Proceedings of the 3rd International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/135/2025.21062

A Review of Space Robotic Arm Technology

Zihan Su[1,a,*]

[1]College of Forestry, Northwest A&F University, Yangling Demonstration Zone, Shaanxi Province, 712100, China
a. 2542105658@qq.com
**corresponding author*

Abstract: This paper summarizes the development of space manipulator technology at home and abroad, analyzing the trend of space manipulator technology is analyzed on task type, configuration, and operation mode. It also summarizes key technologies in mission planning, system control, path planning, vision perception, teleoperation control, and ground test verification. Finally, it summarizes the problems in the current space robotic arm technology and suggests solutions for developing China's space robotic arm.

Keywords: space manipulator, In-orbit service, Path planning, Visual perception, Manned spaceflight

1. Introduction

With the more and more urgent need for in-orbit service of space devices, space robotic arm have become the research hotspot of the world's space powers. With integrated space perception, mobility, and operation capabilities, the space robot arm can complete in-orbit assembly, pollution cleaning, observation and inspection, failure module replacement, in-orbit refueling, consumable load replacement and supplement, orbit cleaning, orbit transfer, and other work through in-orbit operation, ground teleoperation or autonomous operation. It is the core equipment of spacecraft in-orbit assembly and maintenance [1].

The experience in the assembly, construction, maintenance, and application of the International Space Station shows that the use of space robotic arms can assist or replace astronauts in the harsh space environment to complete on-orbit operations, improving the safety and efficiency of space operations and applications [2].

Many enabling techniques have been developed in the past two decades and several technology demonstration missions have been completed. Several manned on-orbit servicing missions were accomplished but unmanned, fully autonomous, servicing missions have not been done yet. Furthermore, all previous unmanned technology demonstration missions were designed to service cooperative targets only. Robotic servicing of a non-cooperative satellite is still an open research area facing many technical challenges [3].

This paper summarizes the development situation and trend of space robotic arms. It summarizes the key technologies of space robotic arms, focuses on the development of China's space robotic arm, summarizes the existing problems of space robotic arm technology, and suggests solutions for the development of China's space robotic arm.

DOI: 10.54254/2755-2721/135/2025.21062

2. Overview of the current space robotic arms

2.1. Shuttle Remote Manipulator System (SRMS)

Early in the development of the Space Shuttle, it became clear that NASA needed a method of deploying and retrieving payloads from the payload bay. The Shuttle Remote Manipulator System (SRMS) was developed to fill this need. The 50-foot-long robotic arm is an anthropomorphic design consisting of three electromechanical joints, six degrees of freedom, and two boom segments. Its composite boom construction provided a lightweight solution needed for space operations. The SRMS is operated using a display and control panel and hand controllers located within the aft crew compartment of the shuttle. Over the years it has been used for deploying and retrieving constrained and free-flying payloads, maneuvering and supporting EVA astronauts, satellite repair, International Space Station construction, and as a viewing aid for on-orbit International Space Station operations. The history and evolution of the SRMS program provided many lessons learned that can be used for future space robotic systems [4].

2.2. Space Station Remote Manipulator System (SSRMS)

SSRMS-type space manipulators play a pivotal role in constructing and maintaining the International Space Station (ISS) and other space assets, with some having operated in orbit for over a decade.

The Space Station Remote Manipulator System (SSRMS, also called Canadarm2) is a redundant manipulator that was designed to make each joint to rotate up to ±270°. The configurations of other manipulators, such as the Dextre (also known as the Special Purpose Dexterous Manipulator or SPDM) manipulator, European Robotic Arm (ERA), and the Flight Telerobotic Servicer (FTS) manipulator are similar to that of the SSRMS, differing primarily in link lengths and offsets. The joints of these manipulators have a similar layout: three joints are contained in each identical shoulder (roll-yaw-pitch) and wrist (pitch-yaw-roll) cluster, and one elbow joint (pitch) connects the two large booms. The three axes of the shoulder or the wrist do not intersect at a common point, i.e. they do not have spherical wrists/shoulders [6].

