

Origami Actuator with Tunable Limiting Layer for Reconfigurable Soft Robotic Grasping

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Abstract— This paper presents a soft actuator inspired by origami and a tunable strain limiting layer, which is proposed for reconfigurable soft robotic grasping. Main structure of the actuator is based on Miura origami which generates extension under pressurized air while a limiting layer with tunable length enables the actuator with different motion patterns. By driving the limiting layer through a servo motor, the range of motion and trajectory of the actuator can be pre-programmed and the gripper's grasping range will be affected accordingly. This paper discusses the design, fabrication, analysis and experimental verification of the actuator. Then grasping performance of the gripper under objects of different shapes, sizes, and weights is experimentally evaluated. The reconfigurable soft gripper can be applied as an end-effector to accomplish adaptive grasping tasks with various targets.

I. INTRODUCTION

Benefited from their inherent compliance, soft robots show some advantages in terms of safety and adaptability over traditional rigid-bodied robots, enabling better human-robot interaction. They are usually made of flexible materials [1] and there are different actuation principles for soft robots including fluid-driven mechanism [2-4], smart materials [5-6], magnetic propulsion [7-8], and so on. Soft robots can change shape and size to adapt to diverse work environments and task requirements [9-10]. These characteristics make soft robots particularly useful in unstructured environments such as disaster rescue [11], medical assistance [12-13], and daily object grasping [14-15] and thus attracts the attention of many scholars.

In the design of soft robots, there is a high demand for flexibility, adaptability, and lightweight. Origami structures, with their unique geometric transformation capabilities, provides an alternative for soft actuator design. By mimicking the morphology of organisms in nature, such as the wings of insects and the fins of fish, origami structures can achieve complex movements and deformations while maintaining structural strength. Not only does it provide the elasticity akin

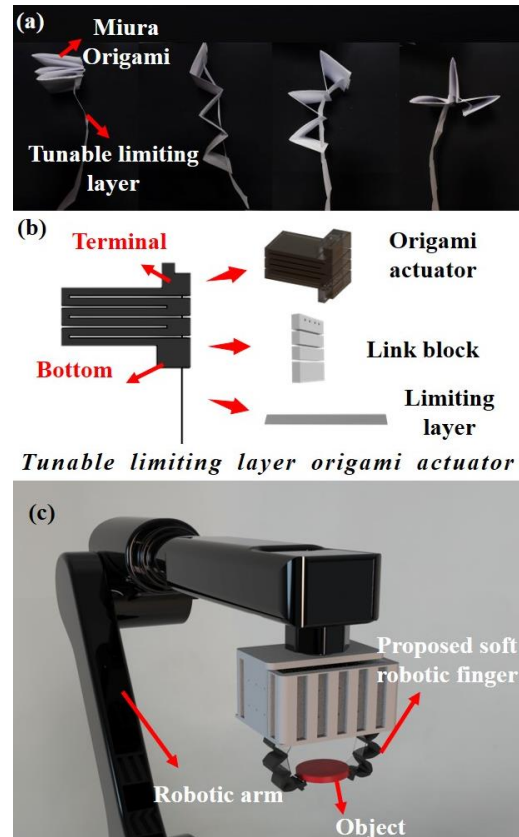


Fig. 1. Proposed actuator design. (a) Origami inspiration. (b) Components of the tunable limiting layer origami actuator. (c) Potential application scenarios: Soft robotic gripper based on this designed applied as end-effector in a robotic arm.

to biological muscles, but it also allows for a wide range of motion in a limited space. Origami-inspired structures have a wide range of applications in the field of soft robotics. For example, For example, Woongbae Kim et al. developed a Dual-mode morphing origami based on the principle of

