

Review Article

A Review on the Environment Perception and Control Technologies for the Hyperredundant Manipulators in Limited Space

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As a typical kind of special robot with high flexibility and maneuverability, the hyperredundant manipulators (HRM) which can work in the narrow and complex space arose much related research work. Due to the particularity of the environment and the structural complexity of the manipulators, there are many problems for the HRM in specific applications. This paper summarizes some representative research works for HRM, including the mechanical design, environment perception, robotic navigation, and trajectory control. In order to make the design of the HRM systems more suitable for applications, the technical problems of current research are analyzed to address the key issues for the improvement. Finally, the prospect of spatial reachability, structural compactness, operation accuracy, and interaction friendliness of hyperredundant manipulators are presented.

1. Introduction

In the development of robotic technology, several kinds of robots have been used in many industrial fields to replace manual operation, reducing the labor intensity of workers and improving the quality of operation. However, in some complex and dangerous operating environments, especially those with narrow space and limited movement, it is difficult or even impossible for operators and traditional robots to enter the operating space. In addition, the operation mode using simple auxiliary tools cannot meet the requirements of operation scope and quality. Therefore, it is an important way to solve this kind of practical application problem to study the robot technology suitable for confined space operation.

Unstructured narrow working space is widely existed in lots of fields such as aerospace [1–4], nuclear power [5, 6], equipment manufacturing, and postdisaster rescue. Figure 1 lists some common usage scenarios of hyperredundant manipulators.

In the aviation manufacturing industry, the gluing, painting, riveting, grinding, maintenance, and other operations required for the assembly of narrow inner cavities such as wing box segment and inlet can only be realized manually at present. It is hard for the workers, and the quality of the product cannot be guaranteed which seriously compromises the safety of aircraft. In the equipment manufacturing industry, welding and maintenance of cabin cubicles, mining hydraulic supports, cathode busbars of electrolytic cells, and so on require workers to work continuously in high temperature, pollution, and narrow space. The environment is hard for workers, and it is difficult to ensure the quality of welding seams. In the nuclear power industry, nuclear power reactor body, fuel rod control pipeline, and other key equipment cross each other, creating a complex environment. There is no efficient maintenance means due to high temperature, strong radiation, and narrow space, which brings serious hidden danger to the safety

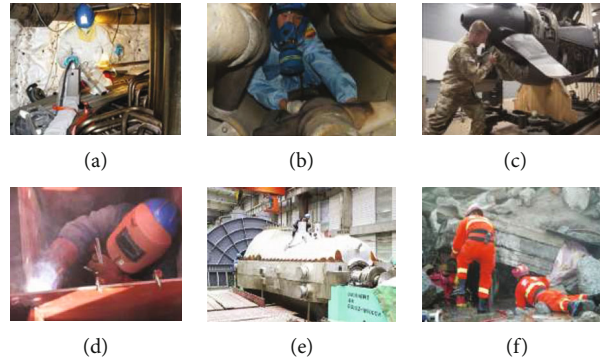


FIGURE 1: Typical complex and narrow operation scenario. Picture (a) is the repair of nuclear power pipeline, picture (b) is closed GIS equipment maintenance, picture (c) is aircraft inlet cleaning, picture (d) is cabin compartment welding, picture (e) is an internal inspection of closed tank, and picture (f) is a search and rescue after earthquake.

of nuclear power. In the power energy industry, when the complex and compact closed switchgear and integrated power distribution control cabinet in the substation need to be repaired due to an internal fault, usually, a large range of parts need to be disassembled to locate the fault, which greatly reduce the maintenance efficiency. In the task of postdisaster search and rescue, the narrow environment formed by collapsed buildings and equipment makes it difficult for search and rescue personnel to directly enter the rescue, to obtain information about trapping people and the surrounding environment, and to implement emergency treatment. After the above analysis, we need to analyze the scene characteristics and tasks in complex and narrow space and develop a robot system that can actively and flexibly avoid obstacles; thus, there is an actual demand in lots of fields.

Narrow and closed operation space, complex obstacle distribution, and insufficient light conditions, a special operating point that located inside the deep cavity, are the common characteristics of this kind of operation scene talked above. To solve the problem of narrow space operations, there is an urgent need to develop a robot system that can actively and flexibly avoid obstacles, which not only can precisely transport operating tools to the operating point, continuously move along the specified trajectory, but also it can adapt to the complex unstructured narrow environment. The robots in such robotic systems generally need to have a compact overall structure, which enables the robots to avoid different obstacles in space, thereby realizing flexible operations in small and confined spaces.

2. Summary of Related Research Work

As a kind of typical special application robot, robots that can work in narrow space have been widely concerned at home and abroad. A lot of researches had been carried out in the field of joint materials, mechanism design, control method, sensing technology, application system, and so on by research institutions in the United States, Germany, Britain, Japan, China, Norway, and other countries. And many fruitful theoretical methods and prototypes have been formed.

2.1. Manipulator Mechanism Design. Environmental adaptability and traversability in confined space are the key points of robot system design. However, in different narrow spaces, the operating conditions and working environments of robots are different. So robot mechanisms based on different operating modes have been developed for different operating scenarios at home and abroad. Figure 2 lists some common drive forms, structural forms, and propulsion methods of snake-shaped manipulators. Among them, the common driving forms and structural forms of the hyperredundant manipulator will be introduced in this section with specific research examples, and the propulsion device will be mainly introduced in the “Robotic Operating System” section.

Due to the limitation of the narrow space, the movement mechanism of the robot generally uses snake mechanism or soft machine. The kinematic joints of the robot mainly adopt rigid joints (with ball joints or hook joints), hollow bellows, and elastic ridge skeleton. As shown in Figure 2, the main driving modes of the robot are micromotor direct drive, wire rope drive, artificial muscle drive, gas drive, and so on. For example, the pneumatic flexible robot developed by the Tohoku University in Japan moves inside the pipe of the pressure vessel of nuclear power plant through the tension and drive of the pneumatic actuator [7]. Chuo University in Tokyo has developed an in-tube detection robot based on artificial muscles, which can achieve peristaltic crawling by stretching artificial muscles [8]. Carnegie Mellon University developed a snake-like robot composed of multiple modular electromechanical joints in series to realize operation control in narrow space [9]. HRM with different driving methods will have different characteristics and technical difficulties. In general, manipulator powered by micromotors provides limited driving force. Driving with gas requires more consideration of gas tightness and control accuracy and flexibility. At present, most high-redundancy manipulators prefer to use ropes for indirect control, which reduces the weight of the manipulator, but brings many control problems such as model solving and control decoupling. Chinese Shenyang Institute of Science and Technology, Beijing Institute of Technology, Shanghai Jiaotong University, National University of Defense Technology, Beijing University of Aeronautics and Astronautics, etc. have also made fruitful research achievements in this aspect [14–19]. For

