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Research on the Structure of Flexible Manipulators for Operation in Confined Spaces

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Abstract. Narrow-space operations are common in certain kinds of manufacturing industry, such as shipbuilding, automobile making and so on. It's very difficult for workers to finish the work in narrow spaces. So scientists try to make a certain tool to help them make it. Flexible manipulators have garnered extensive applications and attention in narrow-space operations due to their morphological adaptability and strong environmental robustness. However, the trade-off between compliance and load-bearing capacity has long been a core challenge that restricts their performance enhancement and application expansion. To address this issue, this paper presents a comprehensive review of relevant research and improvement strategies, categorizing the current state-of-the-art primarily into two directions: structural design and material development. These research efforts have effectively improved the performance of flexible manipulators, enabling them to adapt to more complex operating environments and harsher working conditions. Furthermore, this paper summarizes the limitations of existing research achievements, aiming to provide references and guidance for future investigations.

Keywords: Flexible manipulators, Structural Design, Confined Spaces.

1. Introduction

Operation in confined spaces is a classic challenge for robotics technology, with an urgent demand in fields such as aerospace engine maintenance, industrial pipeline inspection and maintenance, internal assembly of complex equipment, and minimally invasive surgery in human natural lumens. For example, in the shipbuilding industry, although China's shipbuilding industry is large in scale, it has not yet realized large-scale intelligent production. The main reason for this phenomenon is that, with the rapid development of the shipbuilding industry, ship structural design has become increasingly sophisticated. Statistics show that welding operations that need to be completed in a 40-60 mm space account for 30%-50% of the entire ship space. Manual welding is difficult to carry out in such an environment, and the welding quality cannot be guaranteed. In contrast, robotic welding features high efficiency, high precision, long continuous working hours, and better adaptability to harsh environmental conditions than manual operation [1]. In the field of electrical equipment maintenance, due to the large number of power industry equipment, complex maintenance processes, and unpredictable equipment problems, the cost of manual inspection and maintenance is inevitably high, and the high voltage of power equipment is likely to cause injury or even life-

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threatening risks to maintenance personnel. Compared with manual operation, flexible manipulators can perform inspection and maintenance without disassembling equipment, and can also work in hazardous areas such as nuclear power plants and high-voltage power stations, which greatly improves the efficiency and safety of equipment maintenance [2].

Furthermore, traditional flexible manipulators are difficult to apply in such scenarios due to their large volume, numerous kinematic constraints, and high sensitivity to the geometric shape of the environment. In recent years, researchers have drawn inspiration from nature and engineering to invent a variety of variable-structure flexible manipulators to meet these challenges. Some structures are like arbitrarily bendable "electric wires", some are like inflatable and deformable "balloons", and others draw on origami art, capable of folding for storage and unfolding for work. At present, research on the structure of flexible manipulators mainly focuses on suppressing resonance caused by insufficient stiffness during the use of manipulators, improving the kinematic parameters of flexible manipulators through optimizing their structural design and material selection, and modularizing the design of manipulators to enhance transmission convenience and reduce production difficulty. This paper aims to summarize the current major cutting-edge research results related to the structure of flexible manipulators, analyze their advantages and development potential, thereby pointing out the direction for subsequent researchers.

Flexible manipulators are originally designed to use compliance to adapt to environments where rigid manipulators cannot work. However, due to the trade-off between the compliance and rigidity of materials, flexible manipulators may also be unable to adapt to work in certain environments due to excessive pursuit of compliance. For example, they may break due to insufficient stiffness when bearing high loads. Inspired by the variable stiffness of the skin of some organisms in nature, researchers believe that adding variable stiffness capability to flexible manipulators can be one of the ways to solve the contradiction between flexibility and rigidity. There are two main approaches to realizing the variable stiffness capability of flexible manipulators: one is to use materials with inherent variable stiffness, such as shape memory materials; the other is to add variable stiffness structures to existing flexible manipulators, such as deployable structures [3].

