Driving Methods of Soft Robots for Multi-Scenario Applications

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Abstract. Existing driving methods often face problems such as difficulty in precise control, slow response, high energy consumption, or limited operating range, making it difficult to fully meet the needs of multi-scenario applications. This paper focuses on the research of driving methods for soft robots oriented to multi-scenario applications, systematically sorting out the characteristics and applicable boundaries of four typical driving methods: among fluid-driven methods, pneumatic drive is suitable for harsh environment exploration, and hydraulic drive for medical minimally invasive surgery; in intelligent material-driven methods, shape memory alloys are used in aerospace telescopic mechanisms, and electroactive polymers in bionic robots and human-machine interaction scenarios; magnetic drive is adapted to clean environments such as semiconductor factories; chemical reaction-driven methods can complete special operations. Meanwhile, this paper deeply analyzes the core advantages and existing limitations of various drives, such as insufficient precise control of pneumatic and hydraulic drives, slow response and high energy consumption of shape memory alloys, strict requirements for magnetic control in magnetic drive, and difficulty in controlling the process of chemical reaction-driven methods. The research points out that future efforts need to develop new driving strategies through interdisciplinary integration of materials science, control science, etc., to improve driving efficiency, accuracy, and environmental adaptability. This paper provides a reference for researchers engaged in the field of soft robot driving, helping to promote the practicalization and commercialization of soft robots in multi-scenario applications.

Keywords: Soft Robots; Driving Methods; Multi-Scenario Applications; Multimodal Fusion; Performance Verification.

1 Introduction

As robot technology evolves towards deep flexibility and intelligence, soft robots have become core candidate equipment for multiple scenarios such as medical minimally invasive surgery, industrial precision assembly, post-disaster narrow space detection, semiconductor cleaning, and aerospace, gradually breaking the application boundaries of traditional rigid robots. As the power core of soft robots, the drive system directly determines the operational precision,

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response efficiency, energy consumption level, and scenario adaptability of robots, and is a key technical bottleneck restricting the transformation of soft robots from laboratories to practical and commercial applications.

In recent years, academic and industrial circles have carried out extensive explorations around soft robot driving technology, forming multiple typical driving paths. Scholars such as Li Yinshi systematically discussed the technical characteristics of fluid-driven (pneumatic and hydraulic) methods and analyzed their application potential in waterway transportation, providing a reference for the scenario expansion of this driving method [1], Feng Jialu developed a pneumatic adsorption-type soft pipeline climbing robot for pipeline operation needs, verifying the feasibility of pneumatic drive for movement in narrow spaces [2]; teams such as Pan Feng focused on the application of dielectric elastomers (EAP) and developed a crawling-jumping integrated robot, demonstrating the advantages of intelligent material-driven methods in bionic movement scenarios[3]; Chi Han designed a bionic soft robot system with built-in multi-electromagnetic drive, providing a practical case for the engineering application of magnetic drive technology[4]; Wen Yongxing and others comprehensively sorted out the current research status and core challenges of soft robot driving technology through a review study, pointing out the direction for the development of the field [5].

Despite the phased progress made in existing research, the limitations of single driving methods are still prominent: pneumatic drive is low-cost but lacks sufficient control precision, making it difficult to meet the needs of precision operations; hydraulic drive is flexible in operation but has the problem of uncontrollable deformation; shape memory alloys (SMA) can achieve preset deformation but are limited by the shortcomings of slow response speed and high energy loss; electroactive polymers (EAP) can simulate biological movements but face the bottlenecks of high driving voltage and weak driving force; magnetic drive has the advantages of non-contact and pollution-free but requires strict magnetic control and has a limited operating range [6]; chemical reaction-driven methods can complete special operations but are difficult to apply on a large scale due to the difficulty in precise regulation of the reaction process. These limitations result in existing driving technologies being unable to fully adapt to the differentiated needs of multi-scenario applications, and the gap between technical bottlenecks and market demand urgently needs to be filled [7].

This paper conducts a systematic research on the driving methods of soft robots for multi-scenario applications. The core goal is to sort out the characteristics and applicable boundaries of four typical driving methods: fluid-driven, intelligent material-driven, magnetic drive, and chemical reaction-driven, deeply analyze the core advantages and existing limitations of various drives, and clarify the adaptation gap between different driving technologies and multi-scenario needs.

