Space: Science & Technology
A SCIENCE PARTNER JOURNAL

RESEARCH ARTICLE

Design and Application Prospect of China's Tiangong Space Station

Xiang Wang, Qiao Zhang*, and Wei Wang

Institute of Spacecraft System Engineering, China Academy of Space Technology, Beijing 100094, China.

*Address correspondence to: zhangqiao_bit@hotmail.com

As a manned spacecraft operating in orbit for a long time, a space station embodies a country's scientific and technological strength comprehensively. Building a space station is the final target of the 3-step strategy of China's manned space program. This paper introduces the design of the Tiangong space station in terms of its design principles, overall scheme, building process, and special system design. On this basis, the paper analyzes and summarizes the technical characteristics of the Tiangong space station in the aspects of system design and optimization, the large proportion of new technologies, the excellent cost-effectiveness ratio, and the high safety and efficiency of the crew's residence. Finally, it discusses the future application and development of the Tiangong space station.

Citation: Wang X, Zhang Q, Wang W, Design and Application Prospect of China's Tiangong Space Station. *Space Sci. Technol.* 2023;3:Article 0035. https://doi.org/10.34133/space.0035

Submitted 8 December 2022
Accepted 15 April 2023
Published 2 June 2023

Introduction

Manned space technology is one of the hotspots in the development of aerospace in the world. It not only reflects the development level of a country's space technology but also serves as an important mark to measure a country's economic, technological, and military strength as well as comprehensive national strength. China's manned space project was approved in 1992 with a 3-step strategic plan, and building a space station is the final goal of this plan [1]. The completion and operation of the space station will enable China to independently master the technology of long-term manned flight in near-Earth space, carry out long-term human-involved scientific and technological tests there, and comprehensively develop and utilize space resources. China will make pioneering contributions to the peaceful use of space for mankind.

In September 2010, China's manned space station project was officially established [2]. After 11 years of unremitting efforts, on 2021 April 29, the Tianhe core module was successfully launched into orbit by the carrier rocket Long March-5B at the Wenchang Spacecraft Launch Site in Hainan. This starts the building of China's manned space station, marking the beginning of the mission implementation stage of China's manned space station project [3]. As planned, by 11 launches and on-orbit missions from 2021 to 2022, China has completed the assembly and started the official operation of the space station. Up to now, space stations of other countries that have been launched and operated in space include the Salyut and Mir of the Soviet Union, the Skylab of the United States, and the International Space Station built jointly by 16 countries with the United States and Russia taking the lead [4–6]. With the completion and operation of the Tiangong space station, China will become the third country able to build and operate space stations independently after the Soviet Union and the United States.

Mission Goals

The Tiangong space station will serve as a national space lab and a platform for international scientific and technological cooperation and exchange. By building the Tiangong space station, China will set up a national space lab for human-involved scientific exploration and technological innovation in a special space environment. Astronauts and scientists will travel between the space station and Earth frequently for large-scale scientific and technological experiments in space. This can further build China into an innovative country and substantially enhance China's influence in the field of international science and technology.

Specific mission goals of the Tiangong space station include the following 3 aspects [7].

1. Building a space station operating reliably in orbit for a long time, which is basically configured with the Tianhe core module and 2 experiment modules Wentian and Mengtian
2. Providing guarantees for astronauts to live healthily and work effectively in orbit for a long time; ensuring the safety of astronauts visiting the space station with the cooperation of other systems
3. Providing guarantee and support conditions for multifield scientific and technological experiments in space

System Scheme Design

As the third multimodule space station in the world, which was assembled in orbit, the Tiangong space station has fully learned from the experience and lessons of the Mir space station and the International Space Station in its system design [8,9]. Depending on its basic national conditions, China embarks on an independent and innovative path of leapfrog development with the concepts of moderate scale, high safety, high reliability, advanced technology, optimized system, and being cost-effective by fully using the early technical basis of its manned spaceflight and giving full play to late-mover advantages.

Design principles

The following principles are observed during the design of the Tiangong space station:

1. The design should conform to China's national conditions, focusing on critical points and building a moderate-scale space station, with room reserved for development.
2. The design should have outstanding Chinese elements and core connotations.
3. The design should pursue technical progress. Contemporary advanced technologies should be fully used to build and operate the space station, and there is a need to fully master the building and on-orbit operation of large space facilities.
4. The design should pay attention to application benefits to produce major innovative achievements in space station applications.
5. The design should enable an economical operation to realize sustainable development.

Overall scheme

With full consideration of the geographical locations of launch and landing sites and recursive orbits of manned spaceship, the Tiangong space station operates in a near-Earth orbit with an orbital inclination of 41° to 43° and an orbital altitude of 340 to 450 km. It has a designed lifespan of more than 10 years. It has 3 crewmembers in normal cases and up to 6 in the case of crew rotation. The Tianzhou cargo spaceship is responsible for transporting propellants, equipment loads, and other consumables to the Tiangong space station and destroying waste by burning during reentry into Earth's atmosphere. The Shenzhou manned spaceship is responsible for crew transportation.

The Tiangong space station consists of the Tianhe core module, the Wentian experiment module, and the Mengtian experiment module, showing a T-shaped configuration. Specifically, the Tianhe core module is in the middle, with the Wentian and Mengtian experiment modules being assembled on the 2 sides respectively (Fig. 1). The Tiangong space station has 3 docking hatches: forward, backward, and radial ones. The forward docking hatch is mainly for docking with manned spaceship and the Xuntian space telescope, the backward one mainly for docking with cargo spaceship, and the radial one mainly for docking with manned spaceship [10].

The Tiangong space station is designed as a 3-module integrated system. The basic information of each module is as follows.

1. Tianhe core module

The Tianhe core module consists of 3 parts: a node cabin, a life control cabin (including a small column segment, a large column segment, and a rear passage), and a resource cabin. It has a total axial length of 16.6 m and a maximum diameter of 4.2 m, as shown in Fig. 2. The node cabin is used for module connection and spacecraft visiting, providing 1 forward docking hatch, 1 radial docking hatch, and 2 lateral berthing hatches. It also acts as an airlock cabin for extravehicular activities of crewmembers, with a spacewalk hatch arranged above. Sleeping and sanitary areas for the crew are arranged in the small column segment of the life control cabin. A large robotic arm is arranged outside the cabin, and single-degree-of-freedom solar arrays with their drive mechanisms are installed on both sides. Devices for platform and scientific research are equipped in the large column segment of the life control cabin. The resource cabin is equipped with a docking hatch and a material replenishment passage at its rear end.

The Tianhe core module is mainly used for unified management and control of the space station and serves as the target spacecraft to support rendezvous, docking, transposition, and berthing of visiting spacecraft. With the support of manned and cargo spaceships, this module enables the long-term stay

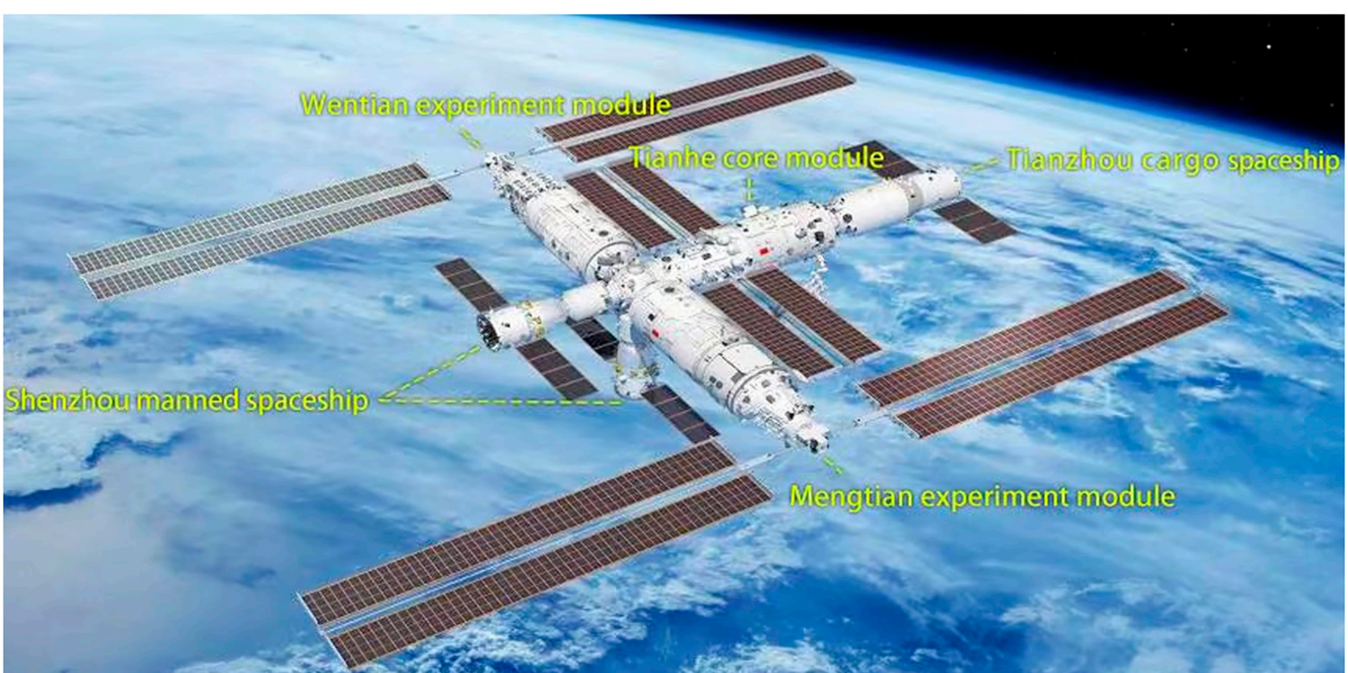


Fig. 1. Configuration diagram of Tiangong space station.

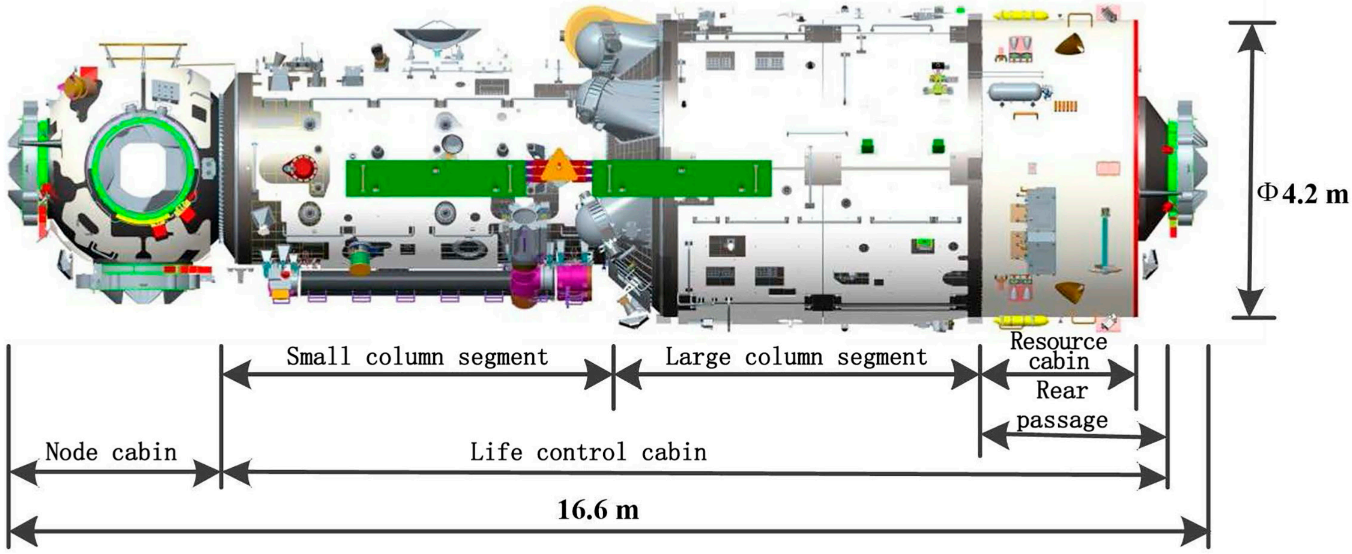


Fig. 2. Configuration diagram of Tianhe core module.

of the crew, providing guarantee conditions for on-orbit living and working of the crew to ensure their safety. The function of an airlock for extravehicular activities is provided to support the spacewalk of crewmembers. In addition, this module supports scientific and technological space experiments in the sealed module.

2. Wentian experiment module

The Wentian experiment module consists of 3 parts: a working cabin, an airlock cabin, and a resource cabin. It has an axial length of 17.9 m and a maximum diameter of 4.2 m, as shown in Fig. 3. A small robotic arm is arranged outside the experiment module, and the experimental platform is arranged outside the airlock and resource cabins to install external experimental loads. A truss structure is adopted at the rear for installing 2-degree-of-freedom solar arrays and their drive mechanisms.

The main task of the Wentian experiment module is to complete in orbit the rendezvous and docking with the Tianhe core module, module transfer, and berthing. Moreover, this module serves as a system-level backup for the critical platforms of the Tianhe core module, such as the energy management system, the information management system, the control system, and the manned environment system, capable of unified management and control of the assembly. It ensures long-term on-orbit stay of the crew, providing a special airlock cabin and an emergency shelter to ensure crew safety. Moreover, it provides guarantee conditions for scientific and technological space experiments both intravehicular and extravehicular.

3. Mengtian experiment module

The Mengtian experiment module consists of 4 parts: a working cabin, a cargo airlock cabin, a load cabin, and a resource cabin. It has an axial length of 17.9 m and a maximum diameter of 4.2 m, as shown in Fig. 4. Two deployable platforms for exposed payloads are installed outside the load cabin, unfolding in orbit after launch. The resource cabin of this module is basically the same as that of the Wentian experiment module.

