Overview of Key Technologies and On-orbit Verification of China Space Station

ZHANG Hao, ZHU Guangchen
Beijing Institute of Spacecraft System Engineering, Beijing 100094

Abstract: Tiangong space station is a space station independently designed and developed by China. In order to build and operate the space station, it was necessary to make breakthroughs in many fields and master several key technologies, which were characterized over a long technological span and underwent difficult verifications. Therefore, in addition to ground verification, on-orbit flight tests of key technologies for the assembly, construction and operation of the space station were planned to be conducted used by the core module, taking into account the differences in the gravity environment between space and the Earth, in order to lay a foundation for the subsequent comprehensive assembly, construction and long-term on-orbit operation of the space station. In this paper, the mission characteristics of the space station are briefly introduced, along with the key technologies for the assembly and construction of the space station, and then the on-orbit verification tests are comprehensively introduced.

Key word: key technologies, on-orbit verification, China Space Station
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1 INTRODUCTION

The Tiangong space station was independently designed and developed by China. It consists of three spacecrafts: Tianhe core module, Wentian lab module and Mengtian lab module. In the absence of a large transport vehicle, such as a space shuttle, the China Space Station was assembled and constructed by means of module rendezvous and docking, and module transposition. The three spacecrafts were launched by carrier rocket LM-5B successively, two lab modules docked to the axial port of the core module in turn, and then through plane transposition operating, they were transferred to either side of the core module, and rigid connected, forming into the "T" configuration. This provided a structure to support the astronauts during their on-orbit residence over long periods enabling a series of experiments inside and outside the space station to be conducted, along with complex extravehicular construction and operational activities [1]. The construction and long-term flight of the China Space Station involved a number of key technologies, such as provision of a large power of space energy supply, a manipulator, a regeneration and environmental protection for the occupants, propellant refueling, which all need technological breakthroughs to be achieved and mastered.

Due to the difference between the Earth and on-orbit gravity environment, some key technologies for the space station construction and flight needed on-orbit verifications. Therefore, the China Space Station mission was divided into three stages: the verification stage of key technologies, the construction stage, and the application and development stage. Firstly, the launch of the Tianhe core module was achieved to verify key technologies for the space station construction and long-term flight. Secondly, the space station was turned into a construction operation after a thorough on-orbit evaluation, including the launch of the Wentian lab module and Mengtian lab module in turn, thus on combining these modules the space station construction was completed. Finally, the space station entered the application and development phase.

At first, this paper provides a summarized account the mission characteristics of the China Space Station, then the key technologies adopted for the China Space Station mission and finally the on-orbit verification will be introduced.

2 SPACE STATOIN MISSION CHARACTERISTICS

2.1 Programme Overview

The China Space Station is a building block plus partial truss structure. Centered on the node of the core module, the two lab modules and other visiting spacecraft are docked with the node, and the assembly stretches out like building blocks. In the tails of both labs, solar wings were installed on a local truss. The solar wings exhibit good characteristics for sun irradiation, and can reduce the shadow from solar wings to antennas and outside sensors, this is a unique feature of the space station. The integrated configuration of China Space Station is shown in Figure 1.

The China Space Station has a mass of 68.5 tons and a design life of at least 10 years, which can be extended through on-orbit maintenance. The flexible solar wing with biaxial rotation is used to provide electric energy for the space station. It is equipped with two manipulators. The operational radius of the large manipulator is 9.5 m, which can transfer astronauts, large payloads and cabins while in orbit. The operational radius of the small manipulator is 5 m, and astronauts can be transferred to conduct payload management [2]. Using a control moment gyro to control flight attitude and electric propulsion technology to conduct orbit maintenance, this can reduce the need for chemical propellant for long-term on-orbit flights [3].

