Design and Analysis of a Soft Actuator Based on Cable-Driven Method

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Abstract: In order to improve the performance of soft actuators, a novel soft actuator is designed, which is driven by a cable. Firstly, the operating principle of this soft actuator is illustrated. Compared with the traditional soft actuators driven by cables, the new designed structure can achieve the forward and reverse bending movements, relying on a single flexible shaft. Secondly, with the help of silicone rubber and 3D printed molds, a fabrication process of the actuator is developed. Thirdly, to verify the bending property, the finite element method is proposed. Some key factors causing the problems of repeatability and hysteresis are analyzed with the results of simulation and experiments. Finally, the grasping tests are carried out, and the integrated soft robotic gripper demonstrates the ability of grasping objects in different shapes and sizes. Due to its high universality and flexibility, this soft actuator shows great potential in industrial manufacturing and medical equipment.

Key words: soft actuator; cable-driven method; flexible shaft; finite element analysis; soft robotic gripper

CLC number: TP242 **Document code:** A **Article ID:** 1004-0579(2021)S1-0179-08

Soft robots have drawn more and more research interests in recent years. Comparing to traditional rigid robots, soft robots have a simpler structure, more flexibility, more adaptability to environment and higher interaction safety[1]. Such features make up the drawbacks of many rigid robots. Soft robots show huge potential in medical equipment[2], industrial manufacturing and household applications.

Current research on soft robots focus on structure design[3-6], actuation methods, material innovation, manufacturing process and control systems[7], among which the structure design and actuation methods are mainstream. Most ideas of the structure design are inspired by bionics, like caterpillar, starfish, tentacles of octopus and elephant's trunk[8]. Unlike rigid robots, which are mostly driven by independent electric motor, hydraulic or pneumatic systems, soft actuators are designed to merge structure and driven power together[9]. Hence the actuation methods and the functions can determine the size and shape. Most soft actuators are manufactured by casting. For instance, Harvard University developed multicavity and fiber reinforced pneumatic actuators[10]. Other examples are cable-driven soft robots[11] like bionic Octopus tentacles, bionic Caterpillar[12] driven by shape-memory alloy (SMA). In recent years, soft actuators have evolved into structures that combine the same or several different driving methods[13].

The common functions of soft actuators are

Received 2020-07-09
Supported by the National Natural Science Foundation of China (51775032); Foundation of Key Laboratory of Vehicle Advanced Manufacturing, Measuring and Control Technology, Beijing Jiaotong University, Ministry of Education
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DOI: 10.15918/j.jbit1004-0579.20081

bending, tension, torsion or combinations. Soft robots belong to underactuated robots. The mechanism and actuation system become bigger and more complicated as degrees of freedom of control increases, such as the designed multi-section continuum robot[14] and the bioinspired octopus arm[15] actuated by different cable arrangements. This paper investigates a geometric configuration in bending, with reference to the structure of the cable-driven soft actuator[16], and designs a soft actuator in circular cross section that can achieve bending in positive and negative directions. Such cable-driven design is closer to human muscle function, and it has the advantages of simple structure and fewer driving equipment. Firstly, the structure and operating principle are introduced. Then the fabrication process based upon molds made from 3D printing is developed. Finally, the results of simulation and experiments are analyzed. This new kind of soft actuator can serve as module to assemble multifunctional soft robots, such as soft robotic gripper, bionic tentacle and medical equipment, etc. The last part of this paper presents a soft robotic gripper assembled from three soft actuators. Experiments of gripping objects in different shapes justify the versatility of this robot. The soft actuator shows promising potential in automation production lines.

1 Structure Design and Operating Principle

Pneumatic actuation is one major method in design of soft robots. Though it is a mature technique and convenient to build a driving system, many issues need to be addressed, such as leaking or bubbling of silicone rubber when pressure increases, complex manufacturing processes due to complicated cavity structure and noise generated by air pump or valves. The cable-driven method is an alternative way in favor of avoiding such problems. Yet other issues emerge like growing size of driving mechanisms, cable mounting and pull-only limitation by a single cable. This paper deploys a flexible shaft as cable, which can remove the limitation that a single cable cannot provide pushing forces. Moreover, the simple dentation structure is compliant enough to bend and easy to manufacture.