2.3. Special Purpose Dexterous Manipulator (SPDM)

Canada has a well-established heritage in operational space robotics and a demonstrated capability to deliver complex and robust space flight robotic hardware. The next generation of space robots for the International Space Station must perform more dexterous tasks than their predecessors [7]. The Special Purpose Dexterous Manipulator (SPDM) will be required to perform delicate tasks such as insert and extract Orbital Replaceable Units (ORUs), actuate hinge-like mechanisms on the ISS truss, and, manipulate and inspect scientific payloads. These tasks involve accurate positioning and trajectory following requirements for successful interface acquisition and mechanism actuation, as well as strict requirements for limiting forces and moments at the contact surfaces to be able to perform peg-in-the-hole type tasks.

Currently, only one SPDM arm can be operated at a time, primarily due to power constraints. In operations where the SPDM is on the SSRMS, the SSRMS is in a braked state. As future upgrades of the control features, it is envisioned that the two arms of the SPDM and the SSRMS can be simultaneously controlled to attain task objectives at the tip of both SPDM arms. MDRobotics has investigated such control methodologies and has developed the necessary arm control algorithms to attain these objectives. These are a part of the algorithms in the Robotic Automated Mission Planning Software (RAMPS) developed by MD Robotics in 1999.[8]

DOI: 10.54254/2755-2721/135/2025.21062

2.4. Research and development of the Canadarm3 robotic arm

As space exploration deepens, Canada, a key participant in the U. S.-led Gateway program, is working with the MDA (MacDonald, in conjunction with Dettwiler and Associates, the Canadarm3 robotic arm is being developed. The Lunar Gateway system will serve as an unprecedented outpost, enabling sustainable human exploration of the Moon. The Canadarm3 robotic arm, which will operate on the Lunar Gateway, consists of a large robotic arm, a small robotic arm, specialized tools for performing scientific missions, and a robotic interface with access to all elements of the Lunar Gateway, designed to enable autonomous decision-making and work. It is equipped to enable autonomous decision-making and operations, including on-orbit maintenance, inspection, spacecraft capture, assisting astronauts during extravehicular activities, and conducting scientific experiments in lunar orbit [9].

2.5. Research and development of MSS (Mobile Satellite Services)

At present, the International Space Station's most representative extra-vehicle robotic arm system is the Canadian Mobile Satellite Services system (MSS) installed on the United States module, which mainly includes a large teleoperation arm system (SSRMS) and a special purpose smart manipulator arm (SPDM). The large extra-vehicular robot system on the space station also includes the European Arm (ERA) on the Russian module and the Remote Robotic Arm System (JEMRMS) on the Japanese experiment module, which is mainly composed of five subsystems [10]: The robotic arm workstation (RWS), Space Station remote control robotic arm system SSRMS, Mobile base system (MBS), Mobile transport devices (MT), and SPDM, among which RWS is the only component of MSS arranged in the cabin. The RWS includes a manual controller, monitor, control panel (DCP), and laptop computer (PCS) (as an interface for the on-orbit operation of the MSS).

The SSRMS in MSS was developed based on the Space shuttle teleoperated Robotic arm system (SRMS). Therefore, its control mode mainly relies on the manned closed-loop operation mode, that is, the astronauts use manual controllers to control the robotic arm in the International Space Station. All mechanical motion instructions are issued by the astronauts using manual controllers and physical converters on the DCP, while video monitors monitor the execution of instructions [11].

In 2002, at the Technology Exchange conference jointly organized by the Canadian Space Agency (CSA) and NASA, a solution was proposed to develop the ground teleoperation mode [10], that is, for some routine detection tasks, the way of ground teleoperation was realized. y 2005, the CSA achieved ground teleoperation for the SSRMS, enabling small-scale maneuvers in free space and gradually expanding to larger joint motions without constraints [12].

2.6. Development of Domestic Space Robotic Arms

Regarding China's space robots, the Tiangong-2 (TG-2) space robot has conducted several key technology verifications inside the TG-2 Space Laboratory, accumulating valuable technical experience for developing the Chinese Space Station Remote Manipulator System (CSSRMS). These on-orbit experiments provided valuable technical experience for China’s manned spaceflight program, laying the groundwork for future innovations in the CSSRMS [13].

