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A Review and Outlook on Space Manipulator Technology

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Abstract: With the continuous development of space exploration and aerospace technology, space manipulators, as the most widely used space robots, play a crucial role in space missions. This paper presents an overview of manipulators and space manipulators, discusses major space manipulator projects both domestically and internationally. It reviews five key technologies: rendezvous and capture, sensing and perception, autonomous planning, intelligent and collaborative control, and system fault detection. Finally, it lists three current challenges faced by the development of space manipulators and discusses potential research directions and future development trends.

Keywords: space manipulator, robot, control technology

1. Introduction

1.1. Basic introduction to manipulators

The goal of using robots to assist or even replace humans in various tasks has been a long-standing pursuit. Among robots, the robotic arm is the most widely used and versatile type. A robotic arm primarily consists of four components: the base, joints, links, and end effector (such as a robotic gripper). In space, robotic arms can replace astronauts in space exploration, assist astronauts in satellite assembly, and perform other tasks. These types of robotic arms are referred to as space manipulators.

1.2. Basic introduction to space manipulators

A space manipulator is a robotic arm designed for operations in the space environment, typically used for spacecraft assembly, space experiments, and space station construction. Unlike ordinary robotic arms, space manipulators operate in environments characterized by microgravity, high radiation, and vacuum. As a result, the technologies employed by space manipulators to perform tasks are more complex.

1.3. Major space manipulator projects domestically and internationally

To date, there have been many space manipulator projects. Table 1 introduces some of the major ones both domestically and internationally.

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Table 1: Major space manipulator projects domestically and internationally

Project/Manipulator Name	Time	Country	Main Tasks	Basic Parameters
SRMS (Canadar m)	1981	Canada	Satellite Deployment, Space Station Module Assembly, Spacecraft Repair.	6 DOF, arm length of 15.2 meters, and a weight of approximately 410 kg.
MKC	1986	Former Soviet Union	Module Docking and Installation, Equipment Maintenance, and Cargo Transportation.	6 DOF, arm length of approximately 4.5 meters, and a weight of 150-200 kg.
ROTEX	1993	Germany	Maintenance and Replacement of External Space Station Equipment, Heavy Cargo Handling.	6 DOF, equipped with various sensors and actuators.
ETS2VII	1997	Japan	Assisting astronauts with extravehicular activities (EVA).	6 DOF, arm length of 2 meters, and a weight of approximately 100 kg.
SSRMS (Canadar m2)	2001	Canada	Supporting the assembly and maintenance of the International Space Station (ISS).	7 DOF, arm length of approximately 17.6 meters, and a weight of approximately 1800 kg.
ROKVISS	2005	Germany	Assisting astronauts with extravehicular activities (especially in microgravity environments).	6 DOF, arm length of approximately 2-3 meters, equipped with a visual feedback system.
ERA	2007	Europe	Performing in-orbit assembly tasks and other extravehicular activities.	7 DOF, arm length of 11.8 meters, and a mass of approximately 850 kg.
JEMRMS	2008	Japan	Enhancing the external operational capabilities of the International Space Station.	6 DOF, arm length of 10 meters, and a weight of 780 kg.
Tiangong- 1	2011	China	Participating in the construction and operation of the Tianhe series of experimental space stations.	7 DOF, arm length of 3-5 meters.
AoLong-1	2016	China	Verifying the application performance of space manipulators in a microgravity environment.	7 DOF, arm length of approximately 10 meters, and lightweight.

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Table 1: (continued).

Tiangong Space Station Robotic Arm	2021	China	Extravehicular activities, module docking, equipment maintenance, and replacement.	7 DOF, arm length of 10.5 meters, and a weight of 780 kg.

2. Rendezvous and capture technology

2.1. Rendezvous and docking technology with cooperative targets

Rendezvous and docking is a critical technology in spacecraft assembly. During this process, spacecraft modules need to achieve autonomous navigation and positioning, and move along an optimized trajectory. By maintaining appropriate motion attitude and velocity at the docking point, these modules ensure proper alignment with other spacecraft modules for executing the assembly tasks.

In space exploration, Autonomous Rendezvous and Capture (AR&C) technology holds significant importance. To ensure that the exploration process is conducted safely and sustainably, AR&C needs to become more standardized and automated. In past exploration missions, docking and capture tasks typically required extensive human intervention. However, with advancements in technology, this process has shown a trend towards automation.