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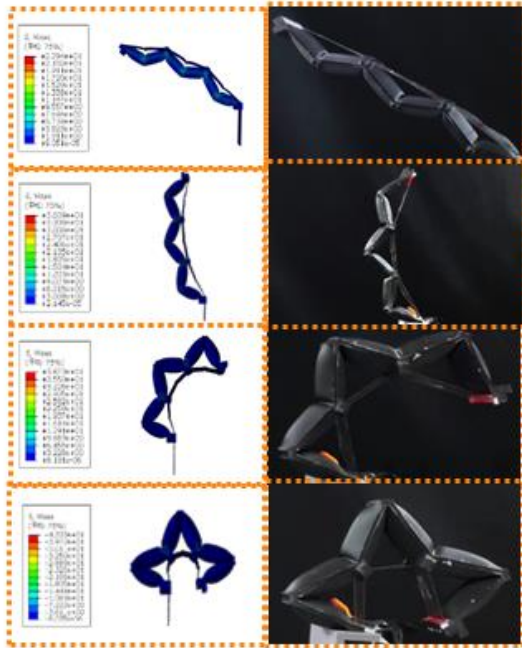
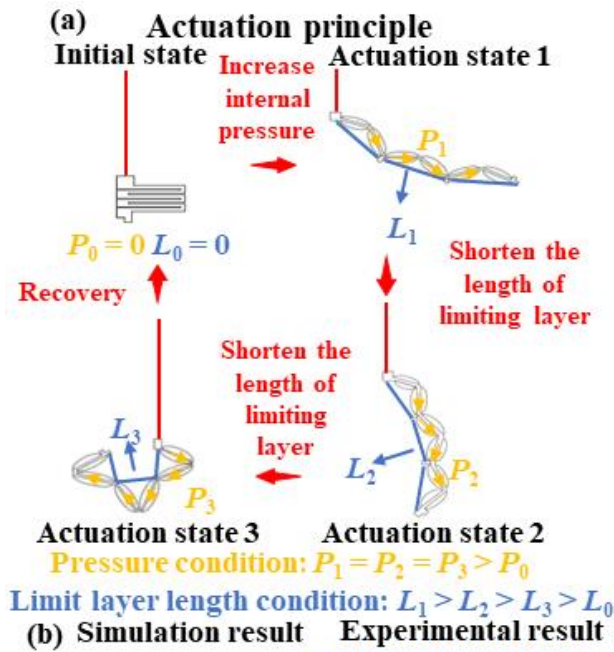


Fig.2. Working principle of the proposed actuator. (a) Role of the tunable limiting layer for the actuator's deformation. (b) Finite element analysis and actual experimental result comparison.

swallowing eel's mouth morphing, and used this structure to make bionic swallowing eels, crawling soft robots, and universal grippers respectively [16]. Li et al. proposed a soft gripper using an origami "magic ball" structure and vacuum actuation to adaptively grasp various shapes of objects through vacuum pressure [17]. Wang et al. proposed a soft robotic gripper with tunable limiting layer length, which is uniquely superior in gripping irregular objects [18]. Haewon Jeong et al. developed an adaptive detachable pneumatic soft actuator utilizing an origami structure, which is adaptive to fit the human body and actively rotate human joints [19]. The authors have also investigated origami-inspired soft robot design such

as soft origami pump [20], amphibious robot [21] and self-sensing twist actuator [22] in previous research.

In this paper, an origami actuator based on Miura origami with a tunable limiting layer is proposed. We use a 3D-printed pneumatically actuated origami structure as an actuator, while thermoplastic polyurethane elastomer (TPU) material is used as the limiting layer. By driving the limiting layer through the servo, the length of the limiting layer can be pre-adjusted according to the size of the grasped object, while the trajectory and range of motion of the actuator can be preset. For different objects, the soft gripper can be reconfigured by tuning the limiting layer length before grasping based on the object's dimension and geometry, in order to achieve desired movement to accomplish the grasping task. The dexterity and adaptability of the gripper are verified by grasping objects of different sizes, shapes, and weights in experimental section. Contributions of this research include:

- 1) A novel soft actuator based on stretchable origami and tunable limiting layer with large range of motion and adjustable trajectory is proposed;
- 2) Finite element simulation and theoretical analysis of the proposed actuator is performed;
- 3) A soft robotic gripper is constructed and its grasping capability through reconfiguration is experimentally verified.

