FABRICATE A SOFT ROBOTIC ACTUATOR USING FDM 3D PRINTING

NGHIÊN CỨU CHẾ TẠO TAY GẮP MỀM BẰNG PHƯƠNG PHÁP IN 3D FDM

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ABSTRACT

This work presents a novel solution for directly 3D printing soft actuators using 3D printers based on fused deposition modeling (FDM) technology. Traditionally, soft actuators are fabricated through molding and forming due to the simplicity of the process and the affordability of the materials. However, the drawbacks of this method include low productivity, a higher likelihood of common errors, and limitations in fabricating soft actuators with complex and sophisticated inner structures. To address these issues, 3D printing offers a highly accessible approach to meet the requirements, utilizing low-cost 3D printers and inexpensive soft materials. In this paper, we design a soft actuator made of a soft material, optimize the printing settings for FDM 3D printers, and examine the application of the soft actuator.

Keywords: *Soft actuator; 3D printing; Soft material; TPU.*

TÓM TẮT

Nghiên cứu này giới thiệu một giải pháp mới để in 3D trực tiếp các tay gắp mềm bằng cách sử dụng các máy in 3D dựa trên công nghệ đùn vật liệu trực tiếp (FDM). Thông thường, các tay gắp mềm được chế tạo thông qua khuôn đúc và tạo hình dựa trên sự đơn giản của quá trình và giá thành vật liệu. Tuy nhiên, nhược điểm của phương pháp này bao gồm năng suất thấp, nguy cơ xảy ra các lỗi thường gặp cao hơn, và hạn chế trong việc chế tạo các tay gắp mềm có cấu trúc bên trong phức tạp và tinh vi. Để khắc phục các vấn đề này, công nghệ in 3D cung cấp một cách tiếp cận khả thi để đáp ứng các yêu cầu được đưa ra từ người tiêu dùng chỉ bằng việc sử dụng máy in 3D chi phí thấp và vật liệu mềm giá rẻ. Trong bài báo này, chúng tôi thiết kế một tay gắp mềm làm từ vật liệu mềm, tối ưu hóa các thiết lập in cho máy in 3D FDM, và nghiên cứu ứng dụng của tay gắp mềm này.

Từ khóa: *Tay gắp mềm; In 3D; Vật liệu mềm; Nhựa TPU.*

1. INTRODUCTION

Soft robotics is a subfield of robotics whereby the robots are made of soft and compliant components. Recently, soft robots have received high attention for the variety of medical, industrial, agricultural applications [1]. There are many production lines that soft actuators are integrated to optimize and increase the productivity such as food and beverage industry, pharmaceutical industry, electronics industry,... They offer several unique benefits, from executing complex ☞

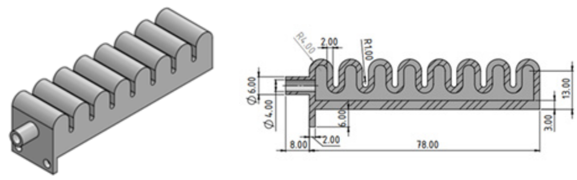
and delicate actions to facilitating processes with specific standards and operating effectively in harsh environments.

Nowadays, the traditional way for fabricating a soft actuator is casting and forming [4]. Despite the fact that it is widely used in mass production, there are many drawbacks of molding that lead to the actuators' limitation of applications. One disadvantage stands out is the number of processes needs to be conduct to fabricate a single actuator, which leads to significant time-consuming, inaccuracy, inefficiency and inability to manufacture soft actuators in a streamlined manner. Other disadvantages are common errors that occur in the molding and forming processes.To address the drawbacks of the traditional manufacturing process, this article makes the following contributions: determines the 3D-printing parameters to fabricate the soft actuator by FDM, fabricates the soft actuator with thermoplastic elastomer, simulates the bending behaviors of the soft actuator, examine the ability of the printing soft actuator in an automative production line.

