Proceedings of 2022 IEEE
International Conference on Mechatronics and Automation
August 7 - 10, Guilin, China

A New Fabrication Method for Soft Pneumatic Actuators based on Paraffin

Fengze Lyu[1,3], Maoxun Li[2], Jin Guo[1,3,*], Shuxiang Guo[1,3]
1 School of Life Science, Beijing Institute of Technology, Beijing 100081, China;
2 China Academy of Electronics and Information Technology, Beijing 100041, China
3 Key Laboratory of Convergence Biomedical Engineering System and Healthcare Technology,
Beijing Institute of Technology, No.5, Zhongguancun South Street, Haidian District, Beijing 100081, China
* Corresponding author

***Abstract* - compared with traditional rigid robots, the soft robots inspired by bionics have attracted extensive attention because of their inherent flexibility and safety. The motion of soft robots is mainly driven by soft actuators. However, the design and control of this kind of soft actuators is still lack of theoretical guidance. In this paper, a soft actuator structure is designed based on the idea of modularization and bellows, and the improved wax loss casting method is used to make the soft actuator. Then we build an experimental platform to test the performance of the soft actuator. The result shows the deformation of the soft actuator under different air pressure. With the increase of the internal pressure, the airbag expands obviously and the elongation increases.**

Index Terms - wax loss casting method, soft pneumatic actuators, soft robots, modularization

I. INTRODUCTION

At present, soft robot is one of the research hotspots in the field of robot [1-4]. Compared with rigid robots, soft robots have good flexibility and human-machine interaction security. In addition, they can adapt to various unstructured environments, and can complete some tasks that rigid robots cannot complete well. The development of soft robotics is a growing interdisciplinary research and experimental field, involving the research of chemistry, material science, mechanics and electronics [5][6]. Different from the rigid-body robots with multiple joints with multiple degrees of freedom, soft robots are made of flexible materials, such as silicone materials. And they are operated through continuous deformation. Because they have many advantages in application, for example they can handle delicate objects, imitate the ability of human body, and work under various conditions that rigid robots cannot achieve, soft robotic technology is about to sweep many industries around the world today.

With the expansion of the application fields of robots, soft robots have broad prospects in the fields of medical rehabilitation, grasping and exploration, such as rehabilitation assistant [7], soft mobile robot [8] and bionic fish [9]. The movement ability of soft robots come from soft actuators, which can be actuated by shape memory alloy (SMA), shape memory polymer (SMP), hydraulic and pneumatic ways.

The soft actuators made of silicone materials powered by electric polymer is an ideal driving mechanism for biocompatible soft robots. A recently designed electric polymer is a hydraulically amplified self-healing electrostatic actuator. It is a mechanism that couples electrostatic and hydraulic pressure to realize various actuation modes. It has firm muscle-like performance and the ability of repeated self-healing after dielectric breakdown [10].

Cheng et al. [11] proposed a new type of soft robot with multiple degrees of freedom (DOFs) driven by shape memory alloy (SMA). In theory, the robot supports maximum nine degrees of freedom motion and good positioning accuracy. Lin et al. [12] designed "GoQBot" using shape memory alloy. The design is a worm-like robot with a driving rate of less than 100 ms. The robot uses the deformation of SMA coil to realize rolling motion.

Another driving method is piezoelectric driving. A group of researchers have developed a new locomotion mechanism for the wireless capsule endoscope, selected piezoelectric driver as the micro driver of capsule endoscope, and have manufactured a 30mm micro robot [13].

The soft pneumatic actuator is the most popular type of actuator in the soft robotic industry because of its simple manufacture. Tang et al. [14] proposed a soft robot that can imitate the crawling movement of earthworms. The movement of the robot can be realized by expanding and contracting the body made of flexible materials. It can flexibly pass through the narrow space, has strong adaptive ability, and can adapt to the unstructured environment. Polygerinos et al. [15] designed a classical pneumatic grid soft actuator. The motion principle of the soft pneumatic actuator is that the parallel square air chambers are compressed and expanded, and then squeeze each other, resulting in their bending motion to the side with limiting layer. Han et al. [16] designed a soft actuator with high shrinkage ratio, which uses 3D printing technology to directly print the soft actuator. However, it is made directly by 3D printing, which has high cost and is easy to leak under repeated inflation.