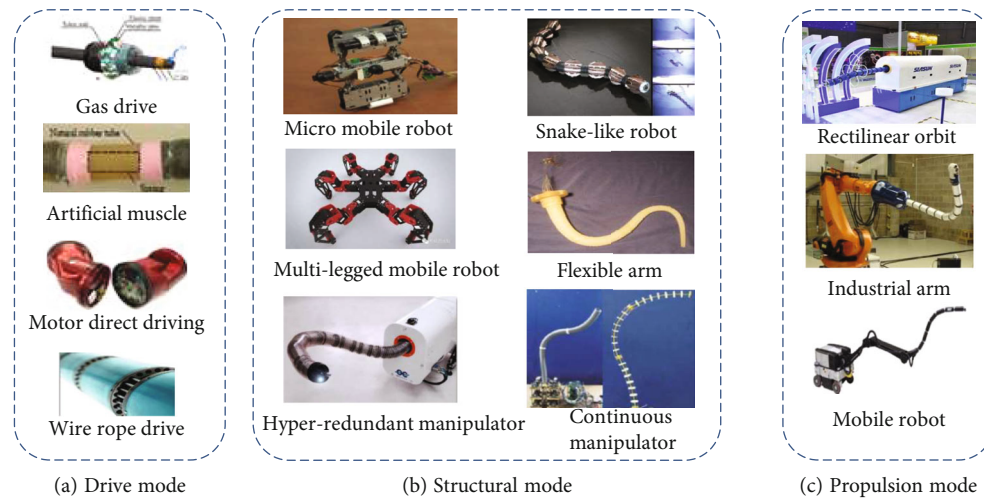


FIGURE 2: Typical robot operation mode in narrow space scenario. The three parts (a–c) introduce the driving mode, the structural mode, and the propulsion mode, respectively. The following is a detailed introduction and source of some images. The first picture in part (a) is a pneumatic drive structure published by the Tohoku University in Japan in 2017 [7]. The second image in part (a) is an artificial muscle actuation structure published by the Tokyo Chuo University in 2012 [8]. The third image in part (a) is a micromotor joint drive structure published by the Carnegie Mellon University in 2014 [9]. The fourth image in part (a), the bottom left picture in part (b), and the second pictures in part (c) are snake-shaped manipulators made by OC-Robotic [1]. The first picture in part (c) is a snake-shaped manipulator developed by Siasun [10]. The middle right picture in part (b) is a soft robot arm made by silicone in the BioRobotics Institute, Scuola Superiore Sant Anna, Pisa [11]. The bottom right picture in part (b) is a hyperredundant manipulator for aircraft fuel tank inspection, which is designed by the China Civil Aviation University [12, 13].

example, a paper published by the Shenyang Institute of Automation of the Chinese Academy of Sciences in 2009 developed a three-dimensional snake-like robot model composed of modular universal units, which can achieve meandering motion, twisting motion, and twisting hill-climbing motion [15]. Later in 2012, they developed an amphibious snake-like robot [16]. The robot consists of 9 universal motion units with hermetic design. And the land and underwater mobility of the amphibious snake-like robot is verified by gait test. In 2008, the Institute of Robotics of Shanghai Jiao Tong University developed a climbing snake-like robot, which consists of many P-R modules (two joints connected in a pitch-roll manner as an execution unit) [17]. The different structural forms that HRM takes are often related to specific tasks. In some detection tasks that do not need to provide working force, a software mechanism can be used to achieve higher flexibility [11–13]. In some industrial scenarios, rigid joints are required to provide sufficient stability and work force [1]. High-redundancy robots with bionic form tend to pay more attention to the realization of shape and bionic motion.

Although snake-like robot and soft robot have better spatial adaptability and flexibility which can help pass through narrow pipes and spaces of different shapes, they can only carry out partial detection tasks and do not have the ability to perform actual operations due to their generally light weight and driving depends on adhesion to the tube wall.

In order to meet the needs of narrow space operation, scholars have carried out research on snake-like manipulator with slender structure. There is plenty of similarities between serpentine high-redundancy robot arm with snake-like robot and also differences. The former is a multijoint manipulator

with fixed foundation for operation, while the latter is a mobile bionic system developed to imitate the movement mechanism of snakes. For the operation in narrow space, the serpentine manipulator can avoid the interference of spatial obstacles to reach the operation target point and can provide enough acting force and positioning accuracy to meet the needs of the operation task.

Scholars have carried out a lot of exploratory research on typical snake-like manipulator, especially in the field of surgical robot, which has formed good technical achievements. In 2009, the CardioARM cardiac surgery robot developed by the Carnegie Mellon University is composed of 50 spherical joints. The internal and external tube structures realize the rigid and flexible alternation and relative movement under the control of ropes [20]. Imperial College London developed a TEMS colon surgery robot in 2017, which is connected in series with 7 joints in different directions, and can actively change the posture of the operating tool to achieve surgical operation in the slender and narrow colon [21]. IREP, an interventional operation robot developed by the Columbia University for single-hole entry surgery, is composed of two flexible arms and a parallel quadrilateral structure with 21 degrees of freedom. The hybrid mechanical structure improves the positioning accuracy of the flexible manipulator and achieves a larger working space [22]. The single-bore surgical robot developed by the Samsung Institute of Advanced Technology (SAIT) is mainly composed of a 6-DOF (degree of freedom) serpentine guiding arm, equipped with two tools and an auxiliary arm, and can reach different surgical sites in the abdominal cavity through incisions [23]. The Harbin Institute of Technology developed a colonoscopy surgical robot composed of a 5-segment continuum driven by steel wire, which can achieve