II. DESIGN, FABRICATION AND MODELING

The grasping capability of a robotic gripper is mainly constrained by the design of its individual actuators. Therefore, design, modeling and analysis of individual actuator units are crucial. These factors collectively determine the adaptability, stability and efficiency of the gripper in practical operations, and have a decisive influence on the overall performance of the soft robotic gripper.

A. Design and Fabrication

As shown in Fig. 1(a), Miura origami promotes the rapid folding of paper into multiple origami units. On the basis of the origami paper, we add a tunable limiting layer. By adjusting the length of the layer, the motion state of the Miura origami can be effectively changed.

Inspired by this origami, a tunable limiting layer origami actuator is designed in this paper. As shown in Fig. 1(b), the tunable limiting layer origami actuator mainly consists of an origami actuator, some connecting blocks, and a limiting layer. The bottom surface features a circle hole for inserting a silicone hose. The origami actuator has four grooves reserved for the installation of connecting blocks. Every connecting block has a channel in the middle, and the size is slightly larger than the size of the limiting layer, so as to allow the limiting layer to pass through. There are four circular holes at the end of the origami actuator and on the connecting block, and the limiting layer, the connecting block, and the origami actuator can be fixed together by screws. As shown in Fig. 1(c), the proposed gripper can be placed at the end of a robotic arm to grasp objects.

The tunable limiting layer origami actuator and connecting blocks are made by 3D printing. The origami actuator is mainly made by thermoplastic elastomer (TPE) material. Connecting blocks are made from polylactic acid (PLA),

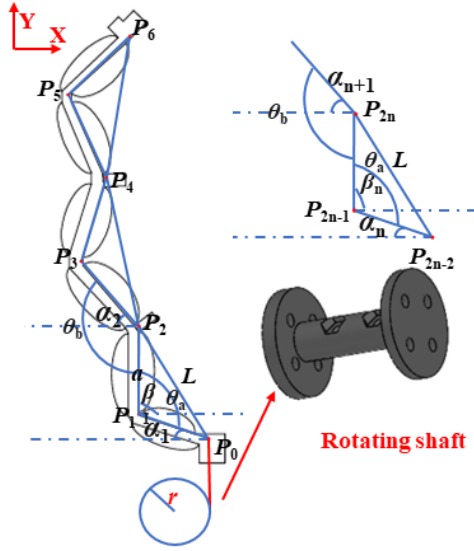


Fig. 3. Kinematic model of the proposed actuator.

which can effectively reduce the friction between the limiting layer and the actuator. The limiting layer needs to have good flexibility and extensibility, and the thermoplastic polyurethane elastomer (TPU) material has been chosen for this purpose.

B. Working Principle and Finite Element Analysis

As shown in Fig. 2(a), the tunable limiting layer origami actuator mainly comprises four operational states. When the pressure $P_0 = 0$ kPa, and the effective limiting layer is in the most contracted state, the origami actuator is in the initial state; when the length of the limiting layer is in its natural state, and the input pressure is P_1 , the origami actuator is in the maximum expanded state; when a part of the length of the limiting layer and the input pressure is P_2 , the origami actuator is in the contracted state; when the entire limiting layer is contracted and the input pressure is P_3 , the origami actuator is in the maximum bending state. In this case, the lengths of the limiting layer follow the order $L_1 > L_2 > L_3$, and the air pressures satisfy $P_1 = P_2 = P_3 > P_0$. Therefore, the tunable limiting layer origami actuator can achieve a wide range of motions, and the motion range can be adjusted through the limiting layer.

In order to gain a better understanding of the morphological structure and comprehend its changing patterns, as shown in Fig. 2(b), we conducted finite element analysis using Abaqus (a finite element analysis software) to simulate the motion of the origami actuator, compared with real-world observations. Initially, a pressure of 100 kPa was applied to the origami actuator without controlling the length of the limiting layer. Then, the length of the limiting layer was gradually shortened and input 100kPa pressure. Finally, we compared the experimental results with the simulation model. As shown in Fig. 2(b), the shorter the limiting layer, the greater the inward bending angle. Throughout this process, the movement trend of the origami actuator is consistent with the experimental results.

