

The Structure and Application of a Flexible Manipulator Based on Octopus Biomimetics

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Abstract. With the gradual development of modern science and technology, robotic arms have become increasingly important equipment, which can replace humans to complete various tasks. It has played an important role in many fields such as science, military, and industry. But the traditional rigid manipulator is often limited in some special working environments. With the development of Bionics, people find that flexible manipulator has better performance in the special working environment. This article studies the mechanical structure, driving mode, control mode, and bionic suction cup of the octopus's biomimetic robotic arm, and conducts application analysis in three aspects: underwater rescue, narrow space operation, and fire rescue. It has been proven that flexible robotic arms have higher flexibility and larger motion space than rigid robotic arms. The octopus's biomimetic robotic arm has high flexibility and large load-bearing capacity, which has great research significance in dealing with special working environments such as narrow spaces.

Keywords: Octopus biomimetic, Flexible manipulator, Special working environment.

1. Introduction

With the continuous development of science and technology, robotic arms are increasingly widely used in various industries, such as scientific fields, military fields, industrial fields, etc. As people's understanding of robotic arms deepens, the importance of robotic arms in various fields is also increasing. The emergence of robotic arms not only improves production efficiency and product quality but also improves the working environment and people's quality of life, driving the development of various industries [1]. However, traditional rigid robotic arms have poor adaptability to the environment and are limited in working in narrow spaces, making them constrained in some fields. With the development of Bionics, people found that Mollusca such as octopuses have high flexibility, and began the research and design of soft manipulators.

This article first describes the mechanical structure of a biomimetic octopus's robotic arm, which is connected in series by a rigid joint rotation axis perpendicular to the axis of a continuously flexible body. SMA wires are installed in the muscle joints and a three-muscle joint is used. The octopus's robotic arm is driven by a PWM drive pulse to control the SMA wire and then controlled by a PC. Design the end of the octopus's robotic arm as a tentacle shape and add a circular suction cup. Afterward, the application analysis of the octopus's robotic arm was conducted from three aspects: underwater rescue, narrow space operations, and fire rescue.

Because the octopus is a Mollusca with no skeleton structure, it has higher flexibility. Moreover, the biomimetic octopus arm robot has the advantages of large load-bearing capacity, adaptability to narrow spaces and underwater environments, and has more application prospects and research significance.

2. Biomimetic octopus robotic arm structure

2.1. Mechanical structure

There are generally two types of joint combinations between robotic arms: series and parallel. As octopi's robotic arms are flexible bodies, the series connection is more suitable. The use of a series connection method where the axis of the rigid joint rotation axis is perpendicular to the axis of the

continuous flexible body can increase the overall spatial motion range of the robotic arm [2]. Therefore, this series connection method is chosen, as shown in Figure 1.

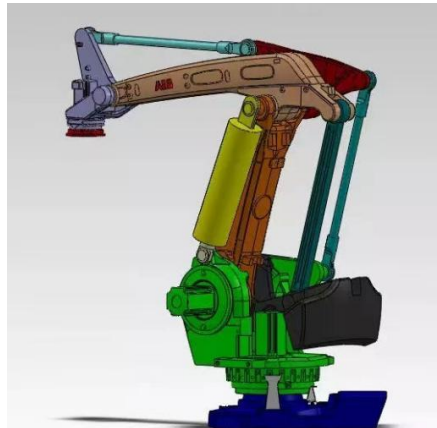


Figure 1. Series connection method [2]

The important biological feature of octopuses is that their volume remains unchanged during flexible deformation movements and materials that are soft and difficult to compress should be selected. So, silicone is chosen as the matrix material for flexible muscle joints. The main structure of flexible muscle joints includes five parts: bottom fixed base, inner spacer, top fixed base, robotic arm base, and SMA wire [3]. As shown in Figure 2.

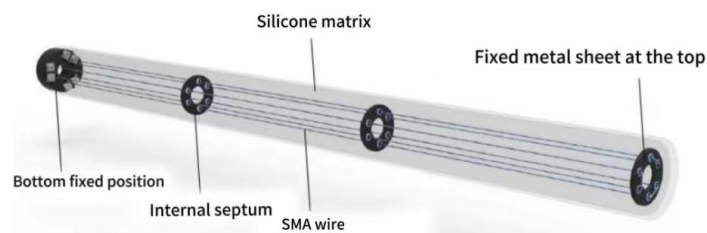


Figure 2. The main structure of flexible muscle joints [3]

Multiple flexible muscle joints can increase the stiffness of a robotic arm, but excessive flexible muscle joints can lead to a decrease in the flexibility of the robotic arm. Therefore, a choice should be made between three flexible muscle joints and four flexible muscle joints. Compared with the four flexible muscle joints, the three flexible muscle joints are lighter and less affected by gravity, so the three flexible muscle joints are chosen [4]. As shown in Figure 3.