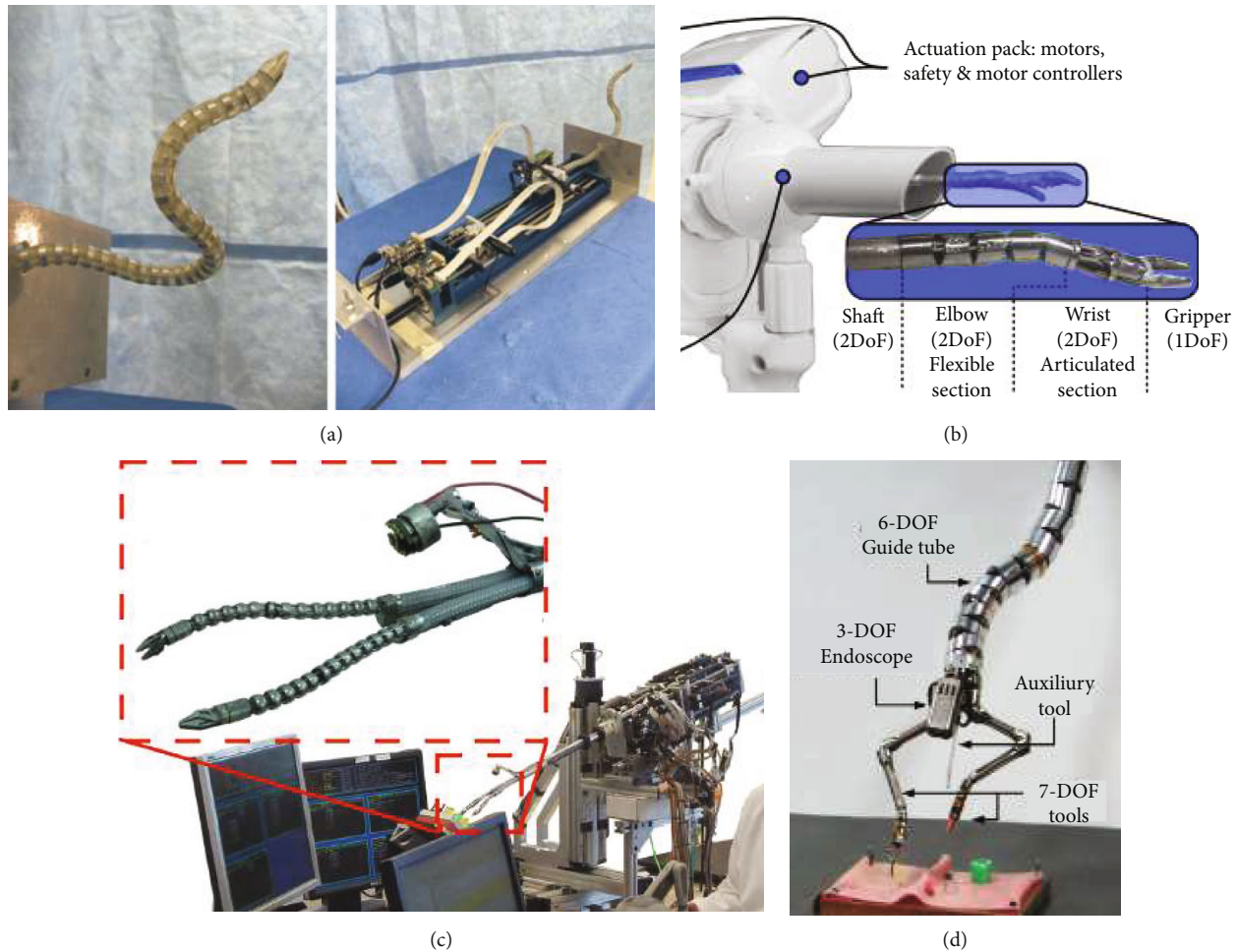


FIGURE 3: Typical flexible operating surgical robot. Picture (a) is a cardiac surgery robot named “CardioARM” developed by the Carnegie Mellon University [20], picture (b) is a colon surgery robot named “TEMS” developed by the Imperial College London [21], picture (c) is an interventional operation robot developed by the Columbia University [22], and picture (d) is a single-bore surgical robot developed by the Samsung Institute of Advanced Technology [23].

multidegree-of-freedom rotation and deformation [24]. Figure 3 shows a physical image of some of the hyperredundant manipulators mentioned above.

In the narrow space of industrial applications, different from the lightweight and dexterity requirements of medical robots, robots are required to have longer arm span, large load, high precision, space obstacle avoidance, and other characteristics, so as to be able to carry out tasks such as deep cavity detection and operation. At present, the most influential robot in the engineering of highly redundant robotic arms is the snake arm robot of OC-Robotics in the UK. They have carried out research for more than ten years and developed a variety of snake arm application systems in nuclear power equipment maintenance, aviation manufacturing, and other industries. These highly redundant serpentine robotic arms move through rigid joints driven by steel wire, which are connected in series by hook hinges [25]. In recent years, Chinese research institutions have also carried out research work on serpentine manipulator in narrow space applications. According to the requirements of aviation assembly, AVIC 625 Institute developed

a robot prototype consisting of 5 sections and 20 sections by referring to the structural characteristics of OC-Robotics [10]. Hit Shenzhen University of Technology developed a superredundant robot with steel wire traction composed of 10 joints, which has good bending characteristics and flexible space movement ability [26]. Tsinghua University designed a spatial redundancy manipulator composed of five segments, with six segments in each segment. The angle of each segment was basically the same through the connecting rope [27]. Researchers at the Beihang University have designed a snake-arm robot. The robot consists of three hollow slender segments consisting of a steel cable-driven spherical hinge. A cage-like structure was designed to drive the wire rope, and a special motor-driven control system was proposed to control the robot [28]. Jing and his team at the Shanghai Jiao Tong University proposed a serpentine arm based on an octahedral variable geometry truss [29–34]. The Shanghai Jiaotong University developed a rope-driven superredundant manipulator with 12 joints and 24 degrees of freedom, which can achieve a load capacity of 0.5 kg at the end through the drive control of 36

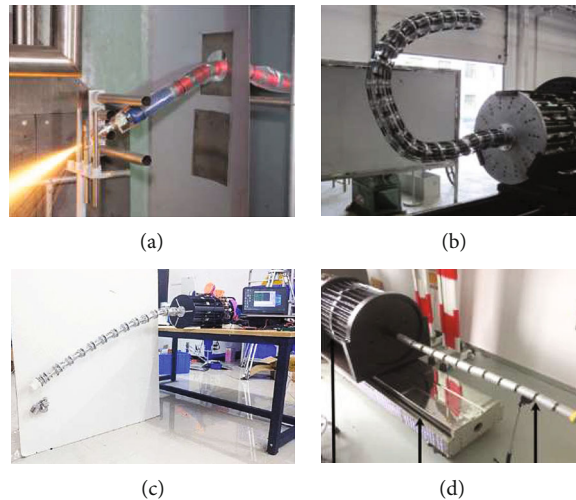


FIGURE 4: Typical snake-like robot. Picture (a) is a hyperredundant manipulator designed by OC-Robotics for welding [25], picture (b) is the hyperredundant manipulator developed by AVIC 625 for the needs of aviation assembly, referring to OC-Robotics [10], picture (c) is a hyperredundant manipulator composed of 10 joints developed by the Harbin Institute of Technology Shenzhen [26], and picture (d) is a rope-driven hyperredundant manipulator with 12 joints and 24 degrees of freedom developed by the Shanghai Jiaotong University [35].

motors [35, 36]. Figure 4 shows a physical image of some of the hyperredundant manipulators mentioned above.

In the above studies, in order to reduce the size of the manipulator and improve the deep cavity accessibility, steel wire is mostly used as the driving mode to meet the operation requirements of narrow space. For medical surgery, the robot has a small load capacity and limited operating range. It is often driven by an elastic skeleton and hollow threaded tube through a few steel wires, and the controlled freedom is far less than the inherent freedom of the mechanical arm. However, for industrial scenes such as cleaning and assembly of narrow space, the required arm span operation range is large, and the rigid requirements are high. Rigid joints are needed to meet the operation requirements. However, for industrial scenes such as cleaning and assembly in narrow space, the robot needs a large working range and high rigidity. Therefore, rigid joints are needed to meet the operating requirements. The high-redundancy manipulator composed of modular rigid joints or segmented joints with multijoint linkage needs to adjust the relative position of joints to adapt to the curvature changes of space. At the same time, the manipulator is required to have a long enough arm span to meet the spatial accessibility requirements. Therefore, the number of joints and the length of rigid joints directly affect the spatial obstacle avoidance capability of the manipulator. The number of independently controllable joints cannot be infinitely increased, so how to design a reasonable joint mechanism of the robot arm, so as to solve the contradiction between spatial obstacle avoidance ability and reachabilities through the limited number of controllable joints, is an important problem in the design of robot motion mechanism.