The main task of the Mengtian experiment module is to complete in orbit the rendezvous and docking with the Tianhe core module, module transfer, and berthing, which provides guarantee conditions for crewmembers working in the sealed module and ensures crew safety. In addition, this module provides guarantee conditions for both pressurized and exposed payloads, as well as a cargo airlock for automatic transportation of loads and equipment into and out of the module.

The overall design of the Tiangong space station takes the "block-building" featured configuration of the Mir space station as reference. The Mir space station suffered from serious intermodule solar array occlusion. In view of this, the 3 modules of the Tiangong space station will be in the same plane during a long-time flight of the whole station to reduce intermodule occlusion. The 2 experiment modules have basically the same configuration and mass and are arranged transversely in 2 opposite directions in the T-shaped configuration. This arrangement in combination with the structural length of nearly 20 m of each experiment module forms a truss structure similar to that of the International Space Station. The large-area solar arrays of the experiment modules are arranged on both sides of the overall configuration, with 2-degree-of-freedom drive mechanisms used. This enables perpendicularity between solar arrays and sunlight at any time to ensure the highest power generation efficiency all the time.

Building process

According to the orbit law, when 2 spacecrafts are in different orbit planes, the relative velocity is maximum at the intersection of the orbit planes. Therefore, the implementation of direct lateral docking for 2 experiment modules are difficult and dangerous. The basic 3-module configuration of the Tiangong space station is completed through space rendezvous, docking, and on-orbit module transfer. As shown in Fig. 5, the assembly-based building process can be divided into the following 5 steps:

1. Step 1: The Tianhe core module is launched, and key technologies for space station assembly are verified in orbit with the cooperation of manned and cargo spaceships.

2. Step 2: The Wentian experiment module is launched to rendezvous and dock with the Tianhe core module at the forward docking hatch so that a line-shaped 2-module assembly is formed.

3. Step 3: Before the launch of the Mengtian experiment module, the Wentian experiment module is transferred in orbit from the forward docking hatch of the Tianhe core module to

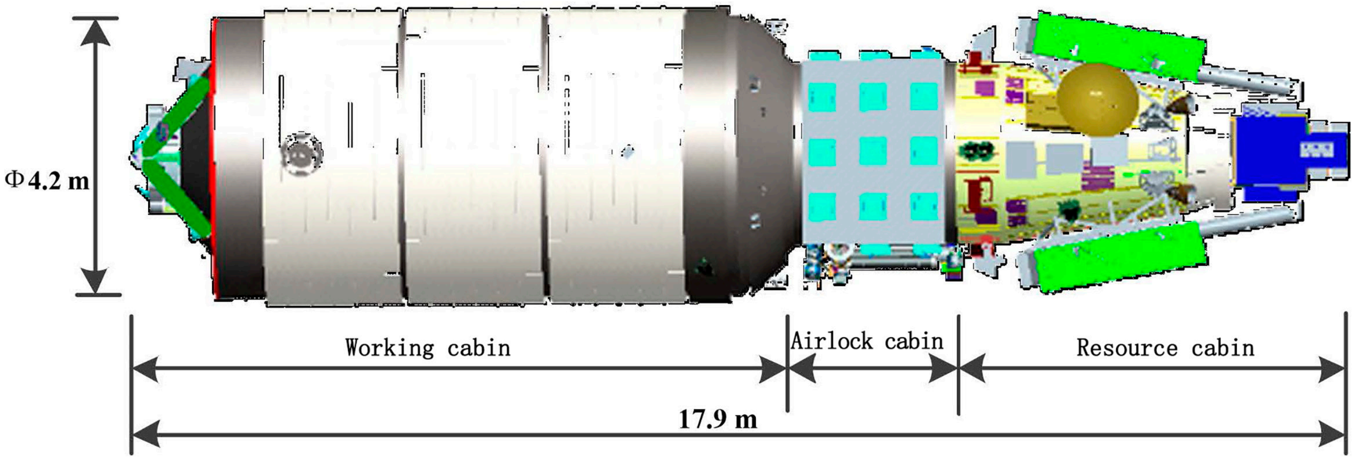


Fig. 3. Configuration diagram of Wentian experiment module.

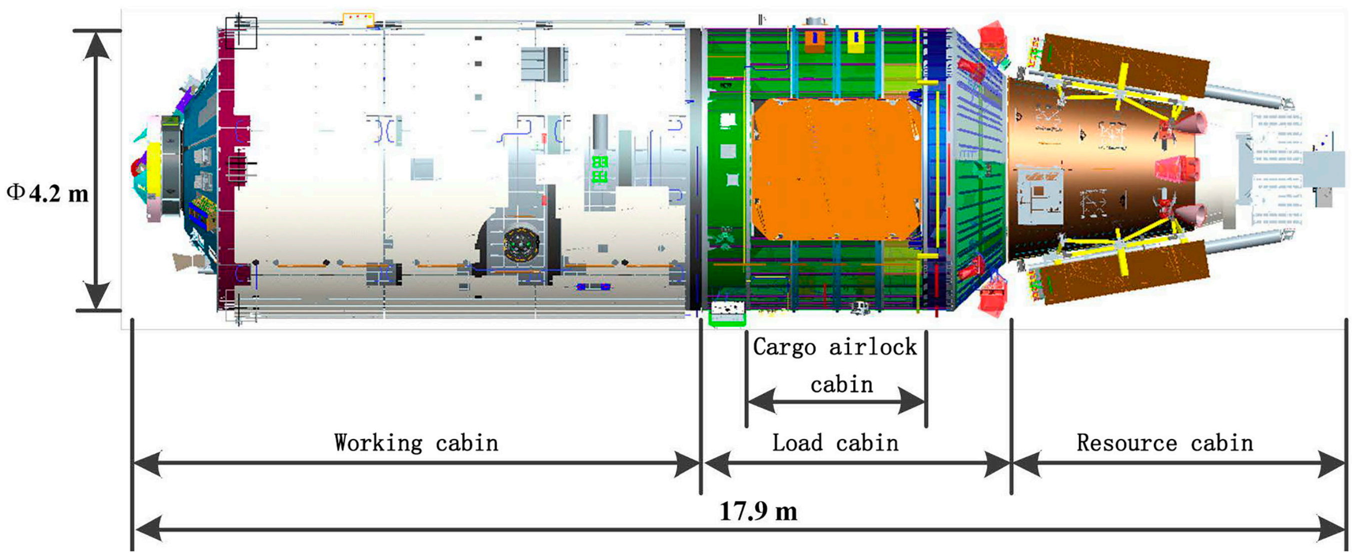


Fig. 4. Configuration diagram of Mengtian experiment module.

the berthing hatch in Quadrant IV so that an L-shaped 2-module assembly is formed.

4. Step 4: The Mengtian experiment module is launched to rendezvous and dock with the Tianhe core module at the forward docking hatch so that a ├-shaped 3-module assembly is formed.

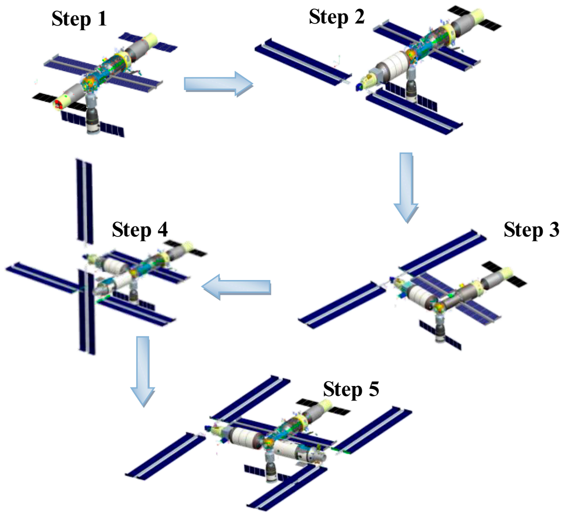
5. Step 5: The Mengtian experiment module is transferred in orbit from the forward docking hatch of the Tianhe core module to the berthing hatch in Quadrant II so that a T-shaped 3-module assembly is formed. In this way, the basic configuration of the Tiangong space station is completed.

System function design

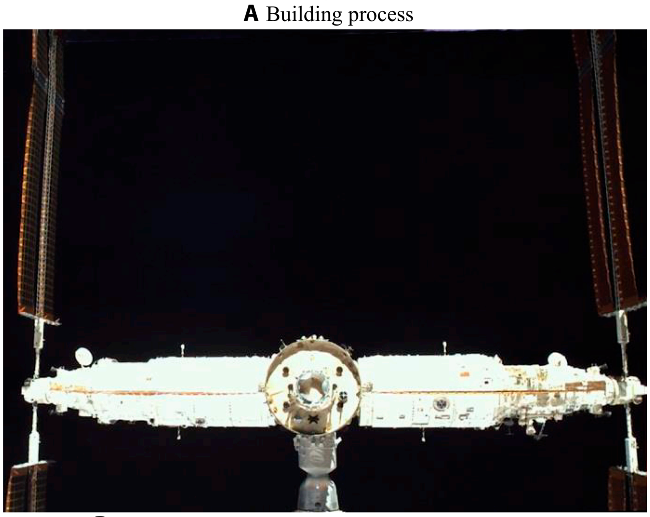
Design of control and propulsion system

The attitudes of the Tiangong space station are controlled by control moment gyros (CMGs) and a reaction control system. For continuously high-precision attitude stability and reduced consumption of attitude control propellants during long-term on-orbit flight, CMG control is mainly adopted, assisted by the reaction control system. With the consideration of module configuration and maintainability, both the Tianhe core module and the Wentian experiment module are equipped with a set of CMGs (6 in each set and thus 12 in total). These CMGs are arranged outside and inside the modules, as shown in Fig. 6. According to specific requirements of different flight attitudes for angular momentum control, the 2 sets of CMGs can be planned to work separately or jointly.

The attitudes of the Tiangong space station are designed in terms of the 3 normal conditions: Earth-oriented flight, inertial flight, and torque-equilibrium forward flight. With full consideration of the power generation efficiency of solar arrays and the consumption of attitude control propellants, a single module and the 2-module assembly mainly adopt the inertial flight attitude, while the 3-module assembly mainly adopts the torque-equilibrium forward flight attitude. Due to its high propellant consumption, the Earth-oriented flight attitude is mainly adopted for specific missions like rendezvous and docking. The Tiangong space station keeps the torque-equilibrium forward flight attitude for a long time, using gravity gradient torque for CMG angular momentum unloading. This can not only avoid the consumption of attitude control propellants caused by thruster jets but also reasonably plan for thruster



A Building process



B Photo of Tiangong space station (on-orbit mission)

Fig. 5. Schematic diagram of assembly of Tiangong space station. (A) Building process. (B) Photo of Tiangong space station (on-orbit mission).

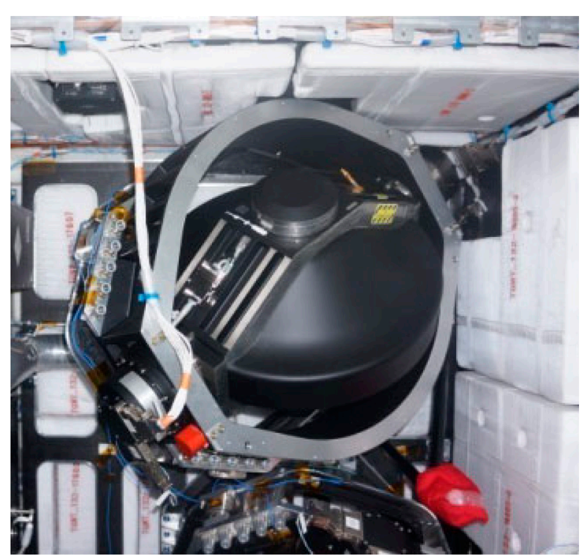
operation to avoid thruster overuse. Simulation analysis and on-orbit verification show that the Tiangong space station has an attitude control accuracy superior to 0.6° and attitude stability superior to 0.008°/s.

Control computers, attitude measurement sensors, rendezvous and docking sensors, CMGs, and thrusters in the modules of the Tiangong space station realize intermodule connection and integrated resource utilization through 1553B buses, which thereby improves system efficiency and reliability. Especially in the case of equipment failure, the space station can still work normally through the integrated use of equipment in the modules and system reconfiguration. Moreover, by connecting its buses with those of a cargo spaceship, the Tiangong space station can select the thrusters of the cargo spaceship to participate in the attitude and orbit control of the whole assembly. This not only improves control and execution efficiency to reduce the propellant consumption of the Tiangong space station but also helps reduce thruster life loss of the space station to prolong service life.

For a long-term on-orbit operation of the Tiangong space station, the Tianhe core module is equipped with a propellant refueling system to receive propellants carried by the Tianzhou cargo spaceship. The refueling system adopts a propellant feeding scheme based on a metal bellows tank and pressurized-gas recycling. It is equipped with a long-life and highly reliable compressor to recycle pressurized gas. Both forward and backward docking mechanisms of the Tianhe core module are equipped with a refueling interface. This ensures propellant refueling to the Tiangong space station by a cargo spaceship at either the forward or the backward docking hatch, thus improving mission reliability. In addition, when a visiting spacecraft, e.g., the Xuntian space telescope, berths at the forward docking hatch of the Tianhe core module, the cargo spaceship berthing at the backward one can provide cross-module propellant refueling services for the Xuntian space telescope or other visiting spacecraft by using the Tiangong space station as a transit node.