The specific content of this paper is arranged as follows: the second part analyzes flexible manipulators for confined space operation made of shape memory materials, polymer materials, and multi-layer composite materials, respectively, briefly introduces the advantages and disadvantages of several major research results of different materials in this direction, analyzes the influence of different materials on the performance of manipulators, and points out the possible research directions of manipulator materials in the future. The third part mainly introduces the research results in the structural direction of variable stiffness manipulators, respectively, from two cutting-edge structures: cable-driven flexible manipulators and deployable flexible manipulators, and summarizes the latest research in this field. Finally, the current research status is further discussed. First, the research results mentioned in the paper are summarized, and then the research in different fields is prospected, indicating the importance of future research on flexible manipulators.

2. Analysis of variable stiffness design for manipulators in confined spaces

There are a variety of organisms with variable stiffness in nature. For example, an elephant's trunk changes its stiffness through muscle contraction, which can be soft enough to roll up a leaf completely and hard enough to be a weapon to repel predators. In addition, a series of marine organisms, such as sea urchins and sea cucumbers, adjust the connection state of collagen fibers through the nervous system to achieve stiffness regulation [4]. Inspired by such animals, researchers have developed different variable stiffness materials for production. This paper mainly introduces

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variable stiffness flexible manipulators composed of shape memory materials, low-melting-point materials, rheological materials, and other materials.

2.1. Analysis of variable stiffness design based on temperature-responsive materials

Temperature-responsive (or thermo-responsive) polymers are one of the most concerned and extensively studied intelligent polymers. According to the difference in their temperature response behavior, such materials are mainly divided into two categories: Lower Critical Solution Temperature (LCST) type and Upper Critical Solution Temperature (UCST) type. In addition, in recent years, studies have reported multi-temperature-responsive characteristics that can present complex states/structures. Such multi-temperature-responsive block copolymers can lay a foundation for the development of variable stiffness design research of flexible manipulators [5].

Shape memory materials are materials that can change their shape under external stimuli such as temperature, light, and electricity, and return to their original shape when the stimuli disappear. Most of the currently applied shape memory materials respond by changing temperature, which is a type of temperature-responsive polymer. Shape memory materials are mainly divided into Shape Memory Polymers (SMP) and Shape Memory Alloys (SMA). SMP has the advantages of light weight, large deformation, and easy processing, and have been widely used in the field of flexible robots.

For SMP, Amir Firouzeh and his research team designed an underactuated robot based on such materials. The underactuated design features a compact structure and easy control and driving, but has limited stable configurations, thus becoming one of the main research objects for increasing strength and load capacity. The research team pointed out that SMP are regarded as one of the choices for developing variable stiffness flexible manipulators due to their mechanical properties that change with temperature, high shape recovery rate, and easy processing and manufacturing. The paper designed a new type of tendon-driven robot with three joints that adjusts stiffness using SMP. The robot consists of four rigid material parts and three flexible joints, and a quasi-two-dimensional structure is constructed by integrating materials into multiple functional layers, which is shaped like a finger for easy research. The research team used the tendon path as the skeleton of the finger, cured glass fiber and other materials to make the frame of the finger, combined hinges with SMP to make the joint part of the finger, and added a stretchable heater in the SMG layer as the heat source for temperature rise. Through a series of experiments, the team obtained a series of experimental data, such as the function of the stiffness of the Adjustable Stiffness Layer (ASL) changing with temperature, the elongation of the ASL, and the calculation formula of the joint angle. Finally, it was measured that the stiffness of the finger joint changed by more than 40 times in the entire temperature change range, and the finger stiffness decreased by 15 times only in the range of 30 to 60 degrees Celsius. Subsequently, the team designed a frame connecting the ASL to the joint, which is composed of glass fiber and silicone resin, effectively reducing the residual strain of the SMP and greatly improving the shape recovery ability [6].

