Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Introduction of a Flexible Adaptive AUV-Capture Device Based on bio-inspired hydraulic Soft Robot*

Hao Deng, Hang Su, Tao Mei, Wenjun Xu, Zhengkun Cheng

Robotics Research Center
Peng Cheng Laboratory
No. 2, Xingke 1st street, Nanshan, Shenzhen 518055 , *China*
dengh@pcl.uc.cn

Xiang Dong

School of Electrical Engineering and Automation

Anhui University
Hefei, Anhui, 230601, China

Abstract - *To capture the non-cooperative and cross-scale underwater objects, an underwater soft bionic robot is proposed according to task function analysis and bionics inspiration. The device was mainly composed of a soft bionic arm and a soft body. It has the abilities of long-distance reachability, end pose adjustment, cross-scale capture, target measurement and recognition. The soft bionic arm is driven by water filling, which has the characteristics of light weight and large shrinkage ratio. It consists of several serially arranged modular soft actuators with diverse functions which can be designed for deep-sea object retrieving. The soft modules are connected by quick-shift joints, which make it possible to adjust the arm configuration specific to the task requirement in situ. The method to test the performance of each functional module is also introduced.*

Index Terms - *manipulator ; soft robot ; bio-inspired; flexible; capture device; modularized-soft actuator*

I. Introduction

With the continuous development of marine engineering, human activities in the sea are more and more frequent. AUVs (Autonomous Underwater Vehicle) are widely used in marine scientific investigation, seabed survey and water environment research[1]. Due to the complex and unpredictable working environment of the ocean, the reclaim of AUV has always been a very difficult problem. Reasonable and effective recovery methods will greatly improve the concealment, safety and autonomy of AUVs [2]. AUV underwater recycle docking has been a research hotspot because of shortcoming in AUV recovery by the mother ship, such as environmental impact, poor concealment, high cost, and low degree of automation[3-6].

In this paper, the flexible Adaptive AUV-Capture Device are studied. Traditional robots are mostly composed of rigid motion pairs based on hard materials, which have low adaptability to the environment and are difficult to meet the application requirements of dynamic, unknown and unstructured environments. Soft structures of soft organisms have little resistance to pressure and can be compatible with obstacles by flexible deformation[7].The bionic soft robot takes the widely distributed soft organisms in nature as its bionic object[8]. By referring to the characteristics of large tissue deformation, light weight and high power density ratio, it can contact the underwater vehicle in a more flexible way. This method has the advantages of light weight, large collection ratio, reusability and low cost. Compared with the capture device made of hard materials, the reaction force from the environment during the capture of the soft capture device is widely distributed on the surface of the soft organization, which can reduce the impact and absorb energy, and is suitable for the capture occasion where there is collision[9,10].

Many works have been done to study about it, such as the fiber-reinforced soft actuator [11], sample correcting under water with soft actuator [12], modular soft robot application [13,14] and so on. Due to the effect of the disturbance, it is quite difficult to control the rigid robot arms accurately in harsh deep-sea environment. Many works have been done to minimize the effect, which makes the robot arms more and more complex, expensive and leads to the decrease of the loading capacity. And sealing is also a challenge for the traditional robot arms in deep sea. It makes soft robot arms a better solution for some of the tasks such as object retrieve in deep sea. Compliant structure of soft robot arm working along with compliant control makes accurate position and force control unnecessary. Driven by hydra power and using a compensation bladder [12] make the soft robot arms barely effected by the hydraulic environmental pressure under water. Driven by hydraulic also show performance advantage compared to pneumatic [15].

The size of the object to be retrieved can be significantly different, and the shape can be very complicated. The arm must be able to adapt to it as much as possible. One method is to design an arm which can deforms a lot to cover a big range of the difference. Another method is making the arm changeable according to the task. Soft arm consisting of serially arranged modular actuators is a way to take advantage of both methods: each of the module can be controlled independently and has different function, so the arm can adapt to different shape and size. If the object exceeds the ability of current combination, the modular design allows the operator easily change one or several modules, even the whole arm, to complete the task.

