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Overview of actuators, modeling, and control methods for soft manipulators

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ABSTRACT
Inspired by the biological organs in nature, many robots have been developed and successfully applied by imitating the characteristics of different animals. The design inspiration of a soft robot comes from the bending movement of an elephant trunk and an octopus arm. They can use their soft structure to effectively adapt to a complex and changeable environment and complete various complex operations. Their excellent flexibility and bending have attracted the interest of researchers. Continuing breakthroughs in materials science, chemistry, control, and other disciplines, and in the observation and modeling of soft organisms such as the octopus, worm, and starfish have led to a new robot research direction—soft robot. Soft manipulators are made of soft materials and can be used to accomplish tasks that rigid manipulators cannot accomplish, such as detecting in an unstructured environment, grasping fragile objects, and safer man-machine cooperation. Many countries are investing in this area; soft manipulators of various shapes and functions have been designed, using different manufacturing materials and driving, modeling, and control methods, exhibiting the uniqueness of each device. The driving ways of the soft manipulator are different according to their task purposes. This paper first studies three main driving ways of the soft manipulator: (1) tendon driving (tendon driving), (2) shape memory alloy driving (SMA driving), and (3) pneumatic driving (pneumatic driving). Modeling and control methods of soft manipulators in different driving modes are then studied. Finally, the development of soft manipulators is summarized and prospected from three aspects: (1) driving way, (2) modeling methods, and (3) control methods.

KEYWORDS:
soft manipulator, drive, modeling, control methods, research progress

1. Introduction

Traditional rigid robotic arms are widely used in industry and manufacturing, and can effectively perform specific tasks. However, when interacting with the environment, traditional rigid robotic arms have problems such as poor environmental adaptability and unsafe human-machine interaction. In essence, traditional robots are mainly made of rigid materials such as aluminum and steel, and because the rigid connections and joints of robots are relatively inflexible, they have certain insecurities and limitations when interacting with humans or the environment, and are difficult to apply to complex unstructured scenarios. In recent years, the handling and sorting of goods in factories and the scalpels used in surgical operations have begun to use robotic arms to assist. These application scenarios have put forward higher requirements on the flexibility and safety of robotic arms.

Inspired by biological organs in nature, many robots have been developed and successfully applied by imitating the characteristics of different animals, such as bionic soft robots [1] and bionic flapping wing flying robots [2]. The soft robotic arm studied in this paper is inspired by the bending movement of elephant trunks [3], [4] and octopus arms [5- 7]. Researchers have used different flexible materials [8], such as resin and silicone, to create soft robotic arms with flexibility, variable stiffness, and multiple degrees of freedom, making them safer for human-machine interaction. In addition, the high flexibility of soft robotic arms enables them to complete different types of tasks and has great economic potential in industrial applications.

In order for soft robotic arms to achieve multiple degrees of freedom, including bending, extension, twisting, and other movements, in addition to requiring materials with good softness and extensibility, the driving method is also very important. The existing driving methods mainly include rope drive (Tendon drive), shape memory alloy drive (SMA drive), pneumatic drive (Pneumatic drive), etc. Among them, Tendon drive is to embed the wire into the robot arm made of flexible materials, and realize the deformation of the robot arm by changing the length of the wire; SMA drive is mainly to achieve the overall movement and deformation of the robot arm by heating the SMA embedded in the soft robotic arm to generate deformation; Pneumatic drive mainly uses gas to drive the movement and deformation of the internal cavity of the robot arm. According to different driving methods, it is necessary to establish corresponding dynamic models and design corresponding control strategies. Due to the complexity of the soft robotic arm structure, it poses great challenges to the kinematics, dynamics modeling and control research of the soft robotic arm. This paper will discuss the current research status of the soft robotic arm driving mode and the corresponding modeling and control methods, and summarize and look forward to the development trend of the soft robotic arm.

2. Overview

Soft robotic arms are a new type of robotic arms with continuous geometric characteristics. Compared with rigid robotic arms, soft robotic arms are mainly made of soft materials (such as silicone, fluid, soft glue, etc.). They not only have advantages such as higher flexibility, compliance and safety, but also have good integration ability. They have broad application potential in many fields, such as medical treatment, field rescue, industrial grasping, etc. [9- 13]. At present, more and more researchers are engaged in the development, modeling, control and other research of soft robotic arm platforms [14- 16]. However, the development of soft robotic arms also faces many difficulties and challenges. Soft robotic arms are a composite application that integrates multiple interdisciplinary technologies such as materials science, bionics, robotics, and control science. This also determines that it cannot achieve great progress by relying on the development of a single discipline. From the perspective of materials science and mechanics, "soft" is the essential attribute of soft robotic arms. Soft materials are the key to making soft robotic arms. In terms of materials, scientists use Young's modulus to define rigid materials and soft materials, that is, materials above 109 Pa are rigid materials. (such as metal or hard plastic), and those below 109 Pa are soft materials (such as skin, muscle tissue, etc.). How to obtain better materials and newer bionic structures puts forward requirements for materials science and mechanics, and also puts forward higher requirements for 3D printing technology. How to efficiently and quickly process the body structure that meets specific needs is also a difficult problem. From the control point of view, the high degree of softness makes it difficult to integrate traditional encoders, potentiometers and rigid force tactile sensors into soft robotic arms. The unlimited degrees of freedom and large deformation nonlinear characteristics make it very difficult to establish the kinematic and dynamic models of soft robotic arms, which in turn brings many challenges to control design. It is urgent to develop new control theories and modeling methods. This paper takes the driving mode as the starting point, introduces the modeling and control of the three mainstream driving modes, and makes a prospect on the research status and future development trend of soft robotic arms.