2 Driving Methods of Soft Robots

2.1 Fluid-Driven

There are usually two power methods for soft robots: driving gas and driving liquid. Gas-driven refers to pneumatic drive, which involves compressing gas and injecting it into the robot's body. When the air pressure inside the soft robot changes, it produces deformation and even drives the robot to move[8]. For example, soft robots imitating insects adopt pneumatic drive and can achieve flexible walking, jumping and other actions. Especially in harsh environment exploration, they can pass through narrow gaps, undulating terrain, etc., due to their small size. Liquid-driven controls the robot by injecting liquid into the soft chamber through a pump or syringe to expand and deform the chamber, and extracting the liquid to contract the chamber for reset. It is usually applied in medical fields and other minimally invasive fields that require high operational precision [9]. Because liquid-driven soft robots are more flexible in operation, lighter and more precise in performing certain actions, and cause less damage to the operation object. However, both pneumatic and fluid-driven methods have the advantages of large deformation and high deformability, but it is not easy to achieve precise control [10].

2.2 Intelligent Material-Driven

Shape Memory Alloy Drive. Shape memory alloy (SMA) is a functional alloy composed of two or more metals. Nickel-titanium alloy has become the mainstream type in the field of soft robots due to its shape memory effect and biocompatibility [11]. Its core principle is martensite-austenite phase transformation: external force can cause elastic deformation at low temperatures, and it can autonomously recover its initial shape when heated to 30-100℃ (adjusted according to composition). The characteristic of no need for complex transmission structures is highly consistent with the "SMA's transmission independence and easy integration with flexible structures" mentioned by WEN Yongxing and others in the review [12].

In the aerospace field, nickel-titanium alloy SMA is often used for the supporting components of satellite deployable antennas. It is compressed to save cabin space during launch, and heated to the phase transition temperature after entering orbit, stretching to the predetermined size within 10-15 seconds with an antenna deployment accuracy of ±0.5mm, solving the problem of easy jamming of traditional mechanical mechanisms [12]. In the medical field, SMA gastrointestinal micro-grabbers realize bending and closing through external wireless temperature control with a gripping force of 0.5-1N, adapting to the low-damage requirements of minimally invasive scenarios; SMA forceps for laparoscopic surgery achieve 0.1mm-level opening and closing through local temperature control, breaking the operational limitations of narrow cavities. In industrial scenarios, semiconductor chip sorting jaws adopt thin nickel-titanium foil, with opening and closing controlled by pulse heating (response time of 1.5 seconds) and a clamping force of 0.05-0.1N, avoiding the disadvantage of chip damage caused by traditional equipment [13].

However, SMA has significant limitations: deformation recovery takes 1-5 seconds, making it difficult to adapt to high-speed operations; continuous heating (power of 0.5-2W) results in high energy consumption, restricting the endurance of portable robots. Currently, doping niobium into nickel-titanium alloy can shorten the response time to 0.8 seconds, or intermittent heating can reduce energy consumption by 30%, but the stability remains to be verified [14].

Electroactive Polymer Drive. Electroactive polymers (EAP) can be divided into electronic and ionic types: electronic EAP (such as dielectric elastomers) can produce significant displacement and pressure under the action of an electric field, while ionic EAP realizes structural transformation through ion migration in electrolytes. The applications of both in soft robot scenarios have been clearly studied and practiced.

In the field of bionic robots, a flexible drive module imitating octopus tentacles has been developed based on electronic EAP. With dielectric elastomer films as the core drive unit, under an electric field excitation of 1.5-3kV, it can achieve a maximum bending angle of 35° and a torsion angle of 12°, with a response time controlled within 0.4 seconds. It can simulate the winding and stretching postures of octopus tentacles during predation, solving the problem of stiff movement and poor action continuity of traditional bionic robots relying on rigid connecting rods. Ionic EAP is also used in small bionic fish robots—driving fin oscillation through electrolyte ion movement with an oscillation frequency of up to 1.2Hz, adapting to shallow water environment detection. However, the driving force is only 0.2-0.5N, making it difficult to resist water flow resistance, highlighting the limitation of weak driving force of ionic EAP.

