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A comparative analysis of typical drive methods for soft robots

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Abstract. Soft robots represent an emerging class of robots characterized by strong adaptability, excellent flexibility, and high maneuverability. Today, they are widely used in fields such as bioengineering, disaster relief, industrial production, medical services, exploration, and surveying. Drive technology is a key factor limiting their performance. Based on a review and analysis of relevant domestic and international literature from recent years, this paper investigates three typical and common drive methods: pneumatic drive, hydraulic drive, and dielectric elastomer drive. The paper elucidates the principles and research progress of these three drive methods and compares their advantages and disadvantages from multiple perspectives, including response speed, execution accuracy, output power, and application scenarios. The results indicate that pneumatic drive technology is highly mature and offers balanced overall performance; hydraulic drive can achieve high output force and power but results in bulky equipment; and dielectric elastomer drive offers fast response speeds but requires a higher drive voltage. This study provides a theoretical reference for the selection of soft robot actuators and the research and development of hybrid drive systems.

Keywords: soft robots, pneumatic drive, hydraulic drive, dielectric elastomer drive, drive methods

1. Introduction

Traditional rigid robots are constrained by their structure and face limitations in unstructured environments and human-robot interaction scenarios. Soft robots, which rely on flexible materials to achieve excellent environmental adaptability, have gained significant attention in the field of robotics [1]. With the rapid development of bionics and flexible materials, soft robots have garnered significant attention from researchers worldwide and yielded numerous achievements. For example, F. Renda et al. at Khalifa University in the United Arab Emirates developed a soft, octopus-like underwater robot driven primarily by pulsed jet propulsion and soft tentacles; C. Larson et al. at Cornell University developed a pneumatic soft crawling robot that can emit light independently while crawling [2]. Actuators are the core component of soft robot motion, and their performance determines the overall capabilities of soft robots.

Extensive research has been conducted worldwide on the three common drive mechanisms: pneumatic, hydraulic, and dielectric elastomer. However, most existing literature and studies focus on in-depth research and optimization of a single drive mechanism, with few studies comparing these three typical approaches and adequately summarizing their advantages, disadvantages, and suitable application scenarios.

This paper primarily investigates three common drive mechanisms for soft robots: pneumatic, hydraulic, and dielectric elastomer drives. A comparative analysis is conducted across multiple dimensions, including operating principles, performance, and applications. On the one hand, this study clarifies the advantages and limitations of these three drive technologies, thereby enriching the body of comparative research on soft robot drives; on the other hand, it provides practical guidance for selecting drive solutions in the development of soft robot prototypes and offers valuable insights for the design of future novel hybrid drive systems.

2. Pneumatic drive

2.1. How pneumatic drives work

Pneumatic actuators operate based on volumetric expansion or contraction and can be designed in various ways to produce specific deformation patterns, such as extension, retraction, bending, torsion, or combinations thereof. Generally, these soft actuators feature high power density and provide soft contact with high flexibility [3]. A pneumatic drive system is broadly divided into four components: the air supply module, the pneumatic control module, the pneumatic actuator, and the sensing and feedback module. The air supply module is primarily responsible for compressing, stabilizing, and filtering the air; the pneumatic control module, consisting of solenoid valves and a control board, primarily controls the inflation and deflation of the gas; the pneumatic actuator module consists of a deformable elastic chamber that undergoes bending, torsion, contraction, and other deformations; and the sensing and feedback module uses sensors to collect gas data, enabling the entire system to operate in a closed-loop configuration. The system's operational workflow is as follows: a control signal is sent to the control board, which drives the solenoid valve to perform inflation and deflation operations, thereby causing the elastic chamber to deform and ultimately achieving the soft robot's intended motion. Pneumatic drive for soft robots is categorized into positive-pressure drive and negative-pressure drive. Positive-pressure drive achieves the soft robot's motion by inflating the chamber with compressed air; conversely, negative-pressure drive enables the soft robot's movement or return to its original state by drawing air out of the chamber.

Among various types of pneumatic actuators, the pneumatic network actuator is the most typical example. Its operating principle is as follows: a pneumatic actuator can be broadly divided into two main parts—the drive layer and the constraint layer. It is important to note that the constraint layer has higher stiffness than the drive layer [4]. When gas is introduced into the cavity, the internal pressure gradually increases, causing the cavity to expand. However, because of the constraint layer, which restrains the deformation of the driving layer, the actuator bends toward the side of the constraint layer—which has greater stiffness—thereby completing the drive. Similarly, if a negative pressure is applied inside the actuator, the chamber collapses inward, causing the actuator to bend in the opposite direction, thereby achieving bending deformation under negative pressure.

