to achieve an optimal mesh configuration for the complex geometry. Figure 4 presents a schematic of the finite element simulations conducted for the pneumatic soft actuator, illustrating the analysis framework employed in this study.

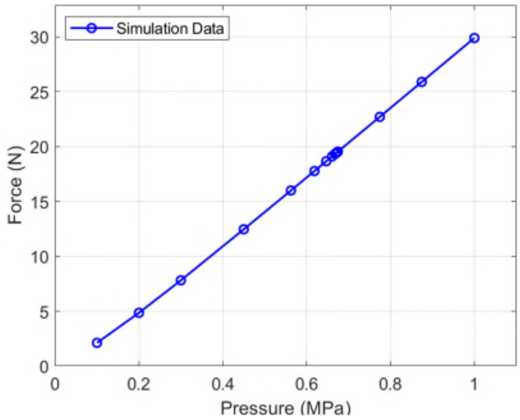


Figure 5: FEM results showing the blocked force generated by the pneumatic soft actuator under varying pressure levels

Figure 5 illustrates the relationship between applied pressure (MPa) and the resulting blocked force (N) in a pneumatic soft actuator, based on simulation data. The data follows a linear trend, indicating that force generation is directly proportional to the applied pressure. This suggests that the actuator's force output can be accurately predicted within the given range, making it suitable for controlled applications.

### 4. Experimental Analysis

The performance of the soft joint was evaluated through experimental tests designed to measure bending angles at various internal pressures.

Figure 6 depicts the control and monitoring system for the pneumatic soft actuator. An Arduino microcontroller(Uno REV3, Italy) interfaces with essential components, including a pressure gauge and gas inlet. A power supply (RD6012-C, Germany) delivers power to a proportional pressure control valve (VPPI-5L-3-G18-0L6H-A4-S1D, Switzerland), which regulates airflow from the chamber and measures pressure. The system is further integrated with a laptop for real-time data acquisition and control using Arduino IDE software.

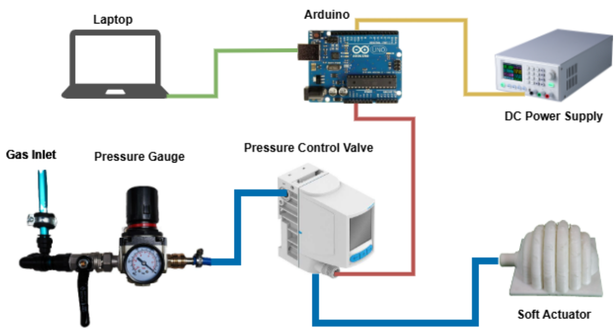


**Figure 6** A schematic of the air control system for bending measurement

The results were compared with numerical simulations to validate the design and modeling approach. Figure 6 illustrates the actuator operating without additional pressure, with all tests conducted at a temperature of 20°C.

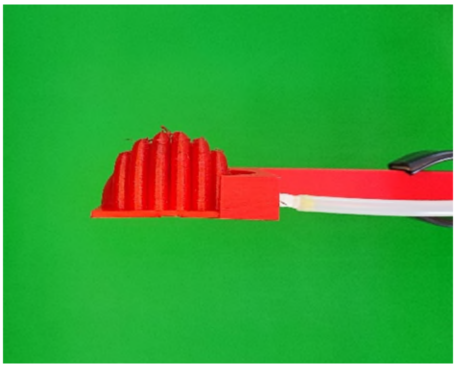

**Figure 7** The soft actuator without extra pressure

To process the testing, gas pressure was increased gradually using the control valve and at every step, the pressure and the angle were recorded. At the pressure of 0.1578 Mpa, the actuator reached its final bending angle as the two sides collapsed each other and the bending angle at this stage was 209 degrees as illustrated in Figure 8.

**Figure 8** The soft actuator under 0.1578 MPa pressure

## 5. Results

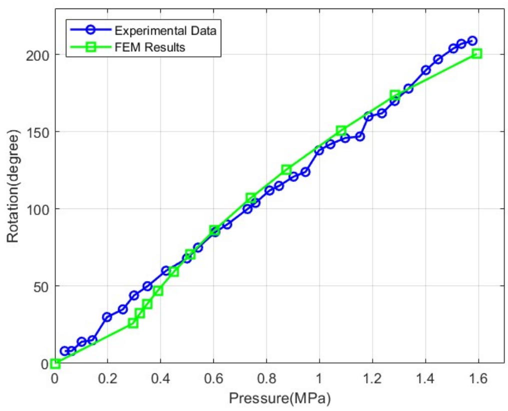


**Figure 9** Comparative Analysis of Soft Actuator Performance

The actuator was tested under varying pressure levels ranging from 0 to 0.16 MPa. At a pressure of 0.1578 MPa, it achieved a maximum rotation of 209 degrees. Figure 8 presents the results from both experimental testing and numerical simulations, which show a notable correlation. The experimental data reveals a relatively linear relationship between pressure and angular deformation, suggesting that the actuator's material and structural design exhibit elastic behavior, with deformation proportional to the applied pressure. However, the FEM simulation results indicate room for improvement, which will be a focus of future research in this area.

## 5. Conclusions

This study presents a novel pneumatic soft actuator with a multichamber fan-like configuration, utilizing TPU material to achieve significant advancements in bending capability. The actuator demonstrates a remarkable maximum bending angle of 209 degrees, showcasing its enhanced flexibility and adaptability for a wide range of applications. The innovative design of the actuator leads to bending from a single axis and providing rotary movement. The single-axis bending mechanism contributes to improved precision in control, allowing for more accurate movements compared to traditional actuators.

Future work will focus on further optimizing the actuator's performance and expanding its capabilities. This includes Refining material selection, with particular emphasis on exploring the properties of TPU and investigating additional configurations to enhance the capabilities of soft rotary actuators in robotic systems.

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