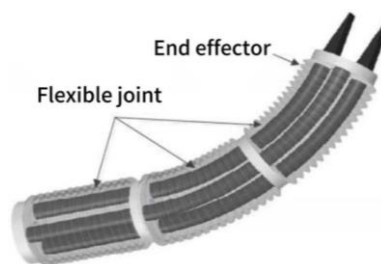


Figure 3. Three flexible muscle joints [4]

2.2. Flexible robotic arm operation

2.2.1 Driving method

The flexible muscle joint of the octopus's robotic arm is equipped with SMA wires, which control the temperature of the SMA actuator through the duty cycle of the PWM pulse [5]. The PWM drive pulse generation circuit diagram is shown in Figure 4. When the SMA wire is electrically heated, the SMA wire will transform Martensite to austenite when heated, and the shrinkage will generate a driving force. The flexible robotic arm will perform a flexible bending motion along the direction of the SMA wire at the driving end, while the other two sets of SMA wires will be passively stretched.

When driven by a single set of SMA wires, the robotic arm can perform flexible bending movements in three directions in space.

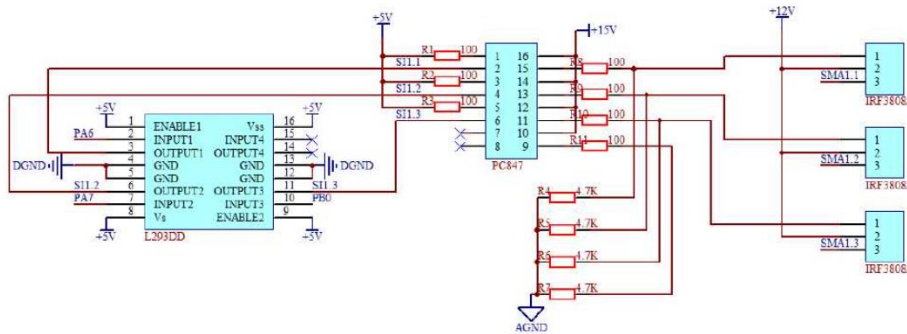


Figure 4. The PWM drive pulse generation circuit diagram [3]

2.2.2 Control method

The PC completes human-computer dialogue through a human-computer interaction interface. The PC sends instructions to the micro control system, which is used to store control programs and dynamic data transmitted by the PC. The micro control system drives the circuit and generates PWM driving pulses through the action of MOSFET switches to electrically heat the SMA [6]. Drive the robotic arm through an SMA actuator. To prevent the interference of analog end drive pulse signals on digital end pulse signals, photoelectric isolation should be carried out. The SMA actuator provides feedback to the micro control system through current sampling and analog-to-digital conversion circuits.

2.3. Biomimetic suction cup

The end of the octopus’s flexible robotic arm is designed in a tentacle shape, using the same driving and control methods as the robotic arm, but the difference is that the tentacle part adds an octopus biomimetic suction cup. The suction cup is designed as a circular ring, as shown in Figure 5. There are grooves on the surface of the suction cup, which can first subject the groove area to stress concentration. Under the action of force, the suction cup groove extends towards the surrounding area, producing a larger adsorption area. The circular suction cup has a greater degree of attachment to the object, which is conducive to sealing formation and has a certain degree of stability in the sealing effect [7].

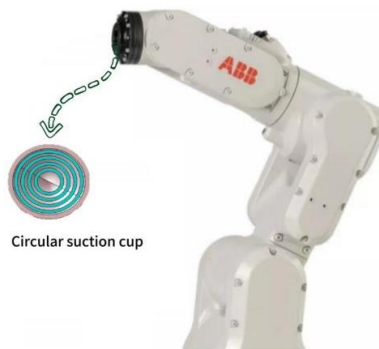


Figure 5. Octopus biomimetic suction cup [7]

3. Application Analysis

3.1. Underwater Rescue

Due to the unpredictable nature of the ocean and the frequent occurrence of marine accidents, robotic arms have been increasingly widely used in underwater rescue operations. The terrain in the ocean is more complex than on land, and traditional rigid robotic arms cannot fully function in water.

The movement space of the octopus's biomimetic flexible robotic arm is larger than that of traditional robotic arms, making it more advantageous to work in water.