C. Theoretical Model

In order to further explore the theoretical model of the tunable limiting layer origami actuator, we carried out its

theoretical derivation and analyzed the relationship between the length of the rotary axis and the end trajectory of the origami actuator.

Firstly, the theoretical model of the origami actuator is simplified in order to facilitate the derivation of equations. As shown in Fig. (3), each vertex is set as a P point, and the P_0 point is set as the origin so that its coordinates are $[0,0]$. The angle between each layer of origami structure is set as θ_a , the angle between the bottom edge length and the horizontal direction is set as α_n , the angle between the top edge and the horizontal direction is set as β_n , the angle between two groups of origami actuators is set as θ_b , the edge length is set as a , and the length of the limiting layer between each group of origami is set as L . The coordinates of the point P_6 are obtained by vector recursion.

$$P_{2k-1} = P_{2k-2} + \begin{bmatrix} a \cos \alpha_k \\ a \sin \alpha_k \end{bmatrix} \quad (1a)$$

$$P_{2k} = P_{2k-1} + \begin{bmatrix} a \cos \beta_k \\ a \sin \beta_k \end{bmatrix} \quad (1b)$$

where k is from 1 to 3.

Where a is related to L as follows:

$$a = \frac{L}{2 \sin \theta_a} \quad (2)$$

The radius of the rotary axis is r . For each revolution of the rotary axis, the length of the limiting layer shrinks by $2\pi r$. After n revolutions of the rotary axis, the trajectory of the end at this point is:

$$X_p = \frac{L-2n\pi r}{2 \sin \theta_a} (\cos \alpha_1 + \cos \alpha_2 + \cos \alpha_3 + \cos \beta_1 + \cos \beta_2 + \cos \beta_3) \quad (3)$$

$$Y_p = \frac{L-2n\pi r}{2 \sin \theta_a} (\sin \alpha_1 + \sin \alpha_2 + \sin \alpha_3 + \sin \beta_1 + \sin \beta_2 + \sin \beta_3) \quad (4)$$

III. EXPERIMENTS

A. Motion Trajectory Test

To study the motion trajectory of the end of the origami actuator, as shown in Fig. 4(a), we fixed the bottom end of the actuator and used it as the origin point, and the end point of the actuator was used as the moving point. With different lengths of the limiting layer (L) set at 5cm, 10cm, 15cm, 20cm, 25cm, and without the limiting layer, we used 100 kPa pressure to actuate the actuator. We captured the motion trajectory of the origami actuator and utilized Kinovea (Video analysis software) to analyze the motion trajectory of the actuator. As shown in Fig. 4(b)(i), initially, without the limiting layer, the motion trajectory could be divided into three stages: as the gas slowly filled in, the origami actuator began to expand and move upward; with increased air pressure, the end of the origami actuator gradually descended to the lowest point; finally, the end of the actuator slightly ascended and stabilized. After applying the limiting layer, it played a constraining role in the motion trajectory, resulting in a reduced range of motion for the origami actuator. Additionally, as the length of the limiting layer decreased, the constraining effect became more pronounced.

We set the bottom end of the origami actuator as the origin and considered the angle between the line connecting the