The Tianhe core module of the Tiangong space station is also equipped with a medium-power (0.5 to 10 kW) Hall electric

A Outside installation



B Inside installation

Fig. 6. CMGs on Tiangong space station. (A) Outside installation. (B) Inside installation.

Fig. 7. Test images of electric propulsion system.

propulsion system to supplement the chemical propulsion system. The Hall electric propulsion system consists of four 80-mN Hall thrusters and 2 gas-storage modules. The thrusters use xenon as the working medium, and the gas-storage modules can be replaced in orbit by robotic arms. Ground test images of Hall thruster are shown in Fig. 7. This is the first time in the world to use an electric propulsion system to assist in the orbit maintenance of a space station, and it is an important innovation of the Tiangong space station in terms of propulsion technology. In the case of the electric propulsion system out of operation, the orbital altitude of the Tiangong space station decreases by about 30 km within 100 d. In the case of the electric propulsion system in continuous operation, the orbital altitude of the Tiangong space station decreases by about 7 km within 100 d. Using the electric propulsion system can markedly slow down the orbital decay of the space station. Besides, the electric propulsion system can save chemical propellants of not less than 800 kg per year for the Tiangong space station, reducing the supply transportation pressure of cargo spaceship.

Design of energy system

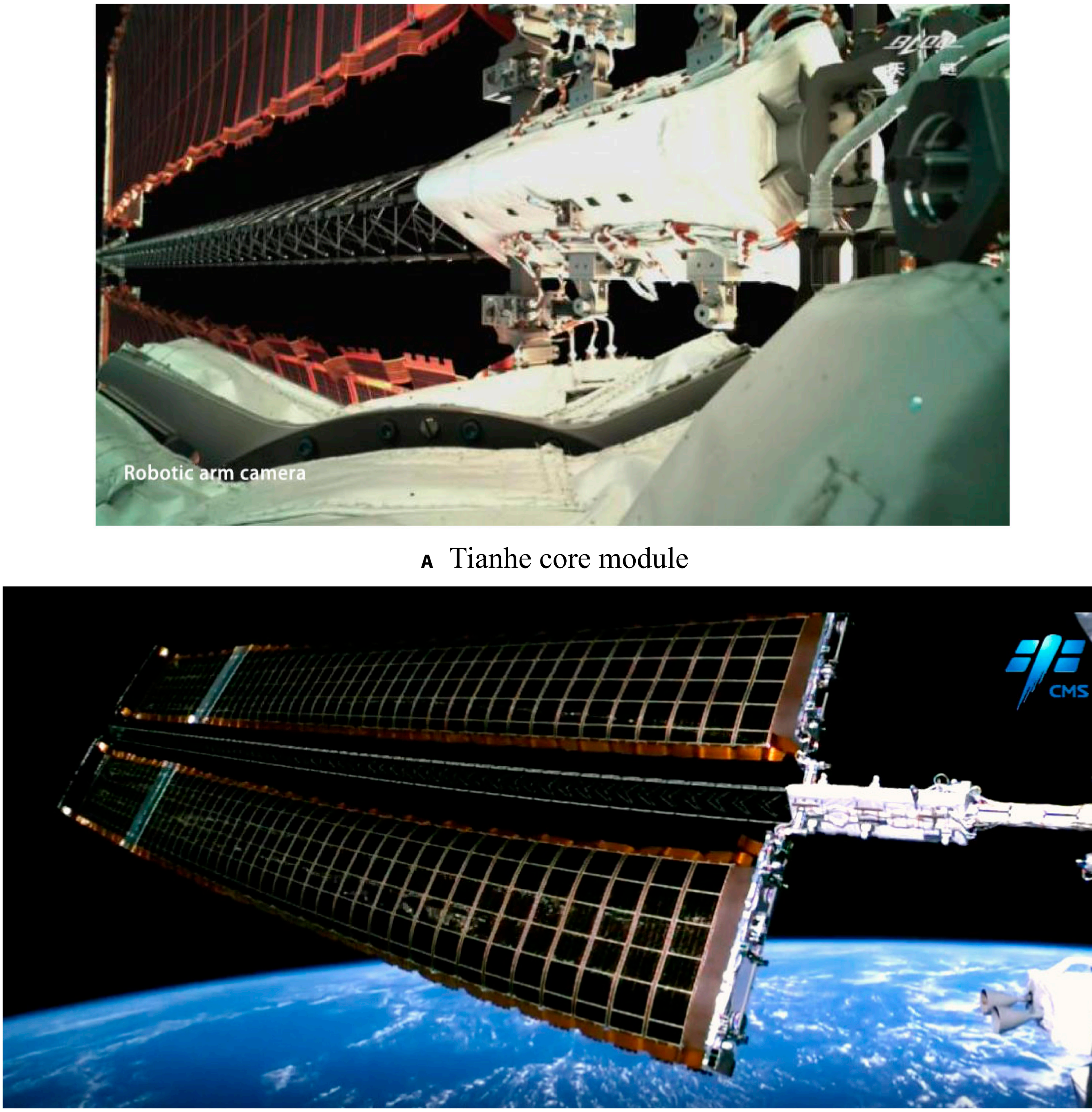
To improve power generation capacity, the Tiangong space station is equipped with a large area of flexible solar arrays (Fig. 8) as power generation equipment, using triple-junction gallium arsenide batteries with a conversion efficiency of 30% and advanced lithium-ion batteries. The solar arrays of the Tianhe core module have a single-sided unfolding length of 12.6 m, driven by a single-degree-of-freedom drive mechanism. The solar arrays of the Wentian and Mengtian experiment modules have a single-sided unfolding length of 27 m, driven by 2-degree-of-freedom drive mechanisms. Solar arrays can be folded and unfolded in orbit and allow on-orbit maintenance and replacement. The Tiangong space station adopts a standard 100-V bus system, supplying power to the modules through grid connection. It can also provide certain power for manned and cargo spaceships berthed. Dynamic energy allocation is available between the 2 experiment modules to support the power consumption of scientific experimental loads in a required module.

After the Tiangong space station completes its T-shaped 3-module configuration, solar arrays of the Tianhe core module are easily blocked by the bodies and solar arrays of the experiment modules, which results in low power generation efficiency. As shown in Fig. 9, the power generation of the whole station can be improved by folding or dismantling the solar arrays of the Tianhe core module and transferring them to the rear parts of the 2 experiment modules. This mission is completed through several extravehicular activities of crewmembers under the joint use of 2 robotic arms. This fully demonstrates the expansion capacity of the Tiangong space station to transfer and reassemble large extravehicular equipment.

Design of manned environment system

Both the Tianhe core module and the Wentian experiment module are equipped with complete regenerative and nonregenerative life-support systems, while the Mengtian experiment module is equipped with a simplified nonregenerative life-support system. The regenerative life-support system of the core module is responsible for the manned environment control of the whole station, assisted by the nonregenerative system. The regenerative life-support system of the Wentian experiment module is used as the system-level backup of manned environment control.

The regenerative life-support systems of the Tiangong space station are based on physicochemical regeneration [11], including 6 subsystems: oxygen generation assembly, CO_2 removal assembly, trace contaminant removal assembly, water processing assembly, urine processing assembly, and CO_2 reduction assembly. The oxygen generation assembly provides oxygen necessary for the crew's lives. CO_2 produced by human bodies is adsorbed by regenerative adsorbents and then subjected to vacuum thermal desorption by extravehicular space [12]. Different trace contaminants are removed by chemical absorption, physical adsorption, room-temperature catalytic oxidation, and high-temperature catalytic oxidation [13]. Regenerative adsorption equipment discharges most of the trace contaminants out of modules through vacuum thermal desorption, realizing adsorbent regeneration. Human urine is distilled by the urine processing assembly to produce urine-distilled water, which together with condensed water collected from a module is then processed by the water processing assembly. Water quality can meet the requirements of drinking water in aerospace medicine and water for oxygen generation assembly. Through the CO_2 reduction assembly,



A Tianhe core module

B Wentian experiment module

Fig. 8. Solar arrays on Tiangong space station (on-orbit mission). (A) Tianhe core module. (B) Wentian experiment module.

the CO_2 collected and concentrated from the CO_2 removal assembly reacts with H_2, a by-product of oxygen generation assembly, to form CH_4 and water. The water is further purified by the water processing assembly to supplement the crew's drinking water, improving the material close loop of life support system. According to the comprehensive evaluation of on-orbit data, oxygen and water are basically no longer dependent on ground support, greatly reducing the supply transportation pressure of the cargo spaceship.

Design of robotic arms

One large 7-degree-of-freedom robotic arm is mounted on the Tianhe core module with an operating radius of 10 m and a maximum load of 25 tons. In addition, 1 small 7-degree-of-freedom robotic arm is mounted on the Wentian experiment module with an operating radius of 5 m and a maximum load of 3 tons. Both robotic arms are equipped with rich sensors of visual measurement, joint torque, and end-effector force. As shown in Fig. 10, they can be used independently or jointly

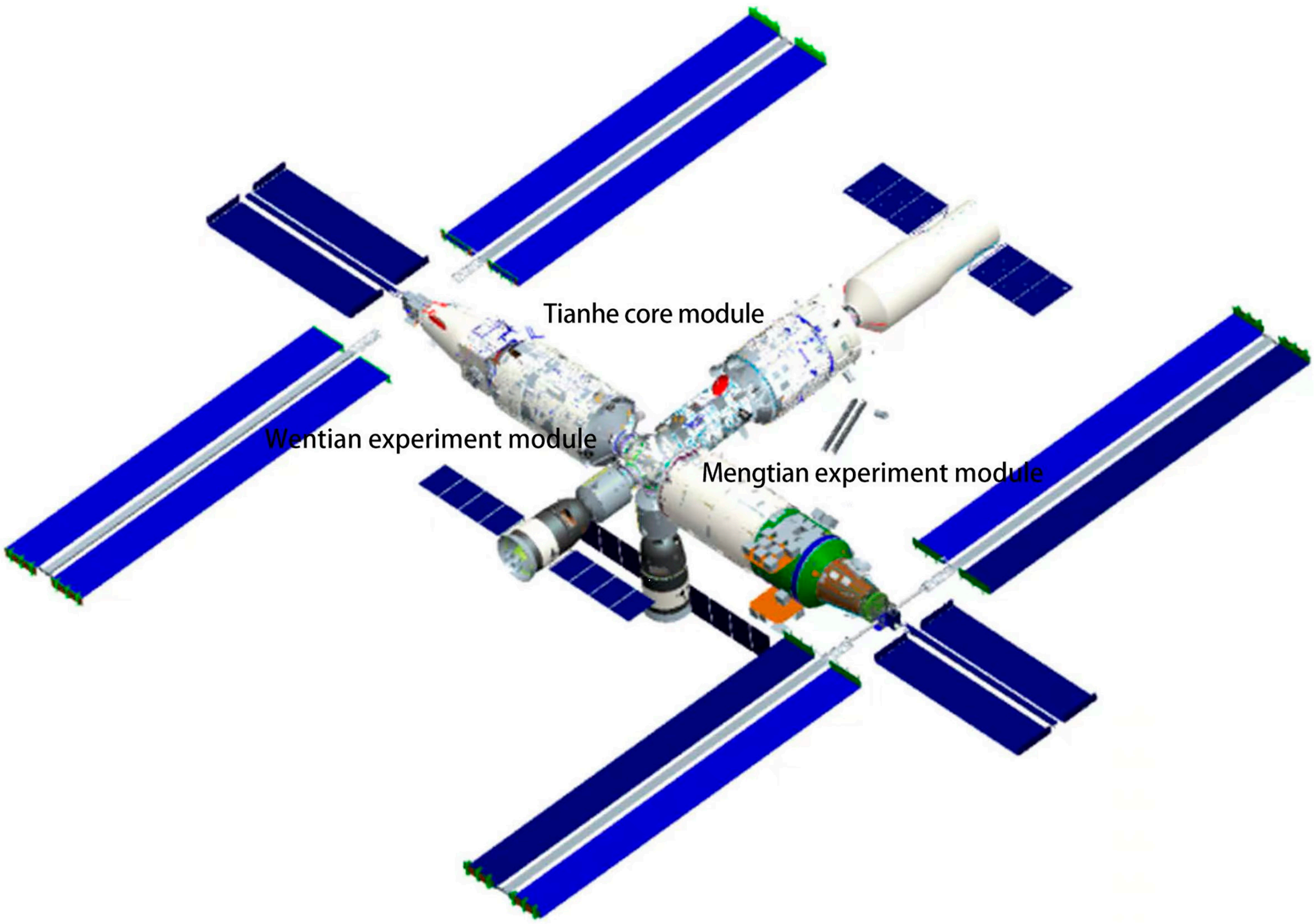


Fig. 9. Configuration after transfer and reinstallation of solar arrays of Tianhe core module.