Compared with SMP, SMA can automatically restore its original shape without additional external stimuli, and also has higher stiffness and mechanical strength. Its excellent mechanical properties make it a usable material for flexible manipulators to achieve variable stiffness. Due to its special crystal structure, SMA mainly exists in two forms: one is the low-temperature phase, also known as martensite, in which SMA has flexibility; the other is the high-temperature phase, also known as austenite, in which SMA has a hard texture. These two states indicate that SMA has the ability to change its own stiffness. The shape memory effect and pseudoelastic effect of SMA also indicate that the material has a strong shape recovery ability. However, SMA also has some

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shortcomings, such as the difficulty in controlling the deformation of SMA due to complex environmental factors, and large hysteresis of deformation when the temperature changes rapidly. To simulate the application of SMA in actual industrial production, Yang and others designed a flexible gripper composed of an SMA wide-range variable stiffness structure and a steel wire skeleton based on the traditional three-jaw grasping structure. In the gripper, the device is fixed on the axial slide rail together with the connector to control the gripper to move only along the axial direction. The SMA spring is fixed and heated by copper connectors on the upper and lower sides. The fingers are made entirely of soft rubber without hard fasteners such as screws and nuts, and are only fixed by the wires inside the soft fingers. In addition, to give the wires more adjustment space and obtain greater friction when grasping the target, the team adopted a hollow design for the fingers. The variable stiffness of the three-jaw grasping structure is mainly reflected in two aspects: first, the motor can continuously compress the SMA variable stiffness structure to increase the contact force for better grasping; second, the stiffness of the fingers can also change accordingly [7].

Another temperature-responsive material highly anticipated in the field of variable stiffness applications is low-melting-point alloys (LMPAs). LMPAs have an extremely low melting point and can be transformed into a more flexible liquid state with a little heating. Chaoqun Xiang and others proposed a variable stiffness electroadhesive finger (VSEAF) based on LMPAs to solve the problems of insufficient rigidity and limited load capacity of soft robots. In VSEAF, the low-melting-point alloy is filled in the comb-shaped cavities inside the shell of each finger, and the heat released by the original circuit, realizing the electro-adhesive structure, is used to change the state of matter, thereby changing the stiffness of the finger structure. The stiffness of the finger is roughly divided into two situations based on the state of the LMPAs: when the temperature is below the melting point of the alloy, the alloy is in a solid state, and the finger is rigid; when the temperature is above the melting point of the alloy, the alloy is in a liquid state and the finger is flexible. At the same time, low-melting-point alloys can also be used to improve the electro-adhesion force to grasp objects more firmly. The team finally spliced three variable stiffness electro-adhesive grippers into a three-finger gripper and realized grasping fragile objects and hard objects in flexible and rigid states, respectively [8].

All the above studies based on shape memory materials and LMPAs have confirmed the great potential of temperature-responsive materials in the field of variable stiffness. At the same time, the above studies also point out some remaining problems. First, there are various types of temperature-responsive materials with complex parameters, and their properties may be difficult to control under variable external conditions. For example, LMPAs cannot maintain rigidity when grasping high-temperature objects. Second, temperature-responsive materials still cannot completely solve the contradiction between stiffness and compliance; that is, they cannot make the manipulator have both flexibility and a certain degree of rigidity.

2.2. Variable stiffness design based on rheological materials

In view of the shortcomings of temperature-responsive materials in the variable stiffness application of flexible manipulators mentioned above, this section proposes a variable stiffness design based on rheological materials. Rheological materials have millisecond-level response performance, which makes them one of the research hotspots in the field of intelligent materials. Such materials can respond to external electrical stimuli, mainly manifested in the reversible changes of physical properties such as viscosity and yield stress. According to the different types of stimuli to which they respond, rheological materials are mainly divided into three types: magnetorheological (MR) materials, electrorheological materials and electromagnetic rheological materials.

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MR materials include MR elastomers and MR fluids, among which MR fluids are more favored in the field of variable stiffness. Such materials have the characteristics that their own stiffness and damping characteristics change continuously and reversibly under an externally applied magnetic field. When an external magnetic field is applied, the state of the MR fluid changes from disordered to a chain structure consistent with the direction of the magnetic field, which will generate resistance to the movement of the mechanism, thereby providing rigid feedback. Compared with other materials, the main advantage of MR fluid is that it is in a liquid state, i.e., a non-rigid body, so there is no need to overconsider the interference of rigid surfaces in the design. Based on these characteristics, Xuanchun Yin and others proposed a MR fluid-filled origami joint with variable stiffness characteristics and capable of remote control. In the design, the MR fluid is injected into the core layer solution with an extremely small thickness for sealing, and the core layer is sealed between two layers of PET film and one layer of adhesive tape layer, thus forming a complete variable stiffness origami joint with four layers of materials, and the production method of the joint can be changed according to the requirements of thickness and shape. When an external magnetic field is applied to the joint component, the MR fluid will generate stiffness to hinder the completion of movement. Subsequently, the researchers integrated the origami joints into complex origami structures with Yoshimura and Kresling mosaic patterns to verify their properties. It is worth noting that when applying the joint, mosaic patterns that do not change the radial dimension should be selected. The study finally verified the effects of the origami joint in the two mosaic patterns, and found that after targeted improvement of the mosaic patterns, The stiffness of the structure was significantly improved under the condition of applying a certain intensity of magnetic field, indicating that MR materials can change the stiffness of the mechanism and improve the performance of the mechanism through responding to the magnetic field [9].

