Space: Science & Technology
A SCIENCE PARTNER JOURNAL

REVIEW

Research and Development of the Tianzhou Cargo Spacecraft

Jianyu Lei, Dongyong Jia*, Mingsheng Bai, Yong Feng, and Xingqian Li

China Academy of Space Technology, Beijing, China.

*Address correspondence to: jiadongyong163@163.com

Citation: Lei J, Jia D, Bai M, Feng Y, Li X. Research and Development of the Tianzhou Cargo Spacecraft. *Space Sci. Technol.* 2023;3:Article 0006. https://doi.org/10.34133/space.0006

Submitted 17 July 2022
Accepted 6 December 2022
Published 15 March 2023

After more than 7 years of development, the Tianzhou cargo spacecraft (TZ), a space station cargo transfer spacecraft, was successfully launched on 2017 April 20. The TZ is robotic spacecraft that is designed to support China space station operation by transporting pressurized cargo, unpressurized cargo, large cargo, propellant, and other supplies. The vehicle is equipped with the crew specifications necessary for astronauts to unload pressurized cargo. TZ can be utilized for a variety of commercial, engineering, scientific, or other proposed activities once its primary mission is complete. TZ is China's first dedicated space cargo transport spacecraft, but the safety designs for crew activities are also particular to TZ. Newly developed technologies were applied to enable high-efficiency cargo shipment. Its development was carried out under the policy of adopting flight-proven technologies to enhance the reliability and safety of a mission. The success of the flight test of the TZ-1 cargo spacecraft marked the perfect end of the mission of the China Space Laboratory and laid the foundation for the smooth implementation of the manned space station project. As a novel manned spacecraft, TZ-1 has broken through key technologies such as cargo transportation, propellant replenishment, and fully autonomous rapid rendezvous and docking. TZ has the characteristics of high transport efficiency, multitasks, and strong self-control ability. The paper describes the phylogeny, main technical schemes, and technological achievements of China TZ.

Introduction

Cargo spacecraft is robotic spacecraft designed to support space station operation by transporting food, propellant, and other supplies. Automated cargo spacecraft have been used since 1978 and have given service to Salyut 6, Salyut 7, Mir, and the International Space Station (ISS) [1,2].

After the retirement of the American Space Shuttle, astronauts travel to the ISS in 2 types of spacecraft: the American SpaceX Dragon 2 and the Russian Soyuz [3–6]. They have been resupplied on board the station carried by a variety of cargo spacecraft: the Russian Progress, European Automated Transfer Vehicle, Japanese H-II Transfer Vehicle, SpaceX Dragon, and Orbital Sciences Cygnus [7–11].

China's Shenzhou spacecraft can meet the needs of space station crews' foreground—trip missions. However, the space station still has a large amount of cargo transportation and propellant supplementary requirements on orbit, and it is necessary to build cargo spacecraft specialized in space cargo transport. Tianzhou cargo spacecraft (TZ) is a Chinese automated cargo spacecraft developed by the China Academy of Space Technology, as part of China's manned space station program. It was launched by China Academy of Launch Vehicles' CZ-7 rocket and designed to transport supplies to the China's manned space station, Tiangong (TG) [12].

The China Academy of Space Technology began to design TZ in 2010. Its main tasks are transporting and storing supplies for the space station, storing and descending waste materials for the space station, controlled falling to a predetermined area, cooperating with the space station to control the orbit and attitude of the combined body, and supporting the development of space applications and technical tests adapted to the capabilities of cargo spacecraft.

As China's first space cargo transport spacecraft, TZ-1 was launched on 2017 April 20, and deorbited on September 22. TZ-1 has broken through key technologies such as cargo transportation, propellant replenishment, and fully autonomous rapid rendezvous and docking. With the TZ-1 mission successfully completed, a chapter is closed on a truly extraordinary period of China space laboratory activity [13]. TZ-2 was successfully launched on 2021 May 29, starting its first operational flight of the TZ series. TZ played a crucial role in station servicing. TZ-3 was also successfully launched on 2021 September 20. It docked at the core module of the space station at the same time as TZ-2. TZ-4, with the same design as the TZ-3, was also successfully launched on 2022 May 10. Certainly, the Tianzhou Spacecraft program has been written in Chinese space history, specifically in the field of human spaceflight. In the next 10 years, about 2 TZ will be launched each year.

This paper gives a detailed description about the design of TZ including the structure, function, and key technology of subsystems. The development and flight missions are presented. A comparison of TZ with other cargo vehicles are given, which provides us a systematic understanding about TZ cargo spacecraft.

Design of the TZ

A schematic of the TZ is shown in Fig. 1. The spacecraft consists of 2 modules: a cargo cabin for transporting pressurized cargo and a propulsion cabin with aviation electronics and propulsion

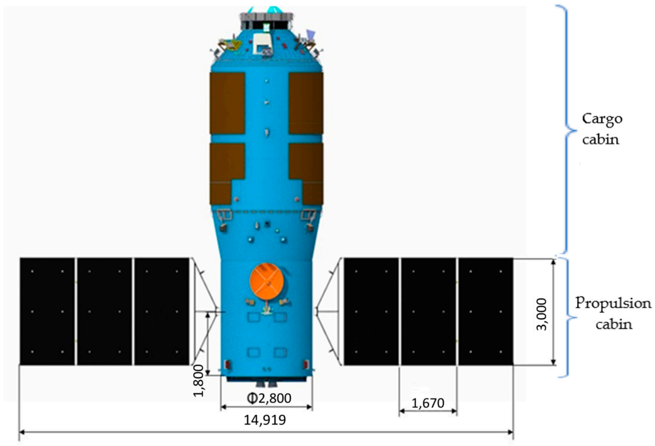

Fig. 1. The configuration of the Tianzhou cargo spacecraft.

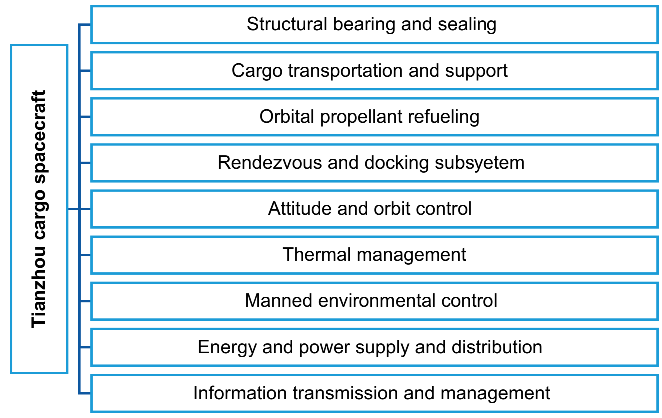

Fig. 2. Functional composition of TZ.

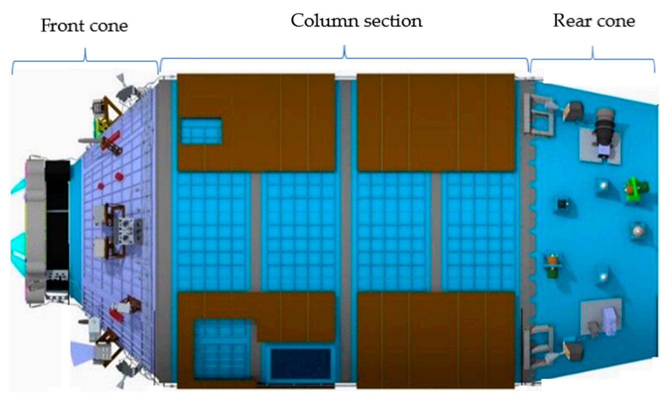

Fig. 3. The structure of the pressurized cargo cabin.

function. It is about 10.6 m long (including maneuvering thrusters at one end) and 3.35 m in diameter [12]. The total mass of the cargo spacecraft is 7 tons with a maximum total payload of 6.5 tons. Pressurized cargo loaded in the cargo cabin includes clothing, food, water, and experimental equipment for astronauts. The propellant for the reboost maneuver and refueling is loaded in the propulsion cabin [12].

TZ's target orbital altitude is 380 to 420 km, and angle of orbit inclination is 41 to 42° (circular orbit). It can stay in the TG approximately 365 days maximum. The supplies were all unloaded before the return trip, and the TZ was fully loaded with various wastes generated by the space station. Both the TZ and up to 6 tons of wastes can be burnt out during atmospheric reentry.

China's TG space station only has TZ as a cargo vehicle. TZ has broken through key technologies such as cargo transportation, propellant replenishment, and fully autonomous rapid rendezvous and docking. A distinctive feature of the TZ is its capacity for transporting pressurized cargo and unpressurized cargo, refueling propellant, boosting the TG orbit, and supporting specific space experiments. It is comparable in function with the Russian Progress, European ATV, Japan HTV, SpaceX Dragon, and Orbital Sciences Cygnus, all of which bring supplies to the ISS [14]. A stepper motor-driven disconnector makes propellant replenishment safer and more efficient, and the system weighs less. The introduction of an autonomous navigation guidance technology reduced the rendezvous and docking time to 6.5 h, with a target of 2 h [15].