Peng Li of Harbin Engineering University studied the hydraulically driven flexible arm and studied a new type of hybrid-driven underwater flexible arm by using the method of BioTRIZ and extents. By analyzing the force and motion of the flexible arm, the superiority of the hybrid drive was verified [8]. Xiaochen Yang of Hangzhou Dianzi University studied the Kinematics modeling of coconut octopus by analyzing the biped walking mode of coconut octopus, and compared it with the same type of underwater robot, proposed a set of flexible limb control method based on the biped walking mechanism of coconut octopus [9]. Yueqin Gu of Hangzhou Dianzi University has designed the DQN control strategy for the bionic octopus's arm by establishing the reinforcement model of the bionic octopus's arm and analyzing it. And by using the U-SLIP model, the analysis of the parameters of the foot gait model of the underwater biomimetic octopus's robot was completed [10].

3.2. Working in Narrow Spaces

Under certain specific working conditions, exploration and detection tasks need to be carried out in narrow spaces. The working space is very small and the shape of the items being grabbed is not regular, which requires high accuracy and reliability in grasping. Traditional rigid robotic arms cannot fully function in narrow spaces, while flexible robotic arms have high flexibility and good adaptability to complex-shaped working objects.

Chunbo Hao from the Hebei University of Technology, based on the rigid body replacement method and the virtual work principle, established the Statics model of the flexible manipulator's angle of rotation and the Statics model of the flexible manipulator's contact pressure and proposed a flexible manipulator design method that is simple in structure, low in cost, and reliable in work [11]. Shize Yu of Nanjing University of Aeronautics and Astronautics analyzed the narrow operating space based on the actual narrow space operation task as the research background. Using the spiral theory and designing a configuration model of biomimetic flexible joints, several configuration modes of flexible joints were analyzed, and the allocation scheme of single branch chain degrees of freedom for flexible joints was finally obtained [12]. Botao Hao of the Xi'an University of Technology determined the bending degree of the flexible manipulator based on the pseudo-rigid body method and the minimum energy method. Through the Kinematics modeling of the whole and single joint of the flexible manipulator, the maximum elongation and maximum bending angle of the single joint at different deflection angles are determined. According to the Monte Carlo method, the point cloud diagram is drawn to describe the workspace of the flexible manipulator [13].

3.3. Fire Rescue

There are many difficulties in the process of fire rescue, such as the walls that collapse at any time at the scene of the fire and the high-temperature hazardous areas that need to be dealt with promptly. Flexible robotic arms can be equipped with cameras to explore the terrain of a fire site and grab important items, and can also be equipped with high-pressure water guns to rescue locations that require timely handling. Flexible robotic arms need to be made of fire-resistant and high-temperature resistant materials, and the flexibility of the robotic arm needs to be ensured.

Qingyuan Ma, from the Dalian University of Technology, aimed at the thermal effect simulation of model stiffness in wind tunnel test, obtained the relationship between the Strength of materials properties and temperature through the mechanical property test of basic structural layer materials and variable stiffness functional layer materials, and designed and manufactured a hybrid composite structure model [14]. Wenhan Li of Yanshan University designed a flexible end-grab mechanism for small objects. A target dataset was created using Lambelimg software, and a deep learning network for detecting small items was designed and trained. A precise and flexible grasping system based on visual guidance has been designed [15]. Langue Huang of Zhejiang University of Science and Technology designed a variable diameter mechanism and flexible joints by analyzing the structure, bending characteristics, and Kinematics of the manipulator, and analyzed the overall bending

performance and local stiffness of the manipulator. The Kinematics model of the manipulator is established, and the motion space of the manipulator is analyzed. Finally, a rigid flexible coupling robotic arm was designed [16].

4. Conclusion

This article investigates the structure, driving method, control method, and suction cup of a flexible robotic arm that mimics octopus biology. In some special working environments, flexible robotic arms have better performance. This article analyzes the application of flexible robotic arms in underwater rescue, narrow space operations, and fire rescue, demonstrating the advantages of higher flexibility and greater movement space compared to rigid robotic arms.

Due to limitations in time, personnel, and other aspects, there are still areas that need to be studied and improved, which are reflected in the following aspects: 1. When a flexible robotic arm controlled by electricity works underwater, it is prone to leakage, leading to the collapse of the entire system. The optimal underwater driving and control methods for flexible robotic arms, as well as the stability of flexible robotic arms, are still challenges in current design. 2. Flexible robotic arms perform well in narrow spaces, but the size and degree of freedom of flexible robotic arms suitable for narrow spaces need to be addressed. 3. Due to the need to work in high-temperature environments such as fires, flexible robotic arms need to ensure both flexibility and resistance to high temperatures. Therefore, the selection of materials for the composition of flexible robotic arms and the application of fire-resistant paint are also issues that need further research.

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