Hydraulic Powered Soft Actuators

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Soft actuators have received extensive attention in robotics and smart device applications due to their distinctive dexterity and compliance. Among them, hydraulic soft actuators play an important role in the area because they have much higher specific power and power density than other types such as pneumatic soft actuators. Nevertheless, the deformation of flexible materials in soft actuators brings about inherent hysteresis and nonlinearity, which severely hinders them from producing the desired movement in the presence of advanced control strategies.

soft actuator hydraulic drive smart material

1. Configuration and Structures

The operation of a hydraulic soft actuator typically involves the generation of working pressure in an elastic cavity using a liquid medium such as water or oil, and the formation of the desired movement under the influence of a cavity structure constraint and external loads. The structure of a hydraulic soft actuator can be classified as fiber constrained, cavity constrained, etc., depending on the various types of constraint. The capability of hydraulic soft actuators to drive can be impacted by several structural factors. Driven by hydraulic pressure, different actuator structures can produce different motion forms such as elongation, contraction, bending, torsion, spiral, etc., so as to adapt to different working requirements.

1.1. Fiber-Constrained Actuator

The earliest proposed artificial muscle structure is a fiber-constrained soft actuator, which is primarily made of an inner hose and an outer wrapped fiber-restrained material [1]. The shape of the muscle changes as the inner hose is filled with high-pressure fluid, and the appropriate displacement and elastic force are outputted. According to the working principle, artificial muscles (AMs) can be divided into contractile and elongated types. Zhao W D et al. [2] designed a retractable and elongated hydraulic artificial muscle manipulator. The inner elastic rubber tube of the contractile muscle is encased in a braided sheath. Due to the preload provided by the braided sheath, the muscle expands radially and contracts axially when the high-pressure liquid is placed in the tube. Elongated muscles consist of an inner elastic rubber tube and an outer spring. Due to the spring's limitation of the inner tube, the muscle lengthens axially rather than radially when the high-pressure liquid is injected into the tube. A contractile AM is used to create a manipulator that can work under extreme pressure and provide powerful pulling and grabbing forces. Bending under 0.8 MPa pressure, the horizontal projection is 50% of the natural length. Although it can only function under low pressure, the manipulator made of an elongated AM is more flexible and can be bent into a semicircle under 0.3 MPa during the test.

On the basis of the classic fiber-constrained artificial muscle structure, researchers have changed the winding and arrangement of one or more groups of fibers, and introduced new manufacturing processes or materials, which makes the type of actuator exhibit more diverse and excellent characteristics and its application has higher flexibility. Chen S et al. [3] proposed a new method to fabricate a hydraulic soft actuator by changing the number of operations of reinforcing fibers on the actuator, which constitutes a fiber-guided actuator (FGA) driven by water pressure, used for bending, twisting, and even other movements. Experiments show that the FGA's pressure resistance increases as the number of fibers increases. The confinement band with a smaller bandwidth can provide a wider range of torque and a greater bending deformation; the maximum torque is close to 0.063 Nm. Phan P T et al. [4] proposed a bio-inspired soft hydraulic filament artificial muscle (HFAM) that can stretch and contract under fluid pressure. An HFAM has a high aspect ratio of at least 5000, a straightforward and inexpensive insertion production process, and high elongation and energy efficiency ratings of 246.8% and 62.7%, respectively. Drimer N et al. [5] introduced a hydraulic equal-strain linear muscle (HELM) composed of two different materials that deflects when internal pressure is applied. To reduce hysteresis and improve driving efficiency, HELM permits the choosing of the strain range that the active material exhibits. Based on the characteristics of premade materials, HELM constructed of nitrile rubber has a 160% elongation.

Fiber-constrained soft actuators generally have the advantages of a simple structure, high output ratio, and high working pressure. Since the fiber structure bears and transmits the main load during work, its maximum bearing pressure is also different according to the difference in fiber distribution density. In practical applications, fiber-constrained soft actuators are the most widely used type of actuator.