2.2. Performance characteristics of pneumatic drives

Due to its unique advantages, pneumatic drive has become the most popular and widely used drive method in today's soft robotics applications. This drive method enables a wide range of deformations, such as bending and twisting, while the gas medium provides excellent cushioning. It also offers good safety for human-robot interaction; the components used with it are readily available and can be manufactured using various 3D printing technologies or casting processes at a relatively low cost. Pneumatic actuators can not only perform various robotic motions through positive pressure but can also achieve corresponding actions by using negative pressure to draw in or draw out air. At the same time, the disadvantages of pneumatic drives should not be overlooked. Since the drive relies on the flow of gas, its response speed is not particularly fast; although the drive is relatively lightweight and cost-effective, it requires external components such as air pumps, making it inconvenient to carry; the drive's chamber is made of elastic, easily deformable material, which is prone to material aging—leading to gas leaks—and also results in low load-carrying capacity.

2.3. Research advances in pneumatic drives

Gas media are widely used in soft robotics [1] due to their light weight, widespread availability, and lack of pollution. Current research on pneumatic actuators primarily focuses on three areas: optimization of manufacturing processes, innovation in chamber topology, and rigid-flexible coupling design. The goal is to address practical challenges associated with traditional pneumatic actuators, such as limited load capacity, poor performance at low pressures, and complex manufacturing processes. In terms of manufacturing processes, traditional casting methods involve long mold cycle times and make it difficult to fabricate complex internal chamber structures. Chabel et al. from the University of Wollongong in Australia have proposed the use of 3D printing technology to rapidly and efficiently fabricate soft actuators directly, providing a new approach for the fabrication of complex pneumatic network structures [3].

In terms of structural optimization, to address the shortcoming of insufficient gripping force in traditional pneumatic network actuators under low pressure, a 2024 study improved the structure of the pneumatic network actuator in a soft robotic gripper. By incorporating a combination of rigid and flexible elements and a stepped chamber structure, the study enhanced the gripper's stability and strength under low air pressure [5]; to address the trade-off between flexibility and load-carrying capacity in soft robotic arms, a honeycomb pneumatic network structure was proposed to enhance both flexibility and load-carrying capacity of soft robotic arms [6].

3. Hydraulic drive

3.1. How hydraulic drives work

Hydraulically driven robots rely on a liquid medium to generate motion. The entire system consists of a hydraulic pump, hydraulic control valves, hydraulic lines, and hydraulic sensors. Both hydraulic and pneumatic drives are fluid-driven systems and therefore share similar fundamental principles [7]. Both achieve robot motion by forcing a medium into a chamber [7], but hydraulic drives are more stable.

The closed-loop operation of a hydraulic drive system is as follows: The hydraulic pump is powered on and applies pressure to the transmission fluid; the pressurized fluid is then delivered through hydraulic lines to the elastic chamber of the flexible actuator; the hydraulic control valve regulates the flow rate and direction of the fluid, while working in conjunction with a hydraulic sensor to continuously monitor system pressure signals, thereby enabling dynamic adjustment of hydraulic parameters and establishing closed-loop control of the system.

3.2. Performance characteristics of hydraulic drives

Because the fluid used in hydraulic drives is incompressible, this results in high output force and power density, as well as stable operation that is less susceptible to interference. Therefore, hydraulic drives have a natural advantage in applications requiring high load capacity; for example, many underwater applications rely on hydraulic drives. However, like pneumatic drives, a complete hydraulic drive system requires external components—such as a bulky and heavy hydraulic power source—thereby reducing overall portability. Should a leak occur at the connections between pipes and chambers, it will not only cause a drop in drive pressure and robot malfunction, but the leaked fluid may also contaminate the operating environment. At the same time, these external components also affect, to varying degrees, the soft robot's flexibility and adaptability to its environment. The entire drive system has a complex structure and relatively higher maintenance costs.

3.3. Research advances in hydraulic drives

To mitigate the drawbacks of hydraulic actuators while leveraging their advantages, a number of studies have been conducted in this area. In terms of manufacturing processes, traditional casting methods struggle to produce micro-hydraulic actuators with complex microchannels. Yanbin Li and colleagues at North Carolina State University designed a fully 3D-printed, multi-material micro-soft hydraulic actuator [8]; such actuators can be printed directly in a planar configuration, making them relatively convenient to operate. Under hydraulic drive, they can rapidly deform and reversibly transform into programmed two-dimensional and three-dimensional structures. This approach simplifies the fabrication process for micro-hydraulic soft actuators and offers new insights for the manufacturing of micro-hydraulic soft robots.

In the field of structural optimization and underwater applications, Xie Qi and colleagues at Zhejiang University invented a three-chamber hydraulically driven actuator in 2020 [9] incorporating a double-helix fiber structure for reinforcement. This device is highly responsive and capable of performing movements such as bending and extending underwater, demonstrating good overall stability during operation. Its modular structural design also allows for the direct expansion and assembly of multi-segment soft robotic arms.

4. Dielectric elastomer drive

4.1. How dielectric elastomer drives work

Smart material drive is currently one of the most promising drive methods, encompassing shape memory alloys, electroactive polymers, and dielectric elastomers, among others. Among these, dielectric elastomers are the most common and representative materials. A dielectric elastomer is a classic type of electroactive polymer material that can convert electrical energy into force or various forms of motion under the influence of an external electric field. It is currently a typical flexible actuator in soft robotics. The structure of a dielectric actuator consists of three layers: a dielectric elastomer base film in the middle, with flexible, deformable electrodes above and below it. The external structure is typically secured by a rigid frame, and the assembly as a whole can function as a deformable flexible capacitor.

