EXPERIMENTAL MODULE MANIPULATOR: 1 YEAR OF CHINESE ROBOTIC ARM ON THE CHINA SPACE STATION

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ABSTRACT

On July 24, 2022, the Experimental Module Manipulator (EMM) arrived at the China Space Station (CSS) as a part of the Wentian lab module, which is the first lab module of the space station. Four nights later, orbiting 400 km above Earth, the astronauts unfolded the EMM in Wentian and completed a series of performance tests such as self-inspection, confirmation of crawling ability, and inspection of adapters, solar array and exit hatches. As one of the important components of CSS, the EMM will provide sustaining space missions support for the duration of the 10-year Space Station program. Harbin Institute of Technology (HIT) and Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP) are responsible for the development of the EMM system.

This paper describes the EMM on-orbit servicing tasks from 2022 to 2023, including the combination with the Core Module Manipulator (CMM) to assist astronauts' extravehicular activities (EVAs) and help in the maintenance and repair of the space station. The EMM has the following special features: a) it can carry out complex movements. b) it can complete operations that require a few millimeters of precision. c) it can ride on the end of the CMM and work on all modules of CSS. The EMM improves astronauts' ability to operate in the harsh environment of space. The application of the EMM is beneficial to extend the on-orbit servicing life of CSS and reduce astronaut EVAs risk to obtain more economic returns. We conclude that the success of the EMM over its 1-year life can be made it meet the needs of CSS. This paper further presents the missions and potential enhancements of the EMM for the next decade based on major technical challenges and operational trends of CSS.

Key words: Experimental Module Manipulator, Chinese Space Station Remote Manipulator System, Wentian Lab Module, China Space Station, Space Robotics, Space Operations, On-orbit Service, Extravehicular Activities, Repair and Maintenance of Spacecraft.

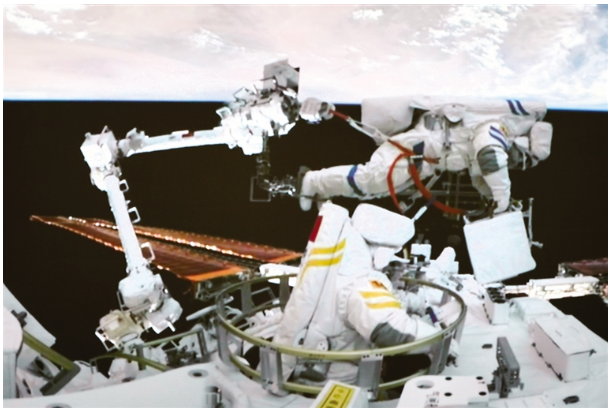

Figure 1. Screen image captured at Beijing Aerospace Control Center on September 1, 2022, shows the EMM on board the Wentian assisted Shenzhou-14 astronauts Chen Dong (Top), and Liu Yang in conducting EVAs.

1. INTRODUCTION

With the launch of the Shenzhou-15 mission on November 29, 2022, the China Space Station (CSS) has entered the stage of application and development, which will last for more than 10 years. Currently, CSS features a basic three-module configuration, which consists of the Tianhe core module and Wentian and Mengtian lab modules. It is also a versatile space lab, capable of accommodating 25 experiment cabinets for scientific exploration [1]. As part of CSS, the Chinese Space Station Remote Manipulator System (CSSRMS) has played a vital role in completing space tasks, such as on-orbit maintenance, payload care, and astronaut on-orbit support. The application of the CSSRMS is beneficial to extend the service life of CSS and payload, and reduce astronaut extra-vehicular risk to obtain more scientific and economic returns.

The CSSRMS consists of a core module manipulator (CMM) and an experimental module manipulator (EMM). The EMM is mounted on the Wentian as shown in Figure 1. It has a similar configuration to the CMM which is located on the Tianhe core module, but about 50% smaller in weight and length. The EMM can

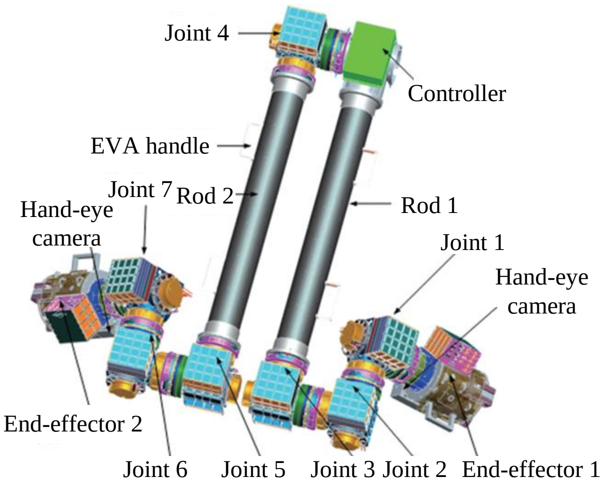

Figure 2. Configuration of the EMM.

