Research on Motion Patterns of Soft Robots Based on Bionic Structure

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Abstract. Bionic soft robot is a new type of robot whose main body is composed of flexible material, with the advantages of adjustable size and strong environmental adaptability, which has a broad application prospect in logistics, medical care, resource exploration and other fields. Novel smart materials also shine in the design of soft robots. This paper highlights the research advancements in the locomotion patterns of bionic soft robots. The mechanism of movement of animals such as inchworms, starfish, earthworms, etc. and the soft robots designed to imitate them are introduced. Novel smart materials required to realise these designs, such as Shape Memory Alloy (SMA), dielectric elastomer (DE), a collapsible actuator (PFA), pNIPAM/CNTs hydrogel composite, are also presented. Methods to drive and control the motion of these soft robots are presented, including thermally driven shape memory alloys, pneumatic airbags, and laser-driven, magnetic field-driven, and electrically driven dielectric materials, among other types. After discussing the materials and methods, the current challenges to the innovation of motion patterns for bionic soft robots are analyzed.

Keywords: Bionic structure, soft robot, movement patterns.

1. Introduction

With the progress of science and technology and the development of productivity, robots in the military, industry, agriculture and many other fields to give mankind a lot of convenience, greatly reducing the risk factors of the human working environment, reduce people's workload. Traditional robots are usually composed of motors, hinges, gears and other components, with the advantages of high motion accuracy and simple drive mode. However, due to the rigid structure, it is difficult for traditional rigid robots to play a role in the face of increasingly complex working environments. In various fields, traditional robots face limitations. For example, to carry out scientific exploration in a narrow space, to complete the task under the condition of ensuring low noise and high concealment, and to collect vital signs data in the human body. Relying on the advantages of changeable size, strong environmental adaptability, high flexibility, and low noise, soft robots are gradually revealing their potential in industrial production, intelligent medical care, high-precision resource exploration and other fields.

Soft robots based on bionic structures integrate the movement patterns of natural animals into their design. By imitating the movement posture and force generation mode of arthropods, echinoderms, annelids and other animals, bionic soft robots can complete a variety of movement modes such as wriggling, swimming, crawling and so on by using various external drive modes such as shape-memory alloys, pneumatic-hydraulic pressure, electrically-activated polymers, electric motors, a steel wire rope and chemical drive. Examples include a pneumatic leech bionic robot and an electromagnetically driven mantis shrimp bionic robot [1-2]. By mimicking the movement of animals, soft robots can achieve the task of high degree of freedom, long-distance movement in a smaller size, which is safer and more reliable compared to traditional robots. This technology has a wide range of applications, including motion simulation assistive robots in scientific research and demining robots in the military [3]. Through the design and fabrication of bionic soft robots, human beings can make better use of nature's intelligence to achieve more efficient, flexible and intelligent robotic systems.

Focusing on these advantages, this paper introduces the locomotion mechanisms, drive modes, and control methods of bionic soft robots, and provides an outlook on the possible challenges of future research on the locomotion modes of bionic soft robots.

2. Research status of bionic soft robot

2.1. Underwater robots

Based on the soft skeleton and centrosymmetric structure of a starfish, a soft-bodied robot imitating a starfish has been designed and fabricated, which utilises shape-memory alloy (SMA) actuators for multi-gait locomotion [4]. The structure shown in Fig. 1 was created utilising 3D printing technology. A kinematic model of the SMA spring was constructed and refined to facilitate motion control based on specified displacement and force criteria. The motion process of the starfish robot can be divided into the following six states. The front two tentacles bend and move forward using friction with the ground. The rear two tentacles then bend and raise the entire body so that the centre of gravity is shifted forward. The last tentacle flexes and the soft structure reaches a steady state and accumulates elastic potential energy for crawling. The first two tentacles relaxed and the centre of gravity shifted forward again. The back two tentacles also relax releasing elastic potential energy to propel the robot forward. The last tentacle relaxes and the soft robot returns to its original body shape, completing the forward displacement. Once there is an obstacle in the path of travel of the Starfish soft robot that can be crossed. The two tentacles in the front could bend ahead of time and hold the obstacle underneath them, propelled by the rear three tentacles. And when it comes to obstacles that must be circumvented, the Starfish soft-bodied robot splits the curved path into straight, angled segments.