2.2. Capture technology for non-cooperative targets

To prevent the accumulation of spacecraft that fail to launch or lose their utility, the recovery of these spacecraft is essential. Unlike the cooperative targets mentioned earlier, these uncontrolled spacecrafts are generally referred to as non-cooperative targets. These targets are unable to actively send signals or instructions, so high- precision control algorithms are required to complete the capture action.

There are three main methods for this: rigid connection capture, flexible capture, and non-contact capture, which are reviewed in [1]. Reference [2] indicates that space tether capture technology, as a representative of space flexible capture technology, has shown good results.

3. Sensing and perception technology

During space exploration, spacecraft need to rely on onboard sensors to acquire external information, such as their own position, attitude, and relative position to other spacecraft, in order to perform various tasks. As robotic arms increasingly replace astronauts in on-orbit servicing, the requirements for sensors have become more critical.

3.1. Visual perception technology

As the most commonly used sensor, visual sensors help robotic arms recognize the surrounding environment, locate objects, and prepare for subsequent actions. Currently, widely used visual perception technologies include stereo vision systems [3], image recognition (convolutional neural networks), and others, which are rapidly advancing.

3.2. Multi-Sensor information fusion

During the execution of space missions, spacecraft are often equipped with multiple types of sensors, such as tactile sensors, force sensors, in addition to visual sensors. By receiving and

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combining information from various sensors, multi-sensor fusion provides astronauts with more comprehensive situational awareness, improving operational accuracy compared to relying on a single visual sensor. However, as the number and variety of sensors increase, so does the potential for interference. To eliminate such interference and simultaneously process and fuse multi-sensor information, researchers have proposed various fusion methods, including Bayesian filtering [4], D-S (Dempster-Shafer) evidence theory [5], and neural network approaches [6].

4. Autonomous planning technology

The entire process of robotic arm grasping requires the planning of several control algorithms. Before the robotic arm performs the grasping operation, trajectory planning is necessary. During the grasping process, compliant control of the robotic arm is required to prevent collisions that may cause the object to be ejected. After the grasping is completed, vibration suppression of the robotic arm and the captured object is necessary. It can prevent the object from falling off again.

4.1. Autonomous path planning technology

In the operation of space robotic arms, it is necessary to autonomously plan a path from the starting point to the target point. This typically involves considering obstacles along the path, minimizing interference, maximizing benefits, and addressing a series of other issues. [7] introduces the main algorithms currently in use for obstacle avoidance. Figure 1 demonstrates the principles of WPA and A*Algorithm.

Table 2: Main obstacle avoidance path planning algorithms

Types of Algorithms	Names of Algorithms	Basic Principles	Advantages
Swarm Optimization Algorithm	Genetic Algorithm (GA)	Transform the problem- solving process into the evolutionary and mutation process of biology.	It can be integrated with other algorithms when solving combinatorial optimization problems.
Swarm Optimization Algorithm	Ant Colony Algorithm (ACO)	Paths with higher pheromone concentrations are more likely to be chosen by ants.	Fast path planning, a short path length, high real-time performance and stability.
Swarm Optimization Algorithm	Particle Swarm Optimization Algorithm (PSO)	The position and velocity vectors of each particle are updated based on specific functions, until the optimal solution is found.	The joint trajectory is smoother, with a higher ability to predict random changes in obstacles.
Swarm Optimization Algorithm	Wolf Pack Algorithm (WPA)	The algorithm simulates the cooperative hunting behavior to reinforce solution space.	Maintain low energy consumption while avoiding obstacle.
Swarm Optimization Algorithm	Grey Wolf Optimization Algorithm (GWO)	The positions of the grey wolf individuals are updated to mimic the hunting process until the optimal solution is found.	The path has high smoothness and optimal path.

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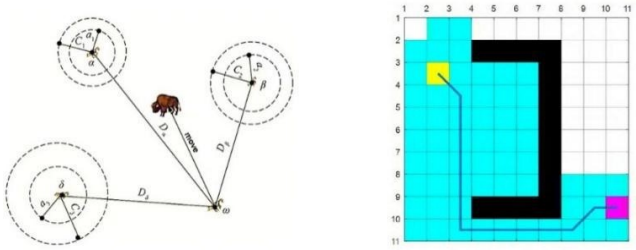
Table2: (continued).