* Please Email Dr. DENG for contact: dengh@pcl.uc.cn

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

The modules in the arm have different configurations as they have different functions. Some module is used to control posture, some is used to locate the object, and some is used to provide holding force. To develop such an arm, the basic job is to design several type of module and test the performance of the modules. In this article, 5 kinds of modules are developed: bending, twisting, twining, extending and expending. The improved fabrication process and test methods are presented. Sensor arrangement also introduced for compliant control.

II. SYSTEM SOLUTION OF A FLEXIBLE ADAPTIVE AUV-CAPTURE DEVICE

A. *Bionic mechanism*

Acquisition of cross-scale targets by single-branch and multi-branch chains: From the bionics point of view, the terminal capture load refers to the operation mode of octopus in the biological world. As shown in Figure 1, octopus is composed of multiple tentacles, which can capture small-scale targets by single-branch chains and large-scale targets by multi-branch chains co-winding. The single-branch chains are redundant in degree of freedom. Redundancy and redundancy of multi-branch chains ensure high fault tolerance and security of the capture device at the system level, and also improve the flexibility of the operation of the capture device.

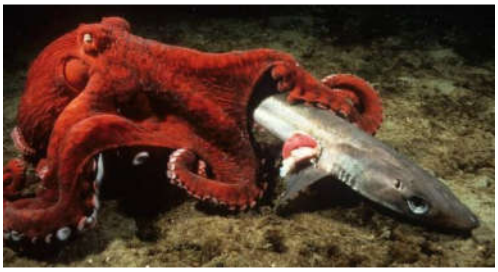


Fig. 1 Octopus winding prey.

B. *Structure and application*

According to the task and functional requirements of flexible adaptive acquisition of cross-scale targets, the overall design of bionic soft robot is as follows.

Different from the domestic and foreign research, the scale of the soft arm of the soft robot is meter, and the water-filled arm is deployed and the winding target is powerful. As shown in Fig. 2, it mainly includes four groups of soft arms, which can flexible capture objects of different scales. The motion of the soft body is realized by a number of bionic vector injection devices. The bionic fins can be arranged at the front end of the bionic robot to control the course. The left and right sides of the bionic body are equipped with acoustic and optical detection equipment, and the bottom is equipped with underwater lighting and high-definition camera.

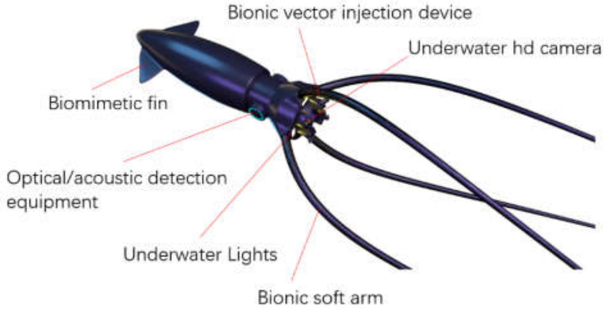


Fig. 2 Components of Soft Robot

Soft biomimetic mechanism realizes reliable capture and compatibility of the target, alleviates collision impact and absorbs energy. Soft arm of the capture device is designed according to the motion mechanism of mollusks in nature. Compared with the capture device made of hard materials, the soft structure has little resistance to pressure, and can be compatible with obstacles through flexible deformation, so it is suitable for non-collision. At the same time, the reaction force from the environment is widely distributed on the surface of the soft organization, which can reduce the impact and absorb energy. It is suitable for dynamic target acquisition occasions with collision and contact.

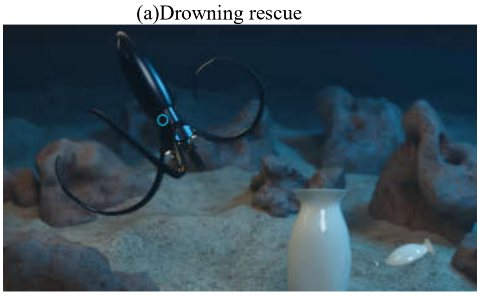
The expansion arm with light weight and large contraction ratio is realized by water filling expansion method. The capturing device can achieve long-distance stretching and closing, and the stretching distance is controllable. Through its controllable multiple degrees of freedom, the relative pose of the terminal capturing device and the moving target can be adjusted close. Its stretching mechanism adopts the way of water filling, which has the advantages of flexibility, light weight and large collection ratio. Reliable adhesion to debris is also achieved by biomimetic adhesion method. Gecko-like micro-nano bristle arrays can be arranged on the surface of the soft arm to achieve the adhesion of the soft arm to the target and further ensure the reliability of grasping.