In this paper, a soft pneumatic actuator with elongation movement is designed based on the corrugated structure. Compared with the traditional artificial muscle with single elongation movement, it has greater elongation, and is

978-1-6654-0853-0/22/$31.00 ©2022 IEEE

manufactured by the improved wax loss casting method. The manufacturing material wax can be reused and the manufacturing cost is low, which provides an idea for making the soft pneumatic actuators with complex chamber structure in the future.

II. Methods and Materials

The traditional soft pneumatic actuator is mainly of artificial muscle type, and its elongation mainly depends on the deformation of elastic materials [17]. However, the deformation of elastic materials is limited, so the elongation of this method is small. The soft axial pneumatic actuator designed in this paper is based on the bellows structure with high scalability.

In this paper, a plug and play structure of the soft pneumatic actuator is designed based on the concept of modularization, as shown in Fig. 1a. The soft pneumatic actuator consists of three parts: the lower and upper ends of the soft pneumatic actuator and the main body of the actuator. The upper end is mainly composed of a 3D-printed part (Fig. 1b) and an inflation tube, and the lower end is composed of the same 3D-printed part and the tube adapter (Fig. 1c). The middle main body adopts bellows structure, and its parameters are shown in Table I. The inflation tube and tube adapter are connected to the main body of the soft pneumatic actuator with casing technology and silicone adhesive (Sil-poxy glue, Smooth-on, USA), and the 3D-print parts can be connected with the external structure.

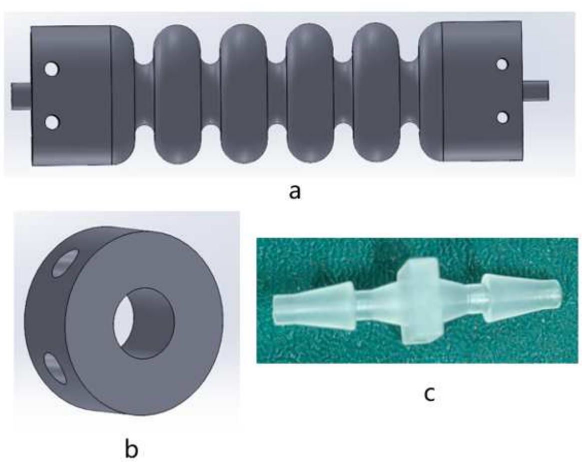

Fig. 1. The design of the soft pneumatic actuator: (a) the bellow-shape soft pneumatic actuator; (b) the 3D-printed fixture for the soft pneumatic actuator; (c) the tube adapter.

TABLE I
STRUCTURAL PARAMETERS OFDRIVER

wall thickness /mm	Total length /mm	Number of ripples /mm
2	74	6

III. PRODUCTION PROCESS

At present, the fabrication methods of soft pneumatic actuators mainly include soft lithography [18], pouring method, wax loss casting method [19] and 3D printing [20]. This paper mainly used the improved wax loss casting method to make the soft pneumatic actuator. The lost wax casting method is mainly made by making the cavity into wax core and melting the wax core after molding. It is not only suitable for the manufacture of this paper`s soft pneumatic actuator with bellow shape, but also the soft pneumatic actuators with the complex chamber structure. In addition, the wax material can be reused many times.

Paraffin wax has the property of thermal expansion and cold contraction, and the volume changes greatly before and after solidification, as shown in Fig. 2. This paper attempts to solve this problem, using two methods to improve this problem. The first method is to increase the pressure. Increase the pressure by increasing the depth of the liquid. As shown in Fig. 3c, add a section of liquid column above the required part to increase the pressure below and reduce the volume change caused by thermal expansion and cold contraction. The second method adopts the idea of 3D printer. We divide the mold into three layers to cool and solidify respectively. Design a container to hold hot water to heat the upper part of the mold to reduce the rate of temperature drop, as shown in Fig. 3d and wrap a layer of thermal insulation material outside the middle part of the mold. For the lower layer, put the lower layer into cold water to increase the rate of heat release of the mold. This causes the lower layer of the mold solidify first, while the upper layer of the mold solidifies later, and the non-solidified liquid in the upper layer moves down to fill the volume change caused by thermal expansion and cold contraction in the lower layer.