2. DESIGN AND FABRICATION

2.1. Design the soft actuator

We can categorize soft gripping in three technologies: by actuation, by controlled stiffness, and by controlled adhesion [5]. To design a soft actuator, it is crucial to choose a technology or a combination of two technologies as a guideline for the inner structure design. In this research, the technology must be beneficial for fabrication, assembly under current working conditions and the mechanical properties is optimized based on the chosen material. In this paper, the Soft Pneumatic Actuators (SPAs), which was driven by applying pressure to the inner walls of cavities and had many cavities connected by channels, was chosen. By changing the applied pressure, the soft actuator can perform contracting [6], rotary [7], and bending [8] motions upon pressurization. Figure (1) shows the general shape of the soft actuator.



(a) (b)

Figure 1. A pneumatic soft actuator: (a) General shape; (b) Geometrical parameters

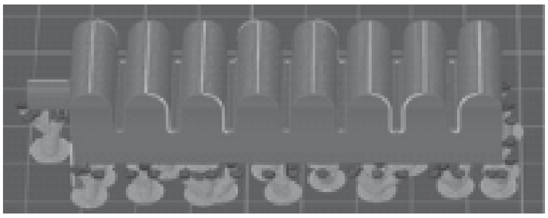
2.2. Fabricate the soft actuator

The material used for printing was eSUN eTPU-95A whose mechanical properties are shown in Table 1. The 3D printing machine was a Bambu Lab A1, and the slicer used was Bambu Studio. The printing environment needed to be ventilated without significant airflow to maintain proper heat at the nozzle and ensure the stability of the material flow.

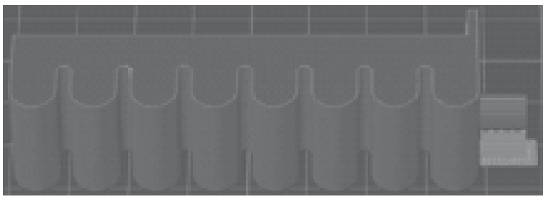
Table 1. eSUN eTPU-95A properties

eSUN eTPU-95A	
	Typical value
Physical Properties	
Density	1.21 g/cm^3
Melt Flow Index	1.2 (190°C/2.16kg)
Mechanical Properties	
Tensile Strength	35 MPa
Elongation at Break	≥800%

The printing orientation was optimized to reduce support structures and overhang. The actuator was printed sideways [9] as there were a few advantages over printing bellows pointing upwards. The printing orientations of the soft actuator were shown in Figure 2.



(a)



(b)

Figure 2. Printing orientation: (a) Bellow pointing upward; (b) Sideway

According to the properties of the eSUN eTPU-95A, the printer settings were optimized after printing a number of TPU specimens and evaluating the quality and the quantity of the successfully printed parts. The final printer settings were illustrated in Table 2.

Table 2. Printer settings for eSUN eTPU-95A

Parameter	**Setting**
Quality	
Layer height	0.12 mm
Initial layer height	0.2 mm
Line width	
Default	0.42 mm
Initial layer	0.5 mm
Inner wall	0.45 mm
Sparse infill	0.45 mm
Strength	
Walls	
Wall loops	4
Top/Bottom shell layers	11
Sparse infill	
Sparse infill density	100%
Sparse infill pattern	Rectilinear
Speed	
Initial layer	30 mm/s
Initial layer infill	40 mm/s
Outer/Inner wall	40 mm/s
Sparse infill	40 mm/s
Support	
Type	Tree
Style	Default
Parameter	Setting

After printing, no post-processing was required and a pneumatic tube was inserted directly to the hole and by using AB glue, the tube was connected tightly to the actuator. The final printed model was shown in Figure 3.

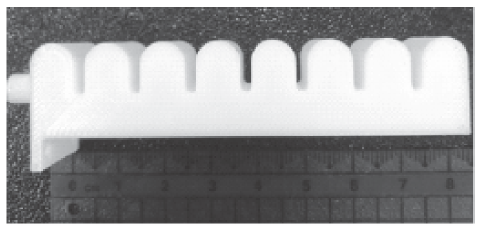
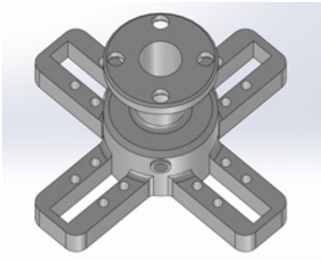