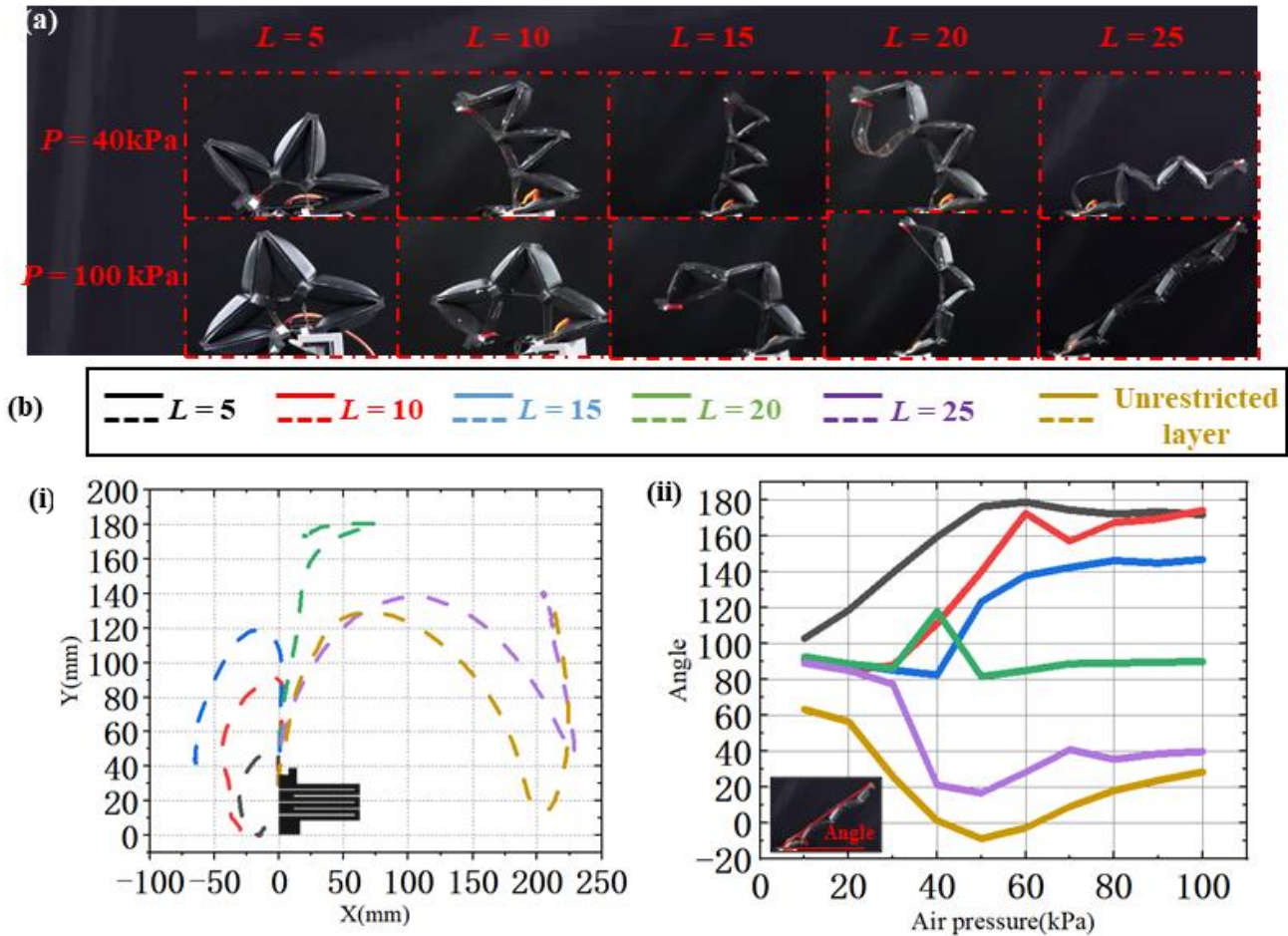


Fig. 4. Motion Trajectory Test. (a) The actuators' deformation with different limiting layer lengths under pressure of 40kpa and 100kpa. (b)(i) End motion trajectories under different lengths of limiting layer. (b)(ii) Bending angle under different pressures and different limiting layer lengths.

origin and the end point of the actuator with the horizontal axis as the motion angle of the actuator. By measuring the variation in angle motion under different pressures, we aimed to study the relationship between motion trajectory and air pressure. The experimental results, as shown in Fig. 4(b)(ii), show that when the pressure is less than 60 kPa, for both cases without the limiting layer and with a limiting layer length of 25cm, the angle motion decreases with increasing pressure. For limiting layer lengths below 15cm, the angle motion increases with rising pressure. When the pressure is more than 60 kPa, there is no significant change in angle motion with increasing pressure.