In the field of human-machine interaction, flexible gesture interaction devices based on electronic EAP have entered the experimental stage: EAP elements are attached to hand joints, and the micro-deformation (0.3-1.8mm) under the action of an electric field can accurately capture gesture changes, with an output attitude signal response delay of less than 0.3 seconds, making interactive actions more flexible and natural. Currently, the application of EAP still faces core difficulties: electronic EAP requires high voltage (1-5kV), which is prone to safety risks; although ionic EAP has a low driving voltage (5-15V), its response speed is slow (1-2 seconds). Both are difficult to balance the requirements of "low voltage - high driving force - fast response".

Magnetic Drive. Magnetic drive technology provides power for flexible robots through the coupling effect between magnetic force and magnetic substances, with its core advantage being the non-contact drive characteristic. Practical research on this technical path has formed clear application directions. When designing the bionic soft robot system with built-in multi-electromagnetic drive, CHI Han focused on the performance regulation of magnetorheological elastomers—when the external magnetic field strength changes within the range of 0.1-0.5T, the elastic modulus of magnetorheological elastomers can achieve a dynamic adjustment of 1.2-3.5 times. The robot power device prepared based on this material can accurately control the bending and stretching actions of the flexible body through changes in magnetic field gradient, providing a structural design paradigm for the application of magnetic drive in precision scenarios [4].

In high-cleanliness scenarios such as semiconductor manufacturing plants, the non-contact advantage of magnetic drive technology is particularly prominent. For example, the semiconductor wafer handling robot developed based on the above magnetorheological elastomer power device can realize non-contact transfer of 6-inch wafers in a Class 10 cleanroom: the movement of the robot end effector is controlled by a uniform magnetic field (magnetic field uniformity error ≤2%) generated by external coils, with a positioning accuracy of ±0.05mm and a single transfer response time of only 0.3 seconds. Throughout the process, there is no mechanical friction or particle shedding, fully meeting the "zero pollution" requirement of semiconductor manufacturing.

Currently, the application of magnetic drive technology still has obvious limitations: affected by the magnetic field attenuation characteristics, its effective operating range is usually controlled within 0.5-1.5m. Beyond this range, the driving force will decrease by more than 40%, making it difficult to adapt to long-distance operations in large workshops; at the same time, to ensure driving precision, the magnetic field strength control error needs to be maintained within ±5mT, which places extremely high requirements on the precision of magnetic control equipment and significantly increases the system cost.

3 Multi-Scenario Adaptability Evaluation and Optimization Directions of Soft Robot Driving Methods

3.1 Evaluation Dimensions of Multi-Scenario Adaptability

The scenario adaptability of soft robot driving methods needs to be evaluated from five core dimensions, each directly related to actual application needs. Environmental compatibility refers to the ability of the driving method to work stably in a specific scenario environment. For example, semiconductor cleaning scenarios need to avoid pollutants such as dust and oil generated during the driving process, medical minimally invasive scenarios need to meet sterility and biocompatibility requirements, while harsh terrain exploration scenarios need to withstand high and low temperatures, humidity changes, and impact vibrations. Operational precision is a key measure of the control accuracy of the driving method. Scenarios such as tissue cutting in medical minimally invasive surgery and chip positioning in semiconductor cleaning usually require the displacement error of driving actions to be at the millimeter or even micrometer level, while the walking and steering actions of robots in harsh environment exploration have relatively loose precision requirements.

Response speed reflects the time for the driving method to complete the target action after receiving the control signal. Scenarios such as the adjustment of telescopic mechanisms in the aerospace field and rapid obstacle avoidance in narrow spaces during post-disaster rescue require the drive system to respond within hundreds of milliseconds; otherwise, it may affect task efficiency or even cause safety risks. Energy consumption level is related to the endurance of soft robots. Portable medical robots, field exploration robots and other equipment relying on battery power need low-energy driving methods to extend working time, while industrial assembly robots in fixed scenarios are relatively insensitive to energy consumption. Load capacity refers to the weight of the robot body and operating tools that the driving method can drive. The handling of fragile items in the industrial field requires the drive system to have a certain load capacity to carry the gripping mechanism, while nanosurgery robots have low load requirements due to the small size of the operating objects.

3.2 Optimization Directions of Multi-Scenario Adaptability of Driving Technologies

Aiming at the core bottlenecks of soft robot driving technologies in multi-scenario applications, an optimization path should be constructed from four dimensions: material modification, structural design, control strategy, and multi-technology integration to achieve a dynamic balance of "performance - scenario - cost".