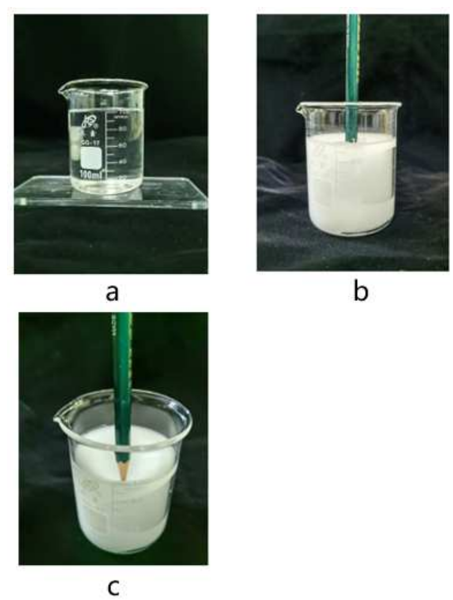

Fig. 2. The volume change caused by thermal expansion and cold contraction of the paraffin wax: (a) the melted paraffin wax; (b) the cured paraffin wax; (c) the volume change of the paraffin wax.

The specific fabrication steps of the soft pneumatic actuator are as follows:

(1) Production of the wax core

Fig. 3 shows the mold required for the production of the wax core. Fig. 3a shows a quarter of the mold. Because it is difficult to demold paraffin, this paper divides the mold into four parts (shown in Fig. 3b), thereby reducing the difficulty of demolding. The specific steps of making the wax core are as follows:

1) Use the 3D printing technology to 3D-print the wax core mold and auxiliary mold.

2) Assemble the wax core mold, assemble the tube with the outer diameter, inner diameter and length of 8mm, 6mm and 10cm respectively on the mold, as shown in Fig. 3c, and apply Sil-poxy glue at the gap outside, waiting for the glue to solidify.

3) A simple heating container is made of a paper cup and a tube with an inner diameter of 8mm and an outer diameter of 12mm, as shown in Fig. 3d.

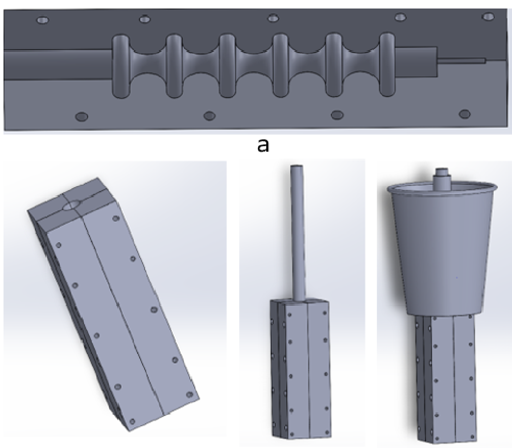

Fig. 3. The fabrication steps for making the wax core: (a) the molds required for making the was core; (b) the assembly of the molds; (c) the assembly with the tube with the outer diameter, inner diameter and length of 8mm, 6mm and 10cm, respectively; (d) heating the tube with an auxiliary mold.

4) Paraffin additive (A-C material) is added to the wax in a proportion of 10% to increase the hardness of the wax.

5) Prepare a 500mm beaker, add water to the height that can soak the wax core mold, and heat it to about 90 ℃. Put the wax core mold into a bag and soak it in the beaker to ensure that hot water does not enter the bag. Heat the wax core mold water bath for 10-20min to ensure that the mold temperature is higher than the melting point of wax.

6) Melt the paraffin with an alcohol lamp and keep the temperature of the paraffin at about 90 ℃.