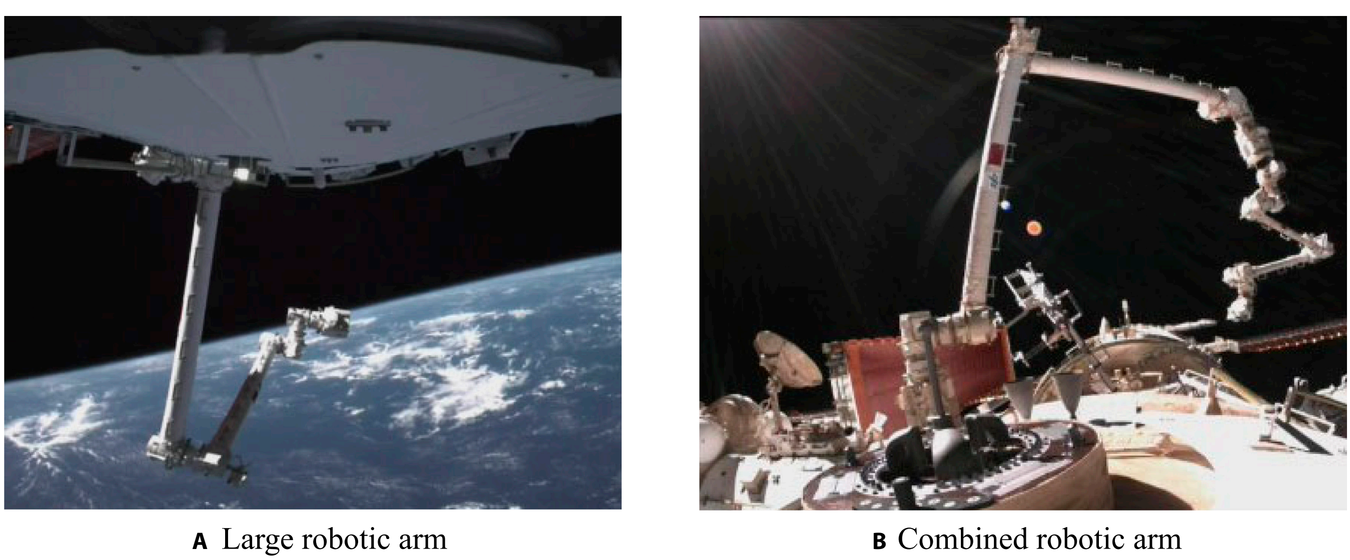


Fig. 10. Robotic arm of Tiangong space station (on-orbit mission). (A) Large robotic arm. (B) Combined robotic arm.

for complex on-orbit missions such as module transfer, extravehicular activity assistance, extravehicular cargo transfer, exposed load operation, and the capture of visiting spacecraft [14]. The large robotic arm is mainly responsible for the large-range transfer of large loads, while the small one is mainly for the fine operation of small loads. The combination of them is used for the large-range operation of astronauts or exposed loads. After the combination, the operating radius can reach 15 m.

Both large and small robotic arms are capable of relocation. Vividly, these robotic arms can "crawl" with a head–tail swap. Several robotic arm adapters are installed on the surface of the Tiangong space station. With the help of these adapters, the 2 robotic arms can move flexibly on module surfaces, which greatly improves mission flexibility and extends movement range.

Design of extravehicular activities

Extravehicular activities are necessary means to ensure long-term reliable operation of the space station, complete extravehicular assembly and other work, and perform exposed load operation. Both the node cabin of the Tianhe core module and the airlock cabin of the Wentian experiment module support the extravehicular activities of crewmembers. During the flight of the core module alone, the node cabin is used as the airlock for spacewalks. After Wentian experiment module docking with the core module, the special airlock cabin is used for this purpose, while the node cabin is a backup (Fig. 11). In addition, equipment installed outside the space station (including exposed loads) can emerge through the cargo airlock cabin of the Mengtian experiment module automatically (Fig. 12). This function effectively reduces the number of spacewalks of crewmembers, improving the efficiency of extravehicular operations and further ensuring the safety of crewmembers.

Design for crew's residence

According to the design concept of habitability, the Tiangong space station provides rich living and working support for the crew with an activity space of no less than 110 m^3. As the main place for living and working of the crew, the Tianhe core module is equipped with complete functions for the crew's residence, including a working area, a sleeping area, a sanitary area, a dining area, a storage area, a health supervision and care area, and an exercise area. As an experiment, exercise, and residence place for the crew, the Wentian experiment module mainly provides working support and partially living support. It is equipped with a working area, a storage area, a sleeping area, a sanitary area, a temporary dining area, and an exercise area. The Mengtian experiment module is mainly to carry out extravehicular space science and application experiments and intravehicular load experiments. It is equipped with a working area, an exercise area, and a storage area. Figure 13 shows the scenes of the crew exercising in the Tianhe core module and the Wentian experiment module.

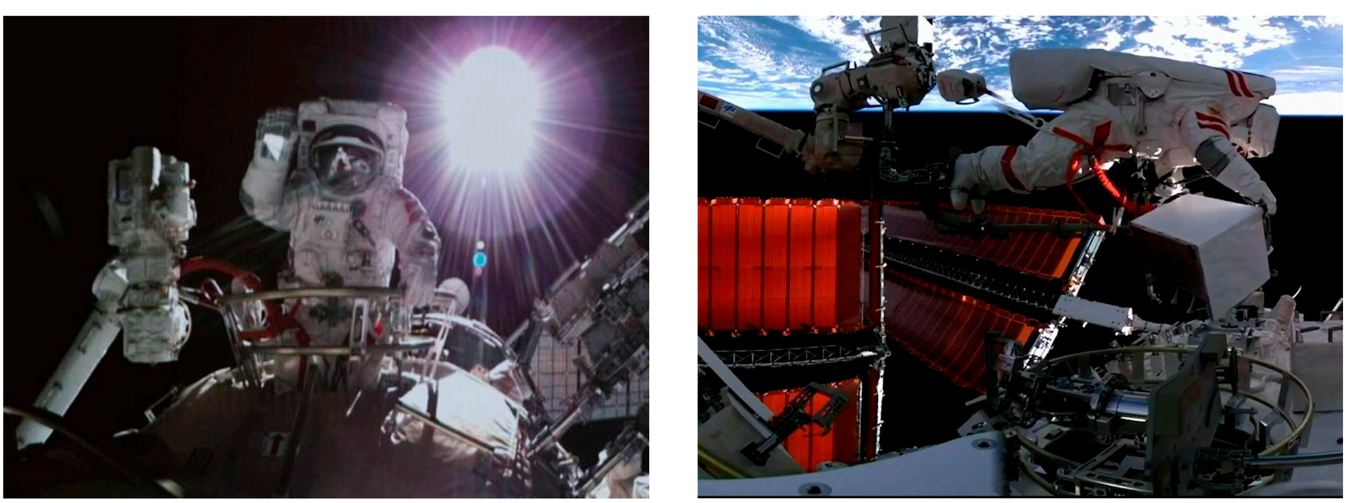
For the mental and physical health of the crew, the Tiangong space station is designed with a cozy and comfortable color atmosphere. The color of the aisle is designed with a warm tone of white dots (Fig. 14). As the exits for extravehicular activities, node and airlock cabins are light gray with high brightness. The brightness and color of lights in the space station can be manually adjusted as required. According to the need of the crew's on-orbit activities, signs for regional positioning, direction indication, cabin indication, operation instruction, and warning are uniformly designed to provide effective action information for the crew so that on-orbit working efficiency can be improved. Each cabin is equipped with body assist equipment such as handrails and body-limiting devices to provide auxiliary support for the crew. After 3 astronauts of Shenzhou-15 crew entered the Tiangong space station and met with Shenzhou-14 crew, a historic gathering that added the manpower at the Tiangong space station to 6 for the first time. The 2 crews conducted an in-orbit rotation and stayed together for about 5 d.

Technical Characteristics of Advanced Nature

Generally, the technical characteristics of the Tiangong space station are mainly reflected in the 4 aspects: the advanced design concept, the high proportion of new technology, the excellent cost-effectiveness ratio, and safe and efficient residence.

Advanced design concept and optimized system framework

The joint development of the International Space Station by different countries has brought about such problems as inconsistent technical systems and low overall optimization, resulting in the incompatibility of many intersystem and intermodule functions [15,16]. For example, the Russian module that can receive propellant refueling uses unsymmetrical dimethylhydrazine as the fuel, while European automated transfer vehicles use monomethylhydrazine as the fuel. As a result, to refuel the Russian module, an automated transfer vehicle needs to carry unsymmetrical



A Emerge through the node cabin **B** Emerge through the airlock cabin

Fig. 11. Crewmember emerges through airlock (on-orbit mission). (A) Emerge through the node cabin. (B) Emerge through the airlock cabin.

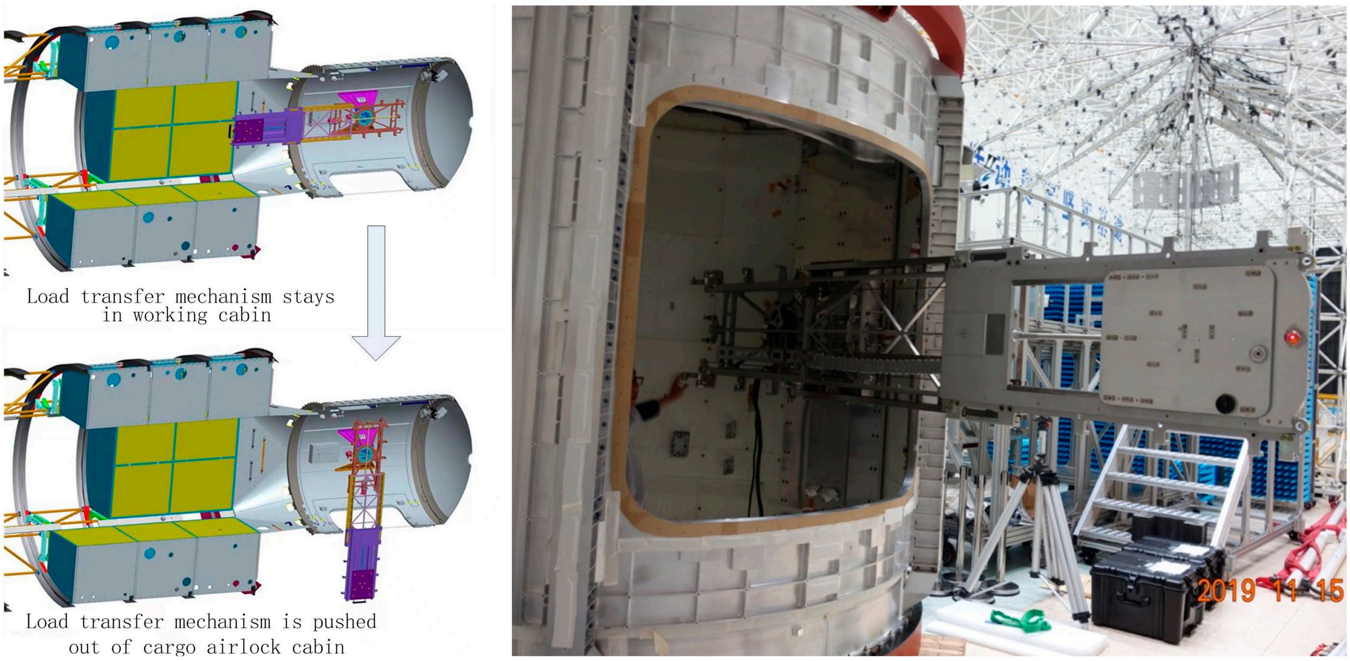


Fig. 12. Special airlock cabin for cargo.

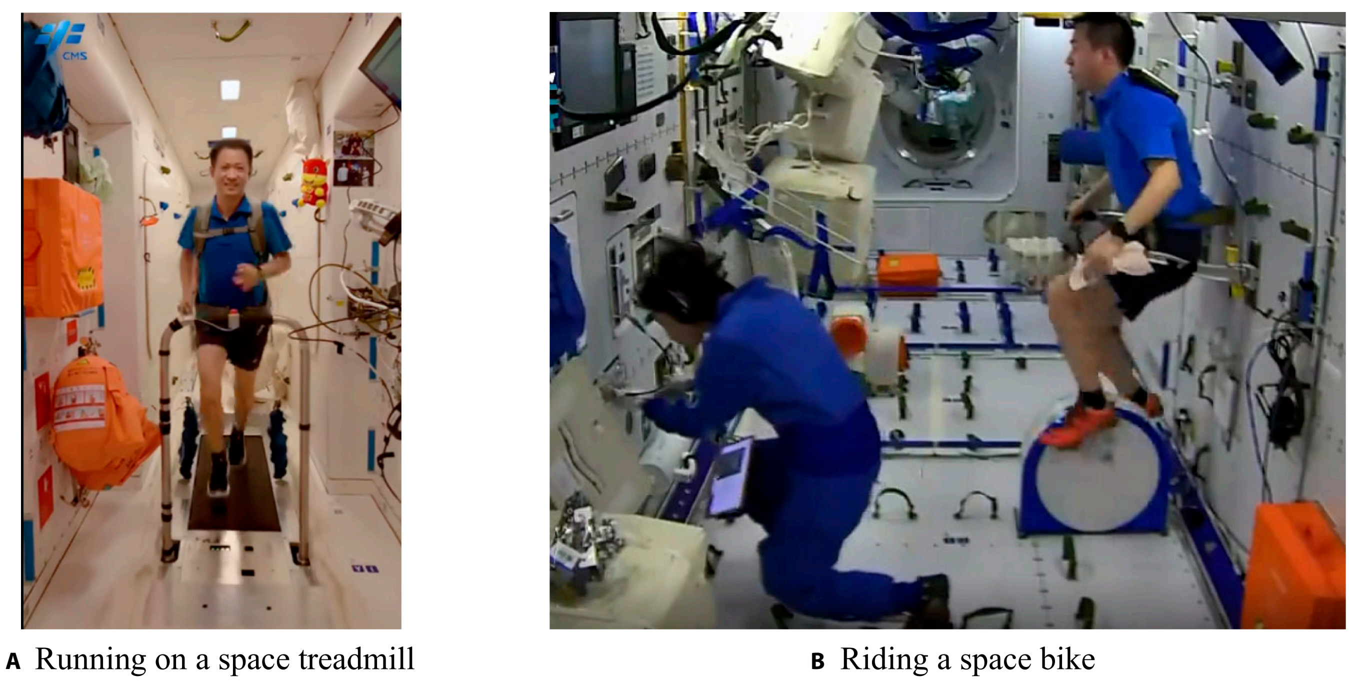


Fig. 13. On-orbit exercise of the crew (on-orbit mission). (A) Running on a space treadmill. (B) Riding a space bike.

dimethylhydrazine additionally. The Russian module uses ethylene glycol as the loop working medium for its thermal control system, while the US module uses water. As a result, the fluid loops of the 2 modules cannot be connected.