Fig. 3 Flexible grab AUV from multiple angles and directions

c. *Application of soft arm*

This paper takes the capture and recovery of underwater objects as a typical task, and cylindrical AUV as a typical target. On the platform of simulation system, through the simulation of typical acquisition tasks, the function and performance of the acquisition device are verified and demonstrated. According to the simulation results, it can be seen that after the water filling of the acquisition device, each soft tentacle moves close to the spherical satellite or cube satellite until contact occurs. After contact, the shape following effect occurs. The continuous inflatable soft tentacle can adapt to the shape of the target and form a reliable connection with the target in a large area. It can be seen that the capture device can capture the debris target by means of water-filled winding, closing and inclusion. The soft mechanism is feasible to capture debris.

(a)Drowning rescue



(b) vase salvage

Fig. 4. Other applications of the soft robot

Ⅲ. DESIGN AND FABRICATION OF THE SOFT MODULES

Soft arm is the key part of underwater robot. For underwater AUV target with a shape envelope of about 300 m, the length of soft arm should be designed to be more than 1 m, and it must be able to withstand a certain tension after winding. Soft arm has infinite degrees of freedom in theory, but the number of actuators is limited, it belongs to underactuated system, and its degree of freedom is not one-to-one relationship with the actuator; moreover, when the distributed load or local deformation occurs due to contact during the capture process, the motion state of the capture device will change adaptively; therefore, it is difficult to obtain the parameters and contacts of the water-filled driver directly in theory. The mathematical relationship of the end position of the hand motion is obtained mainly by simulation and experimental identification.

In order to enhance the flexibility and reliability of the arm capture, the design of each arm is realized by two schemes. One is the monomer scheme. The deformability of the module can be changed by changing the arrangement direction and density of the reinforcement fibers outside the module chamber. The advantage of this scheme is that it has fewer driving sources, but the disadvantage is that it can only realize passive winding.

Another scheme is modular series connection, that is, the soft arm of meter length is composed of many segments, each segment can be independently controlled. Soft arm is divided into expansion module, bending module, axial torsion module, expansion module and winding module to study.

A. DESIGN OF THE QUICK-SHIFT JOINTS

The quick-shift joints are designed to connect two adjacent soft modules. The length of the connecting joint is the key parameter of the component. Since the joint is rigid, reducing its length is beneficial for the flexibility of the arm. Meanwhile, the joint must be easy to connect and disconnect.

Considering that the joints are mainly subject to tensile forces, the design of the joint can be simplified. As shown in Fig. 5, the joint consists of 4 locking feature and a preloaded diaphragm spring. To connect the joint, one must push the male connector to the groove of the female connector, then twist clockwise to the locking position and compress the spring. To disconnect, push the connectors to each other, twist the male connector counter-clockwise from the locking position, and release the joint. The section of the soft module can be different to form an arm, and the diameter of the joints can be different. A big female joint must be able to fit with a smaller male joint. So the locking mechanism is designed to be flexible.

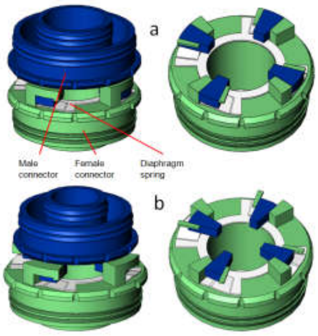


Fig. 5. Module joint. (a) Connection of male and female connector with the same size (b) connection of smaller male connector with regular female connector

The joints will be fabricated by 3D printing in this study. For practical usage, it should be injection moulded with engineering plastic or even metal to ensure the strength and endurance. The pressure tube is connected to the male connector to supply pressure for each module, while the sensor wire is connected to the female connector.

As in [14], internal passages are designed in the modules to accommodate pressure tubes and sensor wires, in order to keep the arm streamline and protect the lines and wires. The soft part of the module is made of liquid silicone rubber.