The basic subsystems of TZ include a structural bearing and sealing subsystem, an attitude and orbit control subsystem, an information transmission and management subsystem, a power subsystem, a manned environment control subsystem, a thermal management subsystem, a rendezvous and docking subsystem, a combined-body berthing subsystem, an orbital propellant refueling subsystem, and a cargo transportation subsystem, as shown in Fig. 2. The cargo transportation and support subsystem and the orbital propellant refueling subsystem are unique to TZ, compared with satellite [2,12].

Structural bearing and sealing subsystem

Structural design of fully sealed module

The cargo cabin is designed as a long-life, low-leakage integral wall panel structure [16], as shown in Fig. 3. The cargo cabin consists of 3 sections: front cone, column section, and rear cone. The docking mechanism and the rendezvous and docking sensor are installed on the front cone section. The hatch door with a diameter of 800 mm realizes communication with the space station. Astronauts enter the column section through the hatch door, which is the main cargo loading area. The rear cone section is a nonpressurized cabin module, and is mainly installed with control, communication, and scientific experiment equipment. The diameter of the column section is 3.35 m, the effective loading space is 21 m^3, and the loading capacity exceeds 5.5 tons.

Structural design of cargo shelf

The integrated design of cargo cabin body and cargo shelf structure reduces the weight by more than 15 %. The shelf structure consists of lightweight high-strength aluminum honeycomb panels and weak links using carbon fiber beam reinforcement.

The shelves constitute a total of 40 cargo compartments, as shown in Fig. 4. The cargo compartment reserves standard interfaces for various cargo installations, including cargo packages and test loads. The divider between the cargo compartments can be removed to form a larger space to install large cargo such as spacesuit installation and high-pressure gas cylinder group, among others.

Structure of propulsion cabin

The propulsion cabin is a cylindrical, unsealed metal structure with an outer diameter of 2.8 m and a height of 3.2 m, as shown in Fig. 5. The bottom of the propulsion chamber is connected to the carrier rocket by a separation belt.

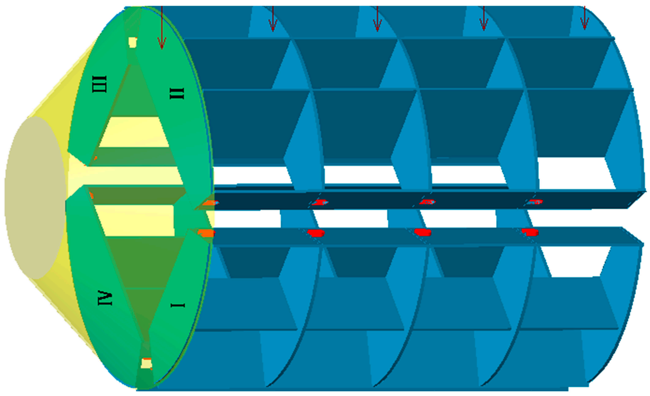

Fig. 4. Shelf structure inside the cargo cabin.

The propulsion cabin structure is connected to the propulsion cabin through double flanges to increase the connection points and the connection area.

Cargo transportation and support subsystem

All the designs of TZ are centered on the main task of cargo transportation. A standard electromechanical heat interface for goods is established to improve adaptability. At the beginning of the design, it is considered as a test platform to carry out space science experiments.

Cargo up-going loading

The space station needs many kinds of supplies and has different forms. In order to meet the needs of different types of cargo transportation, cargo ships have designed standardized loading methods such as standard cargo shelfs, cargo compartments, and standard cargo packages, and provide power, information, and thermal insulation support.

Because of the use of standardized cargo shelves and cargo compartments to load goods in the cargo cabin, it is easier and more standardized to install goods before launch, and all 5.5-ton goods can be installed to a preplanned position within 5 days. More than a dozen detachable handrails are designed on the outer edge of the shelves to support astronauts to operate packages in a weightlessness environment. With a lightweight design, the weight of the shelf reduced by 32 % and the rigidity is guaranteed.

In addition, to make full use of the loading space in the passage and improve the material loading capacity and adaptability, TZ is designed with a replenishment storage platform (RSP; see Fig. 6) that can be removed on orbit. As shown in Fig. 7, a 3-dimensional model is used for cargo loading design. The real scene of goods in the cargo cabin is shown in Fig. 8.

Cargo package is the main carrier of goods, with good adaptability and high efficiency. Soft and elastic package with shaped foam inside can reduce vibration of precision instruments during rocket launch. A special antibacterial and anti-mildew cloth is used on the surface of the package, and an effective component extracted from the crab shell is added to the cloth [17].

The special bracket is designed to install large goods such as extravehicular spacesuits (see Fig. 9), drinking water tanks, and high-pressure cylinders (see Fig. 10).

Low-temperature cargo transporting

Two space refrigerators are designed to transport a small amount of special cargo with low-temperature storage requirements. Figure 11 shows the shape of the space refrigerators.

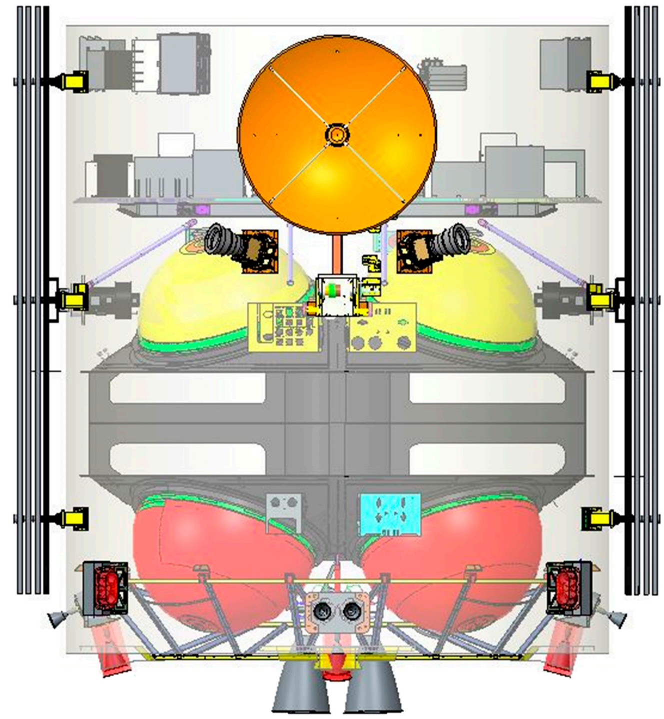

Fig. 5. Overall arrangement inside the propulsion cabin.

According to the insulation requirements of different goods, range is divided into 2 specifications: 0 °C to +4 °C and −20 °C to +4 °C. The space refrigerator is designed with front and back doors. Before the launch of the rocket, the back door of the refrigerator was opened through the specific hatch of the fairing and cargo cabin, and special cargo was placed in the refrigerator. Figure 12 shows the working scene of engineers installing cryogenic goods before the rocket launch. The astronauts take out the special cargo in the refrigerator through the front door in orbit.

Test equipment rideshares

Gaining access to space is currently a major challenge facing test equipment such as small satellites and scientific test devices. TZ can be utilized for a variety of commercial, engineering, scientific, or other proposed activities once its primary mission is complete. TZ supplies reliable, affordable, and, most importantly, compatible rideshares to test or put small satellites on orbit [18,19].

TZ can potentially accommodate up to the equivalent of 1 to 24 U small satellites. Volume for test equipment rideshares is allocated on the cargo cabin. Figure 13 highlights a particular area of interest on the outside of the rear cone.

TZ rideshares would be capable of utilizing power generated from its solar arrays, telemetry, tracking and command capacity, and attitude control capability before deployment. TZ is equipped with a management computer and a distributor to provide information support and power supply for test equipment [20,21]. The spacecraft platform connects the test equipment to the Ethernet network and downlinks the test data to the ground through the data relay satellites. The downlink rate reaches 100 Mbps. At the same time, the spacecraft can supply 1,000 W for the test equipment.

Cargo mass to the TG can be traded for rideshare mass and may vary mission by mission. The cargo mass may be lower than predicted due to volume constraints, rather than actual

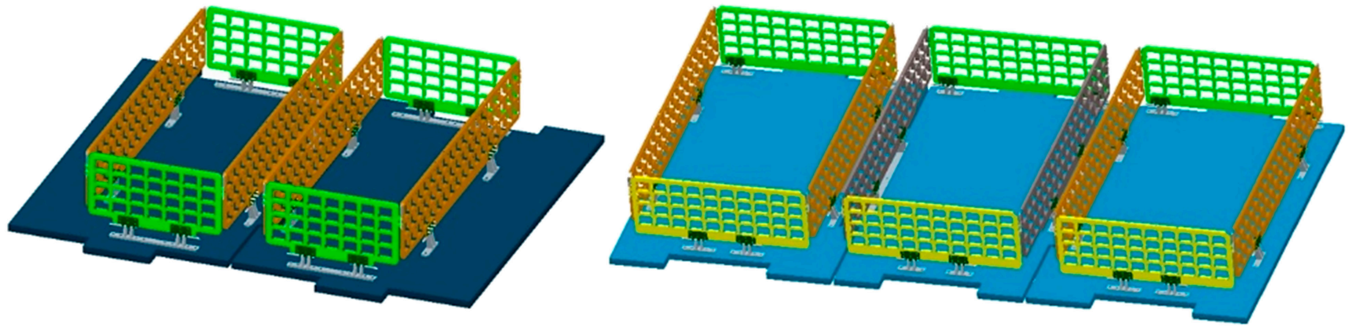

Fig. 6. Diagram of RSP.