Artificial Potential Field Algorithm (APF)	/	The robotic arm moves under the influence of the field formed by target position and obstacle positions.	Suitable for avoiding dynamic obstacle and tracking dynamic targets.
Graph Search Algorithm	Dijkstra Algorithm	Gradually select the node closest to the starting point in order to find the shortest path.	Ensures the shortest path while achieving collision-free obstacle avoidance.
Graph Search Algorithm	A* Algorithm	Only find the shortest path from a single point to another.	The path search efficiency is high, and the path is smoother.
Random Sampling Algorithm	Probabilistic Map Algorithm (PMA)	Construct a probabilistic map of randomly sampled path points to find the optimal path.	High convergence speed, strong stability of the route map.
Random Sampling Algorithm	Rapidly-exploring Random Tree (RRT)	The algorithm constructs a search tree using sampled nodes to explore space.	It can achieve optimal path search in complex environments.



(a)Wolf Pack Algorithm Diagram. (b)A* Algorithm Diagram.

Figure 1: WPA and A*Algorithm Diagram

Compared with ordinary robotic arms, space manipulators often have higher degrees of freedom, which leads to redundancy. To address the issue of redundant degrees of freedom in path planning, Zhang Zexi et al. [8] applied the gradient projection method to solve the inverse kinematics problem of the robotic arm, and Ye Ganghong et al. [9] implemented automated control of the arm's unbalanced vibration. In addition, space robotic arms often have stricter kinematic and dynamic constraints.

4.2. Robotic arm compliant control technology

During the grasping process, compliant control needs to be applied to the robotic arm to adapt to changes in the target's motion state, shape, etc., during contact, and to control the contact force between the two. Compliant control of the robotic arm can be divided into two types: passive control achieved through hardware structures and active control realized through software.

The passive compliant control of the robotic arm relies on its hardware structure, utilizing its inherent properties such as elasticity and damping to respond to external forces. Common methods

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include setting up a "spring-damping" system, adding elastic joint designs, using adaptive stiffness systems and using shape memory alloys (SMA) to design adaptive joints.

Traditional active compliant control methods, such as impedance control and force- position hybrid control, are easily affected by the inherent stiffness of the system, and the results may not meet expectations. With the continuous development of technology, active compliant control methods for robotic arms are also evolving. The study [10] demonstrates a method for actively controlling the robotic arm using a robust control strategy and an adaptive neural network, effectively reducing the contact force between the robotic arm and the target. This method improves the system's ability to resist interference and its adaptability.

4.3. Vibration suppression technology for robotic arms and grasped objects

After the robotic arm captures an object, the system composed of the robotic arm and the captured object needs to quickly return to a stable state. However, due to the unique characteristics of the space environment, the arm's long length and light weight, vibration suppression of the robotic arm is a major challenge. One of the main methods

today is a combination of active and passive control. It means that dampers are added to key parts of the robotic arm, and feedback control (such as PID control, LQR control, and model predictive control) is used to suppress the arm's vibrations. In [11], a hybrid control method was employed to investigate vibration suppression of a flexible space robotic arm with an uncertain floating base.

5. Intelligent and collaborative control

As the tasks of robotic arms become more complex, their requirements for intelligent and collaborative control have correspondingly increased. These can generally be divided into three aspects: autonomous decision-making task allocation, human-robot integration, and multi-arm collaborative manipulation.

5.1. Autonomous decision-making task allocation

When robotic arms replace astronauts for space operations, the requirement for their autonomy continues to rise. This improves task efficiency, enhances precision, and reduces energy consumption. For a robotic arm work system, autonomous decision- making task allocation needs to consider several factors: self-constraint (such as the arm's own capabilities, maximum rotation angles), task priority and their execution sequence, environmental perception and noise elimination, and scheme optimization of the initial plan to achieve optimal coordination for all parties.

5.2. Human-machine integration technology

Human-machine integration technology can highly synergize human commands with machine decision-making, combining the high precision of robotic arms with human safety-oriented decision-making to achieve complementary advantages. In terms of foundational research on human-machine integration, Wang Zhenya et al. [12] conducted preliminary studies on multimodal human-machine hybrid interaction intelligence technology, which is demonstrated in Figure 2. In [13], it is proposed that after robots establish high-precision 3D environmental modeling, astronauts can more accurately perceive their surrounding environment and make correct decisions. Additionally, technologies such as Virtual Reality (VR) and Augmented Reality (AR) are also widely applied in human-machine integration.