When a voltage is applied to the upper and lower electrodes, the electrodes generate a vertical Maxwell electrostatic stress that compresses the base film in the middle [10]. Because the volume of the dielectric elastomer film remains approximately constant, its deformation can be treated as volume-preserving. When compressed by the upper and lower layers of the structure, the film's thickness decreases while its surface area increases, causing the actuator to move.

4.2. Performance characteristics of dielectric elastomer drives

Dielectric elastomers have a high deformation capacity that far exceeds that of actuators made from other materials; they are highly efficient, with energy conversion efficiency reaching up to 90% [11]; since dielectric elastomer actuators can be modeled as variable capacitors, they do not require additional sensors, resulting in a simple and portable design; the drive process relies on electrostatic stress to deform the thin film, eliminating mechanical friction pairs and resulting in virtually no mechanical noise during operation.

Typical dielectric elastomer actuators are prestressed to increase the driven strain; however, prestressing requires a rigid frame for confinement, which reduces the overall compliance of the system [10]. Additionally, these actuators typically operate at voltages in the kilovolt range, which may pose safety risks. Under long-term cyclic operating conditions involving large deformations and high electric fields, the film is prone to electrical breakdown, resulting in permanent damage to the actuator and compromising the reliability of the equipment.

4.3. Research progress on dielectric elastomer actuators

Dielectric elastomer actuators have attracted significant research interest due to their potential applications in soft robotics. Current research primarily focuses on two areas: the development of novel dielectric materials and innovations in actuator configurations. In terms of new material development, traditional dielectric elastomers often require very high electric fields to generate effective driving strain, and these high-voltage conditions limit the practical application of such devices. A team at Tsinghua University has developed a high-performance polar fluorinated polyacrylate dielectric elastomer, enabling the actuator to achieve large driving strain and high energy density under low electric fields [12].

In terms of innovations in drive system configurations, to meet the high-speed motion requirements of micro-soft robots, Zhu Yuanbo and colleagues at Zhejiang University designed a coil-dielectric elastomer actuator that significantly increased the speed of insect-inspired soft robots [13].

5. A comparison of three drive modes

The preceding sections have discussed the working principles, performance characteristics, and recent research progress in pneumatic, hydraulic, and dielectric elastomer drives. To illustrate the differences among these three drive schemes more clearly, this paper compares several key characteristics of each, based on the results of a comprehensive review of multiple literature sources. The results are shown in Table 1.

Table 1. Comparison of the three drive modes

Metric	Pneumatic	Hydraulic	Dielectric Elastomer
Power Density	Medium	Medium	Large
Cost	Low	Medium	High
Efficiency	Medium	Medium	High
Response Speed	Medium	Medium	Fast
Output Force	Medium	Large	Small
Relative Speed	Medium	Medium	Fast
Control Precision	Medium	Relatively High	High
Portability	Relatively Poor	Poor	Good
Control Difficulty	Medium	Medium	Relatively High
Driving Voltage	Low	Low	High (kV level)
Main Limitations	Slow response; requires external parts such as air pumps; limited load capacity	Bulky system; leakage risk; high maintenance cost	Requires kV-level high voltage and pre-stretch frame; risk of dielectric breakdown

Table 1. Continued

Typical Applications	Medical rehabilitation, industrial production	High-load scenarios such as deep-sea operations	High-precision soft grippers, haptic devices for human-machine interaction

As shown in Table 1, each of the three drive types has its own advantages and disadvantages; there is no single, absolutely optimal solution. The actual selection must be based on a comprehensive evaluation of constraints such as the project's load, response speed, cost, and operating environment. Pneumatic drives offer average performance across the board, but their low cost has led to widespread commercial adoption, making them suitable for applications in medical rehabilitation and industrial production. Hydraulic drives, with their high output force, are well-suited for high-load scenarios such as deep-sea operations. Due to their excellent performance characteristics—including fast response times and high energy density—dielectric elastomer actuators hold great promise and can play a role in more advanced fields, such as high-precision soft grippers and haptic devices for human-computer interaction.

6. Conclusion

This paper examines the three most typical drive mechanisms for soft robots: pneumatic, hydraulic, and dielectric elastomer. It explains their operating principles, research progress, and characteristics, and then compares them across multiple dimensions. Each of these three drive mechanisms has its own advantages and disadvantages; the choice among them should consider factors such as cost, output force, and response speed. Pneumatic drive technology is mature and low-cost, but its overall performance is not particularly strong; hydraulic drives offer high output force and stable operation but lack portability; although dielectric elastomer drives offer strong performance and have broad prospects for development in many research fields, they are costly, require high voltage, and face significant technical barriers that must be overcome to achieve widespread application. When designing soft robot prototypes, one should not focus solely on a single performance metric but must instead make trade-offs among various performance characteristics. In the future, soft robotics could also explore hybrid drive solutions that combine the strengths of two or more drive methods to compensate for the inherent weaknesses of single-drive systems.

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