Giving full play to the advantages of independent development, China adopts a unified design framework and technical system for the Tiangong space station. After the top-level design of mission functions and flight modes, the index system for the 5 functional systems of guidance, navigation, and control (GNC), energy, information, thermal control, and manned environment is uniformly decomposed for the 3 modules to ensure the coordinated matching of intermodule interfaces. At the implementation level, all subsystems adopt the same development specifications to uniformly formulate normative technical documents such as the selection requirements of components, raw materials, and general-purpose computers. Subsystems formulate the norms of supporting products in view of the functions of the 3 modules, with a product generalization rate reaching more than 80%. After being assembled, the 3 originally independent modules are integrated. Under the unified management of the Tianhe core module, the GNC, energy, information, thermal control, and manned environment

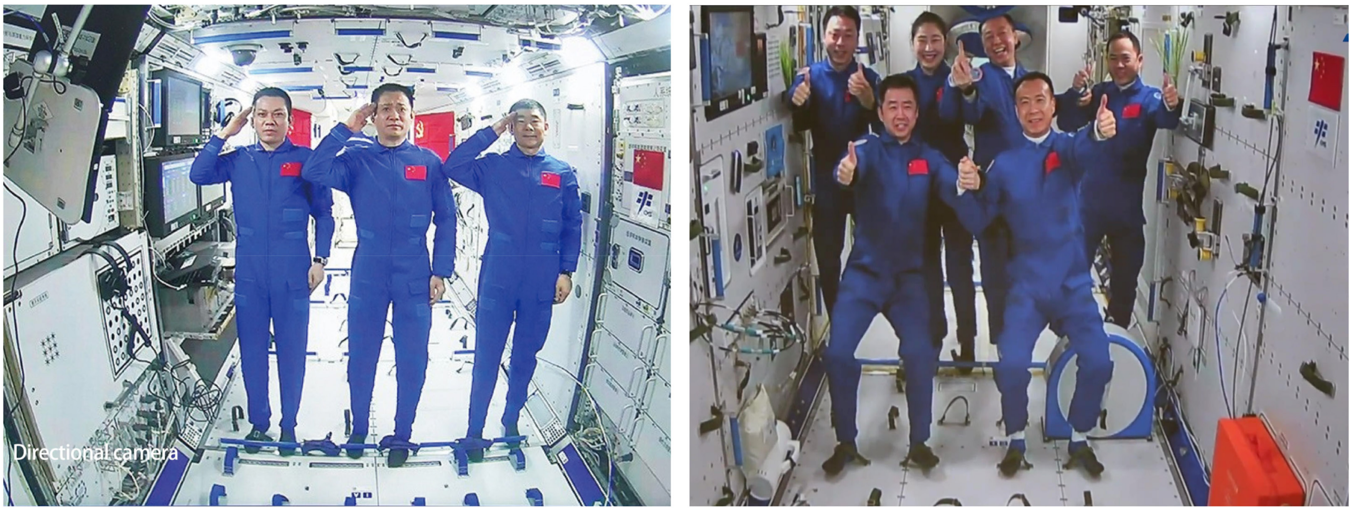


Fig. 14. On-orbit residence of the crew (on-orbit mission).

systems of all the 3 modules will be interconnected to work together. For example, during intermodule kilowatt-level power readjustment, intermodule thermal control fluid loops can be connected for cross-module kilowatt-level heat transfer to balance the heat dissipation capacity of thermal control radiators in the modules.

Besides, fully using advanced information network technology that develops rapidly, the space station integrates intermodule resources efficiently, thus improving its overall capacity and system reliability. For example, when the control, energy, information, or manned environment system of the Tianhe core module works abnormally and fails to be repaired in a short time, the Tiangong space station can automatically switch control right to the Wentian experiment module to ensure the reliable execution of on-orbit missions. In addition, the technical system of the Tiangong space station is also consistent with those of the Shenzhou manned spaceship and Tianzhou cargo spaceship. This makes the Shenzhou manned spaceship and the Tianzhou cargo spaceship able to form an organic whole with the Tiangong space station after docking and thus participate in the management of the assembly. For example, the computers of the Tiangong space station can control the thrusters of the Tianzhou cargo spaceship for orbit and attitude control of the assembly and can also realize data downlink at hundreds of megabytes per second through relay antennas of the Tianzhou cargo spaceship. The Tiangong space station can not only supply power to visiting spacecraft like the Shenzhou manned spaceship, the Tianzhou cargo spaceship, and the Xuntian space telescope through grid connection but also receive power supply from the Tianzhou cargo spaceship. This space station can provide thermal support for the Shenzhou manned spaceship and also receive dehumidification support from equipment in the Shenzhou spaceship.

High proportion of new technology and high degree of intelligence

On the basis of breakthroughs in rendezvous and docking technology during the space laboratory stage, with sufficient verification by ground tests, China introduces new technology to build the Tiangong space station through assembly, embarking on a steady road of leapfrog development. A high proportion of new technology is a prominent feature of the Tiangong space station. Space robotic arms, physicochemically regenerative life support, and the large-area flexible solar arrays of this space station are all brand-new technologies applied in orbit for the first time in China with high application difficulty and development risk.

The high proportion of new technology is also a concrete embodiment of China fully using its late-mover advantages to build the Tiangong space station with new technology. Profiting from the rapid development of information technology in recent years, the Tiangong space station can enhance its platform capability with advanced information network technology. The transmission rates of space–Earth links based on the second-generation relay satellites in China reach up to 1.2 Gbps, twice those of the International Space Station. A service system is directly provided for scientific experiment loads through high-speed Ethernet. This can not only meet the high performance requirements of load data transmission but also provide a great convenience for transferring ground technology to on-orbit spacecraft.

The Tiangong space station embodies a high degree of intelligence from both equipment and system levels. For example, by setting a wireless Wi-Fi network and a voice and image system, the crew can use smartphones and tablet computers to manage their household supplies and on-orbit materials intelligently. The whole space station is equipped with a pressure leakage detection system. In the case of sealed module depressurization, the detection system automatically alarms and reminds the crew to take measures such as leakage plugging and isolation according to depressurization levels. In the case of major emergency failures such as the decline of power supply capacity, propellant leakage, and radiator leakage in the space station, the high-performance computer system can be used to diagnose failures autonomously and isolate danger sources automatically for safe disposal.

In view of risks brought by the application of new technology to on-orbit missions, an on-orbit verification stage of key technology was arranged after the launch of the Tianhe core module of the Tiangong space station into orbit, lasting about 1 year. With the cooperation of the Shenzhou manned spaceship and the Tianzhou cargo spaceship, the Tianhe core module was used to verify in orbit the key technologies of subsequent space station assembly comprehensively. In particular, key technologies that have great space–Earth differences and fail to be fully verified by ground tests were verified in orbit. The main limitation of ground test is about the effect of microgravity. Taking space robotic arm for example, the motion of space manipulator is typically 3-dimensional (3D), but the ground test can only verify its 2-dimensional characteristics by air-floating platform. The 3D motion is supplemented by simulation. After the motion and calibration test in orbit, the control performance and operating accuracy are confirmed finally. After the on-orbit verification of the key technologies, decisions were made to implement subsequent formal assembly missions of the Tiangong space station to ensure reliable assembly.

Moderate scale and excellent cost-effectiveness ratio

The 3 modules of the Tiangong space station weigh about 69 tons in total. Compared with the Mir space station of about 123 tons and the International Space Station of about 423 tons, the Tiangong space station is of a relatively small scale. However, this is a rational choice in line with China's national conditions and practical needs in terms of building costs and application benefits. With an overall unified optimized design, the completed Tiangong space station will reach the contemporary international advanced level in terms of GNC, information, energy, resource recycling, material supply, operating costs, and application benefits. Moreover, it will be superior in some aspects, having more economical and reasonable construction and operation.

1. Power generation efficiency

The energy system of the Tiangong space station has reached the international advanced level in terms of load support power and unit mass power density. The 50 kW of 110 kW generated by the International Space Station is supplied to application loads, accounting for 45% of the total power. With a power supply index of 27 kW, the Tiangong space station supplies 17 kW to application loads, which accounts for 63% of the total. Moreover, the power-to-weight ratio of the Tiangong space station is 0.41 kW/ton, exceeding 0.26 kW/ton of the International Space Station.

2. Application support capability

Intravehicular test support facilities in the Tiangong space station are similar to those in the International Space Station. Adopting standardized mechanical, electrical, thermal, and information guarantee conditions, the Tiangong space station enables experiments on aerospace medicine, life and biological science, space material science, space physics, and new space technology [17,18]. A total of 25 experiment cabinets are installed in the Tiangong space station, while 31 experiment cabinets of about the same size are installed in the International Space Station. The Tiangong space station with a weight of about one-sixth of that of the International Space Station provides about four-fifths of the experiment cabinets of the International Space Station. This indicates that the Tiangong space station has high application support efficiency [19,20].

The Tiangong space station has a strong capability to support extravehicular application loads. In contrast, the Mir space station has no separate extravehicular test platform, while the International Space Station has an extravehicular test platform on the Japanese experiment module Hope. With the independent support of the small robotic arm on the Japanese module, the International Space Station supports the care of 12 exposed loads. The Tiangong space station arranges fixed and deployable exposure platforms on Wentian and Mengtian experiment modules, respectively (Fig. 15), supporting 67 standard exposed loads. The combination of 2 robotic arms with the special cargo airlock cabin enables the Tiangong space station to operate exposed loads with high efficiency.

Overall, the Tiangong space station has a load support capacity of not less than 21 tons, which is less than 33.5 tons

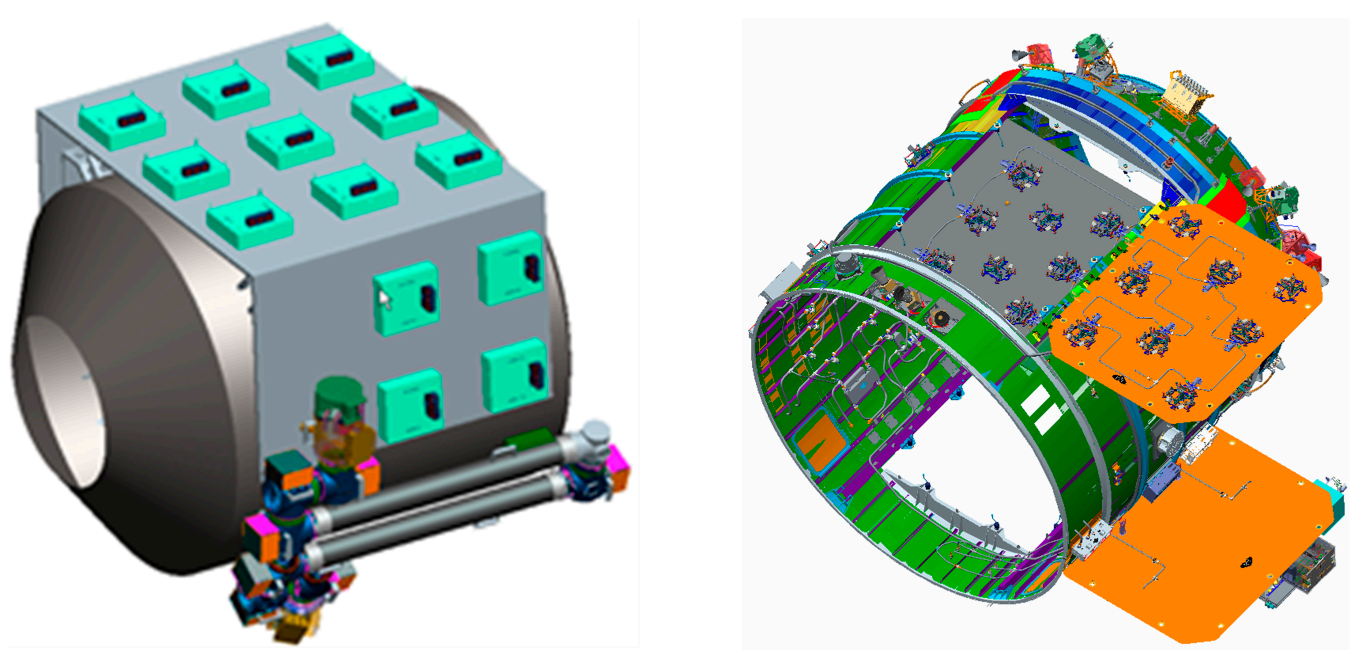


Fig. 15. Fixed and deployable exposure platforms.

of the International Space Station. However, its load-to-weight ratio is up to 30.6%, much higher than 7.93% of the International Space Station.

Besides its conventional application support capabilities mentioned above, the Tiangong space station also has a high-level on-orbit service capability, able to support future human-involved on-orbit assembly and application of space facilities. In addition, the Tiangong space station can be used as a prior verification platform for key technologies of manned deep space exploration in the future. Related key technologies can be verified in orbit by existing application load support facilities or newly built special ones to effectively reduce technical risks in the implementation of manned deep space exploration missions.