7) Slowly add the paraffin liquid into the mold with a 2mm syringe.

8) Take out the mold, divide the mold into three layers, put the lower layer of the mold into cold water, add a layer of thermal insulation material on the middle layer, and heat the pipe with an auxiliary mold to ensure that the pipe and the middle paraffin are in liquid state, as shown in Fig. 3d, for about 10 to 20 minutes.

9) When the paraffin wax at the lower layer of the mold solidifies, remove the thermal insulation material at the middle layer of the mold, put all the mold into cold water and continue to heat the pipe.

10) Allow the paraffin to set completely for approximately one day.

The fabricated paraffin is shown in Fig. 4. The problem of thermal expansion and cold contraction of paraffin is better improved by hydraulic pressure and the layered cooling method.

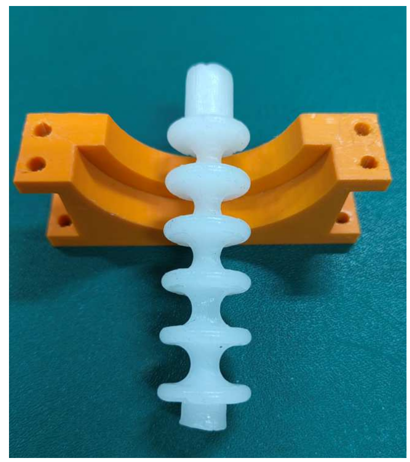

Fig. 4. The fabricated paraffin core.

(2) The fabrication process of the soft pneumatic actuator

The soft pneumatic actuator is mainly made of the silicone material called smooth-sil 960.

1) The 3D printing technology is used to print the molds for making the soft pneumatic actuator and its auxiliary mold, as shown in Fig. 5a and Fig. 5b.

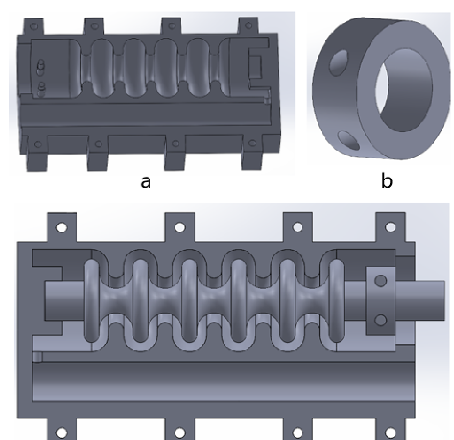

Fig. 5. The mold for making the soft pneumatic actuator and its auxiliary mold

2) Assemble the molds and fix the paraffin core in the mold for the soft pneumatic actuator, as shown in Fig. 5c.

3) Prepare smooth-sil 960 according to the specific weights of 100a:10b, and put it into a centrifuge for centrifugation and stirring for 1min.

4) The method of vacuumizing bubbles is used to eliminate bubbles from the silicone liquid.

5) Pour the prepared silicone liquid into the assembled mold and wait for the silicone material to solidify.

6) After solidification, take out of the soft pneumatic actuator and heat it in the oven to let the paraffin melt out.

7) Remove the remaining paraffin from the soft pneumatic actuator with boiling water. The completed drive is shown in Fig. 6.

Fig. 6. The fabricated soft pneumatic actuator based on the proposed fabrication methods.

IV. Experiments and Results

In order to evaluate the performance of the fabricated soft pneumatic actuator, the pressurized air with the pressure of -90 ~ 210 kPa at intervals of 10 kPa were supplied to the soft pneumatic actuator respectively. Meanwhile, we measured the length variation of the soft pneumatic actuator under different air pressure, as shown in Table II.