B. Drive Sequence Experiment

To study the influence of the driving sequence on the motion trajectory of the tunable limiting layer origami actuator, we conducted the following experimental steps. The bottom end of the actuator was fixed on the workbench and served as the origin of motion. To ensure that the length of each contraction of the limiting layer was consistent, we used a servo motor to drive the limiting layer. The servo motor rotated by the same angle each time, and with each rotation, the limiting layer contracted by 5cm. This procedure was repeated four times for each experimental group. The side of the origami actuator was marked with seven red dots for later

tracking and analysis of the motion trajectory of the actuator using Kinovea. We employed two different driving schemes. In the first scheme, we initially set the limiting layer to its natural state and then injected 100 kPa of pressure. After the actuator fully expanded and stabilized, we gradually adjusted the length of the limiting layer. In the second scheme, we first adjusted the length of the limiting layer and then injected 100 kPa of pressure until the actuator reached a stable state. The experimental results, as shown in Fig. 5, indicate that compared to the first scheme, the second scheme results in a greater bending angle of the origami actuator and a more evenly distributed length of the limiting layer. Therefore, we selected the second scheme as the driving scheme for the actuator.

C. Output Force Test

We conducted the experiment to study the mechanical performance of the tunable limiting layer origami actuator. As shown in Fig. 6(a), we fixed the bottom end of the actuator on the workbench and placed the end of the actuator on the dynamometer. We set the length of the limiting layer to 5cm, 10cm, and 15cm, and gradually increased the pressure from 10 kPa to 100 kPa, recording the force at intervals of 10 kPa. The experimental results, as shown in Fig. 6(b), indicate that when the length of the limiting layer is 5cm, the force at the end of

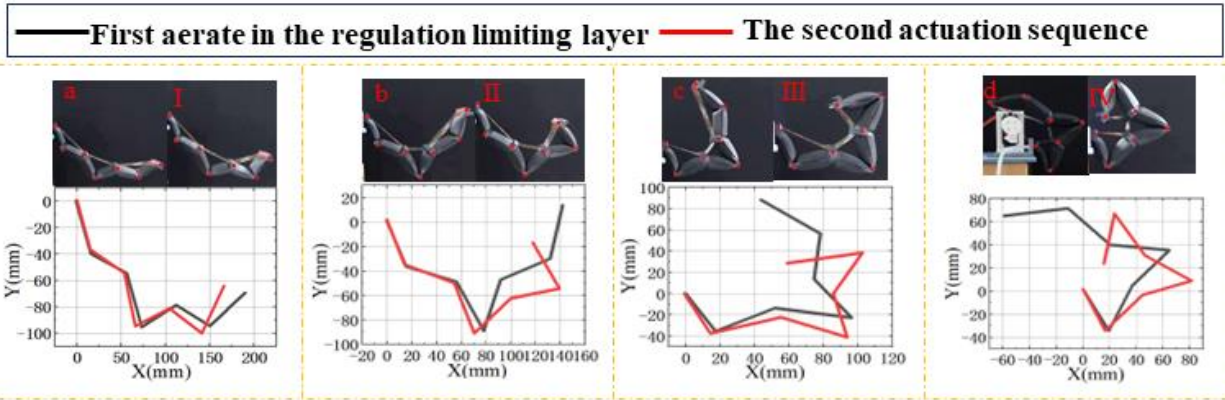


Fig. 5. Motion trajectory with different driving sequences.