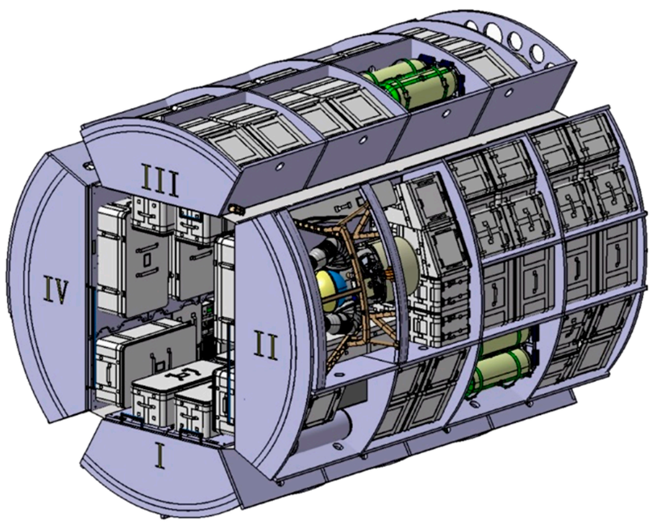

Fig. 7. Chart of cargo loading in the cargo cabin.

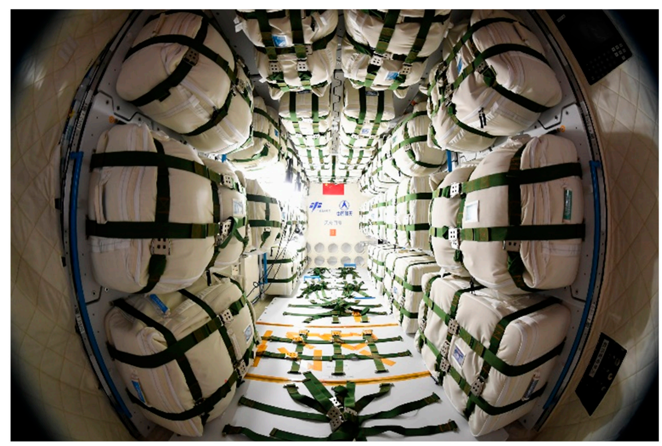

Fig. 8. Cargo loading diagram in the cargo cabin.

mass constraints. Having a low cargo density opens up additional mass margin for rideshares. The current outlook is for greater than 300 kg available for rideshares.

Orbital propellant refueling subsystem

Orbital propellant refueling technology could prolong station life and reduce its cost [12,22]. TZ and TG adopt the gas-recycling method, which is the same as that of Progress and ISS.

Propellant refueling system

The gas-recycling method uses a gas compressor to compress the pressurized gas in the receiving tank back to the gas cylinder, thereby reducing pressure of the gas in the space station tank. The pressure in the tank of the cargo spacecraft is greater than that in the space station, thus creating a pressure difference (greater than 0.5 MPa) between the supplier tank and the receiving tank, and the propellant flows from the supplier tank to the receiving tank under pressure. As a valuable resource, pressurized gas in tanks is not wasted but reused. The high-pressure gas recovery and reuse systems are complex and technically difficult, but the gas resource is not consumed, which is more favorable for the space station.

TZ and TG also use the high-pressure gas recycling method. TZ docks and seals with the propellant pipeline of TG through the electric floating disconnector. The pressurized gas in the TG tank is recompressed back into the high-pressure cylinder by the compressor, which reduces the backpressure of the tank and creates the conditions for receiving the propellant. TG is equipped with 3 compressors, 2 as the main component, 1 as a backup, TZ then transported the propellant to the membrane box tank on the space station in a constant pressure mode. Subsequently, TZ blew the residual propellant in the connection pipeline through high-pressure gas and finally removed the connection pipeline to complete the propellant supplement.

Stepper motor-driven disconnector

Compared with the high-pressure gas-driven disconnectors of Progress, the stepper motor-driven disconnectors of TZ have lighter weight, fewer sealing links, and a 0-N impact force during insertion. Figure 14 shows the shape of stepper motor-driven disconnectors.

The integrated module structure of propulsion and supplement

The modules used for the propellant supplement of Progress are independently designed with the propulsion cabins required for the self-control of the spacecraft, which avoids the technical problems of integration such as pressure system difference and safety isolation between the 2 modules. However, the system has a low propellant utilization rate, poor task adaptability, and less fault response means.

Eight 400-l metal diaphragm tanks are newly developed for TZ, which are divided into 2 functional modules: propulsion and supplement. Figure 15 shows the schematic diagram of the integrated module structure of propulsion and supplement. The lower 4 tanks are the propulsion cabin, and the upper 4 tanks

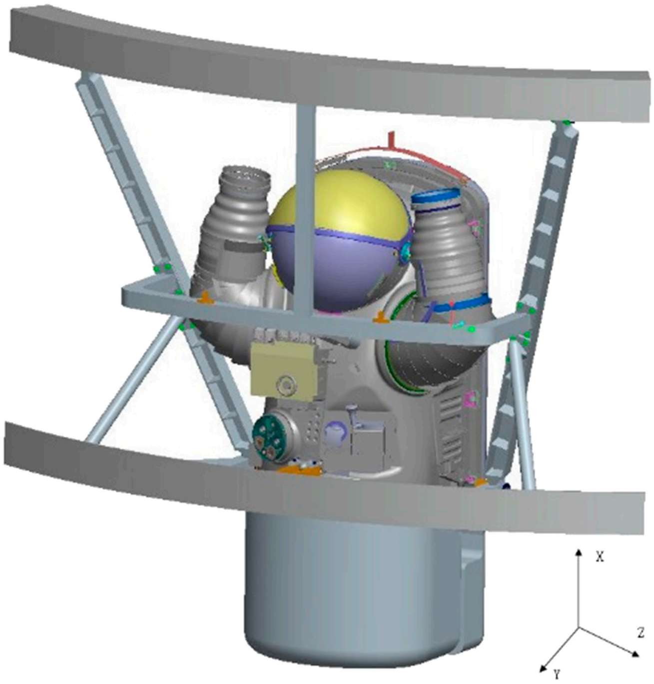

Fig. 9. Transport bracket of extravehicular spacesuit.

are the supplement module. The total carrying capacity can reach 3.5 tons, and the propellant used for the supplement is 2.5 tons. The integrated use between modules meets the requirements of safety isolation and flexible switching of the propulsion/supplement module and improves the propellant utilization efficiency and task emergency capability.

Rendezvous and docking subsystem

The rendezvous and docking of the cargo spacecraft and the space station is the basis for realizing cargo replenishment and propellant replenishment and is one of the key functions of the cargo spacecraft. The all-phase rendezvous and docking expands the launch window of the cargo spacecraft and improves the flexibility of the space station's operation and management. The fully autonomous rapid rendezvous and docking lays the technical foundation for the rapid cargo replenishment and personnel transportation of the space station.

Fully autonomous rapid rendezvous and docking technology

TZ proposed a rapid rendezvous and docking autonomous navigation and guidance technology solution based on absolute positioning data. The period of implementing a fully autonomous rapid rendezvous and docking was shortened to 6.5 h. Designed forward, backward, and radial circumnavigation schemes, which can be docked with different docking ports of the space station, improve the adaptability of the missions [15].

Docking was fully automatic. If there were any last-minute problems, either the TZ's computers, the control center, or the Space Station crew could trigger a preprogrammed sequence of anti-collision maneuvers, fully independent of the main navigation system.

Adaptability of docking target

The TG space station, like ISS, will continue to expand and have dozens of configurations. The space docking mechanism of TZ

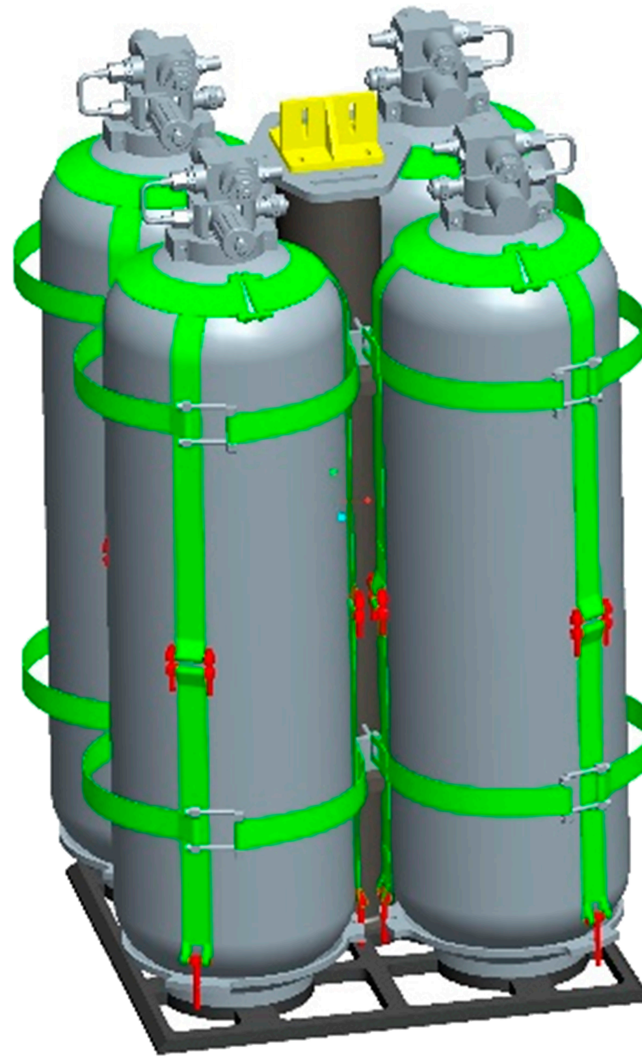

Fig. 10. Transport bracket of high-pressure cylinders.