TABLE Ⅱ
Length Variation of The Fabricated Soft Pneumatic Actuator Under Different Air Pressure

pressure /kPa	length /mm	Length variation /mm	Difference in length variation /mm
-90	58.5	-15.5	0
-80	58.5	-15.5	0
-70	58.5	-15.5	0.5
-60	59	-15	0.5
-50	59.5	-14.5	0.5
-40	60	-14	6
-30	66	-8	3.5
-20	69.5	-4.5	2.5
-10	72	-2	2
0	74	0	2
10	76	2	2
20	78	4	3
30	81	7	0.5
40	81.5	7.5	1.5
50	83	9	1.5
60	84.5	10.5	1.5
70	86	12	1.5
80	87.5	13.5	1
90	88.5	14.5	1.5
100	90	16	1
110	91	17	1.5
120	92.5	18.5	1
130	93.5	19.5	1
140	94.5	20.5	0.5
150	95	21	1
160	96	22	1
170	97	23	0.5
180	97.5	23.5	0.5
190	98	24	2
200	100	26	1
210	101	27	

The experimental results show that the maximum shrinkage of the actuator is 15.5mm and the shrinkage rate is 20.95%. The shrinkage reaches the maximum when the pressure reaches - 70kpa. The maximum elongation can reach 27mm and the elongation is 36.5%. Between -30kPa and 210kpa, the length variation of the soft pneumatic actuator is approximately linear with the air pressure (as shown in Fig. 7), because the shape and performance of the driver are similar to that of the spring, and the elastic force of the spring is directly proportional to its variation within a certain range. Therefore, the test value of the driver between -30kPa and 210kpa is fitted with the data to obtain the fitting relationship between the elongation y (mm) of the soft pneumatic actuator and the air pressure x (kPa) (as shown in Fig. 8):

$$y = 0.1345x + 0.835$$

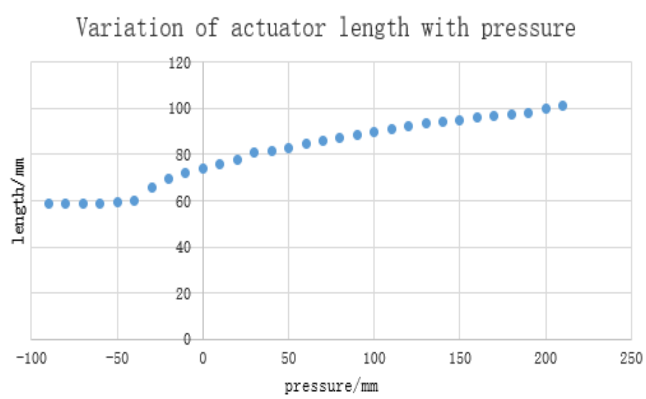

Fig. 7. The relationship between the length of the soft pneumatic actuator and the input air pressure

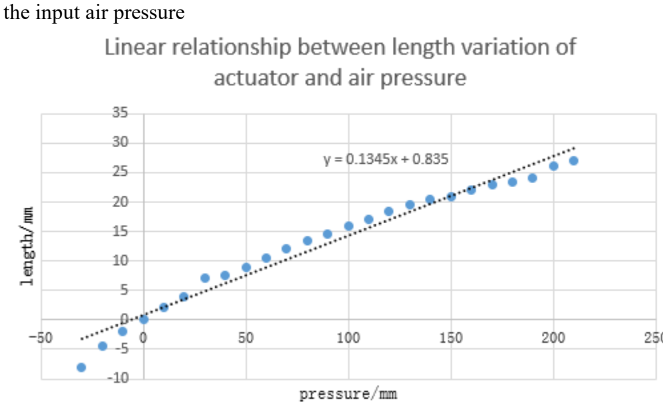

Fig. 8. The linear relationship between length variation of the soft pneumatic actuator and the input air pressure.

V. CONCLUSION

In this paper, an improved wax loss casting method is used to make the soft pneumatic actuator based on the structure of bellows, which is mainly contributed to solve the problems of the thermal expansion and cold shrinkage of paraffin and demolding difficulty. The concept of increasing hydraulic pressure and layered cooling effectively solved the problem of thermal expansion and cold contraction of paraffin. The concept of layered demolding also improves the success rate of paraffin demolding.

REFERENCES

[1] D. Sun, J. Zhang, Q. Fang, P. Xiang, et al. Analysis and control for a bioinspired multi-legged soft robot. Biomimetic Intelligence and Robotics, vol.2, no.1,2022.