1.2. Cavity Actuator

The main structure of the cavity hydraulic soft actuator is composed of elastic rubber materials with low elastic modulus and good stretch ability. Under the action of liquid pressure, the cavity is distorted, producing a corresponding displacement and output force. Because a cavity actuator is more in line with the characteristics of bionics, it has promoted the birth of many bionic actuators. Jiao L et al. [6] designed a bionic robotic fish with a hydraulic soft actuator mechanism that replicated the fish's S-shaped swing using two joints. The average cruising speed of the two-joint soft robotic fish is 0.29 fish length/s, according to experiments, which is faster than the average speed of the single-joint robotic fish under the same frequency and caudal fin swing. Katzschmann, R.K. et al. [7] proposed a hydraulic soft robotic fish. The robotic fish actuators mimic the tail of a fish, including the rear handle and caudal fin. By driving the two lateral cavity structures on each side, the continuous bending of the tail of the robotic fish is realized to complete the bionic motion. The average vertical distance is 0.13 m, the average diving speed is 0.015 m/s, and the horizontal swimming speed is 0.08 m/s. In addition to bionic actuators, bellows actuators are also one of the more common types. Bell M A et al. [8] proposed a simple and highly modular bidirectional soft actuator. The symmetrical bidirectional bellows structure actuator and peristaltic pump are integrated to realize a compact closed hydraulic system. It is experimentally verified that the actuator can achieve a specific bending angle using only 1/15 of the energy required and is more than four times more energy efficient than similarly sized soft actuators and pumping systems reported in the literature. More surprisingly, Giorgio-Serchi F et al. [9] proposed a soft hydraulic actuator using elastic energy storage for pulse jet propulsion of soft unmanned underwater vehicles. Its design is inspired by the swimming of octopuses. A micropump applies pressure to the soft actuator, which is then moved by releasing its elastic potential energy through a valve as needed. The peak hydraulic power amplification of soft actuators is about 75% relative to driving pumps.

Compared with fiber-constrained actuators, the pressure load of cavity actuators mainly depends on the elastic structure part with low hardness and high elongation. Cavity actuators generally have problems of a relatively low working pressure, load capacity, and actuation force. However, at the same time, the cavity actuator has better structural compliance and is more suitable for some scenarios that do not require high actuation force but require high flexibility and compliance.

2. Fabrication Materials

The soft actuation system's main body and moving components are typically comprised of hyperelastic materials such as polymers, rubber, silicone, or other soft materials. Generally, these materials are created by 3D printers or molds, which allows for simple processing and affordable production. Meanwhile, their viscoelastic properties dissipate the energy of shocks and damp oscillations to eliminate discontinuous motion and forces. The proper material can make sure that the soft actuator withstands higher pressures, produces a larger output force, and can execute a variety of natural and flexible movements smoothly. The compliance, flexibility, and robustness of the system will be improved along with the actuation ability and efficiency of the soft actuation system as a result of ongoing research into more suitable and prospective actuation materials.

2.1. Traditional Materials

One of the most common soft actuators is based on anisotropic structures. In elastomers, such as McKibben actuators, that expand in the direction of the lowest modulus, pressurization or decompression by internal fluid generates stress. There are many variables that affect the actuation ability, such as shape, length, inner radius, outer radius, wall thickness, number of fiber turns, and fiber angle. There are few studies on the consequences of various elastomer material types in terms of materials. There are numerous additional possible elastomers that have not yet been researched and have the potential to produce better output effects. Kelageri et al. [10] investigated the effect of different elastomer types on the actuation performance of fiber-reinforced actuators. Comparative studies were conducted on four structurally identical actuators made of four different elastomers: polyurethane (PUR), polyolefin-based thermoplastic vulcanizate (TPE), natural rubber (NR), and polydimethylsiloxane (PDMS). According to the experimental performance analysis, under the same parameters, PDMS shows a higher bending angle, while the TPE material has higher mechanical properties.