Fig. 11. The space refrigerator.

Fig. 12. The working scene of engineers installing cryogenic goods before rocket launch.

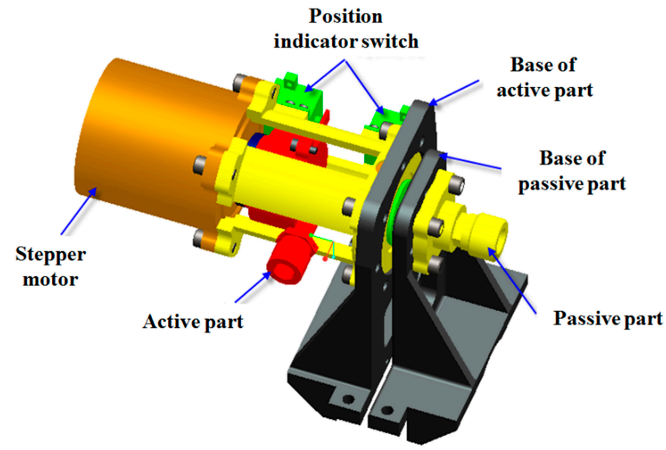

Fig. 14. The stepper motor-driven disconnectors.

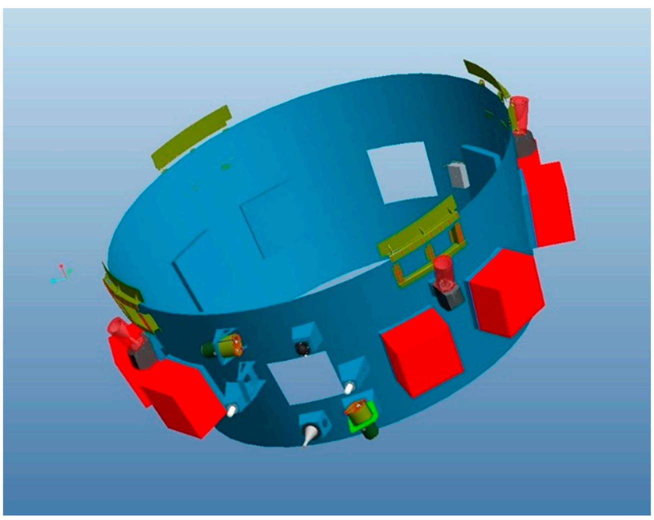

Fig. 13. Potential rideshare mounting location on the cargo cabin (red marking).

is equipped with 3 dampers with active control ability to offset the huge energy generated in the pitching direction and yaw direction of the cargo spacecraft, when TZ is docking with the large eccentric space station (such as the "L" configuration). TZ can dock with space stations of various configurations with mass in the range of 20 to 180 tons.

TG controls the engines of TZ directly

After docking, the TZ could perform TG attitude control and debris avoidance maneuvers and reboots the station's orbit to overcome the effects of atmospheric drag. To save the space station's engine life, the space station preferred to use the engine of the visiting cargo ship. TG can bypass the main control computer of TZ to directly control TZ's engines through the dedicated 1553B control bus.

Attitude and orbit control subsystem

The attitude and orbit control of TZ is realized by pure jet propulsion, like other cargo spacecraft.

Attitude determination

The attitude sensors of TZ include a gyroscope, an Earth sensor, and a star sensor. The attitude is estimated according to the attitude angular velocity measured by the gyroscope and then corrected according to the measured values of the Earth sensor and the star sensor.

In the process of rendezvous and docking, 3 relative navigation sensors are used to measure the relative position and relative attitude parameters of TZ and TG, including a differential GPS navigator, a laser radar, and an optical imaging navigation sensor. In the process of docking the astronaut remote control TZ with TG, it is mainly based on the images provided by the high-definition camera.

Thruster configuration and usage mode

TZ has the characteristics of large inertia and large variation of mass characteristics. Different dry cargoes and propellant loadings can cause the centroid of the x-axis to change by more than 1.5 m. The TZ navigated with 4 main engines (490 Newton thrust), plus 32 smaller engines (25N, 120N, and 150N) for attitude control, 16 of which were located near the front cone and the tail end to ensure the required vehicle maneuverability [23].

The engine adopts the strategy of combined use of group attitude and orbit. A high precision position and attitude controller based on feedforward compensation is designed. The technical problem of near-range quasi-static hovering in close formation flight of noncooperative target safety rendezvous and multi-spacecraft is solved. The docking specification precision for lateral misalignment was 10 cm and the actual precision achieved with the 3 TZs is 1 cm or better.

Thermal management subsystem

TZ has the characteristics of uneven distribution of heat sources, large changes in each flight stage, and a large range of external heat flow. To reduce weight and cost, TZ does not have a fluid loop temperature control system. Instead, passive measures such as heat insulation, heat conduction, and radiation are adopted for equipment and areas to achieve "precise" control objectives. However, designers need to carry out accurate simulation based on practical experience. If the thermal simulation is not accurate, the thermal management cannot achieve the expected goal due to the lack of active adjustment ability.

Passive thermal control design

A thermal control method combining forced ventilation and secondary radiation is proposed to replace the conventional fluid loop thermal control device [24]. The lightweight thermal management system is shown in Fig. 16, accounting for only 2.1% of the aircraft weight.

The ventilation system is designed in a sealed cabin to realize the unified collection and transmission of heat. The rear ball bottom of the sealed cabin is used not only as a heat dissipation surface to achieve controllable heat dissipation in the sealed cabin, but also as a channel for heat exchange between the sealed cabin and the non-sealed cabin, so as to achieve the goal of integrated design of thermal management of the sealed cabin and the non-sealed cabin. By adjusting the heat transfer path and thermal resistance by secondary radiation, the temperature of the heat dissipation surface in the sealed cabin is increased by 3-5 degrees Celsius to prevent condensation.

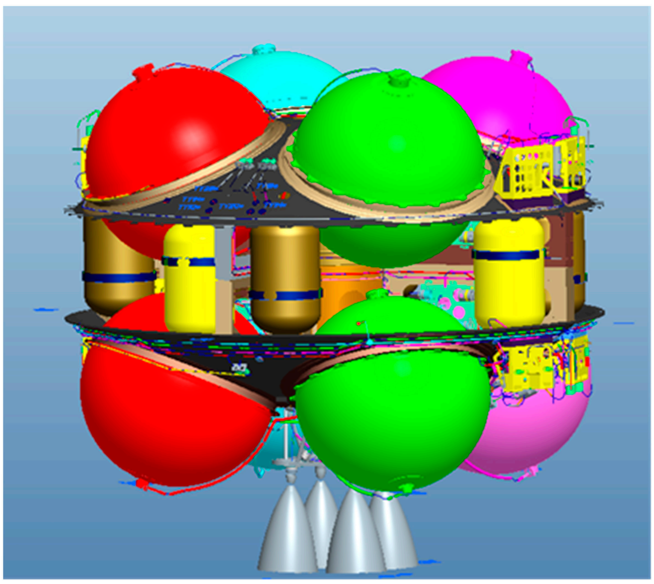

Fig. 15. The propulsion cabins (up) and supplement modules (down).

Prevent low-temperature surface condensation

Three fans are arranged at the rear ball bottom for forced ventilation, which improves the temperature uniformity of the cooling surface and solves the problem in which the sealing bulkhead is prone to condensation as the surface cools. Domestic and foreign manned spacecraft is still the first example.

Manned environmental control subsystem

Cargo spacecraft do not have to use complex environmental control and life support systems like manned aircraft, but there is still a need to ensure environmental safety during the entry of astronauts into cargo cabins. The integrated design of manned environmental control and space station simplifies TZ's own system configuration.