The space station adopts regenerative life support technology to realize recycling of resources. With the support of manned spacecraft and cargo spacecraft, long-term operation with low consumption can be realized. The space station can support long-term continuous residence of three crew members and up to six crew members during rotation. WiFi inside and outside the module supports use of portable computers,

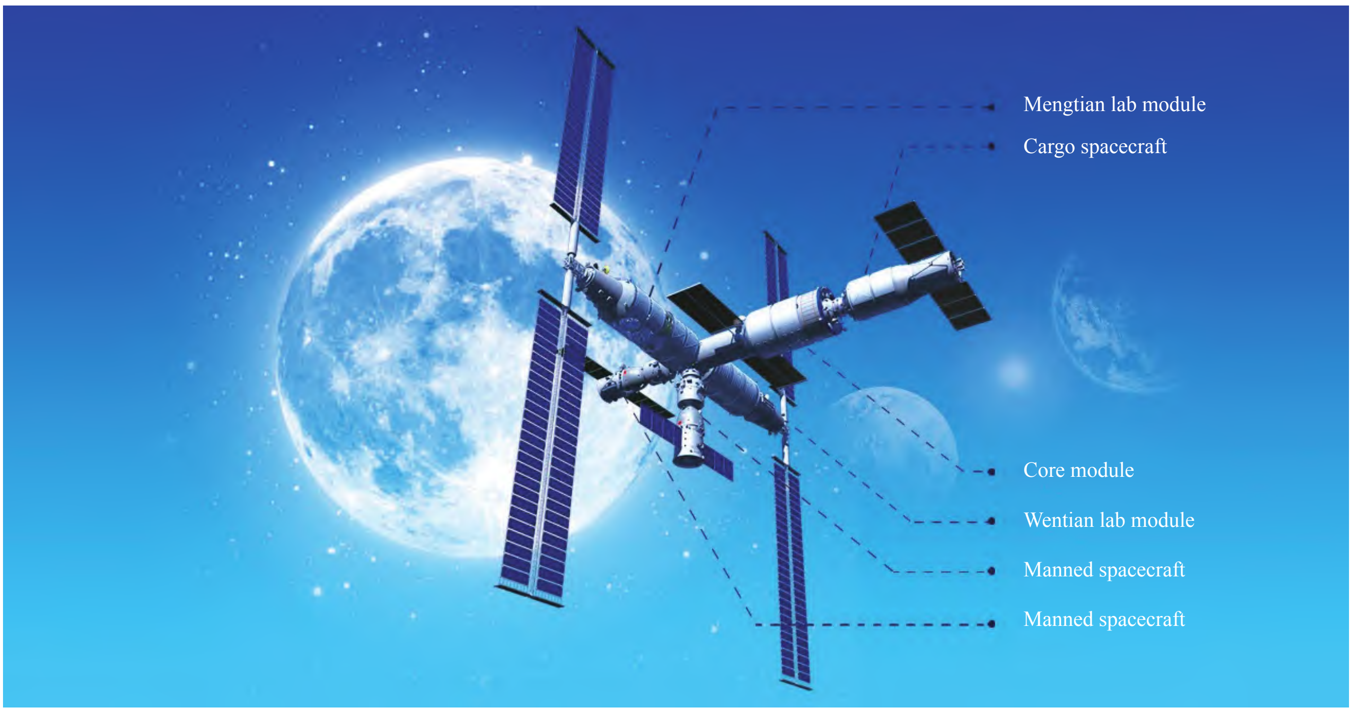

Figure 1 Schematic diagram of China's Tiangong space station configuration

mobile phones, tablets, hand-held cameras and other devices, providing greater convenience for astronauts during their stay in orbit.

In addition, the space station has the capacity to support more than 20 tons of payload equipment, conducting scientific and technological experiments in and out of the module. The payload mass accounts for more than 30% of the total mass of the station, far exceeding the 8% of the International Space Station. The total power of the space station for the application payloads is not less than 12 kW, where the core module is not less than 2 kW. Each lab module is no less than 5 kW respectively, and the power between the two modules can be adjusted. The maximum power of a single lab module can be increased to 7 kW. The space station can supply more than 45% of the power for the payload, which is comparable to that of the International Space Station. The payload network of the space station is used for the transmission of application payload test data. It adopts Ethernet technology and has an inter-module transmission rate of 9.9 Gbps, supporting inter-module data interaction and collaborative computing. It supports a maximum data rate, upstream and downstream, with a maximum uplink capacity of 10 Mbps and a maximum downlink capacity of 1.1 Gbps [4-6].

The Tianhe core module, as shown in Figure 2, is composed of a node section, a small column section, a large column section, a rear end passage section and a resource section, where the body length is 16.6 m with a diameter of 4.2 m. The node section is provided in the forward and radial directions of docking ports, and berthing ports are provided in quadrant II and quadrant IV, and an exit hatch is provided in quadrant III. A total of 5 doors and 1 between-section door of 850 mm in diameter are provided, enabling rendezvous, dockings with up to 4 spacecraft, including 2 lab modules, a manned spacecraft, a cargo spacecraft or another spacecraft. It is also equipped with a large manipulator to support astronaut egress activities.