The diameter of the internal passage and the arm surface can be different. For modules close to the root, there will be more tubes and wires to go through the passage, and these modules have to carry more load than middle and rear modules, so the internal and external diameter of these modules should be larger. For the rear modules, the passage is cancelled since no tubes and lines passing by. In the following sections, only common modules in the middle of the arm are presented. The design concept and fabricate method are similar for other modules.

Sensors for contact need to be distributed over the external surface. It will be a challenge for cost, structure and fabrication. The fiber-reinforced soft actuator has a common feature: Kevlar (or other cloth) fiber distribute over the whole surface of the actuator. If we replace the cloth fiber with suitable metal wire and monitor the resistance, it's possible for the controller to estimate whether the actuator is in contact with the object or not. In this article, all the fiber used to reinforce the soft actuator are copper wires.

B. *Bending module*

The function of the bending module is to curve base on the bottom face as shown in Fig. 6.

The bending module can have 2 chambers which can bend in both direction, or 1 chamber which can bend in one direction. We focus of actuator with 2 chambers in this article. There is a Nylon sheet between the two chambers forming a neutral face which will not extend or shorten in working. The wires distribute beneath the external surface in circular. Wire outlet is also designed on the edge of the neutral face to avoid disturbance, and fixed on the male connector. Fig. 7 presents the fabrication of the bending module. Firstly, liquid silicone rubber is poured into the outer mould (Fig. 7a). Then the inner mould is inserted into the mould guided by the mould cover and fit with the outer mould. The liquid silicone rubber will overflow the mould when the inner mould fully inserted (Fig. 7b). After the rubber cured, remove the moulds (Fig. 7c) and cut off extra part (Fig. 7d). Glue two of the parts fabricated in this procedure with the Nylon sheet, fix each end to the male and female connector, and place the curvature sensor on the edge of the Nylon sheet (Fig. 7e). Attach the copper wire on the outer surface of the module and lead out along the edge of the Nylon sheet (Fig. 7f). Insert this component in the outer finishing mould, and fill the space between them with liquid silicon rubber (Fig. 7g). Insert the inner finishing mould and the rubber will overflow the mould. After the rubber cured, remove the moulds and get the completed bending module.

For bending module, the key parameter is the bending angle and contact situation. Sensor are placed to monitor bending angle. The optical curve sensor is placed on the neutral surface.

C. *Twisting module*

The function of the twisting module is to rotate the end face around its central axis as shown in Fig. 8.

The twisting module has an annular chamber. The wires distribute beneath the external surface in helical shape. The effect of fiber has been studied in multiple articles [14,16]. Wire outlet is located on the male connector. Fig. 9 shows the fabrication process of the twisting module, which is basically the same as bending module.

For twisting module, the key parameter is the rotating angle of the end surface compare to the bottom surface and contact situation. Sensors are placed to monitor the rotating angle.

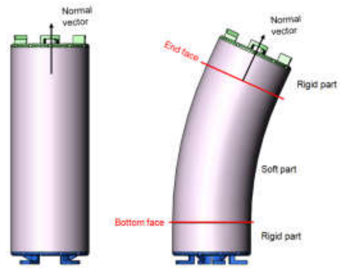


Fig. 6. Bending module function

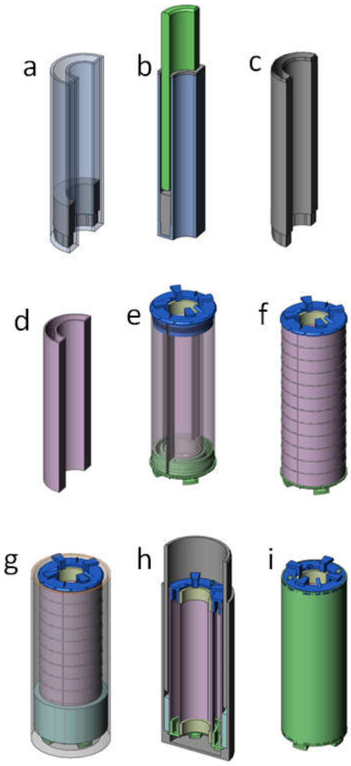


Fig. 7. Fabrication of bending module. (a) Liquid silicone rubber poured into the outer mould. (b) Inner mould inserting. (c) Moulds removed. (d) Extra part cut. (e) Assembly of the bending module. (f) Copper wire attached and leaded out. (g) Liquid silicone rubber poured into the finishing mould. (h) Inner finishing mould inserting. (i) remove the moulds

D. Twining module

The function of twining module is to form a helical shape as shown in Fig. 10.