1.1 Working parts

The soft actuator is presented in Fig. 1. It consists of main body made of silicone rubber, rigid tip and flexible shaft. The rigid tip is bolted to the front end of the main body, in which the flexible shaft runs through, with one end fixed to the tip, and the other connected to the driving system.

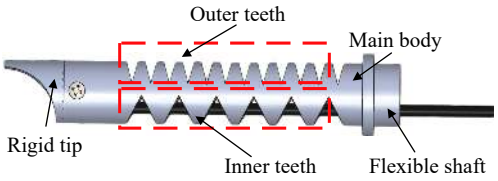


Fig. 1 Soft actuator based on cable-driven method

1.2 Operating principle

The operating principle of the soft actuator is illustrated in Fig. 2. To produce positive bending (red arrow), the flexible shaft needs to deviate slightly from the centroid of the main body. In addition, to mitigate the compression at the inner wall of this silicone rubber caused by bending, which requires larger pulling force, the double-side dentation structure is employed to make soft actuator more compliant and smoother. The inner teeth are wider than the outer teeth in considering that the positive bending is the major direction in design.

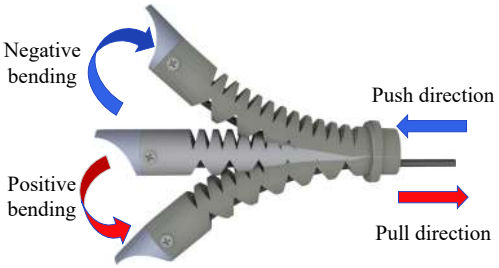


Fig. 2 Schematic diagram of the main body

When the flexible shaft is under tension (traction), the main body bends in the positive

direction; the longer the flexible shaft being pulled, the larger angles in bending deformation of silicone rubber. This paper assumes that curvature remains constant when the main body bends. Similarly, when the flexible shaft is under compression, the main body of silicone rubber bends in the negative direction.

The flexible shaft is chosen instead of steel wires in traditional cable-driven robots, so that it allows one cable to generate bi-direction movements, decreasing the complexity of the actuation system and the main body. Because of the compliance and good resilience of the flexible shaft, this new kind of soft actuator can achieve smooth functioning and fast response of bending bounce. Rotational movement can be realized as well by adding torsion driving.

As shown in Fig. 2, the rigid tip is mounted on one end of the main body, where the flexible shaft is fixed. The design of this rigid tip[17] is easier to grasp and reduces the effect of performance degradation caused by the high friction coefficient between the flexible shaft and the main body.

2 Mold Design and Fabrication Process

For the purpose of reducing the manufacturing complexity and budget, while keeping the convenience of material selection, this paper proposes a 3D printing method to produce the rigid tip and the mold. Then the silicone rubber is poured to make the main body. Finally, the soft robot is simply assembled by modules.

First of all, considering the softness of silicone rubber, which can deform under self-weight, it is necessary to reduce the total mass of the soft actuator without reducing the performance. The rigid tip is made by 3D printing machine, with the printing precision at 0.05 mm. The ABS material is used, and empty rate 30%. Such material in high hardness and lightness is suitable for the rigid tip structure.

Secondly, the main body is one-time forming. The 3D printed molds are poured with silicone rubber, which is made of two-component vulcanized silicone rubber. The silicone rubber has advantages such as fine liquidity, fast solidification, high elasticity and tearing resistance. The molds consist of upper and lower parts, cap and cylinder bar, see Fig. 3.

(a) Mold parts

(b) Assembled mold

Fig. 3 3D printed molds

The 3D printing layer height is set to 0.1 mm, and the ABS material is used. The cylinder bar (2.5 mm in diameter, 130 mm in length, made of carbon fiber) is used to avoid clogged hole for the flexible shaft. The detailed assembly method is as follows: 1) inserting cylinder bar to the lower mold with holes; 2) pouring the appropriate stirred silicone rubber to the upper and lower molds; 3) the upper and lower molds are assembled with the assistance of clamping device. The vacuum unit is used to remove bubbles in silicone rubber; 4) cover the cap on top, waiting for rubber consolidated. Fig. 4 shows this procedure.