The Wentian lab module is composed of a work section, an airlock section and a resource section, with the body length of 17.8 m and diameter of 4.2 m. As a backup module for key platform functions of the core module, it is also capable of unified management and control of the space station. It is equipped with an airlock for astronauts' extravehicular activities (EVAs), and equipped with a small manipulator to operate exposed experiment payloads.

The Mengtian lab module is composed of a work section, a payload section, a cargo airlock section and a resource section, with a body length of 17.8 m and diameter of 4.2 m, the same as Wentian lab module, to enable a balanced construction. It is used for conducting payload experiments in and out of the sealed module.

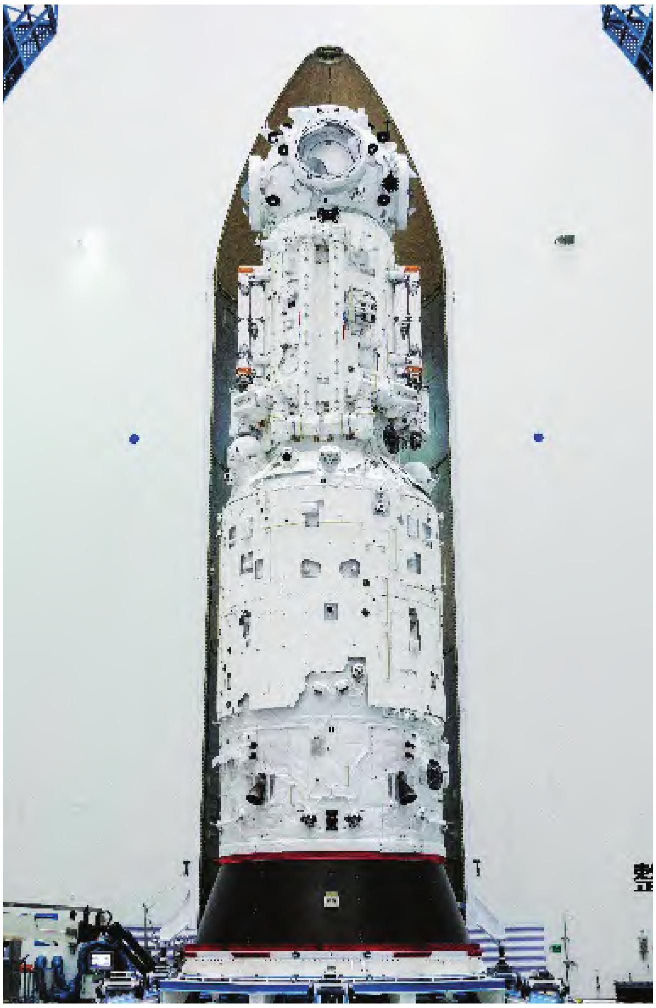

Figure 2 Diagram of Tianhe core module

2.2 Technical Features

The Tiangong space station is the largest spacecraft of China at present. It has the following six technical characteristics. [7]

1) The most complex spacecraft system, the largest number of products, and the largest proportion of newly developed products. There are more than 50 on-orbit probable configurations of the space station. New products accounted for nearly 90%, electric connection points are more than 200,000, and for the module structure and pipeline there are more than 10,000 welds.

2) Long on-orbit life and high reliability requirements. After assembly, the on-orbit working life is over 10 years, and full life mission reliability is more than 0.97.
3) There were many key technical difficulties, and it was difficult to verify on Earth.
4) The interface relationship for the on-orbit assembly was complex. The core module has a total of five docking ports, structural connection, refill propellant capability, a power grid, an information grid, plus other features such as various temperature control fluid loop coupling interfaces.
5) Comprehensive promotion of indigenous electronic components accounted for a large proportion of components adopted. More than 560,000 domestic components were used, example components include 100 V thick film DC/DC, 5.5 million and 3 million gate FPGA circuits, CPU chip 3803, PROM memory, astronaut extra-module operation electrical connector, high-power DC contactor, SSPC.
6) On-orbit maintenance was a fully new design including in-module and out-module maintenance. The design elements and human factors engineering were complicated. Hundreds of on-orbit maintainable units had been identified, and the design of the product maintenance interface, visual access and accessible design, maintenance program design and maintenance tool design need to be fully developed and verified.