The only difference between twining module and twisting module is that the twining module has a neutral line in axial direction beneath the external surface.

The key parameter for a twining module is the diameter of the inner helical line and contact situation. Obviously, the inner helical line is the deformed neutral line. Since the diameter of the inner helical line is very difficult to observe, we monitor the curvature of the neutral line with optical curve sensor arranged along it.

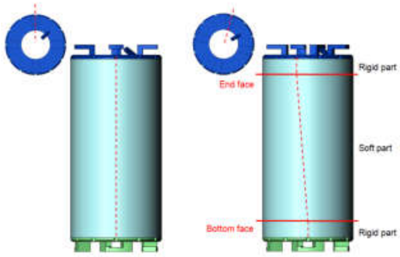


Fig. 8. twisting module function

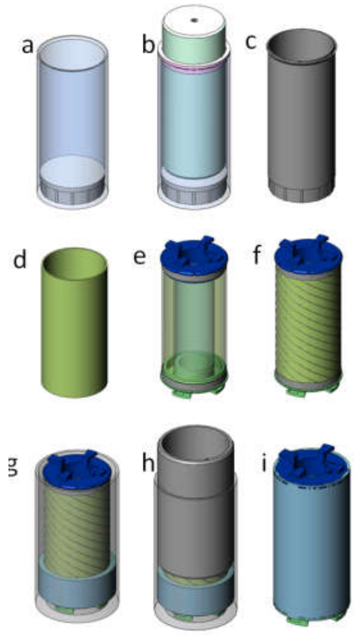


Fig. 9. Fabrication of the twisting module. (a) Liquid silicone rubber poured into the outer mould. (b) Inner mould inserting. (c) Moulds removed. (d) Extra part cut. (e) Assembly of the twisting module. (f) Copper wire attached and leaded out. (g) Liquid silicone rubber poured into the finishing mould. (h) Inner finishing mould inserting. (i) remove the moulds

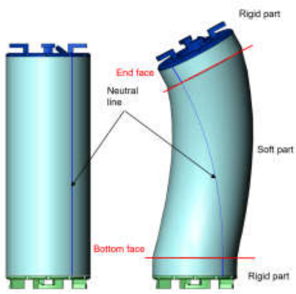


Fig. 10. Twining module function

E. Extending module

The function of extending module is to extend as shown in Fig. 11.

The only difference between extending module and twisting module is that the wires are distributed circularly instead of helically beneath the external surface.

The key parameter for a extending module is the length of the module. Extending module is not designed to contact the object, so the contact monitoring is unnecessary.

F. Expanding module

The function of expanding module is to enlarge the external diameter as shown in Fig. 12.

The only difference between expanding module and twisting module is that the wires are distributed axially instead of helically beneath the external surface.

The key parameter for an expanding module is the length of the module and the contact situation.

Ⅳ. CHARACTERIZATION OF SOFT MODULES

The performance has to be characterized for each module in order to design the sequence of the arm and help to develop the control system. The performance of the modules is determined by material, wire arrangement, pressure medium and so on. All the effects of the factors should be tested by the test system. Since the function of the modules are different, test method has to be designed for each of them. All the tests are performed by a strength test machine, which can give the relationship of displacement and load.

A. Bending module

The performance of the bending module is evaluated by the deviation of the end face normal vector, as well as the radial loading ability. These parameters cannot be measured directly by the strength test machine, so special fixture and data processing is needed.