We summarized the characteristics of some typical hyperredundant manipulator and put the comparison results in Table 1. As shown in Table 1, we list some points such as the amount of DOF, the structural type of manipulators and in which field the manipulator is applied. Consid-

ering some manipulator is combined with other mechanical devices together to form a robotic system, we also give the total amount of DOF of the robotic system in the form of “ $A + B$,” which A represent the total DOF of HRM, and B is the total DOF of other mechanical devices.

2.2. Robotic Operating System. Although the robot arm with high redundancy can achieve strong obstacle avoidance ability by changing its configuration and posture, it must be pushed to the narrow working space by the corresponding propulsion mechanism to work in the narrow working space. Therefore, the manipulator and the propulsion mechanism together constitute a robot operating system that works in a narrow space. The mechanical arm with high redundancy is generally driven by steel wire, and the motor and other executive parts are installed on the base of the root, which makes the base have a large size and weight. A mobile platform is required to push the base and the mechanical arm outward to achieve corresponding movement. Common push platforms include linear guide rail, multidegree-of-freedom industrial robot, caterpillar robot, and so on. OC-Robotics adopts gantry structural beam as push mechanism, which forms a robot system with snake mechanical arm to carry out inspection and maintenance of nuclear facilities [24]. In the aviation manufacturing scene, industrial robots are used as the push platform of the manipulator [1]. The snake-like manipulator operating robot system developed by the Siasun And AVIC 625 Institute pushes the manipulator through the linear slide push mechanism. The whole machine size is larger than the manipulator itself, and it cannot adapt to the compact requirements of narrow space and peripheral sites [10]. The Hopkins University uses UR5 robot as the payload platform and carries wireline driven surgical robot to constitute the surgical robot system [37]. The Samsung Institute of Advanced Technology developed a surgical robot system composed of a 6-DOF serpentine guide arm and a 5-DOF

TABLE 1: Comparison between different HRMs.

Different HRMs	Amount of DOF	Structural type	Applying field
OC-Robotics [1]	20+7	Rigid joints connected by hook hinges	Aircraft assembly
Ringhals 1 [21]	20 are under control	Several discs connected by elastic objects	Nuclear
SAFIRE [25]	18	Rigid joints are connected by a rotation axis	Nuclear
CAUC [12]	6 are under control	Using discs as joints and the discs are connected by fiberglass rods	Aircraft fuel tank detection
CardioARM [20]	105 but only 2 are under control	50 rigid cylindrical links serially connected by three cables	Medical field
SAIT [23]	Guide tube with 6 DOF, two tools with 7 DOF, camera with 3DOF and slave arm with 5 DOF	Six equal-height saddle-shaped linkages (or rings) connected by wire ropes	Medical field
SJTU [36]	24	Rigid joints connected by hook hinges	Prototype for research

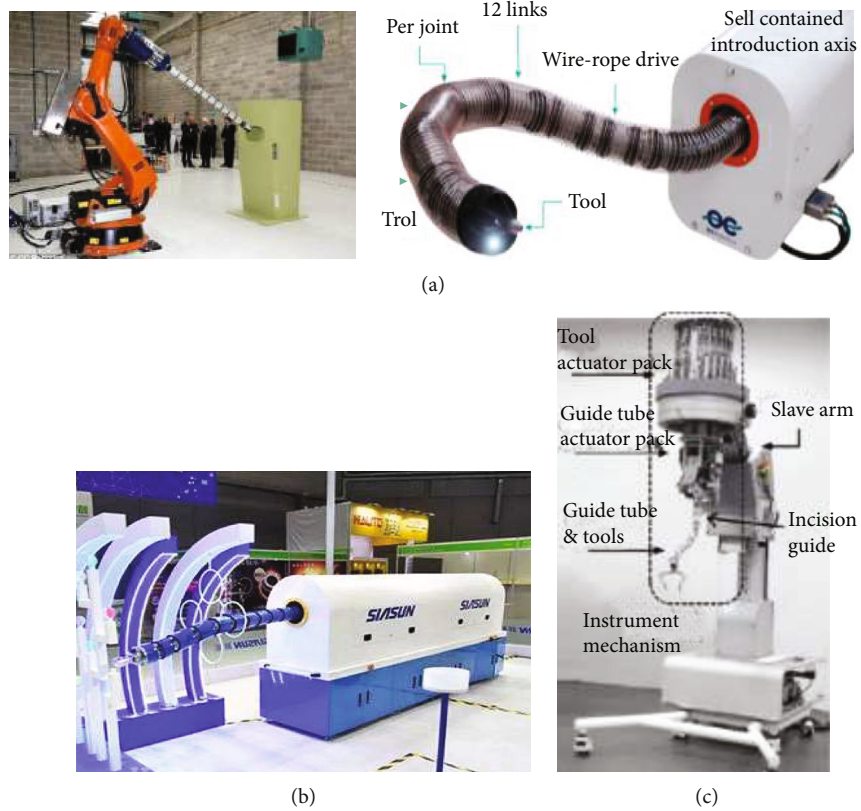


FIGURE 5: Robot operating system. Picture (a) is the hyperredundant manipulator designed by OC-Robotics [1], and picture (b) is the snake-shaped manipulator designed by SiaSum [10], a surgical robot system designed by the Samsung Institute of Advanced Technology [23].

auxiliary arm. The macroarm realized a wide range of propulsion motion, and the guide arm realized the attitude adjustment of the surgical arm [23]. Figure 5 shows a physical image of some of the hyperredundant manipulators mentioned above.

In the above studies, the robot system mainly uses a general or specially designed mobile platform to carry highly redundant robotic arms. Through the composite movement of the manipulator and the mobile platform to achieve movement and operation in the narrow space, this method is relatively easy to design and implement. The motion control of the push platform and the manipulator can be real-

ized through kinematic decomposition, so that the robot system can operate in a narrow space to a certain extent. However, because of the large movement range required by the push platform, a large installation site for the mobile platform is often required in actual use. For example, the size of the moving slide of the robot reaches $3.8\text{ m} \times 0.8\text{ m} \times 1.5\text{ m}$, and its weight reaches 1.4 tons, which is difficult to be satisfied in many working environments (especially post-disaster search and rescue, nuclear power pipeline maintenance, etc.). As a result, although the ultraredundant manipulator itself has good flexibility and can realize the detection of narrow space, its application in practical scenes

is limited by the large size of the push platform and the weight of the whole machine. In addition, the push platform and the manipulator are designed separately, so the manipulator is usually in the extended state when it is not working, which not only occupies a large space but also is easy to be damaged. Therefore, the integration design of high-redundancy manipulator and push platform is an important issue to improve the practicability of robot operating system.