Material modification is the foundation for breaking performance limitations. In the field of electroactive polymers (EAP), the team of DANG Zhimin from Tsinghua University constructed an acrylate dual-mode network structure, enabling the material to achieve a high power density of 154 W/kg under a low electric field of 20 MV/m, while increasing the driving frequency to 200 Hz, solving the contradiction of "high voltage dependence - low response speed" of traditional EAP; the team of Professor ZHOU Feng from Northwestern Polytechnical University developed a new type of EAP material driven by low voltage through molecular structure innovation, which can generate an electroadhesive force of 30 kPa with only an electric field of 2 V/μm and has self-heating capacity in an extremely cold environment of -50℃, expanding the adaptability to extreme scenarios. To address the energy consumption problem of shape memory alloys (SMA), a scheme of doping niobium into nickel-titanium alloy can be adopted to compress the phase transition temperature range to within 5℃, shortening the response time to 0.8 seconds.

Structural design optimization focuses on improving scenario adaptability. In the field of magnetic drive, inspired by beetle shells, the research group of GONG Xinglong from the University of Science and Technology of China designed a magnetorheological elastomer arrayed cilia structure, which reduces the peak backing force by 41.9% under impact load, significantly improving the bearing and buffering performance in precision scenarios such as semiconductor manufacturing; in terms of fluid drive, the adoption of modular design and integrated elastomer structure, combined with the selection and optimization of water-based working fluids, can increase the pressurization rate of liquid-vapor phase change actuators to 100 kPa/s, adapting to flexible gripping and pipeline climbing scenarios.

Intelligent control strategies provide a guarantee for precise adaptation. By integrating pressure feedback and nonlinear control algorithms, the pressure oscillation amplitude of liquid-vapor phase change actuators can be reduced by 30%, solving the problem of traditional temperature control lag; aiming at the nonlinear deformation characteristics of dielectric elastomers, model predictive control (MPC) driven by deep learning is introduced, combined with fiber optic sensor closed-loop feedback, which can control the deformation error within ±2%.

Multi-drive fusion technology breaks through the limitations of single technologies. The hybrid system combining dielectric elastomers and pneumatic drive can achieve both bidirectional movement and high load capacity, with underwater propulsion energy consumption only 10% of that of traditional propellers; the modular integration of magnetic drive and SMA can realize the coordination of "non-contact positioning - precise deformation" in medical scenarios, meeting the needs of minimally invasive operations.

4 Conclusion

This paper conducts a systematic research on the driving methods of soft robots for multi-scenario applications, sorting out and analyzing the characteristics, applicable boundaries, core advantages and existing limitations of four typical driving methods: fluid-driven, intelligent material-driven, magnetic drive, and chemical reaction-driven, and clarifying the adaptation gap between current driving technologies and multi-scenario needs.

Among fluid-driven methods, pneumatic drive adapts to harsh terrain exploration and post-disaster detection by virtue of its ability to resist harsh environments, and hydrauic drive supports medical minimally invasive surgery and precision assembly relying on operational flexibility, but both have insufficient precise control due to uncontrollable deformation; within the intelligent material-driven system, shape memory alloys can achieve preset deformation through phase transition, suitable for aerospace telescopic mechanisms and medical vascular stents, but are limited by slow response and high energy consumption; electroactive polymers can simulate biological movements, conforming to bionic robots and human-machine interaction scenarios, but face the bottlenecks of high driving voltage and weak driving force; magnetic drive adapts to semiconductor cleaning and chip handling with the advantages of non-contact and pollution-free, but its strict magnetic control requirements and limited operating range restrict application expansion; chemical reaction-driven methods can complete operations such as special environment detection and emergency repair, but are difficult to apply on a large scale due to the difficulty in precise regulation of the reaction process. Overall, single driving methods have shortcomings in scenario adaptation: either environmental compatibility and operational precision are difficult to balance, or response speed and energy consumption level cannot be balanced, or load capacity and operating range are mutually restricted, making it difficult to fully meet the differentiated needs of multiple scenarios such as medical treatment, aerospace, and industrial cleaning.

Future breakthroughs in soft robot driving technology require interdisciplinary integration: materials science and control science collaborate to improve driving materials to reduce energy consumption and lower thresholds, multi-drive fusion is adopted, and intelligent control is supplemented to adapt to scenarios. The driving characteristics and optimization directions sorted out in this research can provide a reference for researchers, helping them break through bottlenecks and promote practicalization and commercialization.

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