Software Robot Driver and Sensing Technology

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Abstract. Soft robots have the advantages of high flexibility, strong environmental adaptability, and safe human-computer interaction. They have great potential in medical rehabilitation, industrial grasping, and other fields. Drive and sensing technology is the key to achieving precise and controllable motion, and it is also the focus and difficulty of current research. This article provides a comprehensive discussion on the main driving and sensing technologies of soft robots. In terms of driving, this article focuses on the principles, strengths, weaknesses, and usage scenarios of three mainstream technologies: pneumatic driving, shape memory alloy driving, and dielectric elastomer driving. In terms of sensors, it involves flexible sensor technology for achieving ontology perception and external perception, as well as how to integrate them. Then, specific examples such as soft rehabilitation gloves, biomimetic muscle drivers, soft grippers, and adaptive grasping control are used to describe how these technologies work together in practical systems and provide corresponding completion plans. This study aims to provide technical references for the design and application of soft robots.

Keywords: Soft robot, Drive technology, Sensing technology, Flexible electronics.

1. Introduction

With the development of robot technology from traditional rigid structures to flexible and intelligent directions, soft robots, as a new type of biomimetic robot, are receiving attention from both academia and industry. It is mainly composed of soft materials with strong stretchability, environmental adaptability, and intrinsic safety [1]. It can achieve flexible movement and safe human-computer interaction in nonstructural environments. Therefore, it has a wider application prospect than traditional rigid robots in cutting-edge fields such as medical rehabilitation, post disaster rescue, industrial grasping, and exploration and detection [2]. However, due to the infinite degrees of freedom of soft robots and the nonlinear factors of materials, there are issues with precise and efficient driving and perception of them. Traditional rigid motor drives and sensors are difficult to integrate directly [3]. Developing new driving methods and sensing technologies that match them to achieve precise control of complex deformations and forces in soft robots is a core technical challenge that restricts their development. Therefore, in-depth research on the driving and sensing technologies of soft robots, breaking through relevant theoretical and technological bottlenecks, has important theoretical significance and practical value for promoting the transition of soft robots from the laboratory to practical applications and expanding the application boundaries of robot technology.

2. Software Robot Driver Technology

2.1. Pneumatic Drive Technology

Pneumatic drive technology is the most widely used and mature driving method in the field of soft robots. Its working principle is to accurately fill or discharge compressed gas in the closed chamber or pre-set channel network inside the robot, and through the pressure difference, the flexible structure undergoes expected bending deformation, extension, contraction, and twisting movements. Its main advantages are simple structure, high output force, fast response speed, and good flexibility, which can safely interact with people or fragile objects; However, due to its reliance on external air pumps, valves, and pipelines for control, the integration of the system is poor, which limits the portability and mobility of the robot [4].

2.2. Shape Memory Alloy Drive

Shape memory alloy (SMA) driving is an intelligent material technology based on the thermal mechanical phase transition of materials. The basic principle is that it is prone to deformation under low-temperature martensitic phase. When the temperature of the material rises above the threshold of phase transition by passing current or using an external heating device, it can return to the pre-set shape of high-temperature austenite phase and generate a huge contraction force and displacement motion. The push-pull force generated in this process is very large [5, 6]. Unlike traditional robots, SMA has the advantages of a high power to weight ratio, a lightweight and compact structure without noise, and inherent flexibility. Therefore, it is very suitable for use in various miniaturized integrated soft robot applications [7]. But at the same time, its drawbacks are also obvious, as SMA requires heat to drive, resulting in slow reaction time and limited heat dissipation; In addition, the low conversion efficiency also means that problems such as high-power consumption make control more difficult, and the most critical point is that the presence of strong nonlinear effects can easily lead to hysteresis, making precise control more complex.

2.3. Dielectric Elastomer Drive

Dielectric elastomer drive belongs to a new artificial muscle technology that relies on electroactive polymers. Its working principle is generated by Maxwell stress. When a high voltage is applied to the flexible electrodes on both sides of the film, the Coulomb force causes the film to contract in the thickness direction and expand outward in the plane [8]. Therefore, it can cause significant surface strain and driving force. This technology responds quickly (up to milliseconds), has a large deformation rate (up to 100%), high energy density, light weight, and no noise, and is considered one of the most feasible artificial muscle systems. However, it also faces great challenges, requiring thousands of volts of high voltage as the driving source, which poses safety hazards and increases the difficulty of system integration [9]. In addition, the insulation breakdown resistance, electrical fatigue resistance, and pre stretching process stability of the material. The issues in this regard also pose limitations for long-term reliable use.