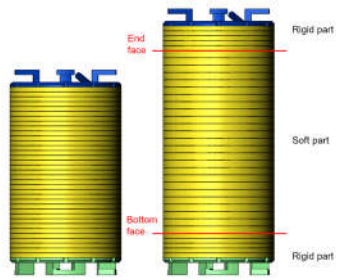


Fig. 11. Extending module function

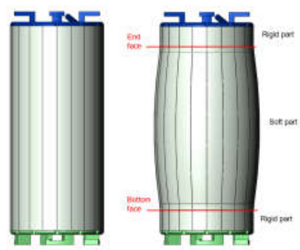


Fig. 12. Expending module function

The purpose is to test the radial force F of the module with the shape of the module force to be unchanged by the test machine, and find out the deviation of the end surface normal vector θ in free load condition. The conception of the test is shown in Fig. 13a. The length of the bending module soft part is L. when it bends, the neutral face of the soft part will form an arc with arc-length L. the end point travel l can be measured by the tester. So the relationship of θ and l can be easily obtained by simple geometry:

$$\begin{cases} l^2 = (L - R\sin\theta) + (R - R\cos\theta)^2 \\ R = L/\theta \end{cases} \quad (1)$$

Derives:

$$l/L = \sqrt{(1-\sin\theta/\theta)^2 + (1/\theta - \cos\theta/\theta)^2} \quad (2)$$

The curve of the function shows in Fig. 9b. The l/L gets to maximum value about 1.26 when θ gets around 234°. It means that the greatest value we can test by this method is 234°, which is big enough for the test.

Also we can have:

$$\begin{cases} \tan\alpha = (R - R\cos\theta)/(L - R\sin\theta) \\ \beta = \theta + \partial - \pi/2 \end{cases} \quad (3)$$

The radial force F we need to measure can be derived by:

$$F = T\cos\beta \quad (4)$$

Be noticed that the length L have to be the length of the soft part, not the whole length of the module.

The test system is shown in Fig. 14. The wire is attached to a wire locator mounted on the free end of the module, and it will locate the wire end to the edge of the neutral face and the boundary of soft and rigid part of the module.

The test performed in 2 steps: firstly, the test machine keeps the module in horizontal position and pressurize the module to a given value, then record the force after the reading stabled. Secondly, control the test machine slowly release the actuator until the force goes to 0 while the pressure in the actuator kept constant, and record the relationship of the force and displacement during the releasing. By convert the value of the displacement and force into normal vector deviation and radial force as described above, we can get the "compliance characteristics" [14] of the bending module.

B. Twisting module

The performance of the twisting module is evaluated by the rotating angle of the end surface, as well as the torque output ability. These parameters can easily be measured by the test machine with a pulley to transfer the toque and rotation into force and displacement. The test system is shown in Fig. 15.

The test procedure is basically the same as bending test: test the force in a certain pressure without shape changing; slowly release the actuator until force goes to 0 while the pressure kept constant, record the relationship of the force and displacement; convert the value of force and displacement into torque and angle.

C. Twining module

The behaviour of twining module is the combination of bending module and twisting module. Bends around the neutral line and twist a little around the central axis so it can form a helical shape instead of a ring. The deformation and force generation are extremely complicated. The performance should be evaluated by the diameter of the helical line formed by the neutral line D, and the radial force it can provide. But these parameter is very difficult to be measured by the test machine. Instead, the helical angle and axial force is measured to evaluate the performance of the twining module.

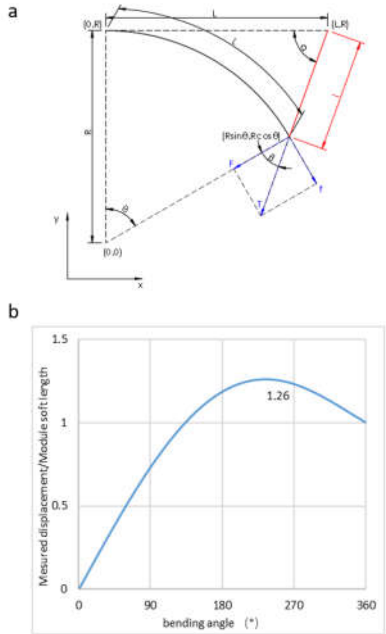


Fig. 13. Concept of the bending test. (a) Bending test analysis in Cartesian coordinate system. (b) Relationship of bending angle and tester's travel