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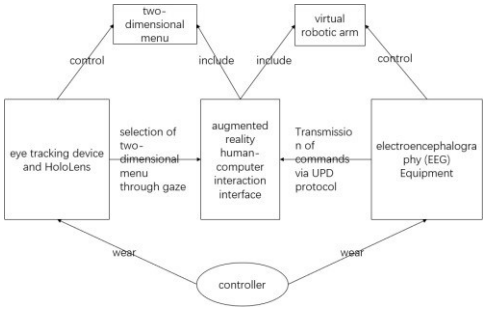

Figure 2: Brain-eye multimodal fusion control logic diagram.

5.3. Multi-arm collaborative manipulation

Compared with single-arm systems, multi-arm systems have a broader range of applications and can accomplish more complex tasks. When performing coordinated tasks in a multi-arm system, robotic arms rely on the actions of other arms to carry out tasks such as perception and path planning. In tasks involving the removal of non- cooperative targets in space, the adaptability of target and the complexity of capture actions are becoming more complexed. Zhang Binghan et al. [14] proposed an envelope capture strategy based on reinforcement learning methods combined with a "multi-arm grouping coordination" mechanism, which enables more efficient grasping.

6. System fault detection technology

The harsh working environment in space, such as microgravity and heavy loads, can cause damage to the robotic arms during task execution, leading to safety issues. Therefore, fault detection within the system becomes particularly crucial.

This technology refers to the identification of potential faults within the robotic arm system through various technical means, enabling prevention and avoiding safety accidents. This requires real-time monitoring of the system, as well as a high level of capability to detect and diagnose faults. To achieve efficient and timely fault detection, various sensors are typically used for monitoring. In [15], the application of intelligent sensors in fault monitoring of mechanical systems is explored. The Kalman Filter [16] is suitable for noisy, relatively complex linear systems but has performance limitations in monitoring nonlinear systems. The Luenberger observer [17] is simple to design but performs poorly in monitoring highly nonlinear systems. The Sliding Mode Observer (SMO) [18] is highly robust against internal uncertainties and external disturbances, but it tends to produce high-frequency chattering in practical applications. Designing a fault monitoring system with strong accuracy, adaptability to different environments, robust performance, and minimal chattering has become the primary research goal in this field today, (demonstrated in Figure 3).

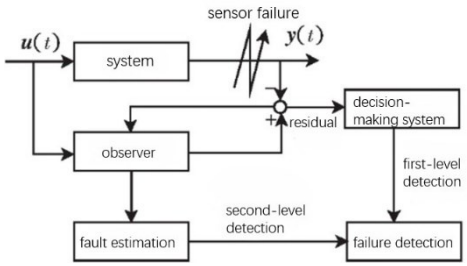

Figure 3: The principle diagram of sensor fault detection based on SMO.

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7. Current issues and future development trends

The development of space robotic arms has made significant progress in various fields. However, there are still many challenges to be addressed. Below are several key issues and their future research directions.

7.1. The balance between autonomy and human-machine interaction

With the in-depth research into autonomous control strategies for robotic arms, the complexity of this technology indicates that achieving complete autonomy in robotic arm systems is currently unlikely. Therefore, while continuing to explore autonomous control strategies, significant research is also needed in human-machine interaction and fusion control technologies. To achieve higher precision in human-machine interactive control, the control methods must be more aligned with human capabilities for easier operation. Multimodal Human-Computer Interaction control (MHCI) can simplify the interaction process, enhance user experience, and improve interaction efficiency. The application of this technology to robotic arm control may become a major development direction in the future.

7.2. Diversification of end effectors

Currently, space robotic arms use different types of end effectors based on the varying task requirements (such as spacecraft assembly, handling heavy objects, capturing non- cooperative targets, etc.). As the complexity of tasks increases, the variety of end effectors also grows. To match the appropriate effector to specific tasks, the diversification of end effectors has become a popular development trend.

7.3. The balance between high precision and high energy consumption

When space robotic arms perform tasks, the demand for precision gradually increases, and the requirements for sensor recognition accuracy and actuator control precision also rise accordingly. However, constrained by current conditions, a manipulator cannot support the required high precision. Therefore, achieving the goal of maintaining high precision while minimizing energy consumption has become a key research direction.

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