In addition to the role of elastomeric materials, reinforcing fibers are also an important factor to improve the strength and actuation performance of soft actuators [11]. Reinforcing fibers can effectively avoid problems such as the easy tearing, puncturing, and tensile failure of soft materials. Y. Chen et al. [12] studied the hydraulic soft actuators of two new fabrics (knitted fabrics and elastic fabrics), aramid fabric actuator (AFA) and elastic fabric actuator (EFA), which are more anisotropic than traditional woven fabrics. They exploited the anisotropy of fabrics to develop high-strength, soft manipulator modules that yield high strength, large ranges of motion (ROM), and high stiffness. The experiments of the manipulators show that the AFA can generate a maximum output force of 608 N with a response time of 1.08 s. The EFA can generate a maximum output force of 534 N with a response time of 1.77 s.

2.2. Smart Materials

Various hydraulic soft actuation systems have emerged with the development of smart materials, opening a broad variety of application possibilities. Shape memory alloys (SMAs), ionic polymer metal composites (IPMCs), responsive hydrogels, and electroactive polymers (EAPs) have all recently been developed as smart materials, greatly advancing the practical application of soft actuation systems in the field of microstructures and promoting intelligent design of soft actuators.

2.2.1. Variable Stiffness Actuator

A soft actuation system can achieve a variety of functions that a rigid actuation system cannot, such as the ability to adapt to unstructured environments, body compliance, safety for human–machine interaction, and excellent bending performance. However, compared with a rigid actuation system, a soft actuation system lack high rigidity, high load capacity, and motion accuracy. Soft actuators with variable stiffness bridge the gap between the traditional rigid actuation system and the soft actuation system, greatly increasing the application range of the soft actuation system. Variable stiffness of the soft actuator can be achieved by phase transitions, magnetorheological fluids, layer disturbances, and flexible shaft drives [13], and the development of smart materials also provides a new way to achieve variable stiffness performance of the soft actuator.

The variable stiffness research of the hydraulic soft actuator is mainly based on the interaction between structures or the variable stiffness properties of materials. Kim G W et al. [14] proposed a hydraulic soft actuator fabricated using the fluidic flexible matrix composites (F2MC). F2MC can contract, extend, or twist in response to the internal actuation pressure of the working fluid due to its exceptional anisotropic elastic characteristics. A wide range in variable stiffness performance may be obtained by altering the F2MC tube’s design parameters, and it also features low axial stiffness and strong axial extensibility. Experiments have shown that the F2MC tube can provide variable stiffness through simple on/off valve control; the transverse stiffness ratio of the closed valve state to open valve state is roughly estimated to be twice that when using the ratio of tip deflections. In addition to the structural interaction used to change the structural stiffness, the stiffness change in materials under specific stimuli can also be directly used to achieve the variable stiffness function. Liao T et al. [13] proposed a hydraulic soft actuator fabricated from fully 3D printed shape memory polymer (SMP). Additionally, they showed how it could be activated by fluid with a range of temperatures (20 °C to 50 °C). The actuator can go from a low stiffness state to a high stiffness state (20 °C to 50 °C) in 12 s when the input fluid is 80 °C and 0.2 MPa. It can also do this by adjusting the input pressure and temperature, which takes 21 s. The actuator also shows a change in output force from 0.17 N to 1.94 N by varying the temperature (20 °C–50 °C) and pressure (0–0.2 MPa) of the input fluid.

2.2.2. Electro-Hydraulic Actuator

Although hydraulic soft actuators are fast and powerful enough, there is limited room for system miniaturization and weight reduction because system implementations frequently call for the use of big pumps, numerous valves, and pipes. It is particularly challenging to design compact actuators utilizing the hydraulic soft actuation system's existing components. As a result, investigation into new soft actuators based on electro-hydraulic actuation is required in order to create a compact system with a hydraulic soft actuator.