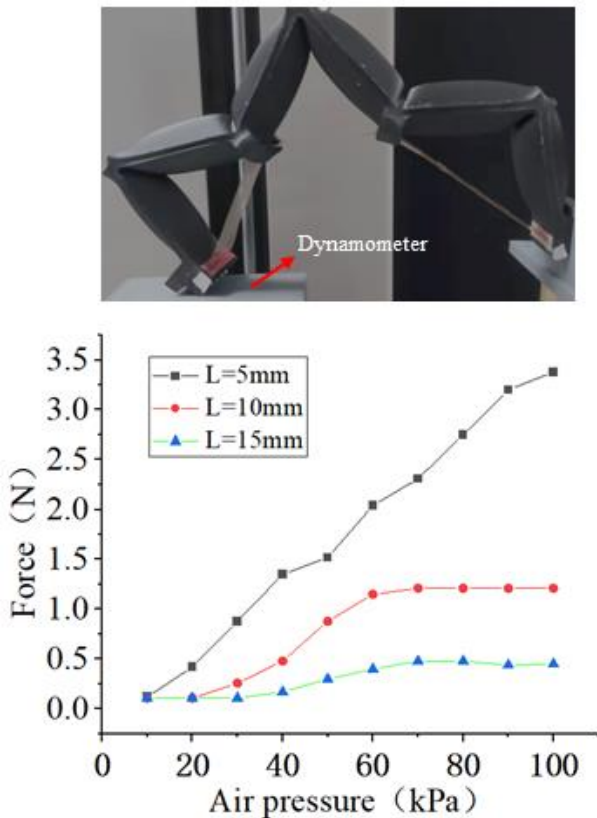


Fig. 6. Output force test. (a) Experiment set-up. (b) Test result.

the origami actuator gradually increases with increasing pressure, reaching 3.38 N when the pressure is 100 kPa. The trend of force increase slows down significantly as the length of the limiting layer increases. When the length of the limiting layer reaches 15cm, there is almost no significant trend in force change. Moreover, when the length of the limiting layer exceeds 15cm, the end of the actuator starts to move upward, making it difficult to apply an effective load.

IV. GRIPPER FABRICATION AND EXPERIMENT

A. Gripper Design

Based on the proposed tunable limiting layer origami actuator, we designed a robotic gripper as shown in Fig. 7(a).

The gripper mainly consists of two origami actuators, two servo motors, and a housing bracket. The limiting layers are connected to the rotation shafts via screws, and the length of the limiting layers can be adjusted according to requirements by controlling the rotation of the shafts driven by the servo motors. The origami actuators are connected to an air pump via soft hoses for actuation and release. Both actuators share a single gas channel to ensure simultaneous driving.

The grasping principle of the gripper is illustrated in Fig. 7(b). When the origami actuators are not driven, the gripper remains in its initial state. With the servo motors inactive and the limiting layers in their natural state, driving the actuators with 100kPa of pressure enables the gripper to reach its maximum grasping range. When the gripper needs to grasp an object, the servo motors can be driven to rotate and retract the length of the limiting layers according to the size of the object to be grasped, thereby pre-setting the gripper's motion.

B. Grasping Demonstration

As shown in Figure 7(c), to validate the performance of the gripper, we conducted a series of grasping experiments. The robotic gripper was fixed on a stepper motor, and there was a support stand directly beneath it for placing objects. During grasping, the gripper descended under motor control to grasp the object. Once the gripper grasped the object was completely lifted off the surface of the stand. If the gripper held onto the object without dropping it for 5 seconds, the grasp was considered successful. We used the gripper to grasp various small objects such as batteries, tapes, jelly shells, and strawberry. Additionally, the gripper was capable of grasping more regular objects like cylinders and spheres. For larger objects such as books and plastic cases, the gripper was able to complete the grasping task effectively by releasing the restraining layer before driving the actuators for grasping. By grasping objects of different sizes, shapes, and weights, the agility and adaptability of the gripper were verified.