3 KEY TECHNOLOGIES OF CHINA SPACE STATION AND VERIFICATION

Seven key technologies were involved in the assembly and construction of the space station and adopted for long-term flight, including large scale flexible solar wings and space power supply technology, regenerative life support technology, propellant refueling technology, on-orbit assembly and construction technology, control technology of a large variable structure assembly, EVAs and on-orbit maintenance technology, which all need to be verified in orbit due to the impact of the Earth's gravitational environment. Since the core module was launched into orbit on April 29, 2021, it has successfully completed on-orbit verifications of the seven key technologies, laying a solid foundation for the subsequent construction and long-term flight of the space station.

3.1 Large Scale Flexible Solar Wings and Space Power Supply Technology

In addition to meeting the power supply requirements of the space station equipment and large-scale space experiments, there was also a need to consider the attenuation of the power generation capacity brought about during its long-life flight, therefore, the space station was equipped with large scale flexible solar wings and driving mechanism. The core module adopted two single-degree-of-freedom flexible solar wings to provide the energy supply for a single flight. The length of a single wing is over 10 m, and the power supply capacity is more than 4 kW by each. The two lab modules were equipped with the two largest flexible solar wings in China, which are oriented towards the sun through two-degree-of-freedom drive mechanisms. The length of the single wing is more than 25 m and the surface area is more than 110 m^2, with a power supply capacity of over 7 kW by each. The solar wing's cell conversion efficiency is more than 30%. At the same time, lithium-ion energy storage batteries are configured to store the electric energy and supply power for the whole space station when the solar wing is not generating power. The solar wing of the space station is shown in Figure 3.

The space station adopts a 100 V fully regulated multi-bus system. The unified energy management of the core module realizes dynamic allocation under various configurations of the space station, and supports the payload power consumption of each module in the assembly. Dynamic energy allocation of 2 kW can be realized between the two lab modules to support the payload power. In addition, the space station has set up a grid-connected system, which provisions power supply interfac-

Figure 3 Solar wing of the space station

es with the Tianzhou cargo spacecraft, the Shenzhou manned spacecraft and other visiting spacecrafts.

During the flight of the core module, the unlocking, spreading and driving control of the solar wings, the power generation capacity of the flexible solar wings, and the charging and discharging technology of the lithium-ion batteries were verified. The solar wings were unlocked and spread in five steps according to the actions of explosive release, lifting, side spreading, sailboard restraint release and final extension. Once spread, the control system controls the solar wings continuous tracking, horizontal/vertical return to zero, and can enable a stop at any angle to accommodate different flight attitudes, EVAs, manipulator movement, rendezvous and docking and other missions. The power generation capacity in the initial stage in orbit was above 8.8 kW. In summary, the control drive and power supply technology of the flexible solar wings in the space station has been fully verified.

3.2 Physical and Chemical Regenerative Life Support Technology

In order to support the astronauts' long-term stay in orbit and reduce the demand for ground supplies, the Tianhe core module and Wentian lab module both equipped physical and chemical regenerative life support systems to control the manned environment system and realize efficient material flow circulation, including electrolytic oxygen production, waste water treatment, urine treatment, trace harmful gas and CO_2 removal [8].

During the assembly period, the core module was unified to control the air composition, pressure, temperature and humidity of the sealed section, as well as water recovery management, microorganism control and waste management. The regenerative life support technology can realize the renewable utilization of on-orbit resources, where the comprehensive water recovery rate is more than 83%, greatly reducing the need for further supply of water, with the purification tank and other non-renewable resources, long-term economic benefits of operation could be achieved. During the application and development stage, carbon dioxide reduction technology, waste treatment and reuse technology will be further developed to improve the level and efficiency of material recycling.

By the Shenzhou 12/13 crew residence, the regenerative life support system had been in continuous operation confirming renewable material flow fully verified circulation and continuous operation ability, along with the technology of the electrolytic oxygen production, waste water treatment, urine treatment, trace harmful gas and CO_2 removal. The utilization efficiency of electrolytic oxygen is above 85.3%, and the water recovery efficiency is about 99.4%, and the CO_2 removal rate can support the long-term residence requirements for the three-person crew. Through sampling, the concentration level of harmful gas in the module was confirmed nearly zero. To sum up, the physical and chemical regenerative life support technology adopted has been verified and has the ability to support long-term stays. At the same time, we will continue to accumulate data on the astronauts' on-orbit metabolism level, consumption level of the regenerative life-support equipment and maintenance cycle, thus determining the long-term operation mode in combination with subsequent resident missions of the crew.