3. Building ways

The space stations of other countries are mainly built in 2 ways. One way is to send modules into orbit by carrier rockets and then assemble them through direct rendezvous, docking, and on-orbit transposition. It features a simple building process and a low cost. The Mir space station is representative of this building method. The other way is to ferry modules into orbit by space shuttles and then assemble them under the cooperation between a large robotic arm and crewmembers in a spacewalk. It features a flexible building process but a high cost and operating risk. The International Space Station is representative of this building method for the integration of non-Russian space modules. The Tiangong space station is built in a more optimized way, comprehensively using the above 2 methods. Rendezvous, docking, and on-orbit transposition can be used for module assembly. Robotic arms can be used to capture the hovering visiting spacecraft for extended assembly. In addition, large extravehicular equipment such as flexible solar arrays and large exposed loads can be transferred and installed through the operations of robotic arms and extravehicular activities of crewmembers.

4. Replenishment demand

The Mir space station had a crew of 3 for long-term residence, requiring an average annual supply of 2 manned spaceships and 4 cargo spaceships, with supplied materials being 16 tons in total. There are 6 crewmembers for long-term residence in the International Space Station, who require an average annual supply of 4 manned spaceships and 8 cargo spaceships, with supplied materials being about 30 to 40 tons in total [21]. During its operation, the Tiangong space station will have a crew of 3 for long-time residence, requiring an average annual supply of about 2 manned spaceship and 2 cargo spaceships, with supplied materials being about 12 tons. Overall, the Tiangong space station has a moderate replenishment scale required for its operation. This replenishment scale is consistent with the overall scale and capacity of the space station, reflecting that it is economical. In addition, the successful application of electric propulsion in the Tiangong space station will also help

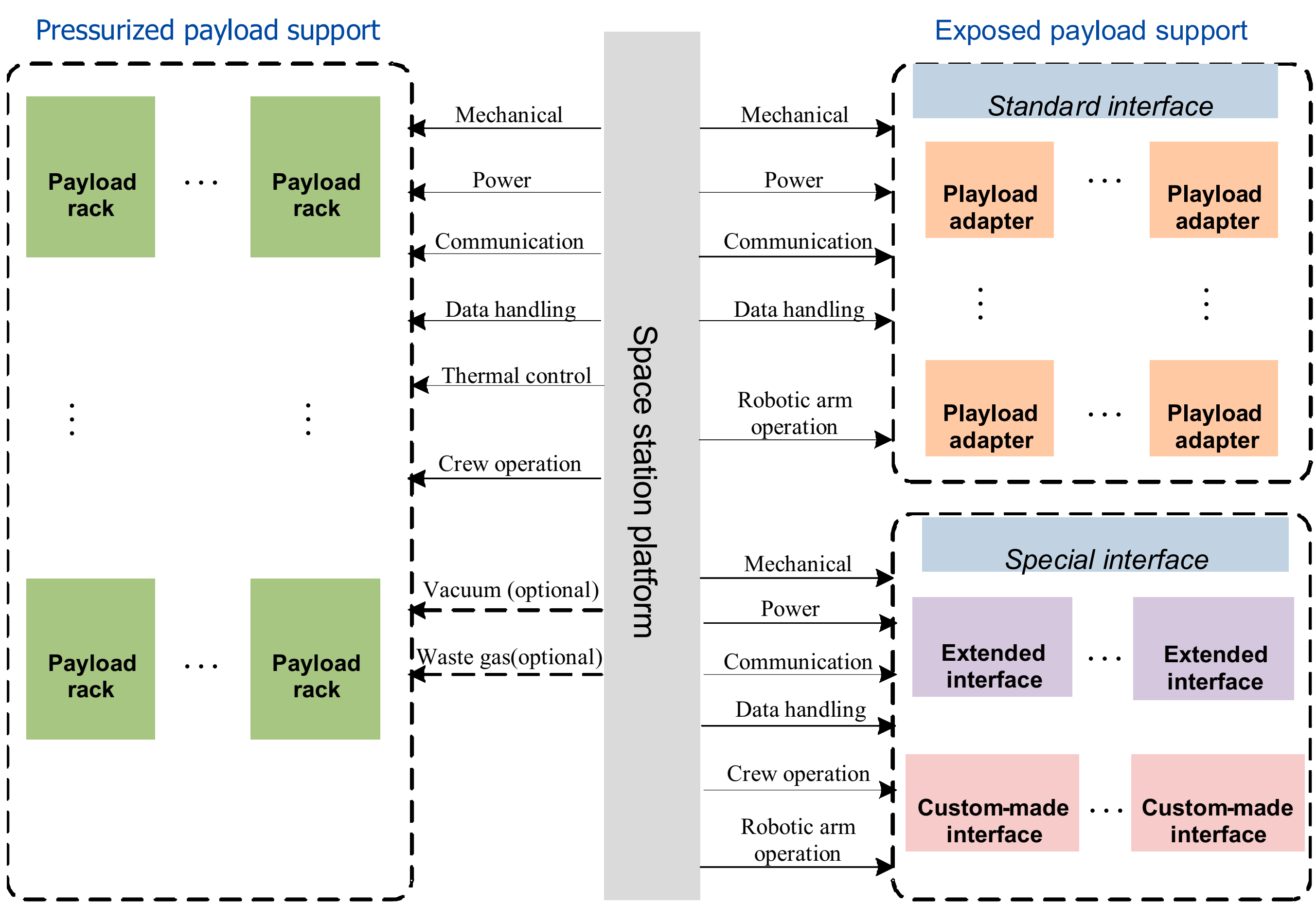


Fig. 16. Systematic framework of experiment support system.

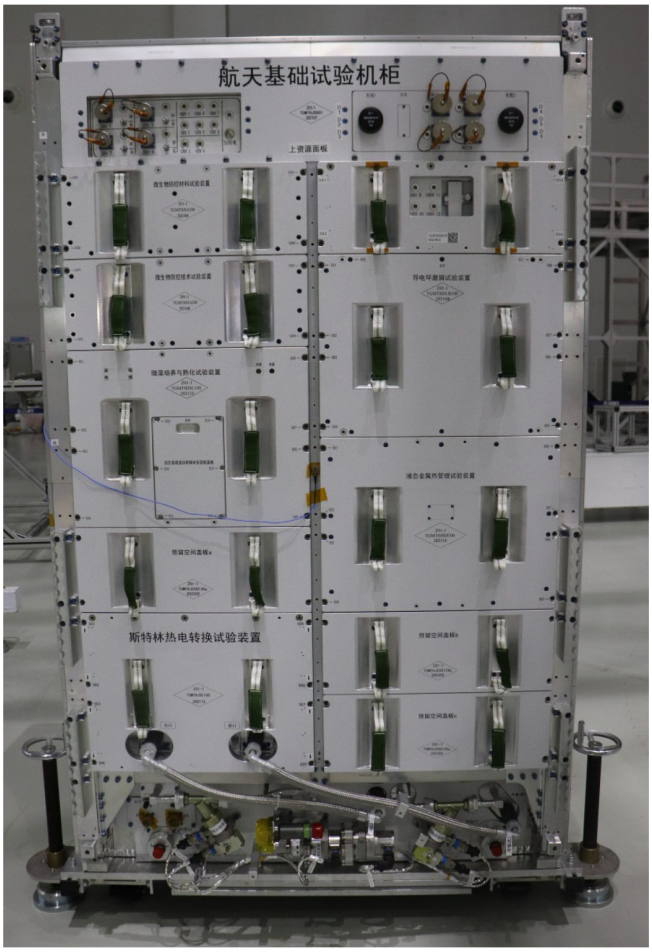


Fig. 17. Basic space experiment cabinet of Tiangong space station.

reduce the replenishment demand for propellants during long-term operation.

Human-oriented design for safe and efficient residence

The Tiangong space station is designed in line with the human-oriented concept. The design not only ensures the safety and comfort of the crew in orbit but also focuses on supporting the effective exertion by the crew's intelligence. For example, the astronauts actively check the condensation situations around the area of cryogenic inner loop and provide timely feedback on the improvement of space station. This fully reflects the unique role of human beings in the building and operation of the space station.

In terms of residence safety, by taking advantage of its characteristics of multiple modules and spaceships and fully leveraging system reconfiguration and redundant design, the Tiangong space station ensures the on-orbit safety of its crew according to the principle of "ensuring mission continuity in the case of single failure and on-orbit safety in the case of double failure". Specifically, in normal cases, the Tianhe core module serves as the control and management center for the unified control of the whole space station. In the case of a failure in this module, its control and management function can be transferred automatically to the Wentian experiment module through module reconfiguration to ensure safe, reliable, and continuous work of the whole space station under the failure of 1 module. The Wentian experiment module is equipped with a complete regenerative life-support system and emergency materials. Thus, in the case of fire or depressurization in the Tianhe core module, the crew can live in the Wentian experiment module for a long time, waiting for fault disposal and rescue. If the Wentian experiment module also fails and cannot be repaired in a short time, the space station can support the crew in safe evacuation to a manned spaceship to return to the ground in a proper time.

In terms of the safety of crewmembers' extravehicular activities, the Tiangong space station not only has a primary airlock cabin configured in the Wentian experiment module but also uses the node cabin of the Tianhe core module as a backup airlock cabin. If the primary airlock cabin fails during crewmembers' spacewalks, the crewmembers can enter the space station through the node cabin to ensure safe and reliable extravehicular activities.

To support high-efficiency on-orbit work of the crew and give full play to the unique role of humans in building and operating manned space stations, the Tiangong space station has been well designed in supporting on-orbit operations of the crew. For example, to support efficient cooperation between crewmembers and robotic arms, the Tianhe core module is equipped with a console inside, through which the robotic arms can be controlled by the crewmembers to adjust extravehicular activity points and conduct an on-orbit inspection. For the on-orbit maintenance of equipment by crewmembers, repairable and replaceable equipment of the Tiangong space station is specially designed according to the ergonomic requirements of crewmembers' on-orbit operations. In addition, on-orbit maintenance tools with full functions are provided for maintenance assistance. For supporting crewmembers' extravehicular activities, the Tiangong space station has been comprehensively optimized from the aspects of communication, lighting, image display, assistance setting, and indicative marking to ensure safe and efficient extravehicular activities.

Prospect for Subsequent Applications

The Tiangong space station is expected to have an on-orbit operation of more than 10 years after its completion, serving as a national space lab for human-involved scientific exploration and technological innovation. Herein, we provide an outlook on the subsequent applications and development of the Tiangong space station in terms of scientific and technological experiments, on-orbit services, technology upgrading, extended building, and international cooperation.

Scientific and technological experiments

During the on-orbit operation of the Tiangong space station, various scientific and technological experiments will be conducted continuously by extravehicular and intravehicular experiment support facilities. The main research interests include space medicine, space life science and biotechnology, space astronomy and astrophysics, microgravity fluid physics and combustion science, space material science, basic microgravity physics, space geoscience and applications, space environment and physics, new space technology, space-based information technology, and space parts and components [22,23]. The Tiangong space station can give full play to its advantages of large scale, manned operation, expandable capacity, upgradeable experiment facilities, replaceable loads, and iterable

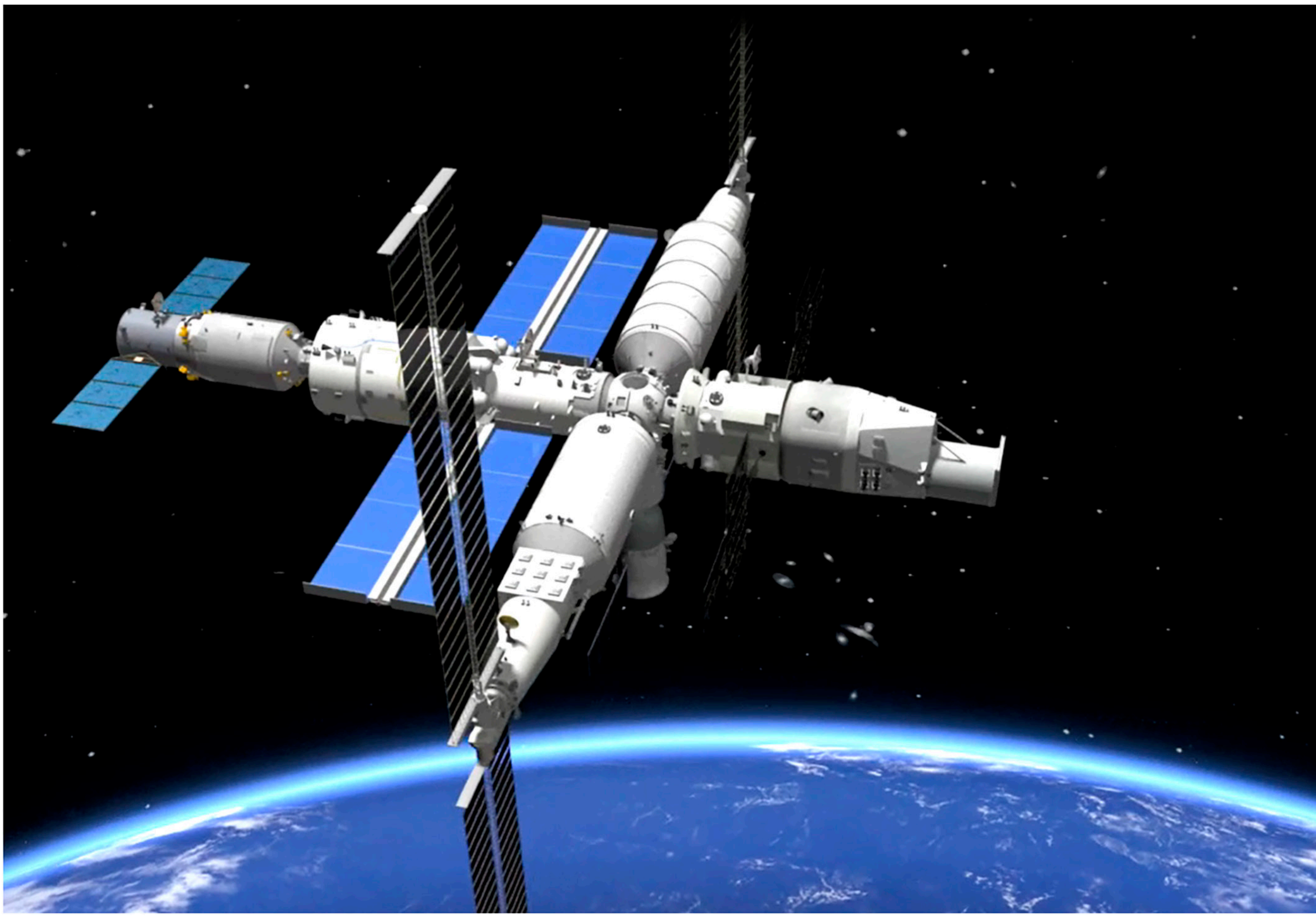


Fig. 18. Assembly of Tiangong space station and Xuntian space telescope.

experiments to continuously promote the innovative development of space science and technology in China. Moreover, the popularization, application, transfer, and transformation of space scientific and technological achievements can drive technological reform and upgrading of related industries, which will contribute to the high-quality development of the national economy and the enhancement of national competitiveness. For effective on-orbit scientific and technological experiments on the Tiangong space station, in addition to professional astronauts, payload specialists in related fields will be sent to the space station, using experiment facilities there to conduct scientific and technological research.