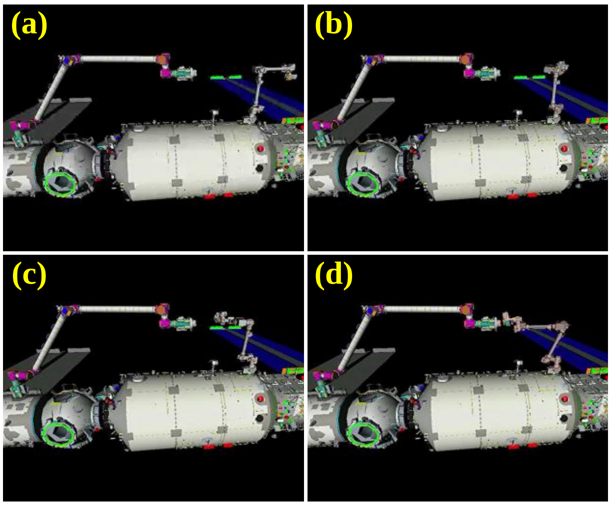

Figure 3. Simulation of the EMM and the CMM combined process.

perform operations with greater precision and can also be held with the CMM to form a combined arm, which is capable of performing extravehicular operations with a larger range. The main tasks of the EMM are as follows:

- **Payload care for space exposure experiments:**

  (1) Operation of active exposure payloads, including out-of-cabin, installation, maintenance, disassembly, and disposal. (2) Installation, exchange, and disposal of passive exposure payloads. (3) Handling, installation, and disassembly of test payload.

- **Optical platform care:**

  (1) Regular replacement and break-out repair of control modules. (2) Maintenance of optical platform hoods. (3) Removal of the cabin beam at the opening of the optical platform.

- **Workhorse for astronaut EVAs:**

  (1) Repair and maintenance of solar arrays and drive mechanisms. (2) Repair and replacement of the EMM's joint subsystem and end-effector subsystem. (3) Repair of hatches and portholes.

- **Inspection of the space station exterior:**

  (1) Status inspection of the EMM's exterior. (2) Cooperate with the CMM to complete a large-scale inspection of CSS.

- **Extravehicular servicing of payloads and equipment:**

  (1) Handling and installation of EXPOSE payload platforms and truss structures. (2) Handling and maintenance of solar arrays.

The purpose of this paper is to introduce the EMM and describe its operational status and missions in space from 2022 to 2023. The rest of the paper is structured as follows. Section 2 briefly describes the EMM system. In Section 3, the testing and integration process of the EMM in the pre-launch phase is presented. Section 4 mainly describes the missions performed by the EMM on CSS. Section 5 summarizes and concludes.

2. EMM SYSTEM DESCRIPTION

As shown in Figure 2, the EMM is a 7-DOF robot arm system, wherein its 2 wrist parts have a total of 6 DOF (each has 3 DOF) and the elbow joint has 1 DOF [2]. One end-effector is used for connection between the EMM and Wentian as the work base; the other end-effector is used as the tool for payload operation and can be also used for docking with the CMM to compose a 15-meter series-connected arm (see Figure 3). Both end-effectors are configured with hand-eye cameras and elbow cameras. The controller is placed on the main body of the EMM and moves with it.

2.1. Joint Subsystem

Joints are the core components of the movement of the EMM. As shown in Figure 4, the EMM joint consists of a brushless DC motor, a harmonic reducer, a joint torque sensor, a joint angle sensor, a thermal control system, etc [3]. In addition to meeting the important technical indicators, such as output torque, speed, limits, precision, and life expectancy, the EMM joint also has the following functions:

- The standard interface for on-orbit can provide mechanical, power, and data capabilities between joints, between joints and rods, and between joints and the end-effector.