The CSSRMS, designed primarily by the China Academy of Space Technology (CAST) and HIT, consists of the Core Module Manipulator (CMM) and Experimental Module Manipulator (EMM)[14]. The CMM and EMM can walk around on the CSS. The CMM, with its extended length, is optimized for large-scale transfer tasks. Its main OOS missions include module transfer, auxiliary docking, equipment installation, on-orbit maintenance, state monitoring outside the cabin, and supporting astronaut EVAs [15]. Because of its relatively short length, the EMM enables high positioning accuracy and is applied to certain delicate operations. Its main tasks include payload maintenance, payload handling, state monitoring outside the cabin, and EVA support for astronauts [16].

3. Key technology

Many key technologies are involved in the implementation of in-orbit service tasks for space robotic arms. For large space robotic arms and experimental robotic arms, it is generally necessary to go through some or all the following stages: the rendezvous and maneuver stage with the target object, the observation and planning stage, the capture and grasp stage, and the stable control stage. Accurate target detection and recognition are critical for identifying the target object. Precise orbit control and stable attitude control ensure the robotic arm reaches the correct position without compromising stability. The stable control phase requires ensuring that the object captured or controlled by the robot arm remains stable with the service system and performs precise operational tasks. For humanoid robotic arm, additional critical technologies come into play: precise control technology, sensing and perception technology, and human-machine integration control technology [9].

3.1. Mission planning and system control

As space exploration progresses, the operational demands on space robotic arms have increased significantly. Traditional path planning methods often struggle to meet these complex requirements, especially in environments with multiple constraints. This section proposes a novel multi-constraint task planning method based on a hierarchical structure.

3.1.1. Mission planning framework

The mission planning for a space manipulator is divided into two levels: mission profile analysis and mission intermediate point planning. The task profile analysis decomposed the complex task into the original task combination, and the task intermediate point planning decomposed the original task into a simple path. The manipulator control system is divided into mission planning, path planning, and motion control of three layers, mission planning is responsible for receiving, analyzing, and dismantling mission objectives, and scheduling resources [17].

3.1.2. Mission profile analysis based on hierarchical task network

The foundation of a hierarchical task network: HTN planning disassembles tasks in layers, including target tasks, original tasks, and compound tasks. The planning domain is composed of operator sets and method sets, and the task network is simplified by specific algorithms. Space manipulator application: clock with the state matrix and state yan) work environment, mobile, capture, release the three original tasks defined and operator, according to the specific network routing Jane space manipulator task [17].

3.1.3. Mission intermediate point planning based on improved A* algorithm

Planner interface: Input task start and end points and other information, output decision vector, task intermediate point planning involves resource optimization, and decision vector dimension is related to the number of intermediate points. The intermediate point planning process integrates a heuristic search algorithm to optimize resource usage and generate decision vectors for task execution. The improved A* algorithm includes variable topology adjustments and refined cost calculations, enabling precise navigation and resource-efficient operations in complex environments [17].

3.1.4. Test and simulation

The object transfer task is verified in a specific simulation environment with an 8-DOF manipulator as the object. Then the original task sequence is obtained through the analysis of the task profile, and

DOI: 10.54254/2755-2721/135/2025.21062

the intermediate point planning of the moving task successfully bypassed the obstacle by improving the A* algorithm, which proves that the method is effective [17].

3.2. Path planning

Traditional global path-planning methods face limitations when applied to high-degree-of-freedom systems. These methods are often computationally intensive and prone to falling into local optimal solutions. It is limited by time consumption and exponential complexity in the application of a high degree of freedom manipulator, which makes it difficult to deal with dynamic environments and complex tasks. Although the local method can describe the task, it has the defects that the robot falls into the concave of the obstacle, and it is difficult to control the key indicators of the problem. A new method for path planning of a high degree of freedom manipulator is proposed. In this method, task implementation and anti-collision constraint are separated, and a local model of configuration space is constructed by distance calculation and hierarchical description. The collision problem is dealt with by the velocity damper and tangential separation plane method, and the task is transformed into an optimization problem and a constraint solution is added. Tests using a hierarchical CAD model have demonstrated the method’s effectiveness. Although the process is not real-time, significant improvements are achieved, particularly when combined with machine learning to integrate local and global planning, which is of great significance for robot path planning [18].