Figure 1. Structure of Starfish Soft Robot [4]

A recent study reported that an underwater bionic crab soft robot based on dielectric elastomer (DE) possesses unique motion patterns [5]. The bionic crab robot controls obstacle avoidance capability in water by regulating power and frequency on one/both sides of the foot to achieve multi-directional movements such as ascending/descending, underwater advancement and lateral crawling. The underwater bionic crab soft robot is powered by a combination of a voltage source, a signal generator and a voltage amplifier that can generate voltages in the order of kilovolts. When a strong electrical charge is passed through the electrode regions on either side of the connection, the film undergoes deformation due to Maxwell stresses. These stresses cause compression in the thickness and expansion in the length and width of the film. When the joint is no longer energized, the Maxwell stresses dissipate, causing the joint to revert to its original bent position. By employing the described deformation mechanism, cyclic bending deformation of the actuator joints can be induced through periodic alterations in voltage. The robot's ability to regain balance post power cessation is facilitated by the elasticity inherent in both the dielectric material and the robot's body. Crabs swim through the water by swinging their flattened appendages and swinging their legs to either side. When a low-frequency excitation voltage is simultaneously administered to both ends of the actuator, it induces a slow and symmetrical oscillation of the robot's two feet with a substantial amplitude. Conversely, the application of a high voltage to both ends of the soft robot concurrently results in a rapid contraction of both feet. The bionic crab robot can swim freely in the water under the reaction force of the current.

A composite-based soft underwater bionic snake robot powered by light has been designed. The R&D team used a pNIPAM/CNTs hydrogel composite [6]. When the material is illuminated by a xenon light source, the carbon nanotubes on the illuminated side rapidly absorb the light energy and convert it into heat. As a result, that side loses water and decreases in volume. The volume of the other side remains constant, causing the material to bend towards the light side. Once the light source is extinguished, the thermal energy in the water diminishes rapidly, causing the contracted side to reabsorb water and consequently restore the original volume. By controlling the thickness of the hydrogel, the time of exposure to the light signal, and the intensity, it is possible to regulate the degree of bending deformation, as well as the response and recovery times, of the hydrogel material. When the robot needs to move in concertina locomotion, a beam of light is shone from above onto joint 1, causing the soft-bodied robot's head to lift. Next, a beam of light is directed from below to joint 2, resulting in the upward arching of the robot's torso and the contraction of its body. With the illumination source removed, friction provides thrust and propels the robot forward. When the robot needs moving in serpentine locomotion to change direction, the laser scans from right to left to make that robot can achieve linear motion under continuous periodic irradiation.

2.2. Invertebrate soft-bodied robot

Wu P reported that a soft robot modelled on the movement pattern of an inchworm has been designed, consisting of two parallel rows of airbags, kicking legs, forefeet, hindfeet and sensors [7]. The key factor determining the different movement patterns of the robot is the inflation sequence of these two rows of airbags. The Differential Drive soft robot possesses the ability to navigate in two dimensions due to its distinctive foot configuration. The front feet are positioned beneath the skirting board, while the rear feet are located at the rear of the robot, aligned at a 60° angle to the skirting line. During inflation, the front and back feet have different sizes of contact area with each other resulting in different amounts of friction. The end with high friction serves as the anchor point and the other end moves as the airbag flexes. Therefore, the differential drive soft robots can move forward when both actuators are bent at the same time and the turning motion will be generated as a result of the varying bending angles exhibited by the two soft actuators. The control of two motions can be achieved through the utilization of a three-axis electronic compass sensor, an RBF model, and a pre-existing closed-loop control model. In the event of deviation from its intended path, the robot is capable of executing trajectory self-correction.

A new soft robot with three modes of rolling, Omega crawling and vermiculation has been designed [8]. Energy storage and discharge can be accomplished through the manipulation of the robot's physical configuration, and the robot can be moved with the help of gravity or friction. To achieve the three motion modes, as shown in Fig. 2, the soft robot is equipped with three distinct functional units: the deflection unit, honeycomb unit, and separation unit. These units are responsible for managing posture deformation, supplying driving force, and collaborating with the deflection unit to facilitate the transition between two motion states. By cooperating with the three basic functional units, three motion modes can be realized and switched between them. The integration of a deflection unit and a honeycomb unit can create the combination of a deflection unit and a honeycomb unit can form a freely bendable kinematic module. The whole robot is composed of eight such kinematic modules and a separation unit. The entire robotic system is composed of eight such kinematic modules along with a separation unit. In this soft robot, SMA is used as an actuator and the stiffness of the SMA is increased by heat. So by varying the temperature of the SMA through controlling the amount of load current, the soft robot can deform appropriately. Each SMA board deflection unit includes three SMA board pairs. Heating the enameled wires tightly wound on the SMA board causes the SMA board to bend axially, resulting in a change in the robot's motion pattern.