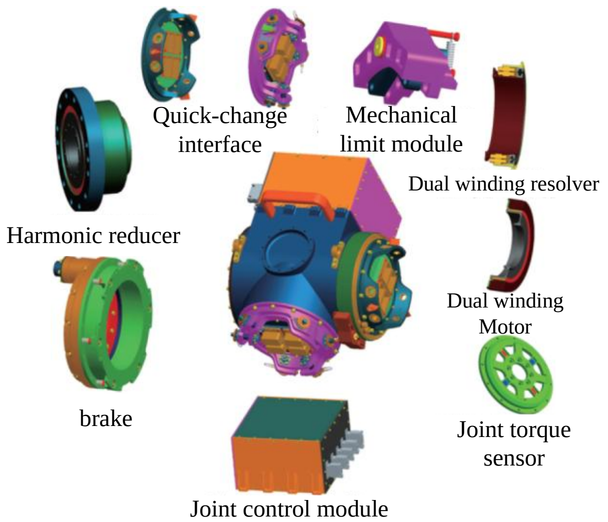

Figure 4. The major components of the EMM joint.

- Collect joint information by answering or sending it periodically and transmitting it to the controller of the EMM.
- Active thermal control of joints is achieved by collecting temperature sensor data.
- Complete electrical safety self-assessment, program self-test, and joint movement test.
- It has the ability of astronaut control drive.
- Supports on-orbit replacement of joints.
- Equipped with a mechanical interface for launch locking.

2.2. End-effector Subsystem

The end-effector subsystem is installed on each end of the EMM, one serves as the base point through grappling the cooperative grapple fixture, and the other conducts various operation tasks with the operation tools [4]. Several grapple fixtures are installed on CSS, so the EMM can walk around by changing its base point. Figure 5 shows detailed structure of the end-effector subsystem.

The functions of the end-effector subsystem are listed below:

- **Self-relocation:** the end-effector subsystem is attached to the grapple fixture so that the EMM can step over from one base point to another or perform an inchworm-like movement with the exchange between the wrist and shoulder.
- **Payload handling:** one cluster's end effector is attached to the grapple fixture stably so that the

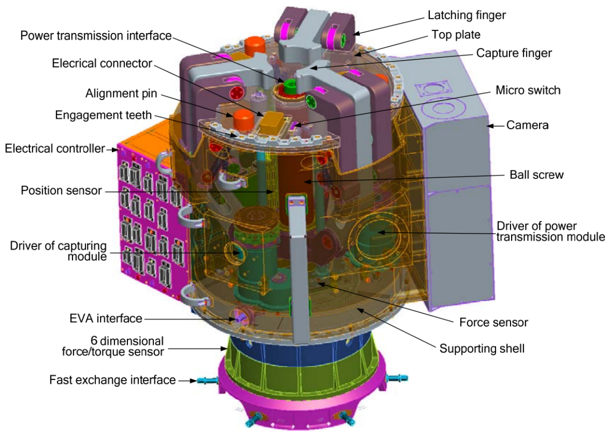

Figure 5. The major components and layout of the end-effector [4].

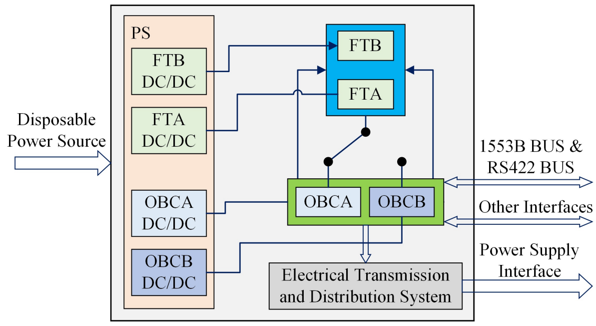

Figure 6. The configuration of the EMM's controller.

cluster acts as a shoulder base, while the other cluster's end effector acts as a hand to perform kinds of operation tasks.

- **Power transmission:** the end-effector subsystem can transmit torque to drive the attached tool to accomplish certain on-orbit servicing tasks.

2.3. Controller Subsystem

The controller subsystem is an important part of the EMM, which mainly completes the communication, control, power management and other tasks. The controller subsystem is installed on the outer surface of the EMM and consists of a processor module, a fault-tolerant module, a power distribution module, a bus backplane, and a chassis. As shown in Figure 6, the controller subsystem adopts the architecture of "secondary power supply + computer OBC dual-mode cold standby + fault-tolerant dual-mode cold and hot standby + power supply and distribution switching". The controller subsystem consists of the following modules:

- **On-board controller (OBC):** it adopts dual-link cold backup, which is divided into OBCA and