Environment monitoring

TZ's manned environmental control and space station integrated design and simplified equipment configuration, while reducing weight and cost. Before launch, the sealed cabin is carefully wiped to remove surface microbes and is injected with clean air. During the independent flight, the cargo ship has no astronauts, and only one high-pressure cylinder is equipped as an emergency supplement gas source in the sealed cabin. After docking, the space station uniformly controls the manned environment in the sealed cabin. The cargo spacecraft continuously monitors pressure, temperature, humidity, and oxygen and carbon dioxide concentrations, and issues an alarm if these

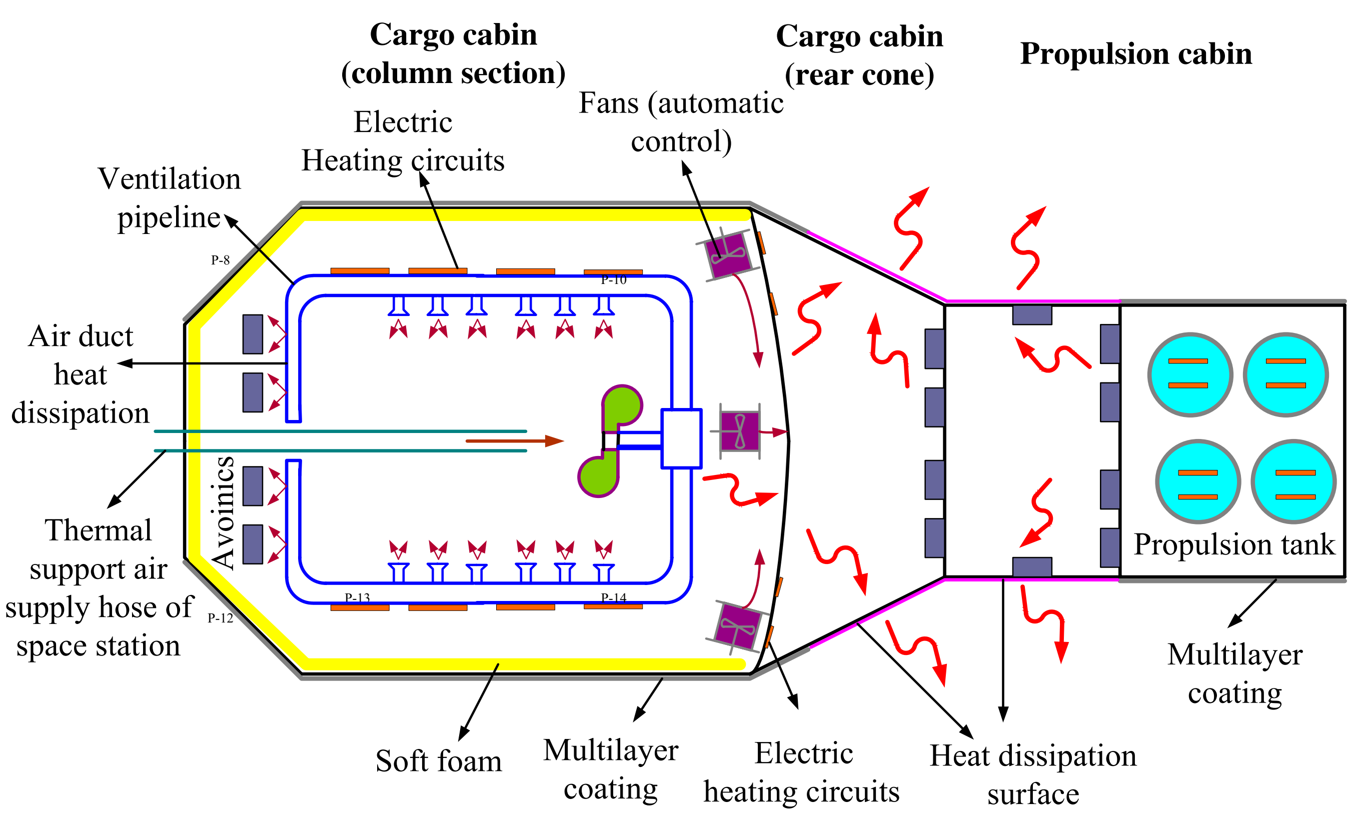

Fig. 16. Lightweight cargo spacecraft thermal management system.

exceed the safety threshold. At the same time, lighting facilities are provided to support astronauts' cabin operation.

Docking at the space station, the space station sends dry and clean hot air to the cargo spacecraft's sealed cabin through the hose. The air volume is not less than 8 m^3/min and the temperature is not less than 20 °C, which can maintain the normal temperature and humidity level in the cabin.

Noise control

The steady-state noise source in TZ is the thermal control ventilator. TZ placed the ventilator in a sound insulation box (see Fig. 17), reducing the noise from 65 dB to less than 55 dB, which is a low level of noise for manned spacecraft.

COVID-19 detection

Before launch, in addition to routine microbial colony count and harmful gas composition detection, a new COVID-19 detection link was added to ensure that the spacecraft did not carry the virus to fly to the space station, polluting the living environment of astronauts in orbit. As shown in Figs. 18 and 19, the viral sample collection site was the surface position of the sealing cabin and the package.

Energy and power supply and distribution subsystem

The photovoltaic power supply system uses a solar wing-lithium battery pack; the bus voltage is stable at 100 V [25].

Power system

The propulsion cabin II and IV quadrants are respectively equipped with left and right semirigid solar wings. Each wing is composed of 3 solar panels, with a size of 1,670 mm × 3,000 mm × 25 mm and a total area of 30 m^2. The 3-junction gallium arsenide battery sheet with an average conversion efficiency of no less than 29% was adopted, and the sheet distribution coefficient was no less than 88%.

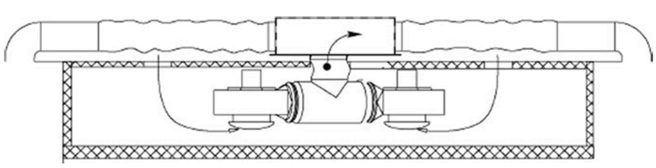

Fig. 17. The thermal control ventilator in a sound insulation box.

The rotation of the solar cell wing is driven by a single degree of the freedom drive mechanism, and the control of the solar cell wing is realized by the GNC subsystem.

Three groups of 60-Ah lithium-ion batteries were selected as energy storage batteries. Each group of batteries was composed of 2 modules (see Fig. 20) in series, and each module was composed of 2 parallel 11 series of 30-Ah lithium-ion battery monomers.

Distribution system

A high voltage direct distribution design scheme for spacecraft is proposed, which transmits a 100-V bus voltage directly to the load end. Compared with the 2-stage transformation distribution scheme, the 1-stage transformation link is reduced, the advantages of a high-voltage (100 V) transmission are better exerted, and the overall transformation efficiency of the system is improved by 8.1% [26].

Grid-connected power supply

After berthing, the power system of TZ and TG forms a unified network. The grid-connected controller is designed for on—off control and safety isolation. When TZ is short of power, TG can provide no more than 2,000 W of power. When there is surplus power generation, TZ can deliver 1,000 W of power to TG.

Information transmission and management subsystem

TT&C communication mainly relies on space-based systems, such as the data relay satellite system and the "BeiDou" navigation satellite system. Some key flight periods are supported by land-based communication stations. Ethernet technology, which has been successfully applied on the ground, has been transplanted to TZ as the main means of high-speed data communication.

Space-based TT&C

The development of China's relay satellite system has greatly improved the coverage of the space TT&C network. Based on

Fig. 18. COVID-19 detection in the cargo cabin.

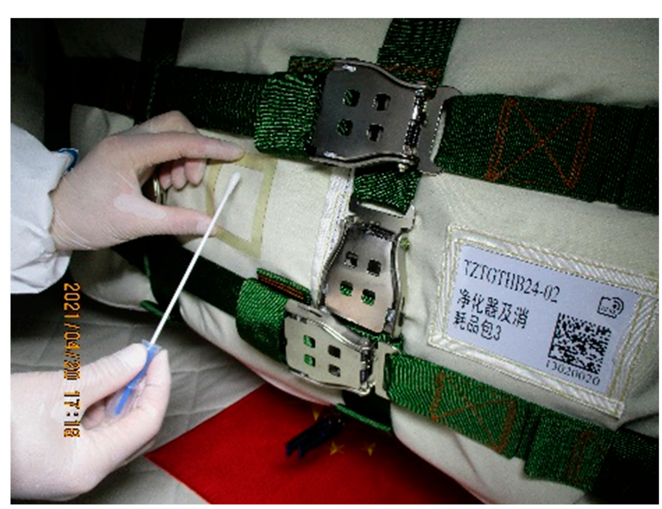

Fig. 19. COVID-19 detection on cargo package surface.

the relay satellite system, the TT&C communication system of TZ is simplified and the function is stronger. Moreover, the support of the sea-based communication station is no longer needed in the process of launch and rendezvous and docking.

Absolute positioning, rendezvous, docking navigation, and time calibration use China's BeiDou navigation system. The precision is equivalent to GPS.

Space—Earth integrated network communication

A space—Earth integrated network scheme suitable for near-Earth orbit spacecraft is proposed. In view of the many advantages of Ethernet technology and its wide application on the ground, the space communication network using Ethernet technology and integration with the ground network has become the main future development trend.

The Consultative Committee for Space Data Systems (CCSDS) has released the Red Data Book of IP over CCSDS Space Link Protocol. TZ has established a space—Earth integrated network communication based on Ethernet technology and IP over CCSDS, and realized high-speed space—Earth communication [27]. The network communication system for TZ is shown in Fig. 21. It can provide at least a 12-channel Ethernet interface and an interface speed of 100 Mbps, and support standard Ethernet protocols.