After the main body of silicone rubber is completed, one end of the flexible shaft is first installed on the rigid tip, then it passes through

the hole in the main body. Finally the rigid tip is fixed to the front end of the main body, as shown in Fig. 5. The cylindrical main body is in milk white with 20 mm in diameter. The total length of the soft actuator is 90 mm and the diameter of the flexible shaft is 2 mm. The rigid tip is glued to one end.

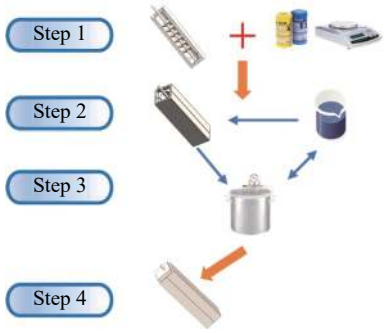


Fig. 4 Procedure of the main soft body fabrication

Fig. 5 Assembled soft actuator

One important issue in manufacturing process is to keep stirred silicone rubber away from bubbles. Failing to void or incomplete de-bubbles will adversely affect the rubber property. Fig. 6 exemplifies a failure rubber shaping. The bubbles have the most effect on dentation structures.

Fig. 6 Failed soft actuator

3 Experimental Results Analysis

Because soft actuators are different from traditional rigid robots, it is difficult to analyze the kinematic models of soft actuators through traditional modeling theories. Soft actuators are made of rubber material, containing no definite joints, which are often classified as continuous robots. In theory, the continuous robots have countless degrees of freedom, it means soft actuators are underactuated. Thanks to its compliance and underactuated mode, the soft actuators have higher flexibility, can realize various postures and adapt to the diversified appearances of objects.

3.1 Construction of test platform

In order to study the performance of the soft actuator, finite element method and experiments are used in this soft actuator study. Several experiments are carried out to analyze the designed soft actuator, and then the performance of this soft actuator is testified by comparing the experiments with FEA results. The test platform is shown in Fig. 7.

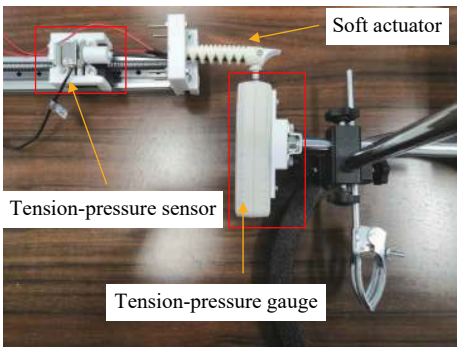


Fig. 7 Test platform of the soft actuator

The S-shaped tension-pressure sensor is used to measure the tension of the rope, and the tension-pressure gauge is installed to measure the gripping force of the rigid tip. The S-shaped tension-pressure sensor is fixed on a slider with one end connected to the flexible shaft. The end of the soft actuator is bolted to the convex plate on one end of the ball screw. In order to measure the bending angle of the soft actuator, a thin film bending sensor (FLX-03A) is embedded in the middle of the silicone rubber.

In this paper, the cable-driven method is chosen to drive the designed soft actuator. The stepper motor drives the slider of the ball screw to push and pull the flexible shaft, and finally completes the forward and reverse bending of the soft actuator. In Fig. 7, the bottom surface of ball screw is fixed to the table, and the tension-

pressure gauge is installed to the experiment holder which is also fixed to the table, the holder platform can adjust the height and the orientation of the tension-pressure gauge.

The control of the stepper motor, as well as the data transmission of the sensor are both realized by Arduino. The serial transmission between Arduino and the computer is realized, and the related experimental data are recorded.