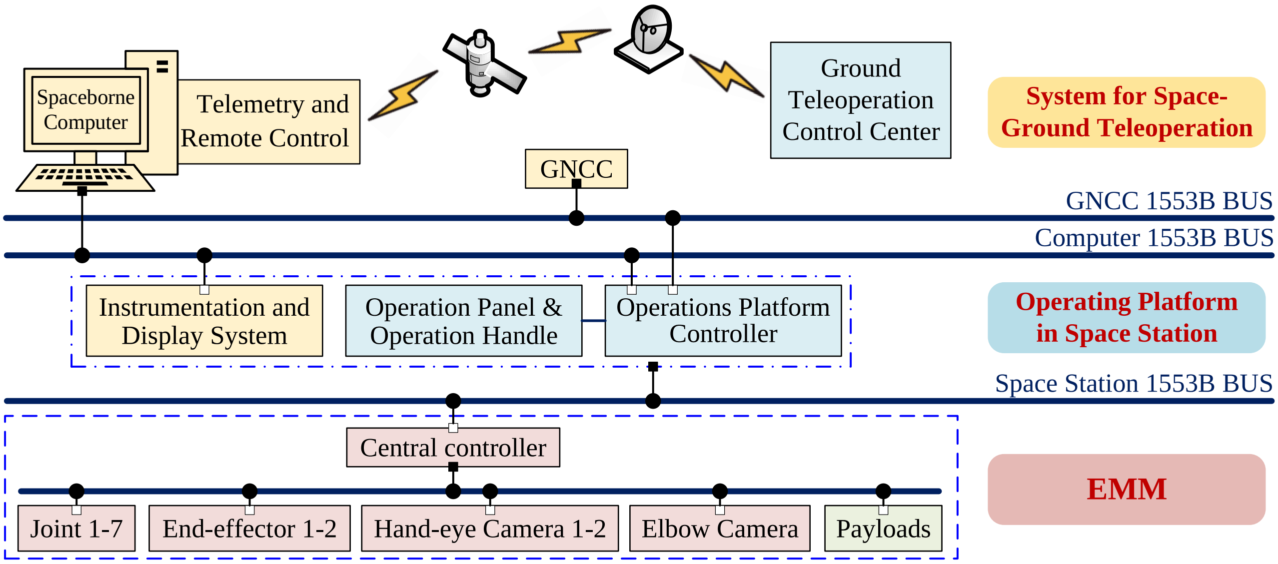

Figure 7. On-orbit operation and ground teleoperation.

OBCB. Moreover, it can be switched directly from the ground remote control or autonomously switched by FT.

- **Fault Tolerance (FT):** it adopts dual-link cold backup, which is divided into the FTA module and FTB module. It is responsible for monitoring the working status of OBC and is responsible for the autonomous switchover from OBCA to OBCB when OBCA fails. It can only be switched by direct command from the ground remote control.
- **Switching power supply and distribution module:** it is responsible for switching 48 channels 100 V power supplies and distribution according to the OBC directive.
- **Secondary power module:** generate secondary power supply for OBC dual unit (+5V, $\pm$12V) and double fault-tolerant FT (+5.5V) based on the disposable.

2.4. On-orbit Operation and Ground Teleoperation

The EMM can be controlled by on-orbit operation and ground teleoperation. Astronauts can switch to the ground teleoperation mode (default state) through the button on the operation platform in Wentian or through ground commands. The system structure of on-orbit operation and ground teleoperation is shown in Figure 7.

- **On-orbit operation:** the astronaut operates the EMM in orbit through the operation platform in Wentian. The motion command is forwarded to the central controller of the EMM through the 1553B bus dedicated to the arm. Then the central controller sends the command to the joint controller, terminal controller, and other terminal equipment for execution. The central controller is also responsible for collecting telemetry data from the EMM and sending it to the operating platform in Wentian.
- **Ground teleoperation:** the mission control experts operate and maintain the EMM through the remote operation platform on the ground. In the ground teleoperation mode, the motion command of the EMM is generated by the ground operation platform, sent to CSS digital tube subsystem through the upstream channel, and then sent to the operation platform in Wentian by the digital tube subsystem through the 1553B bus. It can use online model correction and predictive simulation analysis to predict the state of the EMM. With the assistance of 3D visualization scenes and telemetry data, the impact of communication delay in teleoperation is eliminated or reduced. Moreover, the ground remote operation platform of the EMM undertakes the design, planning and verification before the mission, the monitoring and execution during the mission, and the analysis and evaluation after the mission.