3. Soft Robot Sensing Technology

3.1. Ontology Perception Technology

Ontology perception technology is the foundation for achieving precise closed-loop control of soft robots, which requires real-time acquisition of information such as the robot's own deformation, posture, and internal force state [10]. Due to the continuous deformation characteristics and infinite degrees of freedom of soft robots, traditional rigid sensors are difficult to apply, and it is necessary to develop flexible sensing technology that matches them [11]. Strain sensing is the core, and flexible strain gauges are prepared by incorporating conductive fillers (carbon nanotubes, graphene) into elastic matrices or by accurately measuring tension, compression, and bending using changes in liquid metal channel resistance [12]. The sensing technology based on fiber Bragg grating has been widely used in complex deformation reconstruction due to its advantages of anti-electromagnetic interference, high accuracy, and easy multi-point integration [13]. Pressure sensing, on the other hand, utilizes piezoresistive or capacitive structures to sense internal air pressure or contact force. These flexible sensors can be embedded or printed onto the robot body to achieve distributed conformal sensing, providing important data support for building the body "sensing" system of soft robots and completing their high dynamic motion control [14, 15].

3.2. External Perception Technology

External perception technology enables soft robots to interact with their surrounding environment, which is a key part of their autonomous navigation, safe operation, and making informed decisions. Compared to proprioceptive perception, external perception requires obtaining information beyond

the robot itself, such as object shape, distance, texture, and temperature, which all need to be understood. Visual sensing, in particular, uses small cameras on flexible substrates to bring a large amount of environmental information to the robot, which can be used to identify targets and implement navigation [16, 17]. Tactile sensing relies on the flexibility of the "skin" of adhesive pressure, shear force, vibration, or temperature sensors to make the robot feel the force of contact and the surface characteristics of the grasped object, and perform precise grasping and manipulation based on this. Proximity sensors, such as flexible capacitors or infrared sensors, can detect the presence of obstacles without contact, avoiding collisions [18]. The main challenge faced by these external perception technologies is how to transform rigid sensing elements into flexible ones, or develop sensors with inherent flexibility characteristics that can perfectly integrate into the soft surface of soft robots, and build a complete external perception system without affecting the flexibility characteristics of the entire robot.

3.3. Integration Method of Flexible Sensors

The integration method of flexible sensors is one of the determining factors for the perception performance and reliability of soft robots, with the aim of integrating sensing functions with the robot's body structure [19]. Currently, common integration methods include embedded systems.

There are three types: integration, surface mount integration, and additive manufacturing integration [20, 21]. Embedded integration is an integration method in which sensors are pre embedded in elastic materials during the robot manufacturing process. It has good protection and can achieve deep level perception, but it will reduce the mechanical properties of the body. Surface mount integration, on the other hand, involves bonding or welding sensors onto the surface of a robot, making it easy to install and replace. It is suitable for sensing the environment, but it is susceptible to wear and tear. The most promising method is to use additive manufacturing integration, which can mix conductive sensing materials and structural materials together through multi material 3D printing technology to achieve conformal design and high integration between sensors and driving mechanisms. This not only improves system reliability but also provides higher design freedom.

4. Application Cases of Soft Robot Driver and Sensing Technology

4.1. Medical Rehabilitation Applications

4.1.1. Soft rehabilitation gloves

Soft rehabilitation gloves belong to the typical application of soft robots in the field of medical rehabilitation, with a focus on implementing rehabilitation training for motor dysfunction in stroke or spinal cord injury patients. Its driving methods are mostly pneumatic or cable driven, and the flexible air chamber integrated in the finger part is inflated or the embedded tendon rope is pulled to accurately push the finger to perform rehabilitation actions such as flexion and extension. Sensing technology is also very important. After installing flexible bending sensors at the finger joints, the patient's movement angle and desire to exert force can be detected in real time; By placing the pressure sensor at the fingertips, the strength of the grip can be felt. These sensor data form a closed-loop control system, allowing rehabilitation gloves to dynamically adjust the assistance force according to the patient's recovery situation, achieving personalized training combining "active passive". Compared with traditional rigid rehabilitation equipment, soft rehabilitation gloves have many advantages, such as light weight, comfortable wearing, good safety performance, and natural human-computer interaction. They can help patients improve training compliance and rehabilitation effects, and are one of the important directions for the future development of rehabilitation medicine.