3.2 Experiment results of soft robot

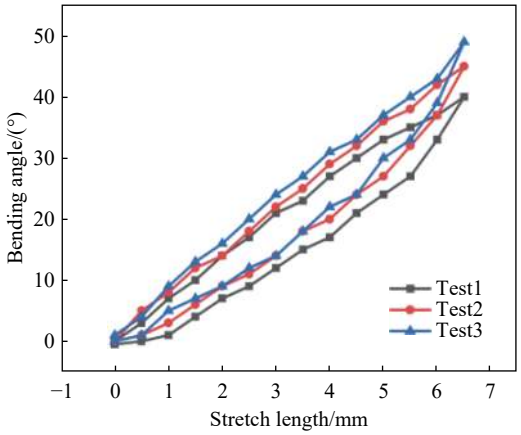
The soft actuator is mainly designed for grasping, so the main purpose of this experiments is to study the relationship between the relevant parameters of forward bending. According to the test platform, two experiments are carried out. The first one is, under no-load conditions, establishing the relationship between the stretch length of the flexible shaft and the bending angle of the soft actuator, as well as the relationship between the stretch length and the stretching force of the cable. The other test is, under a constant bending angle, establishing the relationship between the stretch length of the cable and the grasping force.

In the first experiment, the soft robot, the S-shaped tension-pressure sensor, the flexible shaft and the ball screw are used, as shown in Fig. 8. The experiment under no-load conditions was repeated three times, and the data of bending angle and the stretching force were recorded.

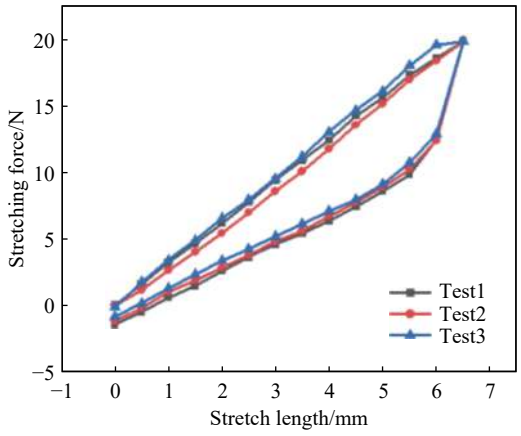
Fig. 8 Test scheme A of soft robot

The results of the first experiment are shown in Fig. 9. Fig. 9 shows that in the process of soft actuator bending and recovering, both bending angle and stretching force curves have hysteresis. As for the bending angle, it has smaller hysteresis but poorer repeatability, while the stretching force has a bigger hysteresis and better repeatability by contrast.

Considering the bending schematic in Fig. 2, we can speculate that the hysteresis phenomenon appears in Fig. 9 is caused by the nonlinear characteristics of the rubber material, as well as the friction between the flexible shaft and the silicone rubber. When the flexible shaft is stretching, it needs to overcome not only the elastic reaction force caused by the deformed soft actuator, but also the friction for pulling itself. During the flexible shaft pushing and stretching, the friction between the flexible shaft and silicone rubber changes and the curves are shown in Fig. 9.



(a) Curves between stretched length and bending angle



(b) Curves between stretch length and stretching force

Fig. 9 Experimental curve A of test scheme

Using the entire experiment platform in Fig. 7, the second experiment is executed. Under no-load situations, the soft actuator's bending angle is set to 0°, 10° and 20°, and then the rigid tip grasping force of soft actuator can be measured by a tension-pressure gauge. The results of the second experiment are shown in Fig. 10, which

have 3 hysteresis curves. It can be seen from the figure that the grasping force of this rigid tip increases with the raise of the stretch length, which is approximately linear. It should be noted that in the case of external loads, the soft actuator will no longer bend at a uniform curvature. Fig. 10 also shows that, at the same stretch length, the rigid tip grasping force increases with a higher bending angle.

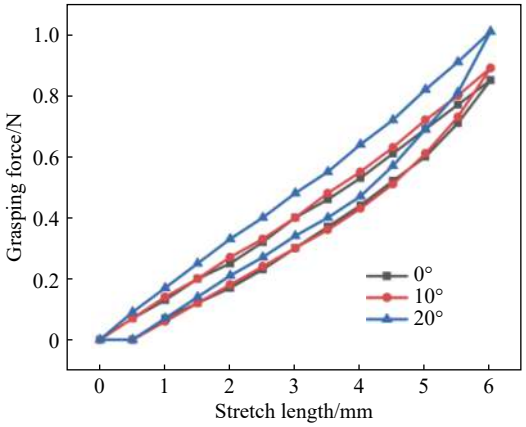


Fig. 10 Experimental curve B of test scheme

4 Simulation and Validation

Due to the complexity of rubber material analysis, this paper involves finite element method to testify the experiments and analyzes the key factors causing the problems of repeatability and hysteresis.