3. TESTING, INTEGRATION, AND LAUNCH

Meant for a low or zero-gravity environment, the EMM could not perform mission operations in Earth's gravity. Therefore, a ground experiment supporting system based on an air-bearing table was built, as shown in Figure 8. Ground experiments were conducted to verify the validity of the EMM's design scheme, including conventional performance parameters test, sine vibration test, random vibration test, and thermal vacuum test.

The integration and launch operations phase is a vital

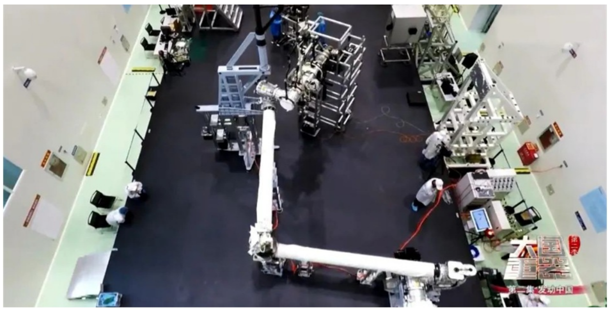

Figure 8. Ground-based reduced gravity testing for the EMM by using an air-bearing table.

Figure 9. Install the EMM outside the Wentian's cabin.

stage for the EMM. As shown in Figure 9, following individual ground experiments, the EMM was shipped to the cleanroom and mated with Wentian. As shown in Figure 10, the rocket took off at 2:22 p.m. Beijing Time on July 24, 2023 from the Wenchang Spacecraft Launch Site. About 495 seconds later, Wentian separated from the rocket and entered the planned orbit. The launch was a complete success. Later, Wentian rendezvoused and docked with the combination of CSS according to the scheduled procedures, and the Shenzhou-14 astronauts entered Wentian to carry out relevant work.

4. PERFORM TASKS ON CSS

4.1. The Tests the EMM Completed

On July 24, 2022, the EMM arrived at CSS as a part of Wentian. Four nights later, the astronauts unfolded the EMM in Wentian and completed a series of performance tests such as self-inspection, confirmation of crawling ability, and inspection of adapters, solar array and exit hatches.

1. Unlocking of aerospace pyrotechnic devices

The first thing to do during the test was to unlock the aerospace pyrotechnic devices. Once unlocked, the EMM can be powered up and run its tests. Aerospace pyrotechnic devices refer to disposable components and devices that ignite gunpowder or detonate explosives for mechanical work.

Figure 10. A Long March-5B Y3 carrier rocket, carrying Wentian, blasts off from the Launch Site.

Figure 11. Testing each joint of the EMM.

2. Self-inspection

Ground researchers examined the various products of the EMM, including controller status confirmation and examinations of joints and distal ends of the arm.

3. Single joint deployment

As shown in Figure 11, single joint deployment was to test each joint of the EMM to make sure that the joints can be properly deployed. The EMM will conduct detailed operations and inspections on CSS, which require it to be able to cover a certain area range.

4. Confirmation of crawling ability

As shown in Figure 12, the crawling ability on the surface of CSS was tested, which is an important basis for the EMM to carry out extravehicular operations.

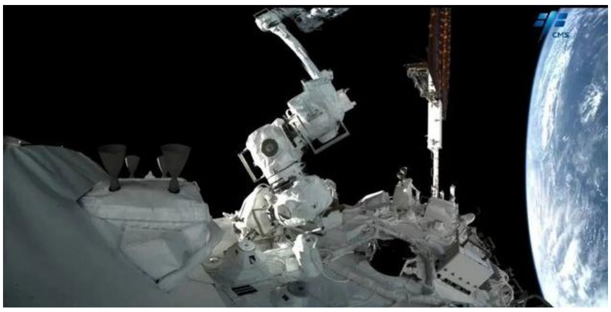

Figure 12. The EMM moves to the next adapter.

Figure 13. The footprint of the EMM.

Figure 14. The EMM inspecting payload adapter.

5. Disengage from the base

As shown in Figure 13, when the distal end of the EMM docked with one of the adapters on the surface of CSS, the other end needed to disengage from its base. This was the "first step" the EMM made. The EMM can "walk" outside by repeating this process.

6. Inspection of adapters, solar array and exit hatches

As shown in Figure 14, the EMM passed four adapters during the crawling process. The adapters are like the "footprints" of the arm (see Figure 13). After passing through all the "footprints", the EMM ensured that every adapter point was tested and verified. Solar array and exit hatches along the way were also checked.

7. Joint test

After the test of the arm, a joint test of astronauts, the EMM and its operation platform was carried out. The astronauts can operate and test the EMM through the operation platform.