2.3. Planning and Control Methods. Compared with conventional manipulators, high-redundancy manipulators have higher control requirements and greater difficulty because of the number of moving joints far more than the degree of freedom in the working space. Research in this area involves kinematics modeling, mechanical optimization, obstacle avoidance planning, positioning control, and other issues.

2.3.1. Kinematic Modeling and Inverse Kinematics Method. In terms of kinematics modeling, for traditional manipulators, the DH [38] method or the POE [39] method can be used to establish the forward kinematics model. For a simple rigid multijoint hyperredundant manipulator, these two methods can also be used to establish a forward kinematics model. However, for hyperredundant manipulators with flexible or a large number of joints, other kinematic modeling methods need to be found. In 1994, Chirikjian and Burdick proposed an efficient hyperredundant manipulator kinematics modeling method that uses “backbone curves” to fit the macrogeometric features of the robot [40]. In 2012, Godage et al. of the Italian Institute of Technology established a kinematic model for a multijoint hyperredundant manipulator using the continuous modal function method [41]. Recently in 2022, Yang et al. established a kinematic model of a multisegment underwater manipulator based on the piecewise constant curvature (PCC) assumption [42]. The rope-driven hyperredundant manipulator has received extensive attention from researchers in recent years, and a lot of research results have been produced on the kinematic modeling of the rope-driven hyperredundant manipulator. Zhao and Gao of the Harbin Institute of Technology derived the relationship between the rope length and joint angle of the rope-pull redundant robot, established a kinematic model, and analyzed its motion space [43]. Zhang et al. analyzed the relationship between the length of the traction wire and the end pose in detail, studied the adjustment process of the PID parameters of the controller on the basis of the control model, and established a kinematic statics model to analyze the tension and stiffness [44]. In 2018, Xu et al. [45] analyzed the multilevel mapping relationship between motors, cables, joints, and end effectors. They established the corresponding rope-driven kinematics model using a combination of analytical and numerical methods and proposed a decoupling method to compensate for the coupled motion between the ropes.

Generally, the inverse kinematics methods of manipulators can be divided into the following categories: analytical methods, numerical methods, geometric methods, and intelligent algorithms. However, for the hyperredundant manipulator,

the increase of degrees of freedom greatly increases the computational difficulty of the analytical method, so here we mainly introduce the last three methods: numerical method, geometric method, and intelligent algorithm. Numerical methods generally use the pseudoinverse of the Jacobian matrix to solve the differential kinematics equations [46]. However, for a hyperredundant manipulator, the result of the solution is likely to make the manipulator reach an odd isomerism, which makes the solution invalid. Using the damped least squares method [47] or the singular value decomposition method [48] can alleviate this problem, but it will lead to a decrease in the accuracy of the solution. For the geometric method, Chirikjian and Burdick [40] proposed the concept of “ridge line” function, through which the macroscopic structure of the hyperredundant manipulator is described. Based on this, they proposed the modulo function method [49], which divided the “ridge line” into segmented continuous curves and represented by a series of modal functions, and finally, used a fitting algorithm to obtain the joint angles. Mu et al. [50] used the piecewise geometry method to divide all the joint variables of the hyperredundant manipulator into three parts, shoulder, elbow, and wrist, and transformed the complex hyperredundancy problem into a low-redundancy problem. With the development of artificial intelligence algorithms, some new solutions are provided for the solution of inverse kinematics of hyperredundant manipulators. In 2014, Melingui et al. of Polytechnique Paris adopted qualitative modeling method based on RBF neural network to solve its linear and uncertain problems and selected specific inverse kinematics model from redundant manifold through remote supervised learning framework [51]. In 2021, Neng of Harbing University of Technology proposed an adaptive search space genetic algorithm [52], which can efficiently and accurately solve the inverse kinematics of a hyperredundant manipulator. In 2022, Yang et al. implemented the inverse kinematics solution of an underwater multijoint manipulator using a deep neural network (DNN) with six hidden layers [42].

2.3.2. Dynamic Modeling. In terms of dynamic modeling, Chirikjian [49] proposed a continuum modeling method based on infinite degrees of freedom in an article published in 1993, and this method is called the continuous “Cosserat” method. In 2014, Renda et al. [11] established a dynamic model of a cable-driven continuous soft robotic arm based on a rigorous geometrically accurate method, which fully considered the dynamic interaction and tension coupling conditions of dense media. Later in 2018, Renda et al. [53] proposed a dynamic model of multisection soft manipulator based on discrete Cosserat method. Compared to the previous model, this model takes into account shear deformation and torsional deformation. Recently in 2021, Yang et al. propose a modular-based approach to modeling the dynamics of a cable-driven continuum robot that considers continuous deformations, including extension or contraction, bending, and torsion, and is validated by static and dynamic experiments [54]. Liu et al. proposed a real-time dynamic model of a cable-driven continuum robot, using the

covariant formula to describe the motion of the cable-driven continuum robot and using the virtual power principle to establish a dynamic model [55].

2.3.3. Positioning Control. In the aspect of positioning control, the wire traction mode has certain elastic deformation, and its control accuracy is lower than that of the rigid drive mode. Therefore, the deformation compensation of the wire should be considered to improve the control accuracy. Alambeigi et al. of Samsung Research Institute used model analysis and off-line measurement system to measure the clearance in order to reduce the error problem of the snake arm casing wire and realized the clearance compensation in the wire control process [37]. The backgap of wire traction mode is an important factor affecting the control accuracy of serpentine arm. Agrawal et al. of Purdue University specifically studied the system modeling of the actuator of wire traction for this problem and designed the backgap compensator of wire length control by using the smooth backgap inverse model as feedforward [56].

2.3.4. Obstacle Avoidance Planning. In the aspect of obstacle avoidance planning, it is generally divided into two steps, the first is to plan the obstacle avoidance path and then control the robot arm to move according to the planned path.

The first step in obstacle avoidance path planning is to find a collision-free path where the end of the manipulator moves from the starting point to the target operating point. In the field of robotics, a common approach is to rasterize the space and then use a suitable search algorithm such as the A^* algorithm and its improvements [57, 58] to find a suitable path. However, as far as the hyperredundant manipulator is concerned, some special path planning algorithms need to be designed for its high degree of freedom and continuum characteristics. In 2010, Marcos et al. [59] proposed a trajectory planning method that combined the closed-loop pseudoinverse method with a genetic algorithm and proposed an optimization criterion for repeatable control of a redundant manipulator, avoiding the problem of joint angle drift. Ananthanarayanan and Ordóñez [60] proposed a multipass sequential local search technique for hyperredundant manipulators in 2017. The method solves the dimensionality problem of the exhaustive search technique through multi-channel sequential local search and solves the sensitivity problem of the greedy method to local minima through the backtracking technique. In 2021, Bulut and Conkur [61] proposed a simple, effective, and robust geometric method for real-time path planning of hyperredundant robots in a limited space full of obstacles.