A dielectric elastomer (DE) is an electroactive polymer featured by large strain with a maximum of up to 1692% [15], and it has the advantages of a high energy density, fast response, and low weight. By using the properties of DE materials, many scholars have carried out research on electro-hydraulic actuation soft actuators. Zhang M et al. [16] proposed a hydraulic soft actuator composed of a DE and hydrogel with excellent actuation performance. When the applied voltage reaches 5 kV, a maximum bending angle of 23° can be achieved with an internal pressure drop of 1.36 kPa. Palaniswamy M et al. [17] used a DE actuator for a soft robot. In order to overcome its main disadvantage of a low output force, a nanomaterial composite electrical insulator was added to increase the dielectric constant of the actuator. The results show that the maximum force output of the controlled insulator sample is increased by 72%. Lee D et al. [18] proposed an electro-hydraulic soft zipper actuator that can be used as a micropump. The actuator achieves a high displacement and actuation force through silicone oil, and improves durability against high voltage through the high dielectric breakdown voltage characteristics of silicone oil. The actuator shows the maximum force of 136 mN when the voltage of 4.7 kV is applied. Furthermore, the maximum displacement of the silicon film is 1.46 mm, and the fast response time is 39 ms. Xu S et al. [19] proposed an ultra-high power density dynamic DE actuator, which is actuated at 500 Hz or higher. Compared with the dynamic DE actuators in the previous work, the DE actuator generates a 300% higher blocking force, and the load power density reaches 290 W kg−1 under working conditions.

Park T et al. [20][21] proposed a novel electro-hydraulic actuation gripper. The designed gripper utilizes a hydraulically amplified self-healing electrostatic (HASEL) actuator. Similar to the principle of a DE actuator, the HASEL unit consists of electrodes and an elastic soft bag containing the self-healing insulating liquid. When the voltage is applied to it, the positive and negative electrodes attract each other, thereby squeezing the liquid to generate a hydraulic actuation force. At 10.8 kV, the displacement value reached 41% of the length of the expansion bag [20]. The maximum blocking force of the electro-hydraulic gripper is 0.08 N. At a relative fluid volume of 0.5, the force per unit mass of the actuator is 8.57 N/kg [21]. Gyeongji Kang et al. [22] proposed a simple rectangular HASEL actuator. They compared the performance in terms of shape deformation such as the size or ratio of the actuator and electrodes. Kim S et al. [23] proposed a soft multimode actuator that utilizes the principle of HASEL to create different operating directions and modes. The maximum measured tip displacement of the actuator is approximately 4.28 mm, and the twist angle is approximately 9.8°. Furthermore, bending and twisting are achieved in both directions, with a stable response within 1 Hz.

Electro-conjugate fluid (ECF) is a dielectric and functional fluid that can generate a powerful jet when subjected to a high DC voltage. Furthermore, it is clear that the power density of the ECF jet is higher when the electrode pair is miniaturized. Therefore, it is suitable for a miniaturized hydraulic soft actuator. The Takemura K team proposed a series of hydraulic soft actuation systems based on the ECF principle, and verified the performance of the mechanism through experiments: (1) a McKibben-type micro artificial muscle actuator based on the ECF effect [24]. The contraction of the ECF artificial muscle is 2.8 mm, and the generated force is 0.5 N; (2) the inchworm-type in-pipe mobile robot [25]. When a full-step input from 0 to 8 kV is applied, the full-step response is 1.3 s under unconstrained conditions, and is 0.4 s under equidistant conditions. When a pressure of 60 kPa is applied, the maximum axial elongation is 81.4%, and the maximum volume increase is 140.6%. This means that the maximum axial extension and maximum volume increase are 17.1 mm and 0.6 mL, respectively. The ECF pipe robot can move in a φ14 mm acrylic pipe at a speed of 0.043 mm/s; (3) ECF fingers with bidirectional movement [26]. When the applied voltage is 4.5 kV, the ECF finger can achieve a bidirectional movement with a left displacement of 9.2 mm and a right displacement of 6.4 mm, and the maximum generated force is 6.6 mN.

The electroosmotic flow (EOF) effect can generate electroosmosis (EO) under the applied electric field, pumping fluids from one location in a device to another. Smela E et al. developed a series of hydraulic soft actuators based on EOF: (1) A novel polymer hydraulic actuator [27]. When the applied voltage is 10 kV, the maximum applied force is 3.7 g. The maximum deflection can reach 80% within 5 s and 94% within 10 s. (2) a voltage-controlled hydraulic actuator [28]. The microfluidic device employs a new benchtop lamination process. When the voltage is 600 V, the actuation stroke can reach 400 μm, and forces can reach 30 g. The actuation speed is fast, and the time consumption is less than 0.1 s.