Figure 3. The printed soft actuator

When designing the fixture for the soft actuator, a cavity was integrated to optimize its internal structure and functionality. Additionally, there were tubes directly inserted into the fixtures to route air from the fixture to actuators. Moreover, to adjust the working zone of the actuator, the process was simplified by fastening the bolts at the predefined positions. This fixture was cost-effective, highly flexible, and easy to operate, which helped reduce manufacturing cost and increase the versatility. The model of the soft actuator was shown in Figure 4. ☞



(a)

(b)

Figure 4. The soft actuator fixture: (a) The designed model; (b) The fabricated fixture

2.3. Modeling the soft actuator

In this work, the finite element method is used as a mathematical tool employed to test and simulate soft grippers behaviors before the fabrication process. The software is ABAQUS/CAE (Simulia, Dassault Systems). The pressure was directly applied to all the internal walls of the internal cavities of the soft actuator as an external load with maximum applied pressure as 0.7 MPa. ENCASTRE boundary condition was applied to the fixed end of the actuator. In meshing process, all the components of the actuator were modelled by using solid 10-node quadratic tetrahedron hybrid elements (Abaqus element type C3D10H) [10]. The bending behaviors of the soft actuator under air pressurization obtained with the FEM models and at the real test are illustrated in Figure 5.

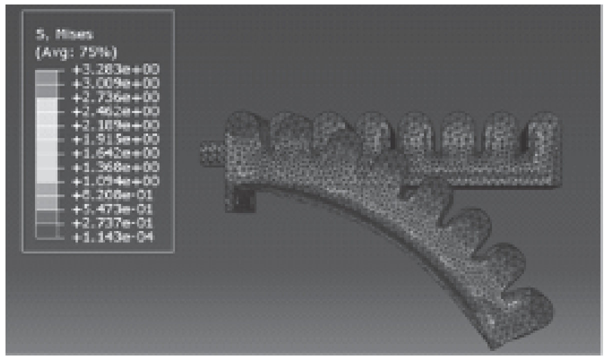


Figure 5. FE-simulated bending behavior of the soft actuator

3. RESULTS AND ANALYSIS

3.1. Bending experiment

The characteristic of the printed soft actuator was to bend when pressure was applied to the inner walls. The experiment model (Figure 6) was designed with the same elements as the simulation. Previously, the simulation was conducted on Abaqus/CAE, with the cavities in the actuator being subjected to a pressure range from 0.1 MPa to 0.7 MPa. 0.7 MPa wass the maximum pressure applied to the printed model by the pump. The relationship between the applied pressure and the bending angle is presented in Figure 7.

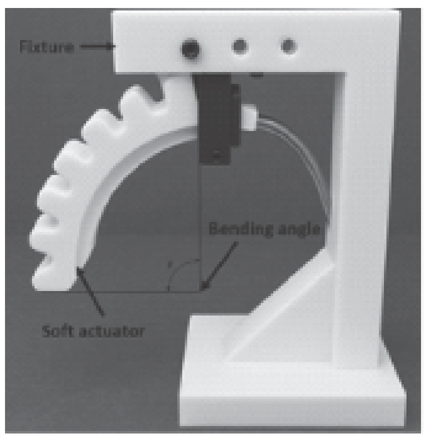


Figure 6. Bending behaviours of the soft actuator at 0.7MPa

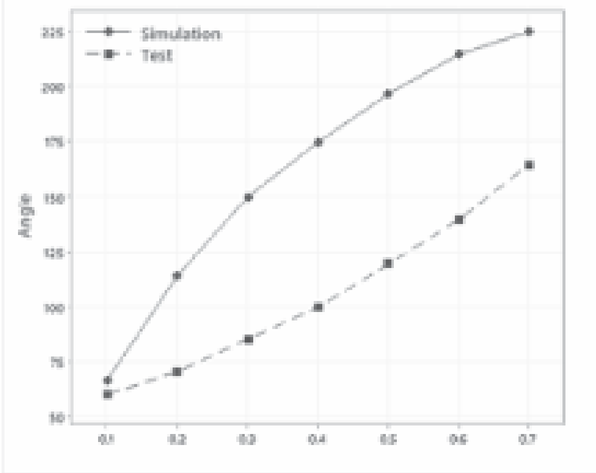


Figure 7. Bending angle and the applied pressure relationship of experimental and FE-simulated