The second step of obstacle avoidance path planning is to control the manipulator to move according to the planned path. The traditional method is to obtain the joint angles of a group of manipulators through some inverse kinematics methods according to the target path. The inverse kinematics solution method of the hyperredundant manipulator has been introduced in detail in the “Kinematic Modeling and Inverse Kinematics Method” section.

However, in practical applications, in most cases, the characteristics of the environment in a narrow space are

unknown, so it is difficult to establish an accurate three-dimensional space model for robot motion planning. In most instances, the scene is gradually constructed in the process of robot moving. The follow-the-leader mode [62] is based on the head movement, and the subsequent joints follow the space running track of the head to move, which can ensure that the mechanical arm can avoid obstacles and reach the target point during the moving process, and there is no need to replan the posture of each joint during the movement. Conkur [63] proposed a hyperredundant manipulator path planning algorithm based on the follow-the-leader model in 2003. The algorithm decouples the coupling between the manipulator joints and uses numerical methods to establish the position of each joint relative to the curve. Finally, the motion of the highly redundant manipulator on the curve is realized.

However, in actual motion control, there is a big difference between the reachable space of other joints of the manipulator and the reachable space of the end joints, and there is a tension singularity problem of wire tension under different joint positions, which may lead to the situation that there is no solution for some joints, and thus, the obstacle avoidance function cannot be realized. At the same time, the task also has certain requirements on the stiffness and karma of the manipulator. Therefore, it is necessary to study reasonable obstacle avoidance planning and control strategy and solve the optimal pose suitable for the whole robot arm according to the obstacle model. At the same time, the stiffness of the manipulator is controlled according to the requirements of the task to achieve fixed-point operation tasks.

2.4. Environment Perception and Navigation Technology. Before robots operate in a narrow space, they often lack accurate prior models for the environment space. Therefore, it is necessary to use a variety of sensors to perceive the environment in a narrow space and to control the navigation process of the robot. The key of environment awareness technology is to extract effective feature information in the environment through algorithm and process and analyze it. Then, an environment reconstruction model that can be understood by the robot is formed to express the information of the robot’s surrounding environment. The feature information in the environment is mainly spatial information, that is, the position and size of points, lines, and planes that constitute the environment space. In the unknown environment, the robot needs to know its precise position and then continuously correct its position by using the relative location of the environment features, so as to conduct localization and map construction (SLAM).

Different from the perception and navigation technology of mobile robots in conventional scenes, robots operating in narrow spaces are difficult to carry large size and multiple types of sensors to sense the environment due to the limitations of their own volume and load capacity. In the aspect of snake robot sensing technology, relevant research work has been carried out at home and abroad. Tanaka et al. of Tokyo University of electrical and communication realized the obstacle avoidance movement of the robot in limited space

through the small camera and laser ranging module installed on the head of the snake robot, combined with the infrared ranging sensor installed on each joint [64]. Tian et al. of Ritsumeikan University proposed a SLAM algorithm using single line lidar, which is fixed outside the robot head joint and can generate a two-dimensional environment map for navigation [65]. Chavan et al. used ultrasonic sensor and passive infrared sensor to create and navigate snake robot map and realized wireless control through ZigBee [66]. Morse and Choset of Carnegie Mellon University used rgb-d camera to build sparse attitude map and three-dimensional color point cloud map [67], but the quality of the map is closely related to the path quality, and the operator needs to reduce the robot speed in a specific gait to improve the image acquisition quality.

Sensors such as lidar and ultrasonic wave can measure environmental depth information, but they are not suitable for robot systems in narrow space because of their large volume and high energy consumption. Chinese and foreign scholars have carried out relevant research on compact sensor configuration and sensing technology. Ponte et al. of Carnegie Mellon University designed a triangulation sensor to adapt to the size and power constraints of snake robot using laser sensor and camera. When the robot raises its head, it scans the 3D point cloud of the environment in combination with the information of color camera [68]. Girerd of ubfc University in France and others carried out job navigation through a monocular camera fixed on the head of the tracheal surgery robot and proposed an automatic end guidance method based on dso-slam [69]. Sareh et al. of the University of London used optical fiber pressure elements to form tactile sensors to provide tactile feedback for flexible manipulators [70]. Figure 6 shows the block diagram of this tactile sensor. Beijing University of information technology uses cross laser combined with binocular stereo vision to form an environmental perception system for visual obstacle avoidance of snake manipulator in narrow space [71]. At present, the SLAM method of mobile robot is still used in the research of narrow space sensing technology. Some improvements have been made in sensor configuration and navigation methods. Therefore, it is necessary to carry out targeted research according to the characteristics of the scene. Table 2 summarizes and compares the performance of the environment perception and navigation methods in the above-mentioned papers.

The environment perception in narrow space scene has the following characteristics. First of all, light is often insufficient in narrow and closed scenes, so the contrast is low, and the target features are not obvious. Conventional visual processing methods are difficult to extract effective feature information from the collected images, which brings great difficulties to environment perception and target recognition. Secondly, due to the narrow cavity channel, conventional sensors are easy to enter their perceptual blind area and are blocked by obstacles, so the field of vision is severely limited, resulting in insufficient effective output information of sensors. Therefore, adaptive light filling and image enhancement are needed in narrow space. Then, the image data can be well recognized and resolved for the scene fea-

tures. In recent years, with the development of artificial intelligence and deep learning, many effective methods have been generated in image enhancement. In 2017, Ignatov et al. used the GAN model as the basic framework to propose a photoenhancement solution that can effectively convert ordinary smartphone cameras into high-quality DSLR cameras [72]. In 2018, Huang et al. proposed a scale-scaling global U-Net (Range Scaling Global U-Net, RSGU-Net) for image enhancement on mobile devices and won the ECCV-PIRM2018 (Perceptual Image Enhancement on Smartphones Challenge), the first place in the image enhancement task in the challenge [73]. Recently in 2020, Guo et al. proposed a Zero-Reference Deep Curve Estimation (Zero-DCE) method, using a lightweight deep network DCE-Net to estimate pixel-level and higher-order curves. This method achieves effect enhancement on low-brightness images [74]. At the same time, multisensor data with spatio-temporal continuity is used to deeply fuse the collected data in the scene and eliminate the wrong data caused by occlusion and other problems. Finally, the scene is constructed with offline map information to provide a basis for robot navigation control.

3. Key Technical Issues Analysis

Flexible manipulator with high redundancy is an effective technology to solve the problem of working in narrow space and has clear application requirements in many industries. It is of great practical significance to develop a highly redundant robot operating system adapted to the actual environment, to study the environment perception and navigation and positioning methods in complex scenes, and to propose a control method to improve the performance and efficiency of the robot operating in narrow space.