The most common electrorheological material is electrorheological fluid (ERF), which is a type of intelligent material whose rheological properties can change reversibly under the action of an externally applied electric field. ERF is mainly composed of two parts: the liquid phase and the particle phase. The liquid phase usually has insulating properties, while the particle phase has a strong ability to respond to the electric field due to its high dielectric constant. Under the influence of the electric field, the particles in the particle phase will be polarized, generating an attractive force of interaction, changing from a disordered state to a chain or columnar structure consistent with the direction of the electric field, thus producing a stiffness change. At present, scholars have designed many variable stiffness mechanisms based on the variable stiffness characteristics of ERFs, including various dampers, grippers, manipulators, and so on. Yiyi Pan and others proposed a variable stiffness device designed based on the stretchability of ERF, named VSERF. The device adopts a sandwich structure, with stretchable electrodes placed on the outer sides of the top and bottom layers, respectively, and the ERF is sandwiched between the two electrodes and encapsulated with an elastomer. The encapsulation layer isolates the ERF from the motor, making the device present a five-layer liquid-elastomer composite structure. In the VSERF, the two electrodes are connected to a high-voltage power supply through wires to apply an electric field to the ERF between the electrodes, and the stiffness of the device is controlled by the intensity of the electric field. When the electric field is enhanced, the particle phase in the ERF forms a chain or columnar structure along the direction of the electric field, the strength of which increases with the increase of the electric field intensity, and the strength of the structure can affect the stiffness of the VSERF. After a series of tests, The stiffness variation range of the device reached 14.8 times, and it had excellent conformability in the flexible state and excellent load-bearing capacity in the rigid state. In

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addition, based on the characteristics of the ERF itself, the device also has the advantages of continuously controllable stiffness and short response time [10].

The above variable stiffness designs based on MR materials and electrorheological materials show that rheological materials have excellent performance in the field of variable stiffness structures, and rheological materials may become a research hotspot in the future. On the other hand, it must be pointed out that the application of rheological materials still has problems to be solved. For example, the stiffness change of rheological materials has anisotropy, which undoubtedly brings challenges to the design of related structures; at the same time, due to the viscosity of rheological materials, some stiffness modulation strategies may lead to changes that require manual recovery or even irreversible changes, which greatly reduce the reusability of related structures. Paper Title (style to use: Title)

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3. Analysis of the structural design of variable stiffness continuum manipulators

Some organisms represented by snakes can survive and move in various confined spaces due to their large number of continuous variable stiffness body structures. Inspired by these organisms, researchers have designed variable stiffness continuum manipulator structures at the macrostructural level. This paper mainly introduces two structural designs: cable-driven structure and deployable structure.

3.1. Cable-driven variable stiffness manipulators

Cable drive is one of the classic driving methods for manipulators. A cable-driven manipulator usually consists of multiple interconnected rigid links forming a spine, and realizes bending by pulling and regulating multiple sets of cables through force transmission components such as pulleys and spherical hinges. The cable-driven structure has the advantages of slenderness, high redundancy, and high strength, and can be remotely controlled with electronic drive modules. The cable-driven structure has been widely used in related fields such as precision large-scale mechanical maintenance and deep-sea detection, and is one of the ideal structural choices for manipulators working in confined spaces.