4.1.2. Biomimetic muscle driver

The biomimetic muscle driver is a new type of driving device that mimics the structure and function of biological muscles, and has great potential in the field of medical rehabilitation, especially suitable for the application of powered prostheses and exoskeleton systems [22, 23]. This type of

driver often uses soft driving technologies such as pneumatic artificial muscles or dielectric elastomers, which can simulate the contraction and relaxation movements of real muscles, producing smooth and natural force output and motion trajectories. The main advantages are inherent flexibility and high-power density characteristics, which can provide strong auxiliary power while ensuring safe interaction with the human body without causing rigid impact. In order to achieve precise control, strain sensors are installed inside the driver to monitor shrinkage.

Externally, force sensors are used to detect the interaction force between the human body and the quantity. This perceived information will be fed back to the control system to adjust the corresponding parameter values, making the movements of the prosthetic or exoskeleton more in line with the user's motion intention. The biomimetic muscle driver imitates the parallel or series layout of muscles on the body, which can reproduce the complex movements of human joints and provide patients with more natural and efficient walking and limb function recovery assistance.

4.2. Industrial Grabbing Applications

4.2.1. Flexible claw design

Flexible grippers are the core components of soft robots in industrial grasping applications, aimed at addressing the limitations of traditional rigid grippers in grasping fragile, irregular, or deformable objects. Its design usually adopts pneumatic drive, by inflating the multi finger or multi chamber structure made of elastic materials such as silicone, causing it to bend or wrap, thus adaptively conforming to the shape of the grasped object. This passive compliance enables it to stably grasp objects of various shapes, such as fruits, glassware, or electronic components, without the need for complex visual positioning and trajectory planning [24]. In order to improve the intelligence level of grasping, flexible pressure or strain sensors are often integrated into the fingertips or the inner surface of flexible grippers. These sensors can sense the magnitude and distribution of contact force in real time, determine whether the object has been stably grasped or if there has been slippage, and provide feedback to the control system. This fusion of driving and sensing enables flexible grippers to demonstrate significant advantages in automation sorting, food processing, and precision assembly, including high efficiency, safety, and strong versatility.

4.2.2. Adaptive grasping control

Adaptive grasping control is a key technology for the intelligence of flexible grippers, which relies on sensor feedback to autonomously and stably grasp unknown objects. It relies on a flexible pressure, strain, or tactile sensor array in the gripper to obtain timely information on contact force, deformation, and slip. The control system dynamically adjusts the gas pressure and tension driven by pneumatic or cable based on this, rather than following predetermined open-loop instructions [25]. For example, once you feel that the contact force is too small, you will add more air to increase the wrapping force. When you perceive that the force distribution is asymmetric, you will also adjust how much air is filled in each chamber, so as to change the grip until equilibrium is formed, and respond accordingly; This control strategy enables flexible grippers to handle objects of different sizes, shapes, and weights, achieving a transition from "blind grasping" to "perceptual grasping". Adaptive grasping control greatly improves the flexibility and efficiency of industrial automation production lines when handling different and non-standard products, which is a key technology for achieving a "black light factory" and flexible manufacturing.

5. Conclusion

The driving and sensing technology of soft robots is the pillar of their movement, from aerodynamics to shape memory. The diverse driving methods from alloys to dielectric elastomers provide soft robots with unprecedented flexibility and adaptability. The combination of flexible sensing bodies with external sensors in the environment builds a "nerve" for intelligent perception and control. While there are still challenges in driving efficiency, control accuracy, sensor fusion, and

system reliability, it has shown tremendous innovative energy in fields such as medical rehabilitation and industrial grasping. With the continuous integration and penetration of materials science, manufacturing technology, and artificial intelligence, it will break through existing constraints and integrate more deeply into human society, playing an increasingly important role in this era.

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