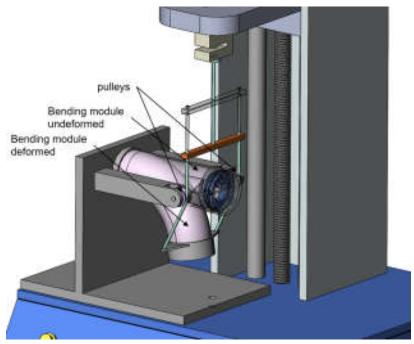


Fig. 14. Bending test system

The lead angle of the neutral line formed helical line γ will decrease with the rising of the pressure. Since the length of the neutral line L will not change, the axial length will decrease in this process. If the helical line unfolded around its central line, the relation of the lead angle γ and axial length change l shows as Fig. 16.

Obviously we have:

$$\gamma = \arcsin((L-l)/L) \quad (5)$$

There is another dimension needs attention:

$$C = L\cos\gamma \quad (6)$$

It's the circular portion of the helical line. If we know the revolution n of the helical line, we have the diameter of the helical line:

$$D = C/\pi n \quad (7)$$

The test machine can detect the axial length change and the axial force generated by the twining module. The test system is shown in Fig. 17.

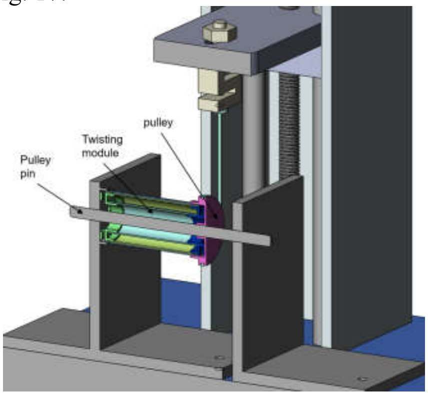


Fig. 15. Twisting test system

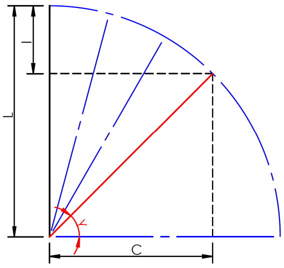


Fig. 16. Concept of the twining test

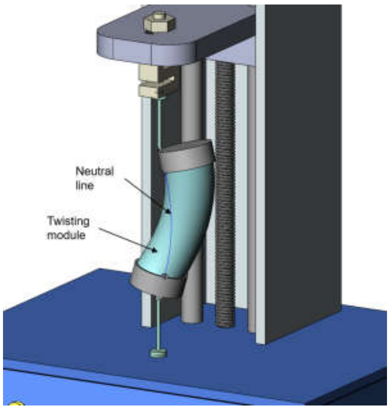


Fig. 17. Twining test system

The test procedure is basically the same as bending test: test the force in a certain pressure without shape changing; slowly release the actuator until force goes to 0 while the pressure kept constant, record the relationship of the force and displacement; convert the value of helical angle.

D. Extending module

The performance of the extending module is evaluated by the travel of the module, as well as the force output. These parameters can directly be measured by the test machine. The test system is shown in Fig. 14.

The test consists of two part: extending test and shortening test. Procedure of both test is basically the same as bending test: test the force in a certain pressure without shape changing; slowly release the actuator until force goes to 0 while the pressure kept constant, record the relationship of the force and displacement.

E. Expansion module

The performance of the expansion module is evaluated by the diameter change and the radial force it can provide. These parameters can directly be measured by the test machine. The test system is shown in Fig. 15. The test procedure is basically the same as bending test: test the force in a certain pressure without height changing; slowly release the actuator until force goes to 0 while the pressure kept constant, record the relationship of the force and displacement.

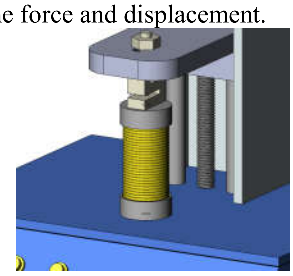


Fig. 18. Bending test system

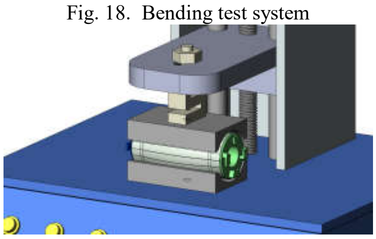


Fig. 19. Expansion test system

The quantitative metrics of each kind of module's performance are defined and the characterizing methods are introduced. These metrics not only used to compare the influence of different wire arrangement, different soft material and different pressure medium, but also the foundation parameters for future automatic control of the soft arm.