Cable-driven structures mainly change stiffness in two ways: adjusting the pre-tightening force of the structural spine itself or introducing additional stiffness adjustment cables. A large number of studies have shown that the main problem of the variable stiffness design of cable-driven structures is that both adjusting the stiffness of the spine itself and introducing additional variable stiffness components will lead to the reduction of the stiffness and load-bearing capacity of the entire system, while introducing additional components to make up for the reduced stiffness of the system will lead to an increase in the system volume, which violates the principle of operation in confined spaces. The current research direction is to find a balance that can maximize the performance and environmental adaptability of the manipulator among these contradictions, and at the same time reduce the complexity of the mechanism to lower the difficulty of kinematic planning when the manipulator is in use.

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Cable-driven hyper-redundant manipulators are shaped like snakes, with lightweight, slender, continuous or nearly continuous structures, which are especially suitable for operations in long and narrow confined spaces. However, too many redundant structures also bring challenges to the mechanical structure and kinematic planning. In terms of mechanical structure, under-constrained continuous manipulators, similar to soft organisms, can achieve highly flexible movement, but usually do not have strong load-bearing capacity. Fully constrained discrete manipulators have relatively strong load-bearing capacity, but it is difficult to make full use of redundant degrees of freedom due to their overly complex structure. In addition, the limited base will also lead to the limited activity space of the cable-driven hyper-redundant manipulator. In terms of kinematic planning, due to the adoption of remote cable control, the model cannot directly reflect the movement of the structure with high precision, and the existing redundant degrees of freedom will lead to great difficulty and cost in finding the optimal inverse kinematics solution. Based on this, Mingrui Luo and others designed a highly compact coiled cable-driven hyper-redundant manipulator similar to a snake. Inspired by the hunting behavior of snakes, Luo's team believed that the coiled structure could achieve a large amount of compact feeding with a small displacement. The manipulator combines continuous and discrete types according to the force characteristics of different parts, and adopts spiral feeding to obtain a larger range of motion. The feeding base includes a rotating base, planetary gears, a gear ring, and a floating backlash eliminator, among which the floating backlash eliminator is mainly used to compensate for the center offset of the gear ring to reduce feeding errors. The tractor of the manipulator is driven to rotate by cables. A twin-screw tractor is equipped with a synchronous gear connected to the joint motor, and the meshing of the motor input gear can make the two screws rotate synchronously to realize the change between the relaxed and tight states. Experimental verification shows that this manipulator design can adapt to more diverse scenarios, and for the same situation, the design better meets the requirements of the inverse kinematics algorithm of the cable-driven hyper-redundant manipulator. In the prototype test, the manipulator showed extremely excellent flexibility and maneuverability, and could accurately complete some complex movements [11].

Inspired by space-folding mechanisms such as umbrellas, the research team led by Deshan Meng designed a novel variable-diameter-stiffness cable-driven serpentine manipulator, realizing the integrated adjustment of the shape and stiffness of the continuum serpentine manipulator. The manipulator model proposed by the team consists of an arm segment with synchronous diameter and stiffness adjustment and a drive box, in which the arm segment is composed of an umbrella-rib-type variable-diameter unit and a cardan universal joint, and springs are used to increase the stiffness of each unit. When the synchronous variable-diameter mechanisms move away from each other, the angle between the connecting rod and the central threaded rod will gradually decrease, making the surrounding frames close to the central threaded rod and reducing the outer diameter of the manipulator, which is called the closed state of the variable-diameter unit. When the synchronous variable-diameter mechanisms approach each other, the connecting rod will prop open the frame, thereby increasing the outer diameter of the manipulator, which is called the open state of the variable-diameter unit. The above-mentioned variable-diameter synchronous mechanism is controlled by the bottom motor connected to the central threaded rod through screw transmission. According to the modeling research of the experiment, the stiffness of the device is mainly affected by the outer diameter and joint angle. When the outer diameter of the manipulator increases, the end stiffness will increase significantly, and the stiffness change rate is roughly proportional to the square of the outer diameter change rate. The joint angle is positively correlated with the end stiffness and negatively correlated with the tensile performance. In the subsequent prototype test, the

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team proved the accuracy of the previously established model, and the manipulator has the ability to integrate adjustment of outer diameter and stiffness, and can complete high-precision operations in the fields of aerospace equipment maintenance and medical supplies processing [12].