4.2. The Tasks the EMM Completed

1. Support to EVA astronauts in a variety of tasks

September 2, 2022, was the day of Wentian's first spacewalk, which lasted about six hours. As shown in Figure 15, with the help of the EMM, Shenzhou-14 astronauts Chen Dong and Liu Yang went outside the cabin and returned safely to Wentian after completing the scheduled tasks. Under the coordination between space and Earth, and coordination with astronaut Cai Xuzhe inside the lab module, Chen and Liu completed a series of tasks, including the installation of the extended pump set of Wentian, lifting the lab module's panoramic camera, and the verification of capability for independent transfer and emergency return to the spacecraft. The EVAs tested the cooperation ability between astronauts and the EMM and tested the function and performance of Wentian's airlock cabin and support equipment related to EVAs.

This is the fifth spacewalk that has been conducted outside CSS with "new people, new module, new status". With the help of supportive equipment and the EMM, future preparations for spacewalks will be done more easily. Moreover, from now on, EVAs will mostly be done from Wentian's airlock cabin.

2. Combination with the CMM to assist astronauts' EVAs

On November 17, 2022, astronauts Chen Dong and Cai Xuzhe completed their third round of EVAs, as shown in Figure 16. It was the first round of EVAs after CSS's basic T-shape configuration was formed, and the EVAs lasted around 5.5 hours. It was also the first time that the EMM docked with the CMM to compose a 15-meter series-connected arm to assist astronauts' EVAs. During the EVAs, the two astronauts outside the cabin worked together and installed a connection "bridge" between the three modules that could assist astronauts with crawling outside the module and better stabilize the CSS's T-shaped structure.

These EVAs tested the cooperation ability between astronauts and the combined arm and tested the function and performance of Wentian's airlock cabin and support equipment related to EVAs. At the same time, the combined arm will provide strong support for the subsequent completion of difficult tasks, meeting the needs of delicate operations at different locations throughout CSS.

As shown in Figure 17, on July 20, 2023, with the assistance of the combined arm, astronauts Jing Haipeng, Zhu Yangzhu and Gui Haichao completed all set tasks during the eight-hour spacewalk. During the spacewalk, the astronauts completed tasks including bracket installation and lifting of panorama camera B of the core module and the unlocking and lifting of panorama cameras A and B of the Mengtian lab module.

3. Inspection of the space station exterior

Inspection of the exterior is critical for CSS. The hand-eye camera and elbow camera of the EMM can be used to inspect the exterior of CSS and accomplish several functions:

- **Track changes in external conditions:** surface anomalies, damage, material degradation, etc.