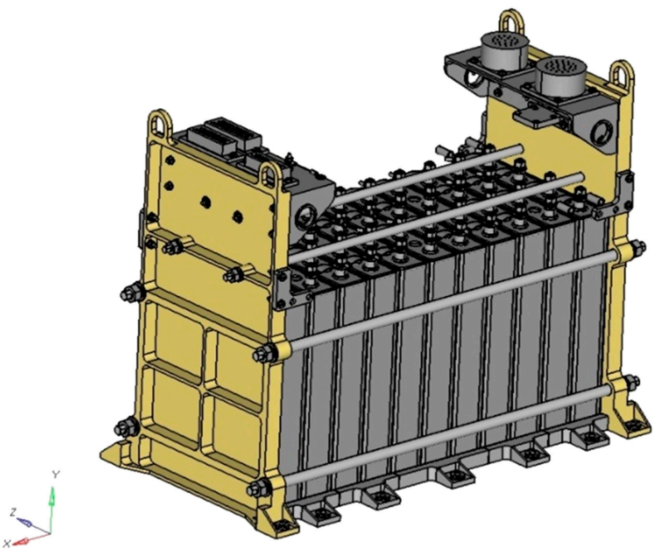

Fig. 20. High-voltage lithium-ion battery pack.

Development, Flight Missions, and Main Achievements

Development

We initiated the development of TZ, which transports supplies to the TG and disposes of wastes from the TG, to support the construction and operation of China space stations. To reduce the risk, flight #1 docked with the Tiangong II Space Laboratory before performing the space station phase mission. Although no astronauts participate in cargo transportation tasks, key technologies such as propellant on-orbit replenishment and aircraft platform design can be evaluated. Overall, it is a sound and economical strategy.

The conceptual design of TZ was begun in 2010, and the preliminary design was started in late 2011. Flight #1 is scheduled to launch after Tiangong II Space Laboratory enters orbit in 2017. On 2021 May 29, TZ-2 carried out the first flight mission of the space station stage. On 2021 September 20, TZ-3

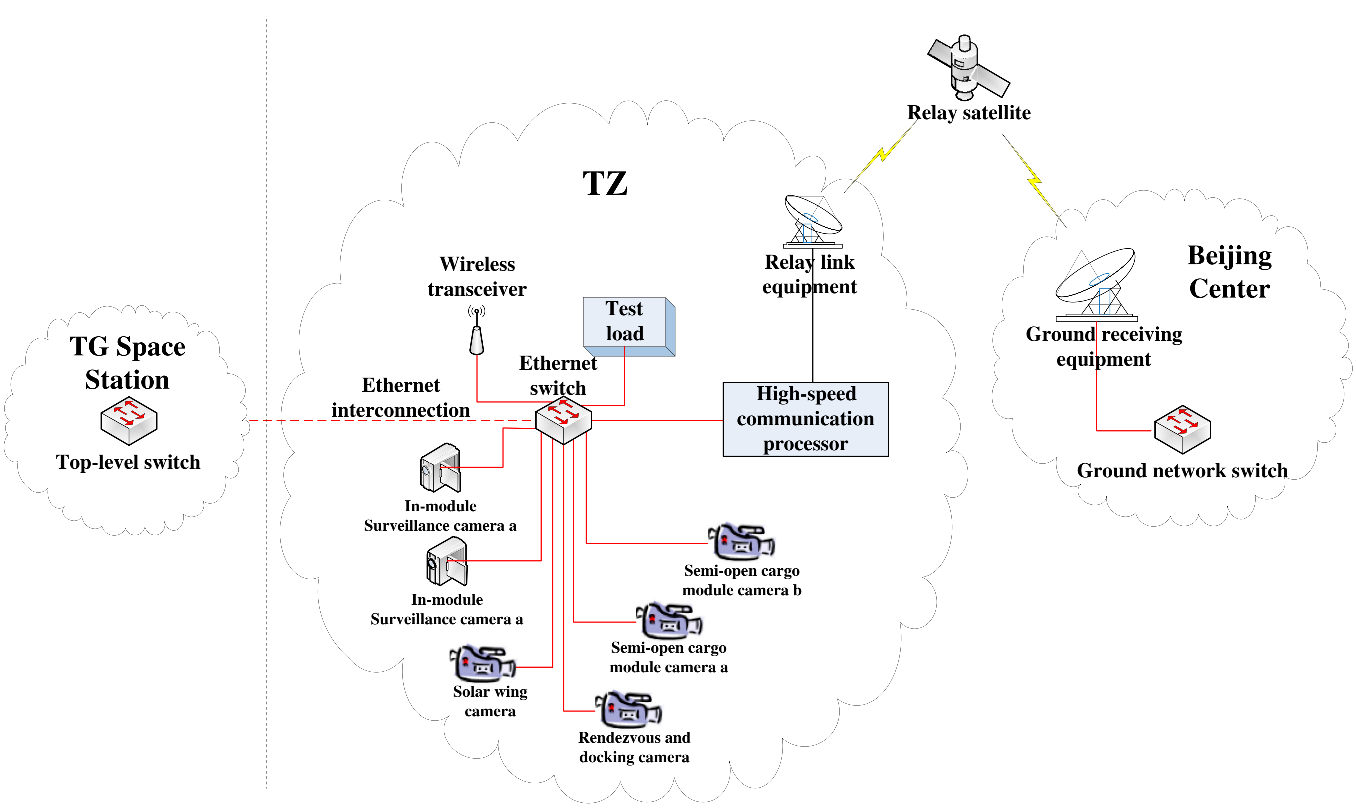

Fig. 21. Space—Earth integrated network communication system of TZ.

began the routine duty of cargo transportation. In the space station stage, 2 TZs will be launched every year.

In the first stage of the TZ design, we formulated 3 configurations—Fully Enclosed TZ, Semienclosed TZ, and Fully Open TZ, as shown in Fig. 22, to investigate module replacement based on the type of supplies being transported. Semienclosed TZ and Fully Open TZ are mainly used to transport large nonpressurized cargo, such as solar wings, small satellites, and space exposure test platforms. Because TG now does not have large nonpressurized cargo transport needs, Semienclosed TZ completed the initial development; Fully Open TZ only completed conceptual design. At present, all the missions are Fully Enclosed TZ.

As China's only cargo spacecraft, TZ has to adopt a multitasking design, which inevitably leads to complex systems and high costs. As the main task, higher transport efficiency and higher transport capacity are also required; thus, the optimization and weight reduction design at the system level runs through the whole development process.

Flight missions

TZ-1

TZ-1 cargo spacecraft took off on 2017 April 20. On April 22, it was docked and locked with a TG-2 space laboratory to form a combination (see Fig. 23). On April 27, the first propellant supplement task was completed.

On 2017 April 28, the TZ-1 cargo spacecraft were transferred to the combined load support mode, and several space experiments such as evaporation phase change, sky/Earth observation, and space environment monitoring were carried out[28–33]. The second propellant supplement was carried out on June 14. On June 21, a 3U CubeSat was released during a 3-month independent flight, which was forward separated from the TG-2 space laboratory. Then, the fully automatic rapid rendezvous and docking test was carried out on September 12, and the third propellant supplement test was carried out. On September 22, the controlled meteorite fell in the South Pacific at 17:59.

TZ-2

TZ-2 was launched at 20:55:29 on 2021 May 29 and docked with the core cabin of TG at 5:01 on 2021 May 30. This is the first time that the Tianzhou cargo spaceship adopts fully autonomous rapid rendezvous and docking. Figure 24 shows the combination of TZ-1 and the core cabin of TG; this is a memorable moment.

On 2021 June 2, TZ-2 and the core cabin of the space station completed the 100-V bidirectional grid-connected power supply test. During the test, the bus voltage of the 2 aircraft was stable and the current output was normal, reaching the expected test level. This is the first time in the history of aerospace that the visiting aircraft provides electric energy supply for the space station.

On 2021 June 4, the combined orbit maneuver was implemented to meet the initial orbit position requirements of SZ-12 manned spacecraft docking.

On 2021 June 18, astronauts arriving at the space station by SZ-12 manned spacecraft opened the cargo cabin and began to transport cargo to the space station.

On 2021 September 18, it was separated from the backward port of the space station. After a small event of separation around the space station, it redocked with the forward port and was the backward interface of TZ-3.

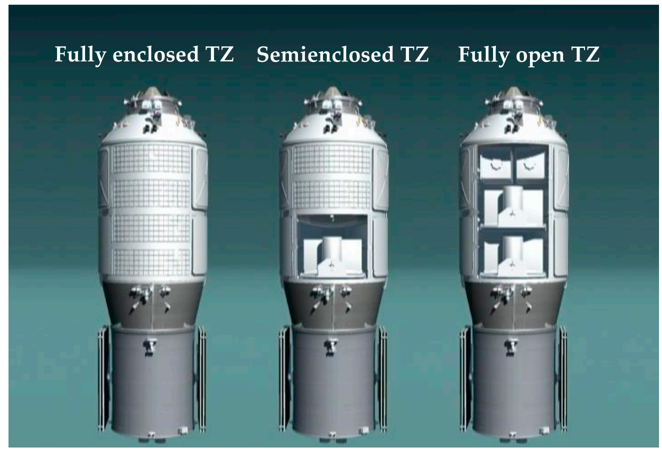

Fig. 22. Three configurations of the TZ.

Fig. 23. Combination of TZ-1 (left) and TG-2 Space Laboratory (right).