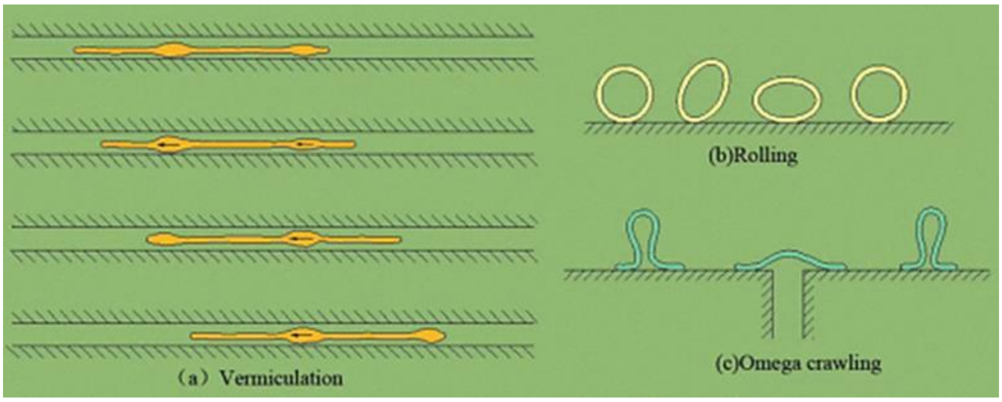

Figure 2. Three Movement Modes [8]

3. Research status of soft robot actuator

A multi-armed magnetic soft robot for object transport has been designed and developed, which consists of six individual small bendable magnetic robotic arms [9]. Individual robotic arms are subjected to a magnetic field from near too far and back again, showing a body-pulling motion similar to that of an earthworm. Subsequently, the magnet is disengaged, prompting the robot arm to revert to its original flat configuration and undergo a forward movement along the x-axis. The robot's six appendages have been programmed to magnetize exclusively in the radial direction, enabling comprehensive motion control of the robot with a single magnetization. Researchers control the robot to move pills over obstacles by changing the position of permanent magnets. There are a variety of barriers for testing, as illustrated in Fig. 3. When a vertical magnetic field is introduced, the robot retracts its six tentacles, while a horizontal magnetic field causes the robot to align its arms accordingly, resulting in three tentacles making contact with the ground. By altering the alignment of the magnetic field, it becomes feasible to control not only the robot's trajectory, but also its attitude, thus enabling it to execute tasks such as grasping or releasing pills. By continuously changing the alignment of the magnetic field, the researchers achieved regulated rolling motion of this robot on the surface.

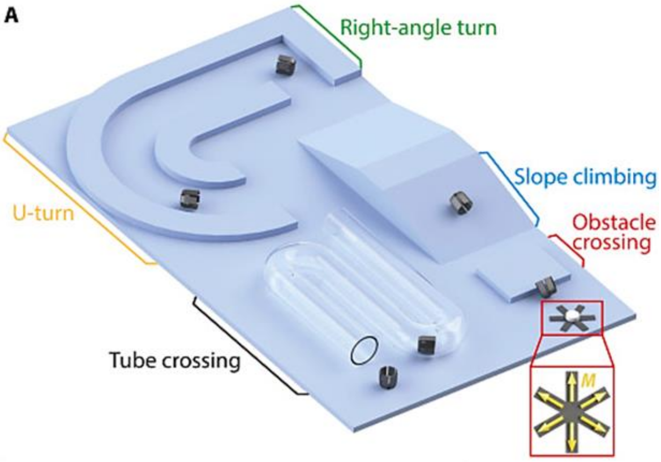

Figure 3. Test Barrier Platform [9]

Based on the Miura-ori pneumatic structure, the researchers have designed a collapsible actuator (PFA), which powers a crawling soft robot [10]. The robot consists of a PFA, a front foot and a back foot, most of which are made of flexible material and a small part of which is made of printed paper. Depending on the parallel structure and different control modes, this robot can perform linear and turning motions. Due to its turning motion capability, it can avoid obstacles, and its flexible structure gives it the potential to be applied in complex and diverse natural environments. It consists of a PFA foldable part, a transition part, a paper skeleton and a sealing part. Silicone outer skin is wrapped around the paper skeleton, and transition parts are added at both ends. The sealing cap is glued on the top of the transition part to ensure the air tightness of PFA and can be made into different shapes according to different requirements. Using the functionality of PFAs, researchers have designed a crawling robot consisting of two independent PFAs that are separated to the left and right, and can perform linear and turning motions based on a parallel structure and different control modes. The air pressure of the two PFAs can be controlled independently. During the folded and unfolded states, the state between the friction of the front and back feet is different, which gives the robot the power to move. The different motion modes depend on the different folding sequences. When both actuators are folded at the same time, the robot adopts a linear motion mode. However, with different elongation rates of the two actuators, the crawling robot performs a turning motion (Fig. 4).