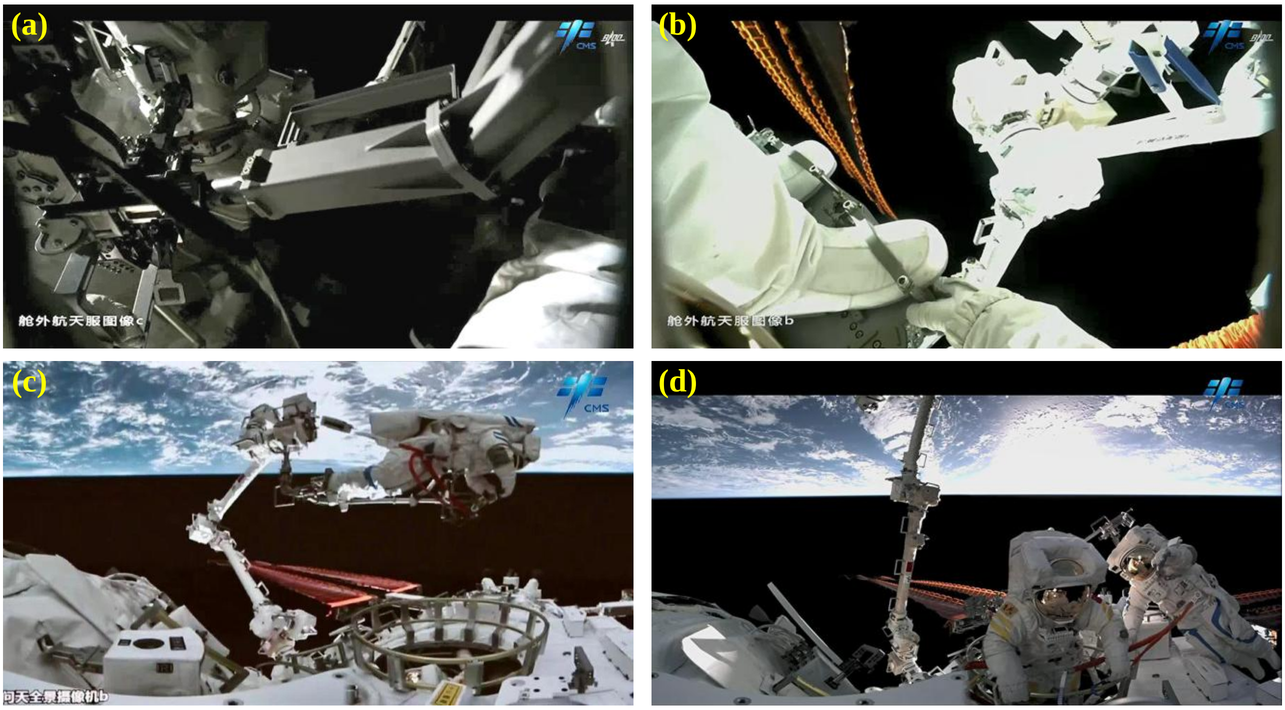

Figure 15. (a) The Shenzhou-14 astronauts install foot limiters. (b) Fixing an astronaut at the end-effector of EMM. (c) An astronaut is lifted to the operating position of Wentian to install pumps. (d) The astronauts return to the interior of Wentian.

- **Configuration verification:** module installation and transfer, deployment of the solar arrays, etc.
- **Anomaly status detection and monitoring:** torn solar arrays, air leak, etc.

As shown in Figure 18, the inspection of CSS is supported by a TV system (through the EMM's elbow camera and arm operations). It is worth mentioning that inspection with the combined arm can cover a wider range of EVAs, transfer for a wider area range, and reach different positions for detailed detections. It will increase the completeness of inspection coverage and reduce the number of blind spots. Of course, it requires very complex operations.

5. CONCLUSIONS AND FUTURE WORK

Space robots can adapt to the extreme environment, break through the limits of human space exploration, and greatly improve the safety and economy of space operation and control. Moreover, space robots are the core equipment to improve the level of space science and technology, providing important support and a strong guarantee for promoting space industry development [5].

The EMM has been successful over its 1-year life on CSS and met its design requirements, including workhorse for astronaut EVA activities and inspection of the space station exterior. In the future, the EMM will further play an important role in the maintenance and repair of CSS. Moreover, the evolution of the EMM to increase its servicing potential is currently in progress.

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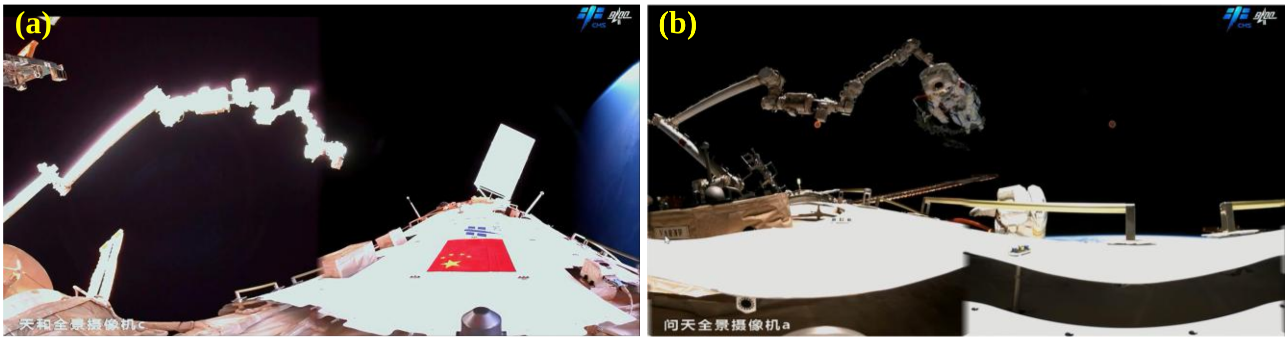

Figure 16. (a) The EMM formed a combination with the CMM on Tianhe. (b) A Shenzhou-14 astronaut on the end of combined arm.