Overall, the differences between the simulation and the experiment exceeded 5% across all pressure values. Firstly, the lowest experimental bending angle of the soft actuator was 60.52°, which was lower than the simulated angle of 66.76°. Secondly, at the maximum pressure of 0.7 MPa, the simulation angle was 224.86° and the experimental angle was 164.63°. The difference was attributed to the quality of the printed soft actuator, as the drawback of 3D printing was the occurrence of leakage between printing layers.

3.2. Grasping experiment

To examine the working ability of the soft actuator, a test was designed for the soft gripper to grasp and hold objects while moving. The soft actuator was fixed to a robotic arm that was programmed to perform a combination of movements. The simulation could verify whether the soft actuator was capable of performing the grasping motion timely and adapting the requirements of the production line.

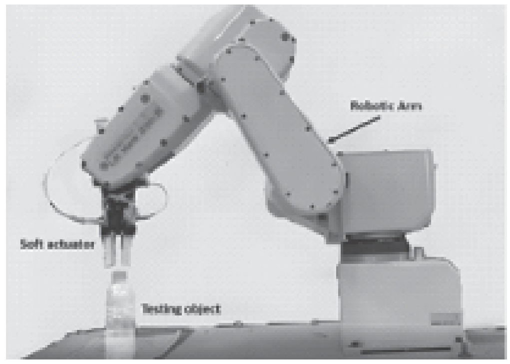


Figure 8. The soft actuator connected to the robotic arm

The objects were categorized into 4 types: convex, non-convex, flat and deformable. In this research, it is crucial to observe whether the gripped objects were lifted and retained the original shape under the gripping force exerted by the soft actuator. The gripping of the soft actuator on the testing object relied on the force applied to the contact surface or the complete placement of the object within the soft actuator's working zone. Considering the object's deformation, a successful gripping test required the object to be lifted without any distortion, as the advantage of the soft actuator lies in its ability to perform delicate actions with fragile objects. The gripping test is shown in Figure 9.

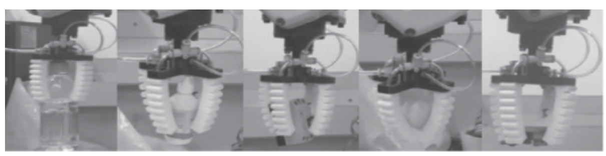


Figure 9. The gripping test with different objects

The experiment results showed that the soft actuator was highly advantageous to convex and non-convex objects. Objects with smooth surfaces were challenging to grip securely from the starting position. Additionally, a piece of clay was chosen as the deformable object. The outcome was similar to that of convex and non-convex objects, but due to the deformation of it, the test was deemed a failure. On the other hand, the flat objects in this research were an acrylic sheet and a paper and the soft actuator failed to grip both objects.

Additionally, to assess the maximum payload at the maximum applied pressure at 0.7MPa, a 350ml bottle of water was used as the testing specimen. By adding more water, the weight was increased from 50g to 350g. The experiment showed the maximum payload was approximately 330g with the testing object was convex. The result of the experiment was presented in Table 3.

Table 3. Experimental weight and result

Weight (g)	30	50	100	150	200	250	300	330	350
Result	Success								Fail

4. CONCLUSION AND FUTURE WORK

In this paper, a method for fabricating soft grippers using 3D printing is presented. The 3D printing parameters are determined experimentally by producing printed samples with different parameter settings. After the experiments, a set of parameters is proposed that can be applied to the fabrication of similar soft grippers using the same TPU material. To verify the mechanical properties of the 3D-printed soft gripper, finite element analysis is conducted using Abaqus/CAE. Subsequently, bending tests of the soft gripper are performed under different force values and compared with a hyperelastic model to evaluate the quality of the printed product. To assess the applicability of the soft gripper in a production line, tests are carried out to evaluate its ability to grip objects of various shapes and weights.

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