3.3 Propellant On-orbit Refueling Technology

The space station mainly uses chemical propellants to complete orbital changes, large attitude maneuvers, control monent gyro (CMG) offpayloading and debris avoidance, while electric propulsion is used for orbit maintenance during long-term flights. In order to complement the consumption of chemical propellant, the space station uses propellant on-orbit refueling technology, based on a bellows tank and pressurization gas propulsion refueling scheme, where the core module configuration oxidant, burners road compressor, the metallic bellows tank, and liquid circuit breakout, accept the propellant from the cargo spacecraft [9]. Through the pressurization and reuse of the compressor module, the low-pressure gas in the tank of the core module bellows is forced back into the high-pressure gas cylinder, so that the pressure of the core module tank is lower than that of the cargo spacecraft tank, and the propellant can flow from the cargo spacecraft to the core module tank. The core module has a maximum refueling capacity of 1800 kg and can fly in orbit for more than 1 year without refueling from the cargo spacecraft.

Both the front and rear docking mechanisms of the core module are equipped with liquid circuit breaker interfaces for refueling, which not only ensures the reliability of the propellant refueling, but also meets the requirement of providing cross-module refueling for other visiting spacecrafts.

Through the core module and the Tianzhou 2 cargo spacecraft we can realize a backward docking port and forward docking port propellant on-orbit refueling capability, adding a total of more than 800 kg. The backward and forward interface refueling mode, refueling control mode, refueling and propulsion integrated design and safety isolation compatibility, compressor, and pipeline valve system technology were comprehensively verified. The propulsion system and refueling system pipelines adopt an integrated design. During refueling, the gas/liquid valve in the transverse pipeline is automatically closed, so that one pair of fuel tanks can be kept operational for the thruster while the other two can be refueled, realizing the safe isolation of the propulsion and refueling functions.

3.4 On-orbit Assembly and Construction Technology

The space station was assembled and constructed on orbit through rendezvous and docking of the core module with two lab modules, and module transposition. First, the Wentian lab module was connected to the forward docking port of the core module, and then it was transferred from the forward docking port to the lateral docking port by using the transposition mechanism configured on Wentian lab module. The same occurred for the Mengtian lab module, which was transferred to the docking port on the other side of the core module. It should be noted, the large manipulator on the core module could also have used as a backup means to complete the transfer of the lab module. The space station construction process is shown in Figure 4.

The lab modules' transposition was China's first implementation of a 23-ton level spacecraft transfer operation on orbit, where the space station was carrying out the multi-disciplinary integrated analysis of dynamics, control, TT&C, energy, thermal control, analysis of the flight attitude, not only ensuring controllability during the transfer operation of the combined structure attitude, but also ensuring the measurement of the whole transfer process.

During the Shenzhou 12/13 missions, the space station completed the verification of rendezvous and docking modes, including forward, backward and radial rendezvous and docking, cargo spacecraft orbiting rendezvous and docking, and manual remote-operated rendezvous and docking. Meanwhile, using the cargo spacecraft and the large manipulator, the space station verified module transfer technology. Through the above on-orbit missions and experiments, the space station assembly and construction technologies such as those for manipulator, rendezvous and docking, and module transposition have been comprehensively verified, where the positioning accuracy of the manipulator was better than 15 mm/0.5°, and the positioning accuracy of the transposition cargo ship met the requirements for re-docking.

3.5 Variable Structure Large Assembly Control Technology

The space station was the largest spacecraft in orbit for China at present. There were more than 50 kinds of on-orbit configurations from the key technology verification stage to the application and development stage, which brought difficulties in terms of controlling.