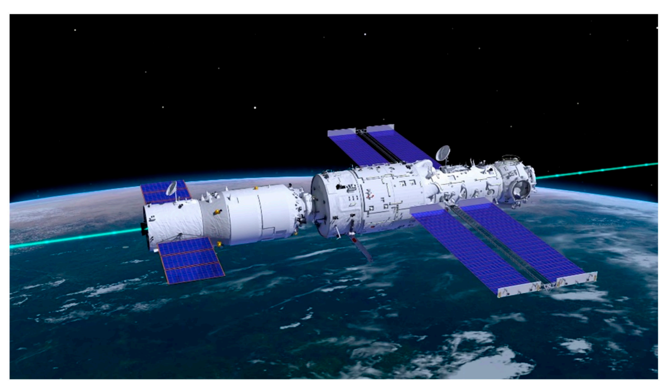

Fig. 24. Combination of TZ-2 and the core cabin of TG.

On 2022 January 6, TG's Manipulator Transfer TZ-2 Test was successfully launched. Test results show that the space manipulator can be competent for large spacecraft operation. The main test process is shown in Fig. 25.

On 2022 January 8, after a short time separation from TG, the astronauts remote controlled TZ-2 docked with TG again (see Fig. 26). When the autonomous rendezvous and docking system fails, astronaut remote control docking is an important backup design.

TZ-3

TZ-3 was launched at 15:10:11 on 2021 September 20 and docked with the core cabin of the space station at 22:07 on September 20 (see Fig. 27).

On October 17, astronauts who arrived at the space station by SZ-13 opened the cargo cabin and began to transport cargo to the space station. The engine of TZ-3 at the backward port worked regularly to lift the orbit of the space station and provide unloading power for the saturated moment gyroscope. Before SZ-13 returns to Earth, TZ-2, TZ-3, and SZ-13 will continue to dock at the core cabin of the space station at the same time, as shown in Fig. 28.

Main achievements

TZ is a new manned spacecraft developed by China for space station missions. Its cargo proportion and propellant supplement function are comparable to those of other active cargo spacecraft.

TZ-1 implemented China's first on-orbit propellant supplement, laying the foundation for the assembly, construction, and operation of the space station.

Based on the principle of a space-based measurement and control system, the whole-course tracking of key events and the timely disposal of on-orbit faults are realized.

All the autonomous rapid rendezvous and docking methods are adopted, and the navigation and control are completed entirely by the equipment on the spacecraft. The rendezvous and docking are realized by autonomous planning and multiple orbit changes within 6.5 h.

To maximize the platform efficiency, the cargo spacecraft can carry a variety of experimental load equipment to complete multiple types of on-orbit tests.

TZ-1 is the first large spacecraft in China to implement active control of reentry into the atmosphere, strictly fulfilling the international obligations to reduce space debris.

Comparison of Space Station Cargo Vehicles

At present, the US space shuttle has retired. European ATV also exits active service after completing 5 freight missions. The current ISS cargo transport mainly relies on “Progress”, “HTV”, “Dragon”, and “Cygnus” cargo spacecraft.

Progress is an uncrewed version of Soyuz and launches on the same vehicle, a Soyuz rocket. The first mission was originally intended to be launched in 1978. It is a cargo freighter and has been used to deliver supplies to the Salyut, Mir, and ISS space stations. It docks automatically with the Russian segment of the ISS and can deliver 2,230 kg of cargo. More than 170 Progress were launched between 1978 and 2021 [3,34–37].

The Automated Transfer Vehicle, originally ATV, was an expendable cargo spacecraft developed by the European Space Agency. ATV was launched to orbit 5 times to the ISS between 2008 and 2014. It functioned much like Progress for carrying upmass to ISS but could deliver up to 7,667 kg of cargo [3,38]. The ATV no longer gets contract to transport goods to ISS due to higher costs.

H-II launch vehicle (HTV) is an automated cargo spacecraft. The Japan Aerospace Exploration Agency (JAXA) has been working on the design to resupply the ISS. The first mission, HTV-1, was originally intended to be launched in 2001. The total mass of the ATV when empty is 10.5 tons, with a maximum total payload of 6,000 kg. Nine vehicles were launched between 2009 and 2021 [39–44].

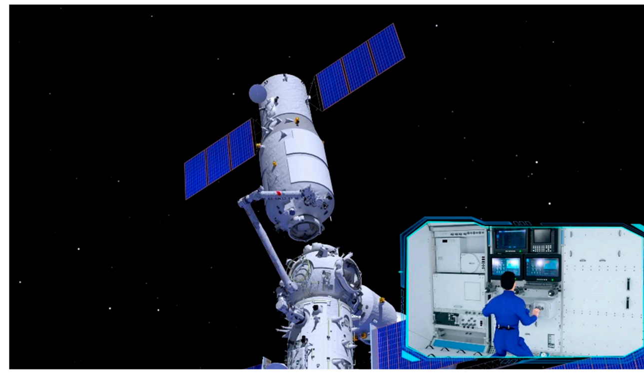

Fig. 25. TG’s Manipulator Transfer TZ-2 Test.

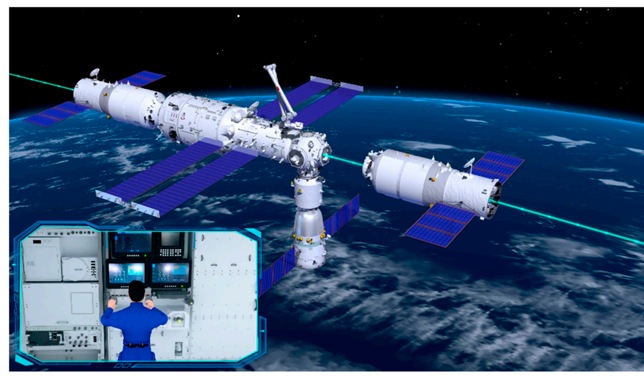

Fig. 26. The astronaut’s remote control TZ-2 docking with TG.

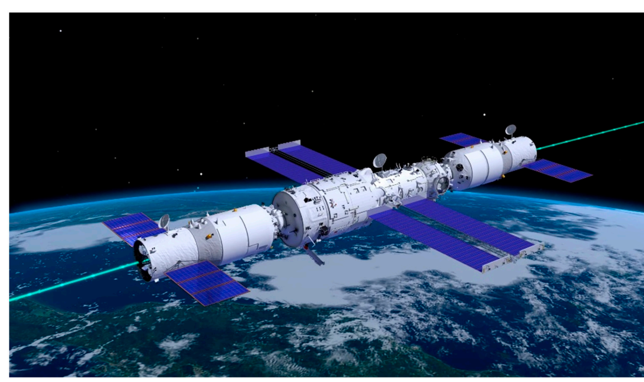

Fig. 27. TZ-3 docked at the back port of the core cabin.

Dragon is a reusable cargo spacecraft developed by SpaceX as part of NASA’s Commercial Resupply Services (CRS) program. On 2012 May 25, Dragon became the first commercial spacecraft to successfully rendezvous with and attach to the ISS. It can deliver up to 3,310 kg of cargo [25,45,46]. In a valuable service, it can also return cargo to Earth. With the second CRS contract in place, flights are planned to continue into 2024. Dragon 2 spacecraft’s first flight in 2020 ferried crews to and from the ISS.

The Cygnus spacecraft is also an American automated cargo spacecraft developed by Orbital Sciences as part of NASA's Commercial Orbital Transportation Services developmental program. The first 4 Cygnus spacecraft used the standard

Pressurized Cargo Module (PCM) with a volume of 18 m^3. Later enhanced variants have had a volume of 27 m^3. The enhanced model can deliver up to 3,200 kg of cargo to the ISS [11,47].

Among them, the payload of ATV is the largest, reaching 7.67 tons [3,8]. Although the payload is less than ATV, the payload ratio of TZ reaches 0.51 (payload ratio = payload/launch mass). The cargo transport efficiency of TZ is the highest for active cargo spacecraft.

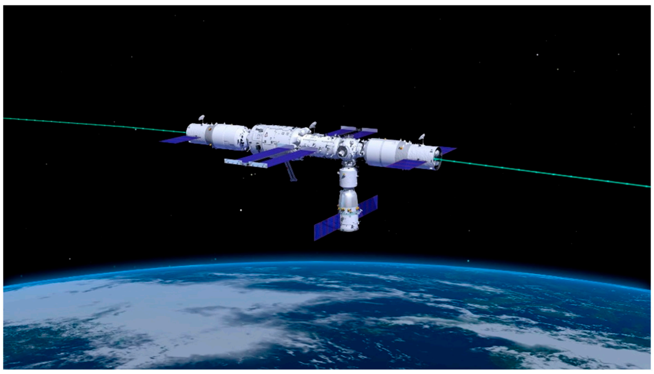

Fig. 28. TZ-2, TZ-3, and SZ-13 dock at the core cabin.

The comparison of space station cargo vehicles is shown in Table.

TZ has the comprehensive task ability of cargo uplink, waste downlink, combined support, and expansion test in the space station. The dragon can carry goods back to Earth and can be used repeatedly. TZ does not currently have these capabilities. After China's space station project enters the operation and application stage, the demand for efficient and low-cost cargo replenishment will become stronger. The high-value products that need to be sent back to the ground will increase rapidly in on-orbit production. It is an inevitable trend for the future to develop the return and reuse ability of TZ.