The experiment support system serves payloads with both standard interfaces and special interfaces. The standard interfaces are majority to provide payload uniform mechanism, electric power, communication and data handling, and thermal control, whereas the special interfaces are minority to provide unique resources to payloads. Special interfaces could be designed due to the demand of payloads. In this view, payloads can be classified into 3 categories: pressurized payload, standard exposed payload, and special exposed payload. The systematic framework of experiment support system is shown in Fig. 16.

1. The basic accommodation of pressurized payloads is payload rack (PR), shown in Fig. 17, which provides payload standard interface in terms of mechanisms, power, communication, as well as thermal control. The pressurized payload is packed into united module named payload unit. Crew can operate and replace payload units in-orbit repeatedly.

2. The basic accommodation of standard exposed payloads is payload adapter, which provides standard interface (mechanism, power, communication, and data handling). Robotic arms operate the payload, which enables the assembling/disassembling of exposed payload by payload adapter automatically.

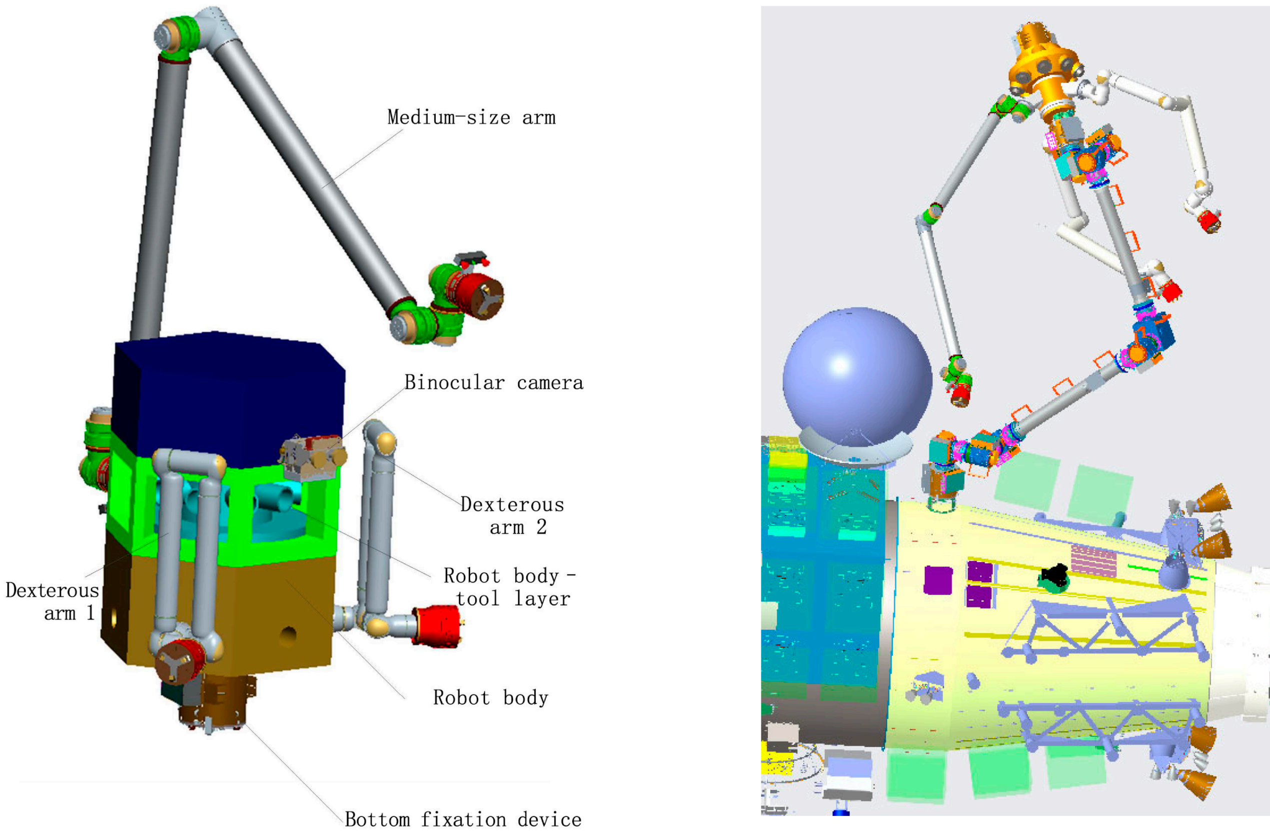
3. The accommodation of special exposed payloads is custom-made or extended interface. Special exposed payload fixed on custom-made interface will be launched by a cargo spaceship. In addition, extended interface reserved on the Wentian experiment module and Tianhe Core module can support special exposed payload assembling in-orbit.

On-orbit service

The Tiangong space station can be used as an on-orbit service platform of a low-Earth orbit, providing on-orbit services of co-orbital motion and on-orbit facility construction services.

1. On-orbit services of co-orbital motion

During the operation of the Tiangong space station, the Xuntian space telescope will be launched to fly co-orbitally with the space station. It is the first large-aperture large-field-of-view space astronomical telescope in China, which is used for scientific research of space surveys. The Xuntian space telescope will fly co-orbitally with the Tiangong space station for a long



A Configuration of intelligent robot

B Joint operation of intelligent robot and robotic arms of space station

Fig. 19. Intelligent robot for space operation. (A) Configuration of intelligent robot. (B) Joint operation of intelligent robot and robotic arms of space station.

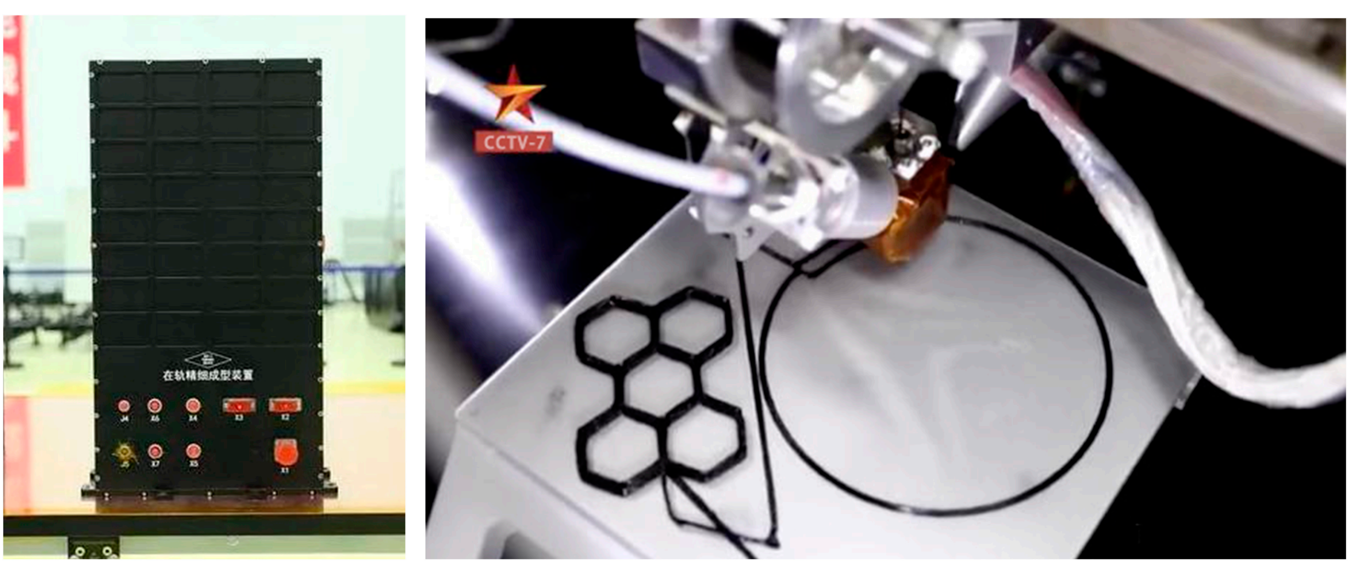


Fig. 20. 3D printer equipped in the test ship of a new generation of manned spaceship in China.

time and dock with the space station for a short time. On-orbit services such as propellant refueling and maintenance for the Xuntian space telescope will be done through the space station. Figure 18 illustrates the assembly of the Tiangong space station and the Xuntian space telescope. The on-orbit service mode of long-term co-orbital motion and short-term docking is an important innovation in the operation mode of the Tiangong space station. In addition to the Xuntian space telescope, more spacecraft will probably fly co-orbitally with the Tiangong space station to receive on-orbit services. Thus, the Tiangong space station will gradually play an important role as a “space home port” [24].

2. On-orbit facility construction services

The Tiangong space station can also be used for on-orbit assembly of complex facilities such as large space antennas and telescopes. At present, such facilities are mainly deployed by on-orbit unfolding after launch. This mainly faces 2 problems. First, with the increase in size, unfolding mechanisms become more and more complex, which greatly increases the risks of on-orbit unfolding. Second, the sizes of related facilities will be increasingly enhanced, and their deployment by on-orbit unfolding after launch will not be feasible technically. Using the Tiangong space station to build related facilities in orbit can effectively solve the above 2 problems. In view of on-orbit unfolding risks, as the space station supports on-orbit maintenance by crewmembers, failures during construction can be repaired in orbit to reduce mission risks. Moreover, the microgravity environment in the space station is conducive to the on-orbit fabrication of super-large facilities. This can overcome the restriction of launch on facility sizes effectively.

The on-orbit facility construction services of the Tiangong space station can be realized through crewmembers' extravehicular activities or equipped large and small robotic arms. They can also be operated by subsequently developed special intelligent space robots. On the basis of the successful application of large and small robotic arms, it is an important and necessary way of technological development to develop intelligent space robots to assist or replace crewmembers for extravehicular operations. Figure 19 illustrates a typical intelligent space robot, which consists of 2 dexterous arms, 1 medium-size arm, and a body. The robot can be used as a dexterous actuator at the end of the small robotic arm or fixed separately outside the space station. By multiarm coordination, it can complete high-risk long-time equipment care and extravehicular patrol.

In addition, 3D printers (Fig. 20) can be configured in the Tiangong space station to provide on-orbit fabrication services of space facilities, which can further enhance the capacity of the space station to provide on-orbit facility construction services.

On-orbit technology upgrading

Since the equipment of the Tiangong space station can be maintained in orbit by crewmembers and robotic arms, the software of the space station can be upgraded through uploading from the ground. Therefore, the Tiangong space station can continue to upgrade its technology in orbit according to technological development during its operation, thus continuously improving its technical level. Technical upgrades can be considered in the following aspects:

1. Intelligence upgrade

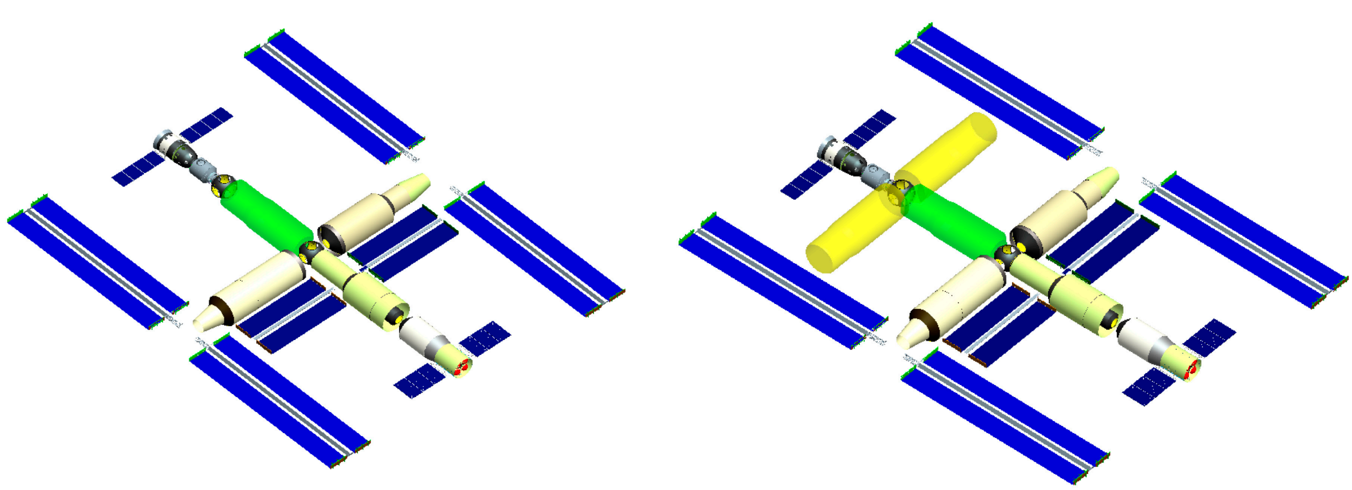
At present, advanced information technology such as artificial intelligence and big data has developed rapidly. The Tiangong space station can fully use related technology for intelligence upgrading during its more than 10 years of operation. For example, intelligent assistants can be configured for the crew for efficient interaction between the crew and the space station through intelligent speech interaction technology, thus providing on-orbit support for the crew. Intelligence upgrading can be performed on the autonomous fault diagnosis and disposal of the Tiangong space station to improve the on-orbit fault handling abilities of the space station. Module cleaning robots can be employed to assist crewmembers in cleaning the modules to reduce module cleaning time.