Cacucciolo V et al. [29] described a class of soft bidirectional pumps based on charge injection electrohydrodynamics (EHD). These pumps are flexible, stretchable, modular, expandable, quiet, and fast. For a temperature difference ΔT = 6 K and a flow rate Q = 100 μL/s, the power consumption of the pump is about 0.1 W, which shows its effectiveness as a wearable thermal regulation device. As a wearable actuation device, the actuator bends over 40° relative to its rest position. J. Avery et al. [30] proposed a self-sensing soft actuator with a conductive working fluid. Tomographic reconstruction is performed using six-electrode-based electrical impedance tomography (EIT), and a new frequency division multiplexing (FDM) EIT system is developed. Experiments show that the actuator can measure a 66 dB signal-to-noise ratio with a 20 ms temporal resolution.

In essence, the electro-hydraulic soft actuator is a new type of actuator that uses the electrical characteristics of a series of new intelligent materials to enable the hydraulic fluid to achieve controllable movement in a small or even microscale. Electro-hydraulic soft actuators are generally characterized by a high power density and small size and weight, which makes them have great application potential in biological, medical, and other fields. However, the complex electrical–mechanical characteristics of intelligent materials and the motion hysteresis of soft materials make the control of electro-hydraulic soft actuators an urgent problem.

3. Control Strategy

Typically, hydraulic soft actuators produce internal fluid pressure to control their retraction and extension movements. Hysteretic nonlinearity is caused by a difference between the relationship among contraction and internal pressure during compression and decompression due to the material’s elasticity and friction between the elastomer and the fibers. Furthermore, the hysteresis curve is distorted based on the rate of contraction and extension as well as the force delivered to the actuator. This complex nonlinear behavior can lead to inaccurate and difficult control of the hydraulic soft actuator. It is of great significance to study the accurate modeling method and advanced control strategy of soft actuators to improve the actuation efficiency and system robustness of hydraulic soft actuators.

3.1. Control Strategies Based on Model

Mathematical modeling is the basic step for designing a controller with higher performance. Many scholars have further improved the control performance of hydraulic soft actuators based on the establishment of accurate models and incorporating control strategies. A model-based control and adaptive parameter estimation method was put out by Kobayashi W et al. [31]. Recursive least squares (RLS) is an adaptive identification technique that the system uses to update parameters changing with demand. Additionally, it makes up for modifications in muscle characteristics brought on by garments such as inner tubes and sleeves. Liu S et al. [32] deduced the dynamic equation of the hydraulic rigid–flexible manipulator by using the Lagrangian principle and hypothetical mode method, and proposed an integral sliding mode control scheme. The stability of the closed-loop system is proved by using the Lyapunov function. The simulation results demonstrate that the approach is capable of achieving the required levels of vibration suppression and ballistic tracking performance. Slightam J E et al. [33] introduced a sliding mode impedance control method for hydraulic artificial muscles based on the Filippov equivalent dynamics principle. A nonlinear lumped parameter model of the system is proposed, and a sliding mode impedance controller is derived. Experiments show that the model-based approach outperforms the classical approach for hydraulic artificial muscles with a 41% reduction in maximum tracking error. Feng Y et al. [34] proposed a second-order impedance control strategy with braking method. The results show that with the proposed impedance control, the hydraulic soft manipulator can easily move with external forces of several kilograms and can safely cope with sudden load changes at low angular velocity. Cao G et al. [35] proposed an observer-based continuous adaptive sliding mode controller, which consists of a HOSM-based observer, a nonsingular fast terminal sliding mode surface, and an STA-based controller. Experiments show that under this control scheme, the proposed control scheme has an adaptive tuning gain, continuity, no singularity, stronger robustness, and a higher tracking accuracy.

In general, model-based control is used to design the controller and conduct parameter tuning on the premise that the target model is known or can be established. Therefore, the effect of converting the controller obtained under model-based verification into an actual controller is consistent.