The above designs prove that the cable-driven variable stiffness structure has certain reliability and broad prospects in the application of manipulators working in confined spaces. At the same time, it must be pointed out that the current designs in this direction still have some limitations. For example, the insufficient accuracy of the dynamic model and the complex mechanical structure led to huge operation and maintenance costs, which are still urgent to be solved. On the whole, the cable-driven structure has great advantages in variable stiffness manipulators, and the main research direction in the future should be to improve the comprehensive performance of the structure.

3.2. Deployable structure continuum manipulators

In confined working spaces, the volume and activity space of manipulators are greatly limited. Continuum manipulators with deployable structures can change their own volume and size, thus having an advantage in some confined spaces. For example, in long and narrow spaces or working environments with small entrances, deployable structures are easier to deploy than other structures. At present, deployable mechanisms are widely used in space equipment.

Deployable mechanisms are mainly divided into single-degree-of-freedom deployable mechanisms, multi-degree-of-freedom deployable mechanisms, and irregularly shaped deployable mechanisms. Among them, origami mechanisms, as an emerging deployable mechanism, have been widely sought after in recent years. Origami mechanisms realize morphological changes based on origami-like deformation characteristics. In order to make the deployable structure continuum manipulator designed based on origami mechanisms have strong foldability, flexibility, load-bearing capacity, and a relatively simple structure, the research team led by Ziqiang Zhang proposed a rigid-flexible coupling origami unit, and designed a redundant rigid-flexible coupling deployable manipulator composed of such units based on this. In the classic Kersling origami unit, the upper and lower layers are connected by several parallel thin rods. The connecting line between adjacent thin rods and their endpoints on the upper and lower layers forms a parallelogram. Based on the geometric characteristics of the parallelogram, when folding is required, the angle between the thin rod and the connecting layer gradually decreases, and the upper and lower layers gradually approach, realizing volume compression. Based on the Kersling origami unit, Ziqiang Zhang's team proposed a rigid-flexible coupling equivalent unit. In the Kersling origami unit, the longer diagonal of each parallelogram is generally called the valley, and each connecting rod is called the peak. Based on the principle of the origami mechanism, the team equated the crease rotating around the fixed axis in the fixed top coordinate system to a revolute pair, and equated the crease rotating around the moving axis to a Hooke's joint, which is placed at the midpoint of each crease. At the same time, Hooke's joints are set at the midpoints of the line segments of the valley and peak points of the plane, where bending deformation may occur to simulate its flexible deformation. It is not difficult to find through simulation experiments that the mechanism can simulate the folding behavior of the Kersling origami unit, and at the same time, realize the uniqueness of the path and the simplicity of the structure. Subsequently, the team spliced six rigid-flexible coupling equivalent units into a redundant rigid-flexible coupling deployable manipulator as a prototype for the prototype test. In the folding motion experiment, the top surface of the manipulator can not only move vertically, but also perform various posture changes, showing a significant folding ratio. In the load experiment, the stiffness of the manipulator changes with the change of the load, and it shows a stronger load-bearing capacity compared with the flexible manipulator constructed of flexible

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materials. In the reaching point experiment, the manipulator showed a high degree of flexibility and could reach the target point with different postures with high precision. A series of prototype tests shows that the redundant rigid-flexible coupling deployable manipulator has excellent performance and good application prospects [13].