3.3. Visual perception

In the field of robotics research, how to make robots as efficient as humans to grasp operations is a key problem. Insights from the physiological and neural responses of human infants, which evolve during their growth process, offer valuable ideas for robot learning. Applying insights from neuroscience and other fields to the design of robot architecture, we provide basic mechanisms for the cognitive development of robots by simulating the growth process of infants, focusing on the fusion of tactile and visual perceptual modes in robot-reaching tasks. The proposed framework covers closed-loop control, dynamic modeling, etc. The experimental results show that the grasping performance can be improved. In the aspect of visual context recovery, the relevant visual features are learned and achieved. At present, the tactile and visual learning stages are not closely integrated, and the Magilla platform will be used to deepen the research in the future to promote the development of robot intelligence [19].

3.4. End effector

With population growth and a shortage of agricultural labor, the development of agricultural picking robots is increasingly critical.

3.4.1. End-effector key elements

Picking methods involves common grabbing and pulling, stem grabbing and pulling cutting, rotation, adsorption. Each method has unique advantages and disadvantages. These methods are often combined to improve efficiency and crop protection. For example, combining grabbing and cutting mechanisms can safeguard crops and branches during harvesting. Actuator type is sub-contact grabbing (fruit or stem), rotary, scissors/saw tools, adsorption four categories, contact grabbing is the most used, and can be subdivided according to the number of fingers, different crops adapt to different types. Sensor applications: including switch, touch, vision, and measurement sensors, can provide information, improve intelligence, and multi-sensor fusion can optimize picking decisions. Operation requirements cover load, power, geometry, motion, drive, time, contact characteristics, accuracy, and

DOI: 10.54254/2755-2721/135/2025.21062

the design needs to consider the crop and robot system. Through four steps of research requirements, design, prototype development and testing, traditional methods and existing achievements are studied to determine requirements, software and hardware are designed and simulated for verification, testing and optimization are conducted after prototype development, and cycles or comparative selection are repeated if necessary [20].

3.4.2. Application case analysis

Ground picking can be used in pumpkin and other heavy crops with a five-finger knife gripper; tomatoes use a grasping and cutting combination, strawberries need to prevent damage and deal with the problem of clustering, apples are suitable for a three-finger soft gripper, bell peppers need cutting devices, kiwi fruit can use two-finger soft gripper, other crops according to the characteristics of the appropriate tool. Aerial picking can be used in the early stage, apple picking uses three-finger grippers, pomegranates use three-finger grippers with knives, coconuts use manual cutters, and some use adsorption rotary grippers, which face many challenges [20].

4. Conclusions

Significant advancements have been achieved in foreign space robotic arm systems, such as the Space Shuttle Remote Manipulator System (SRMS) and Space Station Remote Manipulator System (SSRMS) in the United States, as well as Canada’s series of robotic arm systems. Multi-constraint task planning method based on hierarchical structure proposed in task planning has been validated by simulation, which is helpful for space manipulator to perform tasks in complex environments; In the aspect of path planning, the new method overcomes the limitation of the traditional method in the system of high degree of freedom and realizes the combination of local and global planning. Visual perception research provides mechanisms for the cognitive development of robots by simulating infant growth, but the tactile and visual learning stages need to be more closely integrated. The end-effector research has analyzed the relevant situation of agricultural picking robots and provided a reference for its development, but it still faces problems such as performance evaluation and key technology breakthroughs.

Researchers should continue to draw upon advanced foreign expertise while tailoring innovations to its unique mission requirements. Efforts should focus on refining mission planning, path planning, visual perception, and end-effector technologies. At the same time, in application fields such as agricultural picking robots, efforts should be made to overcome existing problems, accelerate the realization of practical landing, and promote the automation upgrade of related industries.