The space station realized attitude and orbit fusion control and solar wing rotation control under the control system of the core module as the main controller with the control system of the Wentian lab module as the backup. Each module control computer, attitude measurement sensor, control moment gyro, propulsion control drive controller, solar wing on the driving mechanism, network control system equipment, were linked

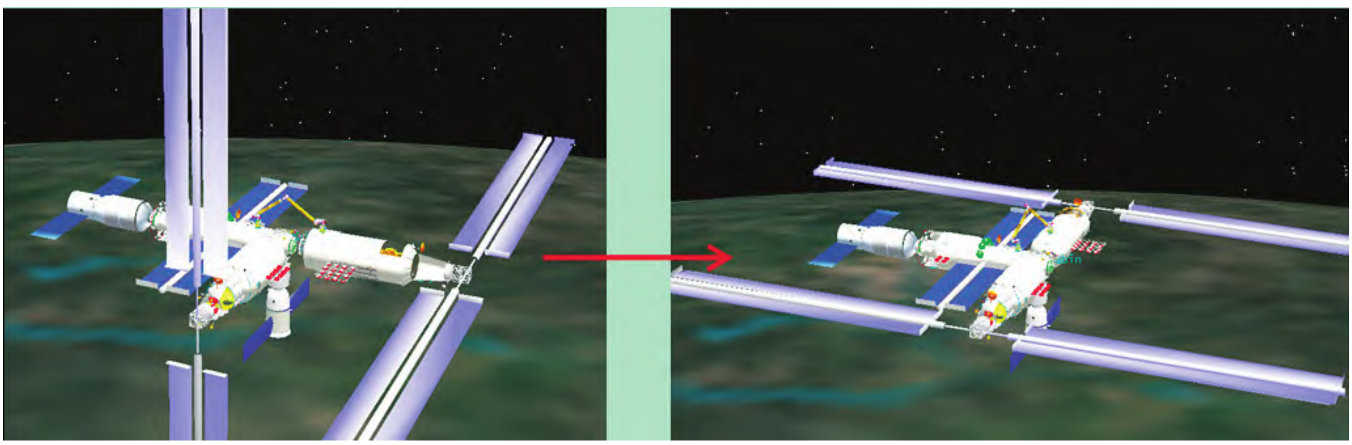

Figure 4 Schematic diagram of space station construction process

via a special 1553B bus, enabling the space station to achieve the interconnection between more than 50 sets of sensors, more than 100 engines, more than 20 units using gyro measurement and control fusion. In addition, it could control the cargo spacecraft thruster through the bus to control the attitude and orbit of the combined orbiting structure.

The core module and the Wentian lab module are equipped with six 1500 Nms CMG each, which can realize the long-term flight attitude control of the space station. When the combination of the core module and Wentian lab module fly in inertial attitude, the CMGs of both modules work. After the completion of the three-module assembly, the space station adopted the forward flight attitude for the orbital system, and a set of six CMGs can be used to control the attitude of the assembly. In addition, the core module is also equipped with four 80 mN Hall electric thrusters, which can compensate for part of the influence of the atmospheric resistance on orbit. The CMG and Hall electric thrusters are shown in Figure 5.

The space station has experienced six kinds of flight configurations including that of the core module only, the core module docked with one cargo spacecraft, the core module then docked with two cargo spacecraft, subsequently the core module docked with two cargo spacecraft and one manned spacecraft. For each combination it was necessary to eliminate initial deviation, triaxial stability of directional flight, inertia moment balance flight, controlling attitude and orbit control. It has been fully verified the correction of attitude control mode design, attitude orbit control, long-term flight angular momentum control management, and information and power control technology of large variable structure assembly, laying a foundation for subsequent assembly and control of the space station.

3.6 EVA Technology

EVA is an important means to ensure long-term and reliable operation of the space station, complete assembly, construction and carry out exposed payload operations. Both the core module and the Wentian lab module can support astronauts' EVAs. During the flight of the core module, EVAs were conducted by means of the node module. After docking, the lab module's airlock could be used to exit the module and the node module formed a backup option. The space station supports two astronauts' exit at the same time. During an EVA, wireless communication mode is adopted. UHF communication is used to transmit voice and astronauts' physiological data, and WiFi is used to transmit video images.

The two manipulators can work independently or cooperatively, or can be combined into one larger manipulator to expand the working range. The large manipulator is mainly responsible for long-range transfer of large payloads, the small manipulator is mainly responsible for fine-scale operations of small payloads, and the combined one is mainly responsible for long-range operational tasks with astronauts or EVA payloads. With the support of astronauts, the manipulator, EVA suits and cargo spacecraft, large space facilities operation and complex EVA construction tasks can be conducted.