[2] J. Gao, P. Gao, W. Rong, D. Li, L. Wang. A grid-assisted 3D printing method for magnetically driven micro soft robot. Journal of Physics: Conference Series, vol.2174, no.1,2022.

[3] B. Han, Z. Ma, Y. Zhang, L. Zhu, et al. Reprogrammable Soft Robot Actuation by Synergistic Magnetic and Light Fields. Advanced Functional Materials, vol.32, no.13,2021.

[4] Y. Yamamoto, S. Wakimoto, T. Kanda, D. Yamaguchi. A Soft Robot Arm with Flexible Sensors for Master–Slave Operation. Engineering Proceedings, vol.10, no. 1,2021.

[5] C. Laschi, B. Mazzolai, M. Cianchetti. Soft robotics: technologies and systems pushing the boundaries of robot abilities. Science Robotics, vol.1, no.1, 2016.

[6] G. Yang, et al. The grand challenges of science robotics. Science Robotics.vol.3, no.14, 2018.

[7] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood. C. J. Walsh. Soft robotic glove for combined assistance and at-home rehabilitation. Robotics and Autonomous Systems, vol.73, pp.135-143, 2015.

[8] M. T. Tolley, R. F. Shepherd, B. Mosadegh, K. C. Galloway, et al. A resilient, untethered soft robot. Soft Robotics, vol.1, no.3, pp.213-223, 2014.

[9] A. D. Marchese, C. D. Onal, D. Rus. Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. Soft Robotics, vol.1, no.1, pp.75-87,2014.

[10] E. Acome, S. K. Mitchell, T. G. Morrissey, M. B. Emmett, et al. Hydraulically amplified self-healing electrostatic actuators with muscle-like performance. Science, vol.359, no.6371, pp.61-65,2018.

[11] C. Cheng, J. Cheng, W. Huang. Design and development of a novel SMA actuated multi-DOF soft robot. IEEE Access,vol.7, pp.75073-75080,2019.

[12] H. T. Lin, G. G. Leisk, B. Trimmer. GoQBot: a caterpillar-inspired soft-bodied rolling robot. Bioinspiration & Biomimetics, vol.6, no.2,2011.

[13] B. Kim, S. Park, C. Y. Jee, S. J. Yoon. An earthworm-like locomotive mechanism for capsule endoscopes. In: 2005 IEEE/RSJ international conference on intelligent robots and systems, 2005.

[14] Z. Tang, J. Lu, Z. Wang, W. Chen, H. Feng. Design of a new air pressure perception multi-cavity pneumatic-driven earthworm-like soft robot. Autonomous Robots, vol.44, no.2,2020.

[15] P. Polygerinos, S. Lyne, Z. Wang, L. F. Nicolini, et al. Towards a soft pneumatic glove for hand rehabilitation. In: 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo: IEEE, 2013, pp.1512-1517.

[16] K. Han, N. H. Kim, D. Shin. A novel soft pneumatic artificial muscle with high-contraction ratio. Soft Robotics, vol.5, no.5, pp.554-566,2018.

[17] D. Trivedi, C. D. Rahn, W. M. Kier, I. D. Walker. Soft robotics: Biological inspiration, state of the art, and future research. Applied Bionics and Biomechanics, vol.5, no.3,2008.

[18] K. J. Cho, J. S. Koh, S. Kim, W. S. Chu, et al. Review of manufacturing processes for soft biomimetic robots. International Journal of Precision Engineering and Manufacturing, vol.10, no.3, pp.171-181,2009.

[19] A. D. Marchese, R. K. Katzschmann, D. Rus. A recipe for soft fluidic elastomer robots. Soft Robotics, vol.2, no.1, pp.7-25,2015.

[20] O. D. Yirmibesoglu, J. Morrow, S. Walker, W. Gosrich, et al. Direct 3D printing of silicone elastomer soft robots and their performance comparison with molded counterparts. In: 2018 IEEE International Conference on Soft Robotics (RoboSoft). Livorno: IEEE, 2018, pp.295-302.