References

[1] *Liu Hong, JIANG Zaian, LIU Yechao. Review on the development of space robotic arm technology [J]. Manned spaceflight, 2015, 21(05):435-443.DOI:10.16329/j.cnki.zrht.2015.05.002.*

[2] *Liu Hong, LIU Dongyu, JIANG Zaian. Overview and Prospect of space robotic arm technology [J]. Acta Aeronautica Sinica, 2021, 42(01):33-46.*

[3] *Flores-Abad A , Ma O , Pham K , et al.A review of space robotics technologies for on-orbit servicing[J].Progress in Aerospace Sciences, 2014, 681-26.*

[4] *Jorgensen, Glenn, and Elizabeth Bains. "SRMS history, evolution and lessons learned." AIAA SPACE 2011 Conference & Exposition. 2011.*

[5] *Nokleby, Scott B. "Singularity analysis of the Canadarm2." Mechanism and Machine Theory 42.4 (2007): 442-454.*

[6] *She, Yu, et al. "Fault-tolerant analysis and control of SSRMS-type manipulators with single-joint failure." Acta Astronautica 120 (2016): 270-286.*

[7] *Werstiuk, H.L , Gossain, D.M., "The Role of the Mobile Servicing System on Space Station", IEEE International Conference on Robotics and Automation, 1987.*

DOI: 10.54254/2755-2721/135/2025.21062

[8] Mukherji, Raja, et al. "Special purpose dexterous manipulator (SPDM) advanced control features and development test results." The 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space. 2001.

[9] Xue Zhihui, and Liu Jinguo. "Review of research on control technology of space robotic arm." Robot, 44.1 (2022): 107-128.

[10] AZIZ S, LAURIE M C. Concept of operation for ground control of Canada's Mobile Servicing System(MSS) [C]// The 55st International Astronautical Congress. Vancouver, Canada:[s.n.], 2004

[11] Xiangyan, G. U. O., L. I. U. Chuankai, and W. A. N. G. Xiaoxue. "A Survey on Teleoperation of Canada's Mobile Servicing System." Journal of Deep Space Exploration 5.1 (2018): 78-84.

[12] TURCO S, PERRYMAN S. Ground control concept for on-orbit robotic maintenance operations on the international space station[C]//The Space OPS Conference. Montreal, Canada:AIAA, 2004.

[13] Ma, Boyu, et al. "Advances in space robots for on-orbit servicing: A comprehensive review." Advanced Intelligent Systems 5.8 (2023): 2200397.

[14] China Space Station's Large and Small Robot Arms have been Completed the Series Test, https://tv.cctv.com/2022/09/18/VIDEIEbeAhNCdcjLkJwMzK8O220918.shtml(accessed: November 2022) (in Chinese).

[15] Astronauts' Extravehicular Activities of China Space Station, https://tv.cctv.com/2021/11/08/VIDEMyq6WEnEpP0vSh7mDdJy211108.shtml?spm=C55953877151.PjvMkmVd9ZhX.0.0(accessed: November 2022) (in Chinese).

[16] H. Liu, Z. Jiang, Y. Li, Manned Spaceflight2015, 21, 435(in Chinese).

[17] Wang Yifan, et al. "Multi-Constraint task planning for space manipulator based on hierarchical structure." Chinese Journal of Mechanical Engineering, 53.11 (2017): 104-112.

[18] Faverjon, Bernard, and Pierre Tournassoud. "A local based approach for path planning of manipulators with a high number of degrees of freedom." Proceedings. 1987 IEEE international conference on robotics and automation. Vol. 4. IEEE, 1987.

[19] Coelho, Jefferson, Justus Piater, and Roderic Grupen. "Developing haptic and visual perceptual categories for reaching and grasping with a humanoid robot." Robotics and Autonomous Systems 37.2-3 (2001): 195-218.

[20] Vrochidou, Eleni, et al. "An overview of end effectors in agricultural robotic harvesting systems." Agriculture 12.8 (2022): 1240.