Compared with the first EVA of Shenzhou 7, the space station EVA has a large technological leapfrogging. The Shenzhou 12/13 astronauts completed EVAs four times, for panoramic

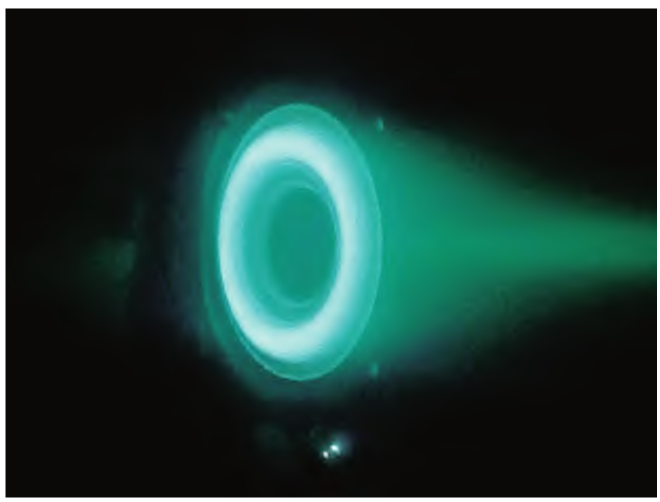

Figure 5 Schematic diagram of space station CMG capability verification test and Hall electric thruster verification

camera manipulation, installing extension pumps and manipulators connecting parts, so the space station capability to support astronauts' EVA technology has been verified, including the auxiliary manipulator to transfer the astronauts, for autonomous crawling, plus astronauts' EVA auxiliary facilities. The functions of air brake pressure relief and gas reuse have also been verified. The gas reuse rate is more than 70%, which greatly saves the up-delivery demand of gas resources. Figure 6 is the photo taken during the astronauts' EVA mission from the node module.

3.7 On-orbit Maintenance Technology

To ensure the space station long-term flight life, taking full advantage of astronauts in orbit, the maintainability design of space station both on the sealed module inside and the equipment outside is critical. The space station's life is prolonged by the utilisation of hundreds of on-orbit replaceable units (ORU), where the three modules use commonly design. Through the use of common parts and products, accounting for over 80%, it is possible to reduce the redundancy of single-module equipment, and improve the redundancy of the whole space station equipment and in turn the reliability of the space station. Figure 7 shows the ground verification schematic diagram of extravehicular maintenance operation.

In addition to the maintainability design of the equipment, the space station also has redundancy design at the functional level to ensure that the platform functions normally during maintenance. For example, each module of the space station is equipped with two independent power supply buses, and the key equipment of the platform adopts double buses for power supply. When a single bus fails and needs repair, the key equipment of the platform can automatically switch to another bus for power supply. The space station is equipped with non-regenerative equipment such as oxygen bottles and purification tanks, which can control the atmospheric composition of the space station in case of failure of the regenerative equipment to ensure the normal stay of astronauts. The information system of three modules adopts the same architecture, and the equipment, software and the communication protocols adopt universal design. Hence after the space station combination was assembled, information management and sharing between each module of the space station and visiting spacecraft can be carried out based on the network technology, which can ensure that the whole space station information system can still work normally when the information equipment of one module fails.

The in-module and out-module maintenance programs, using the ORU and assistive tool technologies were fully vali-

Figure 6 Astronauts conduct EVA from the node module of core module

Figure 7 Ground verification schematic diagram of extravehicular maintenance operation

dated through EVAs and during consumables replacement. The maintainability design of the universal interface for EVA products was verified by lifting the panoramic camera and installing the extended pumps. The Shenzhou 12 crew while in orbit completed the removal of the inner loop pump and install vibration isolation facilities, verified the feasibility of the maintenance mode. During the on-orbit stay of the crew, the consumables in the regeneration equipment are replaced regularly, the regeneration water tank is also replaced, and garbage collection and treatment are conducted, which further verifies the correctness of the maintenance design.

4 CONCLUSION

The space station has the characteristics of a large scale, complex system structure and working mode, using multiple key technologies which underwent difficult verifications. Through the core module on-orbit flight test, verified the assembly and control of the large combined, variable configuration station along with the physical and chemical regeneration life support system, flexible solar wings, propellants refueling, EVAs, on-orbit servicing station key technologies, all laid a solid foundation with the accumulated experience for subsequent space station construction and on-orbit operations for a long time.

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Author Biography:

ZHANG Hao (1981−), graduated from Tsinghua University with Doctor degree of Engineering. His research direction is system engineering of manned spacecraft.