Firstly, to lessen the computation of Abaqus software, as well as to prevent data divergence from causing simulation failure, the 3D model is slightly simplified with the merge of threaded hole and screw. Further, because of its extreme complex internal structure, the flexible shaft is replaced by a cylindrical rod, and the nylon material is chosen as the appropriate substitution. Although the data may vary with the steel made flexible shaft but the tendences of stresses and strains are the same.

Static analysis is carried out with different stretch lengths, and the results are shown in Fig. 11, and the soft actuator bends at the length of 23 mm. The deformed structure shows good bending profile which accords with the assumption from the operating principle. As the bending angle increases, the contact force and strain increase exponentially.

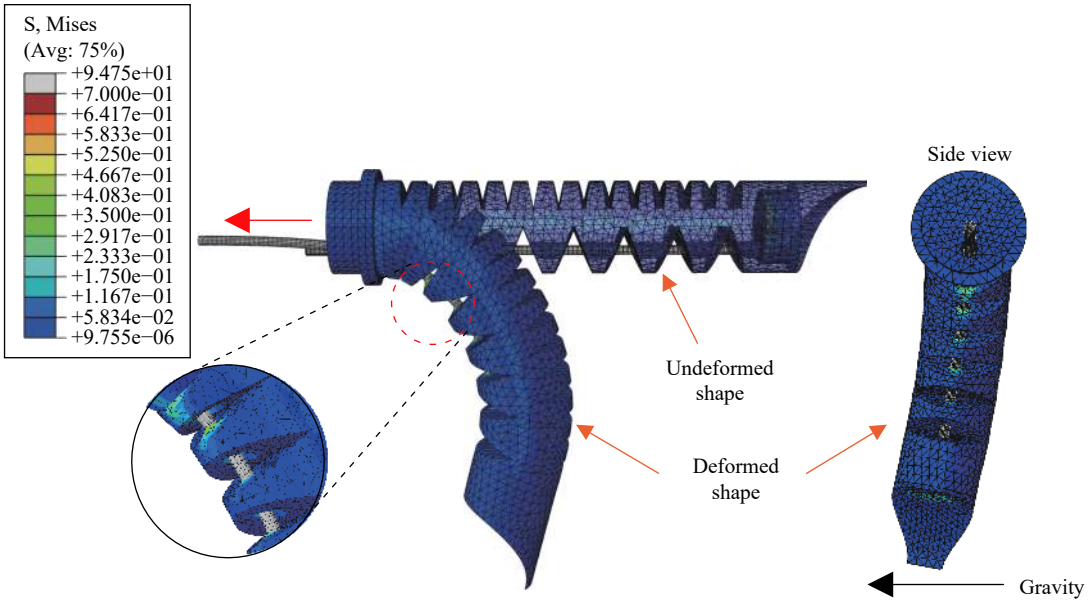


Fig. 11 Von Mises stress for soft actuator

The friction coefficient is set to 0.5. As the stretch length changes, the total friction between the rod and the silicone rubber is calculated from simulation results, as shown in Fig. 12. From this

curve, the tendency of the increase and dramatically decrease of the total friction force is consistent with that in Fig. 9, which explains the hysteresis phenomenon of the stretching force.

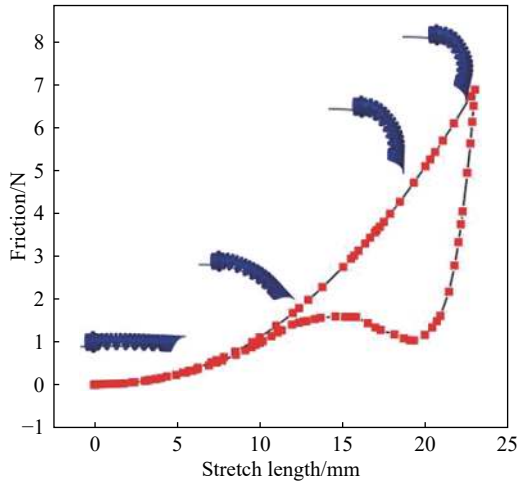


Fig. 12 Friction curves and demonstrated shapes

Fig. 13 describes the relationship between the stretch length and the bending angle, and curves of different colors respectively represent the bending effect under different opening angles of inner teeth.