V. SUMMARY AND FUTURE WORK

In this paper, a flexible adaptive acquisition scheme of AUV for bionic soft robots is proposed. The scheme design and analysis of the soft arm are carried out, and the typical tasks of the acquisition device are simulated and verified. The design of the modules, especially the acquisition of touching signal, is a crucial part of this article. In additional, the fabrication procedure of the soft modules is also introduced.Flexible AUV reclaim scheme is an innovative scheme using soft robots to recover hard AUV.

The further work is required to study the influence of different materials on the performance of modules by using the test method proposed in this paper, and find out the most suitable material for the preparation of trial production. At the same time, the wiring method will be optimized. The validity of the touching signal acquisition method will also be verified and improved in the experiment. The handmade modules will be used for underwater functional testing. The constraints existing in the actual project will be fully considered to promote the engineering of the scheme.

REFERENCES

[1] Xisheng FENG,Yongkuan LIU. Current Situation and Trend of Research and Development of Autonomous Underwater Vehicles [J]. High technology communication, 1999, 9(9):55-59.

[2] Rong ZHENG.Tao SONG. Overview of Underwater Docking Technology of Autonomous Underwater Vehicles [J]. Chinese Ships Research, 2018, 13(6):43-49.

[3] Dawei WANG. Research on data fusion method in the recovery process of AUV for motion ship[D]. Harbin: Harbin Engineering University, 2011.

[4] Yeyi SUN, Haowei WU, Ye LI, et al. Summary of AUV underwater recycle docking technology[J]. Journal of Harbin Engineering University, 2019,40(1):1-11

[5] Yangqing JIANG. Study on critical control issues for AUV docking applications[D]. Harbin: Harbin Engineering University, 2016.

[6] WATT G D, ROY A R, CURRIE J, et al. A concept for docking a UUV with a slowly moving submarine under waves[J]. IEEE journal of oceanic engineering, 2016, 41(2):471-498

[7] CAO Yujun，SHANG Jianzhong，LIANG Keshan，et al. A review on the soft robotics[J]. Journal of Mechanical Engineering，2012，48(3)：25-33.

[8] WANG Tianmiao，HAO Yufei，YANG Xingbang，et al.Soft robotics：Structure，actuation，sensing and control[J].Journal of Mechanical Engineering，2017，53(13)：1-13.

[9] DONG Hongbing. Research on key technologies of a pneumatic soft omnidirectional bending module[D]. Harbin：Harbin Institute of Technology,2016.

[10] ROBERTSON M A，PAIK J. New soft robots really suck：Vacuum-powered systems empower diverse capabilities[J].Science Robotics，2017，2(9)：eaan6357.

[11] Connolly F, Plygerinos P, Walsh CJ, Bertoldi K. Mechanical programing of soft actuators by varying fiber angle. Soft Robot 2015; 2:26-32

[12] Galloway KC, Becker KP, Philips Bt, Kirby J, Licht S, Tchernov D, et al. Soft robotic grippers for biological sampling on deep reefs. Soft Robot 2016; 3:23-33

[13] Onal CD, Rus D. A modular approach to soft robots. In: Proceedings of the 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, Vilamoura, Portugal, October 7–12, 2012, pp. 1038–1045.

[14] Kurumaya S, Philips BT, Becker KP, Rosen MH, Gruber DF, Gallowway KC, et al. A modular soft robotic wrist for underwater manipulation. Soft robotics, 2018.

[15] Focchi M, Guglielmino E, Semini C, Parmiggiani A, Tsagarakis N, Vanderborght B, et al. Water/air performance analysis of a fluidic muscle. In: Proceedings of the 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, Chicago, IL, September 14–18, 2014, pp. 2194–2199.

[16] G. Krishnan. Kinematics of a new class of smart actuators for soft robots based on generalized pneumatic artificial muscles. 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, Chicago, IL, 2014, pp. 587-592.