3.2. Control Strategy Based on Data

For some controlled targets, it is difficult to establish accurate mathematical models, or it is impossible to establish a mathematical model at all. In this case, the model-based control method is difficult to achieve good control effect in practice, and it is even difficult to design an appropriate controller. Thus, the data-driven modeling method is more effective. Kawahara Y et al. [36][37] created a water hydraulic artificial muscle actuator model with a least squares support vector machine (LS-SVM) by using experimentally obtained data, and showed that the proposed model can capture the hysteresis characteristics of the actuator. After this, the state space model of the water hydraulic artificial muscle actuator system was constructed. The model predictive control system is designed on the basis that the proposed LS-SVM model is added to the state space model. Experiments show that the proposed control method has a shorter rise time and smaller tracking error. Tsuruhara S et al. [38] proposed a dynamically linearized data model for the design of model-free adaptive control (MFAC). On this basis, a set of estimation laws and control laws for multiobjective control were derived. Compared with traditional MFAC, MFAC based on virtual reference feedback tuning (VRFT) has a higher control performance for muscles, especially in transient response. Wang T et al. [39] developed a simplified data analysis model to reveal the relationship between the hydraulic pressure, bending angle, and contact force of a soft actuator. The bending angle and hydraulic pressure are measured by vision and pressure sensors, and the output force of the soft actuator is estimated from the model. The estimation method is applied to the closed-loop control of the contact force so that good dynamic and stable control performance can be achieved. Xu H et al. [40] introduced a constant fluid mass control (CFMC) strategy for soft fluid actuators, and proposed a neural network-based supervised learning algorithm for precise pressure control of soft fluid actuators. The results show that the algorithm can predict actuation pressure with 99% accuracy. Sugiyama T et al. [41] proposed a feedforward control method for soft actuators including a simple feedforward neural network (FNN) and an iterative learning controller (ILC). Feedforward neural networks (FNNs) can efficiently learn and obtain inverse models of soft actuators. The results show that the ILC can learn and compensate the deformability of the actuator well.

4. Recommended Applications

With the continuous study of hydraulic soft actuators by researchers, the inherent flexibility and compliance of hydraulic soft actuators show their great advantages over traditional rigid actuators, enabling them to better adapt to different environments and tasks. Hydraulic soft actuators are now capable of cooperating with a variety of smart materials and structures, which demonstrates the multifunctional development trend in the microstructure actuator industry in recent years. Therefore, due to its unique actuation performance, a hydraulic software actuator has good application prospects in environments that require a high load and high safety requirement, such as soft gripper, soft robotic manipulator, bionic robot, interactive robot, assistance wearable robot, and so on.

The most common applications of hydraulic soft actuators are in grippers, manipulators, and assistance wearable robots. Nie S L et al. [42] developed a hydraulic soft gripper that consists of three hydraulic soft actuators, where the soft gripper can maximally imitate the hand-gripping function. Takemura K et al. [26] developed an electro-conjugated fluid (ECF) finger and applied it on a soft gripper. Experimental results show that ECF hands are flexible enough to grasp and release objects. Y. Chen et al. [12] designed a hydraulic soft manipulator in the shape of an elephant trunk. By filling gas with different pressures into three actuators, the manipulator can be adapted to grip objects of various shapes, stiffnesses, and weights within a certain range. Kimura H et al. [43] proposed a hydraulic bag soft manipulator. Experiments show that the manipulator is flexible enough to grab raw eggs without complex controls such as force sensing. Sy L et al. [44] designed an upper-limb assistive robotic fabric sleeve based on a fabric garment and low-hysteresis hydraulic soft artificial muscles. They demonstrated its great potential in rehabilitation applications. Phan P T et al. [4] developed and evaluated an HFAM soft fabric glove that can help grasp a variety of objects. The results show that the soft wearable glove can perform a variety of arbitrary surface grasping tasks, including with apples, lemons, 500 g weights, and glass beakers.

With the deepening of research on hydraulic soft actuators, their application has gradually matured, and a multifunctional development direction has been developed, which has greatly expanded their application. However, at the same time, the problems of hydraulic soft actuators in terms of system reliability and motion control have always restricted their large-scale application.

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