In the existing research work at home and abroad, the research focus is more on joint materials, mechanism design, environment perception, robot application system, and other aspects. Robot is mainly oriented to the detection task application, but the research on fine perception and precise positioning control oriented to the job task is less. In order to improve the kinematic flexibility and operational performance of robotic systems, the following key technical problems need to be solved:

3.1. Design of Mechanism with Both Smoothness Obstacle Avoidance and Operation Stiffness. The robot system based on highly redundant manipulator is most suitable for working in narrow space. Its outstanding feature lies in its good obstacle avoidance ability, because the number of independently controllable joints is a direct factor affecting the obstacle avoidance ability. In the design of wire driven manipulator, there is often a contradiction between the number of joints and the diameter of joints. Due to the limitation of the diameter of the manipulator, the number of joints can pass through the limited number of wires, and the number of joints directly affects the arm span and obstacle avoidance ability. In the existing studies, the basic design of each joint is 1-2 degrees of freedom of rotation. Each rotation angle range is limited due to the effect of wire traction

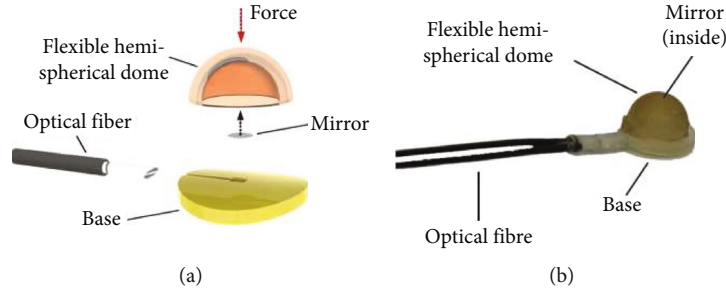


FIGURE 6: Tactile sensors developed by researchers at the University College London, (a) CAD drawing and (b) prototype of an assembled single tactile sensor [70].

TABLE 2: Comparison of different environment sensing and navigation techniques used by serpentine robots.

Reference	Sensors	Key technology	Performance
M. Tanaka [64]	Small camera, laser ranging sensor, infrared ranging sensor	Obstacle positions are estimated using the map data (obtained by Hector SLAM software) and the data from the range sensors in each link	Semiautonomous integral collision avoidance control system manually controlled by the operator
Morse [67]	RGB-D cameras	GraphSLAM, data filtering	Use filtered data to generate clearer and more accurate map images
Ponte [68]	Laser sensors and cameras	A structured light sensor composed of B/W teleoperated cameras, line laser sensors, etc. is designed to construct 3D environment maps	Adapt to snake robot size and power
S. Sareh [70]	Tactile sensor	Using digital optical fiber sensor as the main device, using ABS polymer as material, using the relationship between light reflection distance and intensity to make a tactile sensor	The developed sensor system can be loosely integrated on a soft arm, effectively works independently of the arm, and does not affect the movement of the arm when flexed or extended

efficiency. Therefore, there is a limit to the minimum bending radius of the manipulator, which makes it difficult to adapt to obstacles of different sizes. However, in nature, in addition to the serpentine movement of joint deflection, snakes also flexibly change the bending shape of their bodies through internode telescopic movement to better adapt to the characteristics of the environment.

Therefore, by referring to the movement characteristics of snakes and other animals in nature, it is a key problem to realize obstacle avoidance and operation of mechanical arm to design more flexible multidegree-of-freedom joints and robot mechanism under the condition of limited number of joints and traction wire through bionics principle.

3.2. Spatial Environment Perception Technology in Narrow and Closed Scenes. In the unstructured and unknown narrow application scenarios, the navigation control of the robot must be based on accurate environmental perception information. However, in the actual operation scenarios, not only the contrast is low, the target features are not obvious, but also there are problems such as insufficient lighting and reflection of the cavity wall, which bring great difficulties to the environmental perception. At the same time, because of the narrow cavity channel, the conventional sensor is easy to enter its perception blind area, the occlusion problem is serious, the field of vision is severely limited, resulting in the effective output information of the sensor is insufficient.

Therefore, in a narrow and closed unstructured environment, how to use a variety of measurement methods to build an environment perception system, integrate microsensors under the premise of limited space, and improve the accuracy of environment perception through the effective fusion of heterogeneous perception data are important prerequisites for robot operation. Figure 7 summarizes common approaches for environment perception and map building using multiple sensor data.

3.3. Obstacle Avoidance Planning of Drive Space under Multiple Constraints. The motion planning of the manipulator with high redundancy can adopt the ridge fitting method or the forward following method. The expected pose of each joint was planned from the perspective of kinematics, and then, the elongation of each wire was obtained by inverse kinematics analysis, to realize the motion control of the flexible arm. However, in the actual system, due to the effect of load and gravity of each joint, each wire not only needs to achieve the control of elongation but also needs to make the tension meet the safety threshold of the wire; only in this way can the desired operation accuracy be achieved.

Therefore, how to take wire tension limit as an important factor in the motion planning of high-redundancy manipulator, how to construct multiple constraints by combining three-dimensional space obstacles, operating target pose and interjoint pose relationship constraints, etc., and

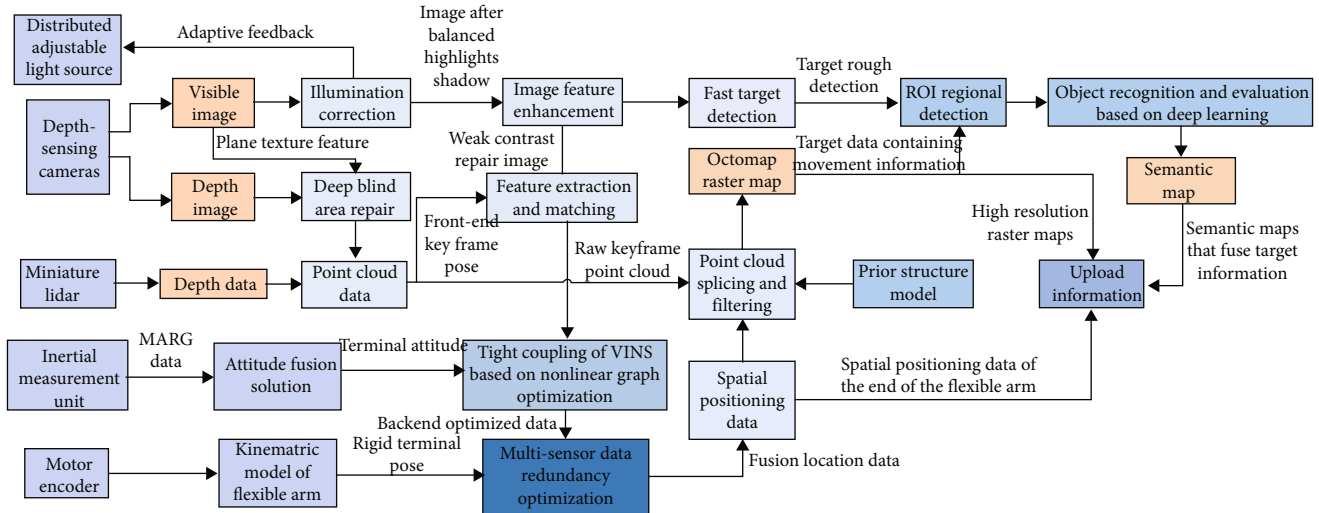


FIGURE 7: Environment perception and map construction in narrow space.

how to obtain joint space motion trajectory through trajectory interpolation and tension optimization are the problems that must be solved in the precise operation control of the manipulator. Figure 8 summarizes some key issues in obstacle avoidance planning for robotic arms, such as kinematic models, path planning methods, trajectory following methods, and some common constraints.