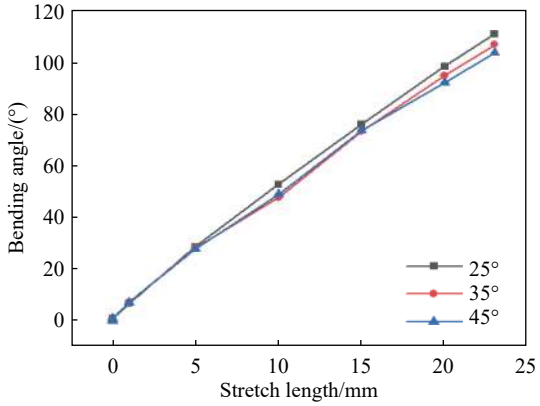


Fig. 13 Simulation curves of bending angle

It can be seen from Fig. 13 that, under the same stretch length, the bending angles of these soft actuators are basically the same, which indicates that the opening angle has little influence on the bending angle. From Fig. 14, as the opening angle increases, the stretching force decreases gradually at the same stretch length. Therefore, the 45° opening angle is adopted as the appropriate choice in this paper.

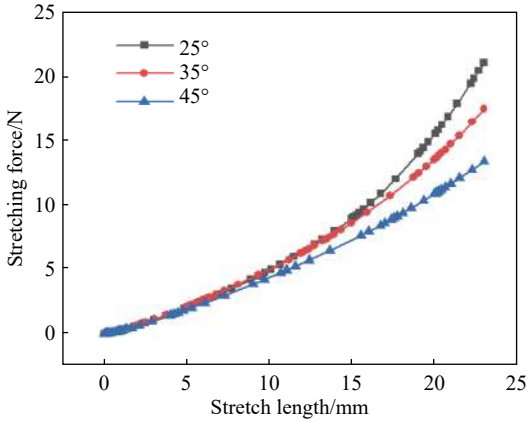


Fig. 14 Simulation curves of stretching force

5 Experiments of the Soft Gripper

In this part, the designed soft actuators are assembled into a robotic gripper to improve the grasping ability. The soft robotic gripper consists of three soft actuators distributed on a fixed bracket at 120 degrees and driven by a ball screw.

Thanks to its flexible and compliant characteristics, this soft robotic gripper can hold various objects, such as apples, tapes, bananas, bottles. The results are shown in Fig. 15.

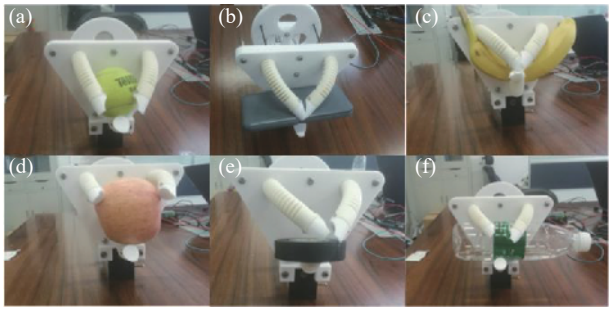


Fig. 15 Gripping experiments

6 Conclusion

This paper presents a novel soft actuator driven by a flexible shaft. The soft actuator is fabricated using 3D printed molds, and analyzed by FEA method and experiments. The experiments show that the relation between the stretch length and the bending angle is approximately linear, as well as the relation between the stretch length and the grasping force. The results of FEA testify that the deformation of the silicone

rubber material and the asymmetry friction phenomenon lead to the repeatability problem and hysteresis. To address these drawbacks, the future work will focus on the influence of structural parameters on bending properties and reducing the friction between the flexible shaft and the silicone rubber. In the end, the soft robotic gripper presents excellent grasping performance in our experiments, which shows great promising in industrial manufacture and medical equipment.

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