2. Upgrade of life-support system

The physicochemically regenerative life-support system of the Tiangong space station can be upgraded during its operation to further improve the closing material cycle of the life-support system and reduce supply demand for the consumables of on-orbit residence. For example, the CO_2 reduction system can be extended so that CO_2 after collection and concentration can react with H_2, a by-product of electrolytic oxygen generation, to form CH_4 and water. After being purified by the water processing assembly, the condensed water can be used to replenish the drinking water for the crew to further improve the closing material cycle.

3. Technical upgrade of robotic arm

The software and hardware of the 2 configured robotic arms can be upgraded during the operation of the space station to improve the on-orbit maneuverability of the robotic arms of the space station. In terms of hardware upgrading, the information processing ability of the robotic arms can be improved



A Four-module assembly **B** Six-module assembly

Fig. 21. Configuration diagram of expanded assembly of Tiangong space station. (A) Four-module assembly. (B) Six-module assembly.

Table. Main characteristics between Tiangong and MIR and ISS.

Index	Main function and specification	Tiangong	Mir	ISS
1	Building ways	Rendezvous and docking, module transfer in plane	Rendezvous and docking, module tilting transfer	Rendezvous and docking, module captured by robotic arm from space shuttle
2	Construction period	2 y	10 y	>12 y
3	System redundancy mode	Equipment, function, and module	Equipment	Equipment and module
4	Crewmembers	3 persons, 6 persons in rotation period	3 persons, 6 persons in rotation period	7 persons, 12 persons in rotation period
5	Propulsion system	Liquid rocket engine and hall thruster	Liquid rocket engine	Liquid rocket engine
6	Life-support system	2 regenerative life-support systems	1 regenerative life-support system	2 regenerative life-support systems
7	Robotic arm	Large robotic arm and small robotic arm	None	Large robotic arm and small robotic arm
8	Weight	69 tons; maximum to 180 tons	123 tons	423 tons
9	Transmission rates of space–Earth link	1.2 Gbps	<100 Mbps	600 Mbps
10	Power-to-weight ratio	0.41 kW/ton	0.25 kW/ton	0.26 kW/ton
11	Load-to-weight ratio	30.6%	17.5%	7.93%
12	Load-to-power ratio	63%	24%	45%
13	Supplied materials	About 12 tons/y	About 16 tons/y	About 30–40 tons/y

by replacing existing control computers with those of higher computational performance. In addition, more advanced cameras can be used on robotic arms to improve visual perception of these arms, or special tools can be installed at the ends of the robotic arms for more diversified operations. Regarding software, on-orbit loading for upgrading can be controlled to improve the autonomy and security guarantee of mission execution.

On-orbit expanded building

After completion, the Tiangong space station will operate in orbit for more than 10 years. With good capabilities of module expansion and application support expansion, it can be flexibly expanded according to the needs of space scientific and technological research, space application, and international cooperation. The future expansion of the Tiangong space station has been planned overall during the design. On the basis of the existing 3-module configuration, the expansion interfaces of mechanical, electrical, and thermal systems are reserved to be able to form a 4-module assembly. The expansion module will permanently berth at the forward berthing hatch of the Tianhe core module; a Tianzhou cargo spaceship will berth at the backward docking hatch of the Tianhe core module; and a Shenzhou manned spaceship will berth at the forward docking hatch of the expansion module. After the formation of the 4-module assembly, subsequent expansion modules can be further launched to form a 180-ton 6-module assembly, as shown in Fig. 21.

An inflatable deployable sealed module can be used as an expanded sealed module of a near-Earth space station [25] as well as a residence module for future space migrants. It can also support commercial space projects such as space residence and tourism.

In addition, 2 expansion interfaces of a large-load interface device are reserved outside the Tianhe core module to support the on-orbit expansion of large-load installation. One large-load interface device and 1 expanded load platform device are reserved outside the Wentian experiment module. They can not only support the on-orbit installation of large loads but also be used to mount an expanded exposure platform to further install exposed loads.

In terms of expanded building methods, an expansion module should generally be able to fly independently and rendezvous and dock with the Tiangong space station, while other expanded facilities such as exposure platforms can be installed after being ferried into orbit through semi-open or full-open Tianzhou cargo spaceship. The configured robotic arms of the Tiangong space station also provide favorable conditions for expanded building, able to flexibly transfer and assemble expanded facilities such as expanded modules and expanded exposure load platforms.

International cooperation

The Tiangong space station serves as a national space lab and a platform for international scientific and technological cooperation and exchange. In line with the principle of "peaceful use, shared development, and mutual benefit", it can provide scientific experiment platforms for countries all over the world and on-orbit flight opportunities for astronauts or loads from various countries. The international cooperation of the Tiangong space station can be divided into 3 levels.

1. Payload cooperation

As described in Scientific and technological experiments of this paper, the Tiangong space station provides standardized and specialized resources for payloads. All payloads that meet the agreed unified conditions of mechanical, electrical, thermal, and robotic arm interfaces can be used in the Tiangong space station. This is the first level of international cooperation, and payloads under cooperation include the following 3 models:

1) Experimental equipment developed independently or jointly with China. It will be installed in a cabinet of the sealed module for operation.
2) Experimental schemes (including experimental samples, units, or designs) developed independently or jointly with China. They will be installed to a cabinet of the sealed module and operated in an experimental device already developed by China.
3) Exposed loads developed independently or jointly with China. They will be installed on load adapters reserved outside the module for operation.

2. Space technology cooperation

As a manned spacecraft with a long-time on-orbit operation, the Tiangong space station can play a good role of a test platform for promoting and developing follow-up space technology. Through international cooperation, substantial breakthroughs can be expected in the following technical aspects. This is the second level of international cooperation.

1) A new generation of regenerative life-support technology
2) Medical protection for long-term on-orbit residence
3) Space robotic arm and space robot technology
4) Space noncooperative rendezvous and docking technology
5) Space debris monitoring, mitigation, and protection
6) New lightweight and high-strength structures

3. Module-level cooperation

The third level of international cooperation refers to large-scale module-level cooperation to jointly expand the Tiangong space station. The cooperation of this level can include the following models:

1) Developing an expanded experiment module to dock with the Tiangong space station so as to expand the basic functions and load support capacity of the space station.

2) Developing a multifunction node module to dock with the Tiangong space station. This node module can further reserve docking interfaces of the dome module or other sealed modules.

3) Developing an inflatable deployable sealed module. The module will be sent into orbit by an open cargo spaceship, installed on the Tiangong space station through robotic arms, and unfolded in orbit.

4) Developing a spacecraft capable of free roundtrips for on-orbit technical tests. The spacecraft can temporarily berth at the Tiangong space station and use resources of the space station for maintenance or resource replenishment.

Conclusions

Fully inheriting technical achievements in the early development of China's manned space project and drawing lessons from experience and lessons of international space stations already in service, the Tiangong space station has realized the leapfrog development of independent innovation depending on the basic national conditions of China. A summary table comparing the main characteristics of Tiangong with the MIR and ISS space stations is shown in Table.

With a focus on system-level design and optimization, the Tiangong space station innovatively uses contemporary advanced technology to improve its overall performance. This is conducive to the full play of the crew's initiative, showing outstanding Chinese elements and core connotations. Focusing on application efficiency, the Tiangong space station has an appropriate scale with reserved room for development and can provide an excellent service platform for subsequent national major missions and international cooperation. The construction of China's Tiangong space station has been completed in 2022 and officially entered the phase of application and development. The Tiangong space station will operate in orbit for a long time as China's national space lab, continuously supporting scientific and technological research and providing on-orbit services. Moreover, it will have technological upgrades and expansions, contributing China's strength to human space exploration and scientific and technological development.

Acknowledgments

Funding: This work was supported by China Manned Space Engineering Office. **Author contributions:** W.X. is the first author and is responsible for data analysis. Z.Q. is the corresponding author and conducted the literature review and paper revision. W.W. offered valuable help and many suggestions. **Competing interests:** The authors declare that they have no competing interests.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Zhou JP. Chinese Space Station project overall vision (in Chinese). *Manned Spaceflight*. 2013;19(2):1–10.
2. Yang H. *Manned spacecraft technologies* Beijing (China): Beijing Institute of Technology Press; 2021.
3. Wang X, Wang W. Key technical characteristics of the Tiangong Space Station (in Chinese). *Sci Sin Tech*. 2021;51(11):1287–1298.
4. Sorokin IV, Markov AV. Utilization of space stations: 1971–2006. *J Spacecr Rockets*. 2008;45(3):600–607.
5. Evans CA, Robinson JA, Tate-Brown J, Thumm T, Crespo-Richey J, Baumann D, Rhatigan J. International Space Station Science Research Accomplishments during the Assembly Years: An Analysis of Results from 2000-2008. NASA/TP-2009-213146, 2008.
6. Giblin TW. The International Space Station: Systems & Science, 20100018503 [R]. Washington: NASA, 2010.
7. Yang H. The "Tiangong" Chinese Space Station project. *Front. Eng. Manag*. 2018;5(2):278–283.
8. Brewster H S. International Space Station: Its history, Challenges, and Successes, AIAA2003-0002 [R]. Washington: AIAA, 2003.
9. Stockman B, Boyle J, Bacon J. International Space Station systems engineering case study, ADA538763 [R]. Washington: Air Force Center for Systems Engineering, 2010.

10. Yang H, Zhang Q. Introduction to manned environment and scientific experimental resources of China Space Station. Paper presented at: The 69th International Astronautical Congress; 2018 October 1–5; Bremen, Germany.
11. Wu ZQ, Gao F, Deng YB, Bian Q, Dong W, Liu X, Zhou K, Li Y, Zhao C. Key technology review of research on regenerative environmental control and life support system for Space Station (in Chinese). *Space Med Med Eng*. 2018;31(2):105–111.
12. Alptekin G, Hitch B, Dubovik M. Prototype demonstration of the advanced CO_2 removal and reduction system. Paper presented at: 35th International Conference on Environmental Systems; 2005 July 11–14; Rome, Italy.
13. Graf J, Wright J, Bahr J. A Regenerable Sorbent Bed for Trace Contaminant Removal. International Conference on Environmental Systems, Denver, 1999.
14. Li DM, Rao W, HU CW, WANG YB, Tang ZX, Wang YY. Key technology review of the research on the Space Station manipulator (in Chinese). *Manned Spaceflight*. 2014;20(3):238–242.
15. Fan WN. Study on system characteristics of international Space Station (in Chinese). *Spacecr Eng*. 2012;21(2):94–100.
16. Yan HJ, Jin YQ, Wei XQ, Xiao YZ. Analysis of on-orbit servicing technique demonstrations on international Space Station and developments (in Chinese). *Sci Sin Tech*. 2018;47(2):185–199.
17. Yang H, Yang B, Wei CF. Design on experiment support onboard manned space station. Paper presented at: The 64th International Astronautical Congress; 2013 September 23–27; Beijing, China.
18. Yang H, Yang B, Wei CF. The open experimental resources to serve payloads for international cooperation onboard Space Station. Paper presented at: Global Space Exploration Conference; 2017 June 6–8; Beijing, China.
19. Fan WW, Han L, Yang F, Wang HM. Review of scientific research and application on ISS in 2018 (in Chinese). *Manned Spaceflight*. 2019;25(2):271–276.
20. Fan WW, Yang F, Han L, Wang HM. Review of 20 years research activities and future elements in Russian segment on ISS (in Chinese). *Manned Spaceflight*. 2018;24(4):553–560.
21. Dong HP, Wang YJ, An XY. The conception of reusable space station replenishment (in Chinese). *Astronaut Syst Eng Tech*. 2018;2(2):22–26.
22. Gao M, Zhao GH, Gu YD. Space science and application mission in China's space station (in Chinese). *Bull Chin Acad Sci*. 2015;30(6):721–732.
23. Su HP, Zhao ZH, Sun YJ, Wang F. Study on space science and technology of manned space station (in Chinese). *J Astron*. 2014;35(9):985–991.
24. Wang TM, Wang H, Li HY. Research on location deployment of space station co-orbital spacecraft for refueling mission (in Chinese). *Manned Spaceflight*. 2017;23(5):582–596.
25. Liu JG, Chen KL, Xie HL. Preliminary design and analysis of space station inflatable deployable extravehicular payload prototype (in Chinese). *Manned Spaceflight*. 2016;22(6):737–743.