3. Conclusion and Outlook

This paper first introduces the definition of soft robotic arms, then focuses on the three mainstream driving methods and the results of the current application of these three driving methods, and then briefly summarizes the modeling and control of soft robotic arms, and analyzes the problems currently encountered in the modeling and control of soft robotic arms.

At present, the driving method of soft robotic arms is still mainly rope-driven, which has the advantages of simple manufacturing and strong load capacity, but the soft robotic arms based on rope drive have weak load capacity and lack modular solutions. The SMA drive and pneumatic drive methods make the model difficult to manufacture, and the modeling and control are not accurate. Its advantage is that the load capacity is relatively strong, and modular and integrated design can be achieved in the future. According to the current research status of soft robotic arms, research needs to be carried out in the following aspects in the future:
From the driving perspective, for SMA drive, although SMA has been widely used, SMA deforms when high-temperature austenite changes to low-temperature martensite, and the recovery process is relatively slow. How to overcome this slow process and maximize its function is also a research direction. For pneumatic soft robotic arms, new materials are urgently needed. New design mechanism, because the deformation of pneumatic soft arms is completed by the contraction and expansion of the air cavity, the air cavity is pressure-resistant. Once the air cavity is damaged, the entire pneumatic system will fail, so the development of a new material that is not easy to break is of great significance to pneumatic soft arms. In addition, the driving structure design of pneumatic soft robotic arms also has a decisive influence on their driving performance. For the rope-driven soft arm, although it can provide a large output torque, and the rope can pass through complex paths and fit well on the soft arm, it requires a set of external devices, which greatly reduces its application space.

How to simplify its auxiliary devices is an important task in the future. From the modeling point of view, in the existing soft robotic arms, there is a problem of low control accuracy, which makes it difficult for soft robotic arms to play their value in fine fields such as medical treatment and assembly. This is because the material of the soft robotic arm has strong nonlinearity and has infinite degrees of freedom. At present, its motion mechanism and related theories are not understood, making modeling and control difficult, whether it is the common PCC modeling, SMA thermal model or Cosserat The model accuracy of the beam modeling is not as good as that of the rigid robot arm. In order to solve this problem, it is very necessary to develop a modeling theory for the soft robot arm. In addition, how to more accurately describe the various state variables of the soft robot arm, such as the torsion and bending of the soft arm itself, is also a difficult problem.

From the control point of view, for the soft robot arm driven by rope, the solution of inverse kinematics still needs a long-term study. The dynamic model should be able to fully describe the movement of the entire robot arm. The control strategy should achieve real-time and accurate control as much as possible, and compensate for the inaccurate parts of the modeling. For the pneumatic soft robot arm, because the way of gas pressurization is limited, there is an obvious time lag between the signal generator and the drive actuator, which has a certain impact on the movement of the soft robot arm. How to solve this hysteresis problem is also a research direction. For the SMA-driven soft robot arm, because SMA has a saturation hysteresis problem during the phase change process, how to use a suitable control scheme to solve this saturation hysteresis problem is also a research direction.

In the research of soft robot arms, the research of sensors is also an important direction. At present, there are several sensors that can adapt to the bending and torsion of soft robot arms, but they all have their limitations. EMI sensors can measure the posture of soft robot arms, but they are easily affected by the electromagnetic environment; flex bending sensors can bend, but in a single direction; FBG sensors can be used to ... Sensors can also measure elastic deformation, but they are easy to break and expensive. Therefore, the research on sensors with soft characteristics becomes particularly important.

Although there have been very encouraging results in the research on soft robotic arms, there is still a long way to go. The future of soft robotic arms must be a multidisciplinary achievement, and it will shine in various fields. In addition, more work needs to be invested in the precise modeling and control of soft robotic arms, multi-sensor and multi-drive modeling and control, modeling and control of collaborative operations of soft arms, path planning control, optimization control, model predictive control, etc. With the continuous maturity and breakthroughs of soft robotic arm technology, in the near future, soft robotic arms will play a more important role in post-disaster rescue, postoperative rehabilitation, minimally invasive surgery, aircraft maintenance, industrial manufacturing and other fields.

4. References

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