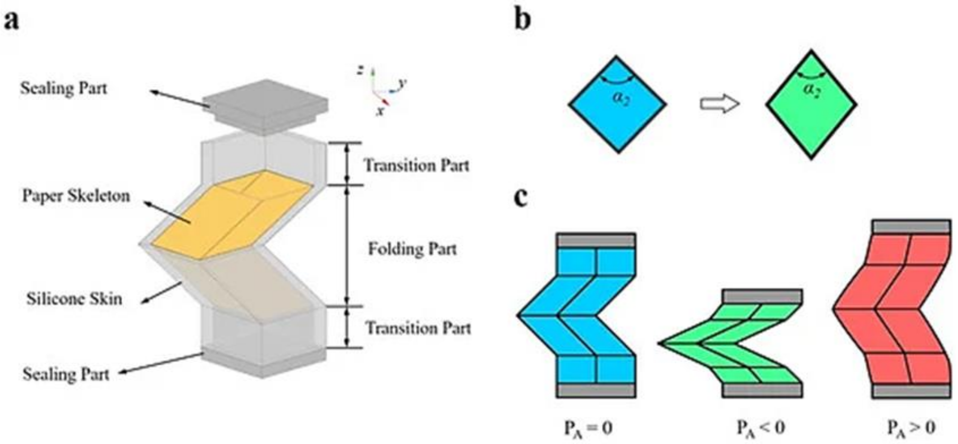

Figure 4. Schematic Structure of Collapsible Actuator (PFA) [10]

4. Conclusion

Research on bionic soft robots is still in its infancy, and despite its exciting prospects for great applications, it still needs to be improved in many areas, including precise gait control, energy supply issues, and the limitations of smart material. First of all, the soft material gives the soft robot a very high degree of freedom. To accurately control the robot's motion attitude requires a large number of calculations in order to simulate a well-fitting dynamics model. At present, no matter whether it is light, electricity, heat and other driving methods, cannot do like rack and pinion drive 100% real-time control of robot movement. Moreover, flexible sensors that can provide high-precision position information also constrain the development of soft robots. Currently, researchers mostly use multi-body discretization to deal with their robots and simplify the dynamics model, in order to try to control the size of the complex deformation of the bionic soft robot. In addition, the energy supply required for bionic soft robots to move is also a problem. The large mass of gas, power, and liquid sources can affect the motion of the bionic soft robot. Methods such as magnetic field drive require external energy intervention, which essentially means that soft robots cannot complete tasks autonomously. Finally, the development of bionic soft robots largely stems from the advancement of new smart materials. The current low service life of smart materials, low response speed, high cost of consumables, and high processing difficulty all constrain the development of bionic soft robots. These challenges need to be addressed to unlock the full potential of bionic soft robots. At the same time, the intelligent development trend of soft robots also needs the support of microelectronic components and flexible electronic technology.

In the future, the movement mode of bionic soft robots will develop in the direction of intelligence, autonomy and humanization, and continue to play a role in solving the problems of human production and life.

References

[1] Huang W, Xu Z, Xiao J, et al. Multimodal Soft Robot for Complex Environments Using Bionic Omnidirectional Bending Actuator. IEEE Access, 2020, 8: 193827–193844.

[2] Li Q, Zhang F, Jing Z, et al. A Hybrid Territorial Aquatic Bionic Soft Robot with Controllable Transition Capability. Journal of Bionic Engineering, 2023, 20 (2): 568–583.

[3] Karakasiliotis K, Thandiackal R, Melo K, et al. From cineradiography to biorobots: an approach for designing robots to emulate and study animal locomotion. Journal of The Royal Society Interface, 2016, 13 (119): 20151089.

[4] Mao S, Dong E, Jin H, et al. Gait study and pattern generation of a starfish-like soft robot with flexible rays actuated by SMAs. Journal of Bionic Engineering, 2014, 11 (3): 400–411.

[5] Li Q, Chen T, Chen Y, et al. An underwater bionic crab soft robot with multidirectional controllable motion ability. Ocean Engineering, 2023, 278: 114412.

[6] Wang X, Yuan Z, Guo Q, et al. An Underwater Bionic Snake Soft Robot with Tunable Deformation and Motion Based on Composite Materials. Advanced Materials Technologies, 2023, 8 (12): 2202012.

[7] Wu P, Jiangbei W, Yanqiong F. The Structure, Design, and Closed-Loop Motion Control of a Differential Drive Soft Robot. Soft Robotics, 2018, 5 (1): 71–80.

[8] Du Y, Xu M, Dong E, et al. A novel soft robot with three locomotion modes. 2011 IEEE International Conference on Robotics and Biomimetics, Karon Beach, Thailand, 2011: 98–103.

[9] Ju Y, Hu R, Xie Y, et al. Reconfigurable magnetic soft robots with multimodal locomotion. Nano Energy, 2021, 87: 106169.

[10] Yu M, Yang W, Yu Y, et al. A Crawling Soft Robot Driven by Pneumatic Foldable Actuators Based on Miura-Ori. Actuators, 2020, 9 (2): 26.