3.4. The End Precise Positioning Control Problem of Flexible Drive Mode. Wire traction is the main driving mode of high-redundancy manipulator. The attitude control of each joint can be realized by changing the length of each wire. But the tension state of the wire has a direct influence on the control accuracy, so the wire tension is usually maintained by connecting springs. However, the tension of steel wire varies greatly under different postures, and the elongation of spring also changes, which brings large control errors. At the same time, both the steel wire and the flexible arm have certain elastic deformation characteristics, which results in certain elastic shape variables in the whole system under different tension and different poses, affecting the control accuracy.

Therefore, we need to find out the factors affecting the tension and deformation errors of the mechanical arm movement, establish a dynamic deviation compensation model under different operating conditions, and eliminate or reduce the end positioning deviation through trajectory tracking compensation and synchronous control methods. These are important problems for precise operation control of highly redundant manipulators.

4. Prospect

In typical industrial application scenarios, all-round precision operation in complex and narrow space is the common feature. It is an inevitable trend for the development of robot technology to form a practical system to solve the problems of confined space operation through the integration of new materials, new configurations, new methods, and new tech-

nologies, closely combining with the requirements of practical application. The technological development of robots operating in narrow and confined space is mainly reflected in the following aspects.

4.1. Spatial Reachability. Working tasks in narrow space require the robot to be able to cross the narrow and long cavity channel, bypass the obstacles of different sizes in the cavity, and reach the operation point located in the deep space. However, many scenarios (such as GIS overhaul and inlet spraying) also require the robot to keep a certain safe distance between the whole body and the cavity wall and obstacles. Under these requirements, motion flexibility and high spatial accessibility are outstanding problems in practical applications. Therefore, hyperredundant robot based on new rigid-soft-soft coupling mechanism is an important development trend for solving complex tasks in confined space.

4.2. Structure Compactness. The overall size of the robot operating system is an important problem affecting its practicability, especially in postdisaster search and rescue, nuclear power pipeline maintenance, and other application scenarios. These scenarios are complex and space-constrained, requiring robotic systems to be able to push robotic arms into deep cavities in a compact structure. Therefore, the integrated systematic and comprehensive design of various parts such as mobile carrier platform, manipulator push platform, and high-redundancy manipulator is an important technical direction to meet the application requirements of confined space.

4.3. Operation Accuracy. At present, robots used in narrow space are mainly used for detection tasks, but few have operational capabilities. Compared with the detection task, the operation task has higher requirements for positioning accuracy, trajectory continuity, and real-time motion. Therefore, it is necessary to carry out research on terminal precise positioning control technology and job path tracking control technology of ultraredundant robots for specific application

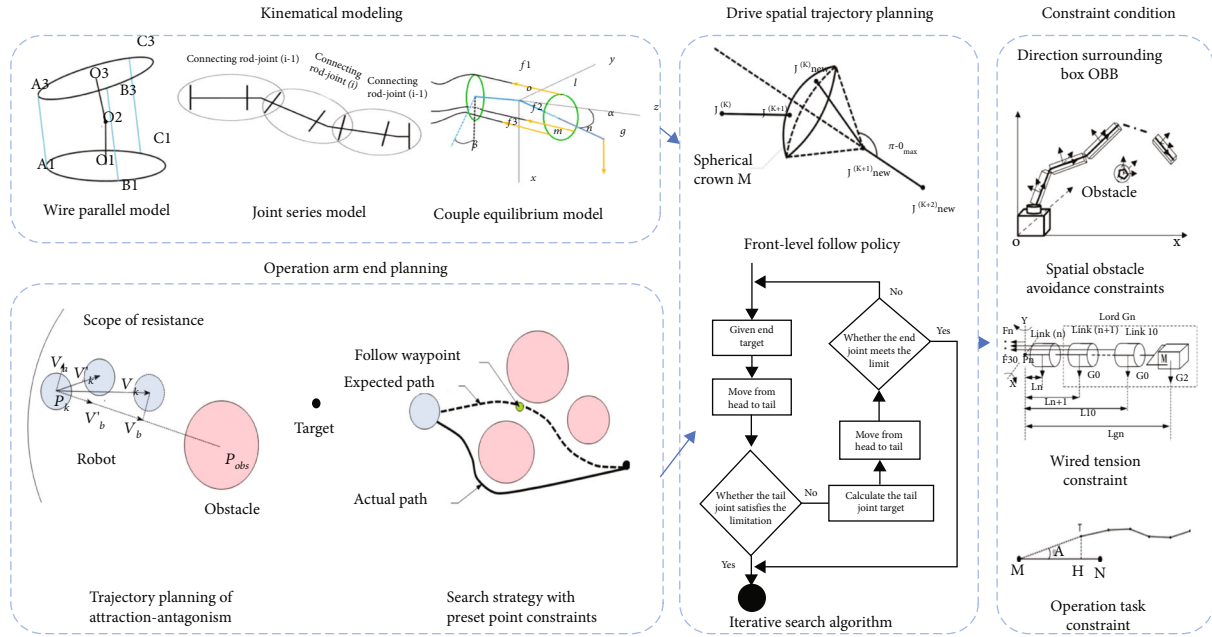


FIGURE 8: Obstacle avoidance path planning of drive space.

scenarios, to provide the precision of the operation process, which is the technical premise for the realization of confined space robot operation tasks.

4.4. Friendly Control. The operation process in complex scenes is difficult to rely on the robot system to complete fully autonomously and often requires the operator’s teleoperation to help complete the operation. However, in some complex scenes, the light is often dim and there are many uncertain and peculiarly shaped obstacles. Content in visual images fed back by a single camera is generally difficult to identify and lack quantitative predictions. In this case, the control effect brought by the operator’s remote control operation is difficult to meet the requirements. Therefore, it is necessary to enhance the presence of human-computer interaction process and improve the control efficiency of robot operation process. There are many technical problems in scene perception of closed and narrow space. Insufficient illumination, low contrast, and obscure features all bring great difficulties to detection and recognition. It is necessary to solve the problem of scene perception and reconstruction in a confined space by means of multisensor fusion and to build a human-computer interaction system with presence for narrow operation scenes. These are important technical approaches for solving the maneuverability of robots.

As a typical special operation robot, high-redundancy robot is an important technical approach to solve the requirements of confined space operation. In-depth study has a larger scope of operation, high control precision, strong flexibility, and high-redundancy and mechanical arm robot operating system and its key technologies, not only can solve the problem of the confined space of a specific homework but also can provide manufacturing tech-

nology and man-machine collaboration with a new solution, thus special task for many industries to provide important technical support.

Conflicts of Interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication.

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