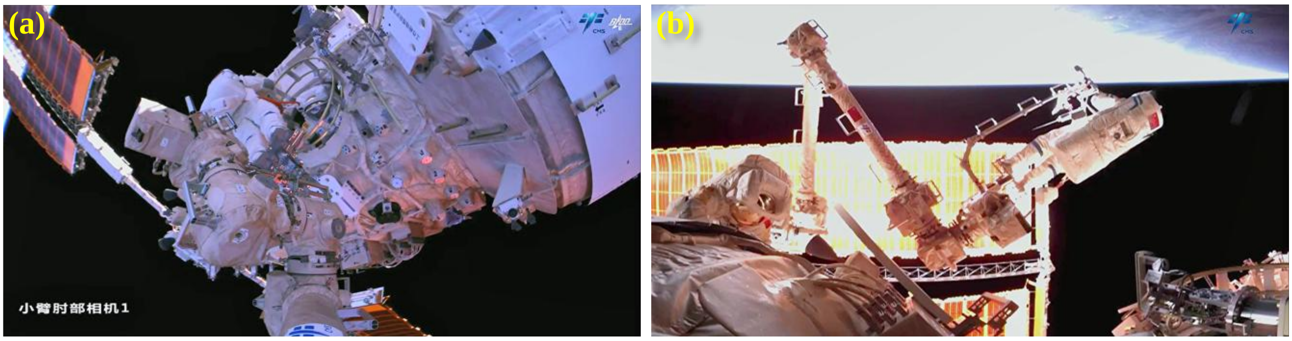

Figure 17. A Shenzhou-16 astronaut during the extravehicular activity.

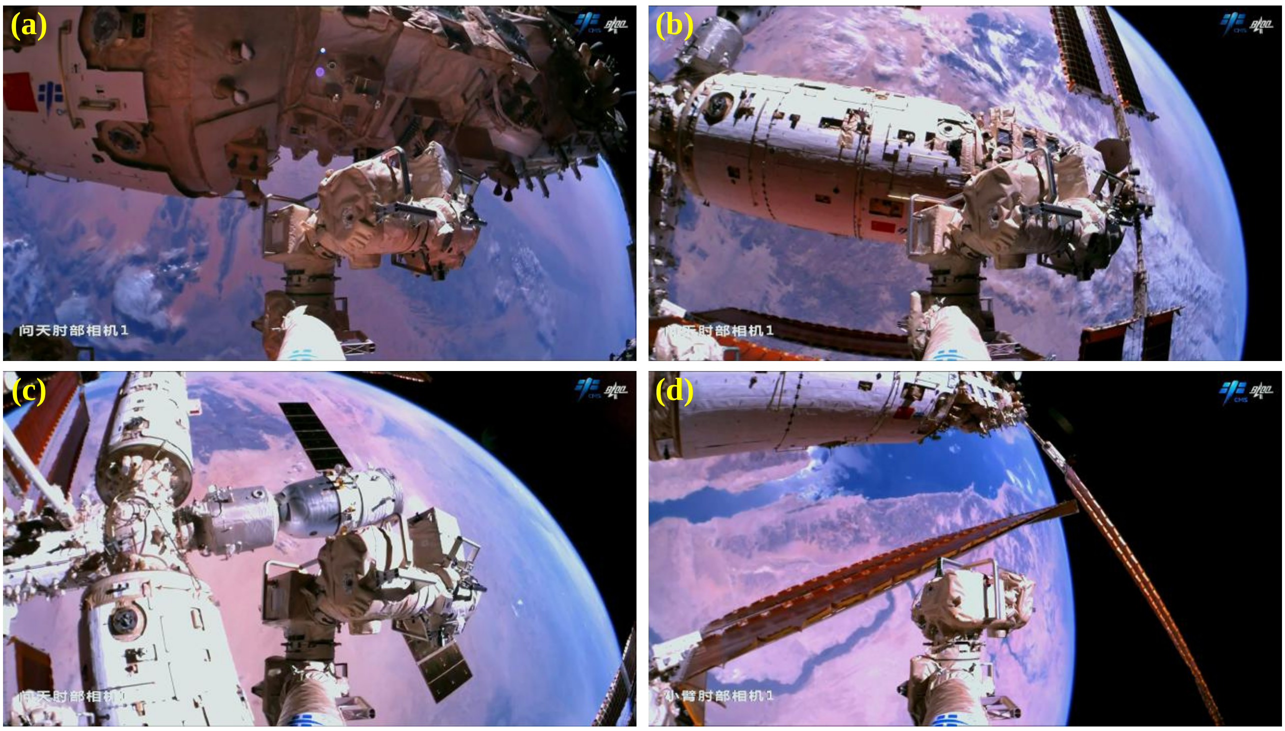

Figure 18. The EMM's elbow camera was used to inspect the exterior of CSS in different views.