The research team led by Yuchen ZHAO summarized the previous research and proposed a cable-driven manipulator capable of reconstruction and expansion to solve a series of problems, such as the difficulty in improving structural adaptability while maintaining mechanical strength and high equipment maintenance costs, to enhance the environmental adaptability of the equipment and reduce the demand for special development. The manipulator is composed of a reconfigurable rigid skeleton and a retractable shell, which can change the number of joints and the length of the manipulator without reducing rigidity, and the shell can shrink outward at the skeleton for easy recovery, greatly reducing the volume of the drive box. The mechanical shell is divided into an upper shell and a lower shell, and the upper shell can be nested with the lower shell when shrinking, thereby shortening the overall length of the manipulator. The shell is connected to the skeleton by the connecting blocks on the inner wall of the upper shell, and cavities are set between the connecting blocks for the controller cables to pass through. The skeleton structure is provided with cylindrical protrusions equipped with grooves for fixing the connection with the connecting blocks. Adjacent skeletons are connected by universal joints to realize the bending of the joints. The inner diameter of the shell becomes gradually thicker along the track direction, and the skeleton gradually becomes thinner along the track direction, which can ensure that the skeleton segment can bypass the basic shell to reach the corresponding module, and also ensure the correct connection sequence of each segment. The side of the skeleton is equipped with a linear platform expansion system, including a tubular track and a drive motor, which can adjust the number of arm segments, and a special design is adopted to greatly reduce the volume of the expansion system. When the manipulator moves along the reconfigurable direction, The motor drives the slider to adjust the number of skeleton segments. It is verified that the modular system of the manipulator can maintain mechanical continuity and structural integrity, can adapt to different storage spaces and working spaces through expansion, contraction and bending, and can independently carry light loads, which has great potential in practical applications [14].

The above studies prove that soft manipulators with deployable structures have great advantages in the application of confined spaces due to their volume change characteristics, such as easy storage and adaptability to diverse working spaces. On the other hand, researchers also pointed out that there are still certain problems with the existing designs. For example, the complex error sources of the hyper-redundant system and the diverse working trajectories of the soft manipulator are very likely to lead to large errors in the motion trajectory of the manipulator during remote control, and the problem of weak load-bearing capacity of the soft manipulator cannot be solved.

4. Conclusion

This paper systematically reviews the research progress of flexible manipulators for operation in confined spaces in terms of variable stiffness materials and continuum structures. At the material level, shape memory materials and polymer composite materials provide a physical basis for realizing local and efficient active stiffness modulation; at the structural level, cable-driven and deployable structures provide engineering implementation schemes for continuous, dexterous, or extremely compact motion. Current research has successfully demonstrated the feasibility of a variety of "combinations of rigidity and flexibility", which has significantly improved the adaptability and functionality of manipulators in confined spaces.

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In terms of materials, the paper first introduces three types of temperature-responsive materials. Shape memory polymers undergo regular changes under external stimuli, with a large change range, light weight, and strong reversibility of changes, thus becoming one of the hot materials for the variable stiffness design of flexible manipulators. Among them, temperature-responsive polymers can change their own mechanical properties with temperature changes, thereby changing the structural stiffness, but the stability of the material configuration is limited and requires the constraint of an external frame. Compared with shape memory polymers, shape memory alloys have higher mechanical strength and also have the ability to change their own stiffness with the environment, but the deformation of shape memory alloys is difficult to control due to many factors, and the shape change rate is slow. Low-melting-point alloys can also realize stiffness modulation through the transformation between their liquid and solid states. However, the above three types of materials still cannot completely solve the contradiction that the stiffness and compliance of the manipulator cannot be satisfied at the same time.

On the other hand, rheological materials, as a type of electromagnetic induction material, are also one of the hot materials in the field of variable stiffness design. The paper makes a specific analysis of the research and application of two types of rheological materials: MR fluids and ERFs. MR materials can produce reversible damping changes when sensing an externally applied electric field, generating mechanical feedback equivalent to rigid materials. ERFs can sense the electric field and directly change their own stiffness through the polarization of internal particles. Rheological materials have a short response time to external changes and can perform variable stiffness tasks. However, it should be noted that the rigidity of the above rheological fluids has anisotropy and viscosity, which need to be taken into full account when designing mechanical structures and stiffness modulation strategies.

In terms of structure, the cable-driven structure, as a classic continuum manipulator structure, can also realize the stiffness modulation of the manipulator, mainly with two strategies: changing the pre-tightening force of the manipulator skeleton and introducing additional stiffness modulation cables. Cable-driven manipulators have slender structures, high strength and high redundancy, and have a stronger load-bearing capacity than other structures, but they also lead to complex remote-control models and difficulty in calculating the optimal motion trajectory.

The deployable structure is also a popular continuum structure in the field of variable stiffness. Deployable structures can change their own volume, which makes them easier to deploy and store in confined spaces. However, deployable mechanisms still have the characteristics of hyper-redundancy, which are difficult to control in practical applications.

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