V. CONCLUSION

In this study, inspired by Miura origami, we designed a tunable limiting layer origami actuator and applied it for soft robotic grasping. The tunable limiting layer origami actuator can generate a maximum output force of 3.38 N, and its adjustable range of motion reaches almost 180°. Based on this

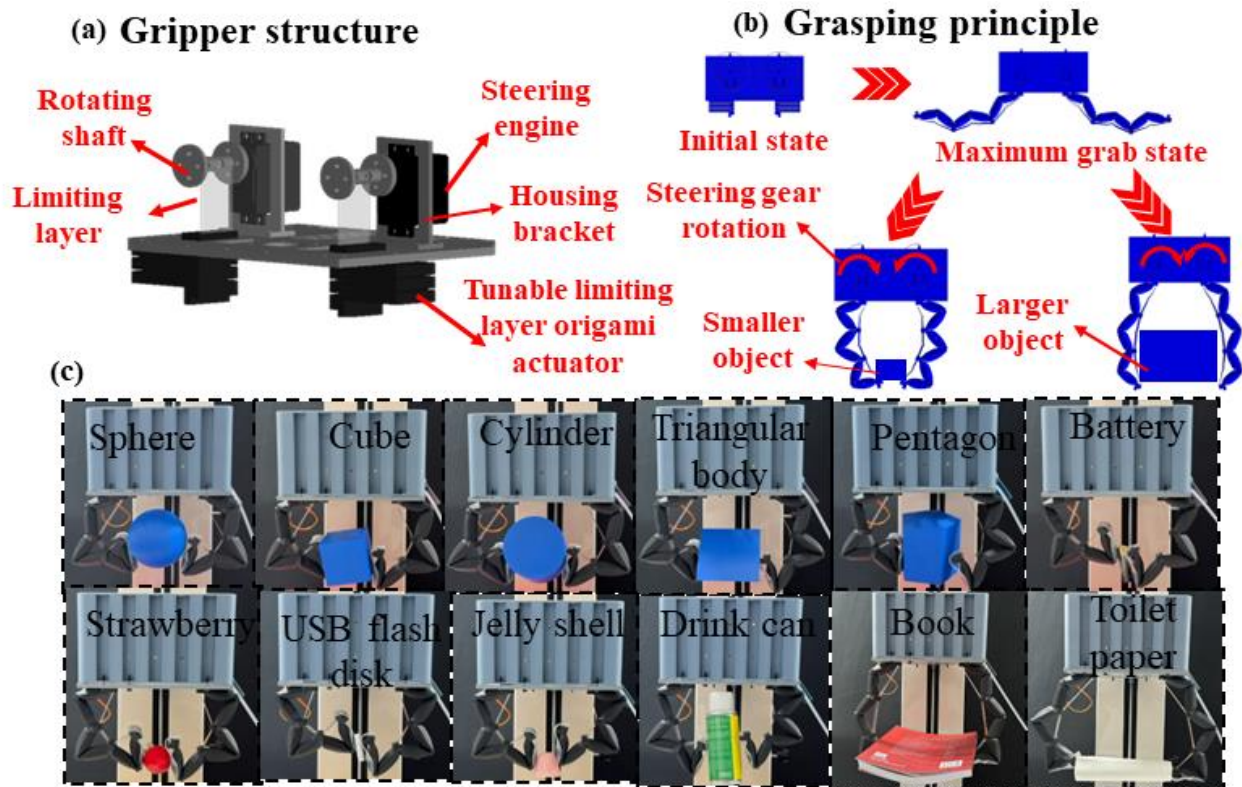


Fig. 7. Soft Gripper configuration and grasping demonstration. (a) Internal structure of soft robotic gripper (b) Diagram of the soft gripper's grasping principle with pre-adjustment of the limiting layer to adapt to objects with different sizes. (c) Snap-shots of the gripper grasping different objects.

design, a soft robotic gripper that can be reconfigured by tuning the limiting layer to achieve a wide range of grasping motions and trajectories is built, demonstrating good dexterity and adaptability through experimental validation.

In future research, the robotic gripper proposed in this paper will be improved in the following aspects: (1) Install flexible force sensors in the origami actuator to provide feedback control. (2) The actuator's geometry and dimensions will be further optimized for better performance. (3) More robotic demos such as locomotion robot and robotic arm based on the proposed actuator design will be investigated.

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