Discussion

Cargo spacecraft came into being with the space station. During the 40 years of development, various types of cargo spacecraft have been launched more than 200 times. It has experienced the gradual opening up from the state-led to the commercial private, the gradual development from a single freight uplink task to the return of goods, and even the return of passengers, from high redundancy and high reliability development mode to fast and low-cost mode.

Table. Comparison of space station cargo vehicles.

Space craft	Manufacturer	Launch system	Length (m)	Dry mass (kg)	Launch mass (kg)	Payload (kg)	Payload ratio	Payload volume (m^2)	Return payload (kg)	Diameter (m)	Generated power (W)
Progress-M 11F615A60	RSC Energeia	Soyuz-U	7.2		7,150	2,230	0.31	7.6	None	2.72	700
H-II Transfer Vehicle	JAXA	H-IIB	10	10,500	16,500	6,000	0.36	14 (pressurized, plus 16 unpressurised)	None	4.4	No solar arrays
Dragon Commercial Resupply Services	SpaceX	Falcon 9	6.1	4,200	10,200	3,310 pressurized or unpressurised in any mix	0.32	10.0 (pressurized), plus 14 (unpressurised), or 34 (unpressurised with extended trunk)	2,500 capsule return	3.7	2,000
Cygnus [4]		Antares	6.3	3,750	7,500	3,500	0.47	18.9	None	3.07	3,500
Automated Transfer Vehicle	Orbital Sciences Corporation	Ariane 5 ES	10.3	10,470	20,750	7,667	0.37	48 (pressurized)	None	4.5	3,800
TZ	China Manned Space	CZ-7	10.6	6,600	13,500	6,900	0.51	40.5 (pressurized)	None	3.35	2,700

JAXA, Japan Aerospace Exploration Agency; CRS, Commercial Resupply Services; ATV, Automated Transfer Vehicle.

As China's only current space cargo transport system, the main mission of TZ is still to serve China's manned space projects. TZ can meet the requirements of the current task. However, in line with the development trend of cargo spacecraft, these improvements have been put on the agenda to develop the spectrum and expand the task function.

1. The commercial computer information architecture is used to reduce power demand and cancel the expansion of solar wing to develop low-cost cargo spacecraft.

2. Based on the current 3 cargo cabins, a large capacity cargo cabin and reusable cargo cabin are designed.

3. The propulsion cabin is developed into the service module with different functions such as short propulsion cabin (reducing the number of tanks), high control precision propulsion cabin, and open loading propulsion cabin (loading large antenna, large cabin load, and releasing satellite).

4. Simplify the docking mechanism, reduce the type and number of rendezvous and docking sensors, expand the hatch diameter, and prepare for the overall transfer international standard payload rack.

5. Provide the potential for a robust, free, and repetitive platform for global rideshares, such as small satellite rideshares and scientific test devices.

Acknowledgments

Funding: This work was supported by China Manned Space Engineering Office. **Author contributions**: J.L. is the first author and is responsible for data analysis. D.J. is the corresponding author and conducted the literature review. M.B. is responsible for paper revision. Y.F. contributed to draft manuscript writing and grammar modification. X.L. offered many valuable help and 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. *Manned Spaceflight*. 2013;19(2):1–10.
2. Yang H. *Manned spacecraft technologies.* Beijing Institute of Technology Press, Beijing, China; 2021.
3. O'Sullivan J. *European missions to the International Space Station: 2013 to 2019*. Cham: Springer; 2020.
4. Seedhouse E. *SpaceX's Dragon: America's next generation spacecraft*. Cham: Springer; 2016.
5. Fibersim helps dragon into space. *Reinf Plast*. 2012;56(4):34–36.
6. Dreyer L. Latest developments on SpaceX's falcon 1 and falcon 9 launch vehicles and dragon spacecraft. Paper presented at: IEEE Aerospace Conference; 2009, Big Sky, MT, USA.
7. CL Davis, K Peek. Feasibility study for using Cygnus as a habitat in deep space exploration. Paper presented at: AIAA SPACE 2016; 2016 September 13–16; Long Beach, CA.
8. Castel F, Novelli A. *ATV, the European spaceship: Stories behind the scenes of an international success*. European Space Agency: Graphic design and layout; 2015.
9. Robinson J, Kwon D. *Small satellite rideshares on commercial resupply missions to the International Space Station*; 26th Annual AIAA/USU Conference on Small Satellites 2012;north logan.
10. Bogomolov NV, Anfalov AS, Borzykh SV, Bakulin VN. Simulation of process of small satellites separation from deployer installed on cargo spacecraft. *J Phys Conf Ser*. 2019;1392:012003.
11. Walz C. *Cygnus beyond low-earth orbit-logistics and habitation in cis-lunar space*. NASA; 2014.
12. Mingsheng B, Yong J, Jianyu L, Song W. Research and development of Tianzhou-1 cargo spacecraft. *Manned Space-Flight*. 2019;25:7.
13. Deng M, Xiao J. Tianzhou 1 cargo spacecraft leaves. *Orbit*. 2017;18(3):62.
14. Yan L, Liyan Z, Wei Z. Preliminary thought on solicitation of Space Station utilization proposals. *Manned Spaceflight*. 2021;27:8.
15. Qiang Z, Changqing C, Zongyu L. All-phase autonomous quick rendezvous and docking technology and in-orbit verification of Tianzhou-2 cargo spacecraft. *Aerosp Control Appl*. 2021;47:7.
16. Yu D, Lai S, Chen T. Review on integral stiffened shell structure technology of large space station. *Chinese Space Sci Technol*. 2011;31:31–40.
17. Dai H, Du R, Yuan W, Wang W, Zhao Q. Design and optimization of automatic conveying equipment for cargo bags of cargo spacecraft. *J Phys Conf Ser*. 2019;1237(2):022173.
18. Wen Z. China's first open cargo spacecaft carrying resources. *Guangming Daily*. 2021.
19. Yuan L, Yifei F. Tianzhou spacecraft carrying project for the first time facing the public collection. *Science and Technology Daily*. 2021.
20. Liang J, Jin H, Sun Y, Tian G. Design of a general flight experimental platform for spacecraft. Spacecraft environment. *Engineering*. 2011.
21. Chen H, Lee HW, Ho K. Space transportation system and infrastructure design for regular interplanetary cargo missions. Paper presented at: AIAA SPACE and Astronautics Forum and Exposition, Space 2017; 2017 September 12–14; Orlando, FL.
22. Jiang MW. Analysis of propellant refueling program for Russian Space Station. *J. Rocket Propulsion*. 2013;36(4):8–12.
23. Wang N, Huang Z, Jijun MA, Chen Q, Tian Y. Spacecraft power system design and application for the rendezvous and docking tasks. *Manned Spaceflight*. 2013;19(3):52–59.
24. Huang J. Experiment study of fluid loop system on manned spaceship. *Chinese Space Sci. Technol*. 2010;(01):65–71.
25. Elkman W, Trinh J, Mccaughey P, Chen W. *EMI/EMC, lightning, radiation shielding design approach for the Dragon COTS spacecraft: Part I*. IEEE; 2011:641–646.
26. Lei YU, Wang H, Wang L, Huijun LI, Dang R, Qzheng T. Research on high voltage direct power distribution system for spacecraft. *Manned Spaceflight*. 2017;23(6):770–775.
27. Long Y, Zhu K, Ding K, Chen S, Xia Y, Deng SF. *Design of space-ground integrated network for LEO spacecraft*. Space Electronic Technology; 2016;(4):67–72.
28. Qian YU, Zang WG, Yang DS, Yuan XX, Tian DB, Ren FY. On-orbit contamination detection data for "TZ-1" cargo spaceship. Equipment. *Environ Eng*. 2018.
29. Liu W, Zhu Z, Liu Q. Ground experiment study of evaporation phase change for space experiment device of TZ-1 cargo spaceship. *Chin J Space Sci*. 2016;36(4):481–486.

30. Wang X, Yan SU, Shi Y, Fan Y. Study on scheme of attitude control experiment based on the first cargo spaceship. *Manned Spaceflight*. 2015;21(1):37–42.
31. Haiyong H, Jiachuan L, Jiashen L. Research on comprehensive cost-effectiveness characteristics of cargo spaceship. *Manned Spaceflight*. 2021;27:8.
32. Liu W, Zhang Y, Li Z, Dong W. Control performance simulation and tests for microgravity active vibration isolation system onboard the Tianzhou-1 cargo spacecraft. *Astrodynamics*. 2018;2:339–360.
33. Lei X, Cao Y, Zhang Y, Qian J, Zhao Q, Liu F, Zhang T, Zhou J, Gu Y, Xia G, et al. Effect of microgravity on proliferation and differentiation of embryonic stem cells in an automated culturing system during the TZ TZ-1 space mission. *Cell Prolif*. 2018;51(5):e12466.
34. Mann A. Crewed launch deepens ties between NASA and SpaceX. *Science*. 2020, 368(6493):811–812.
35. Borisenko NY, Sumarokov AV. On the rapid orbital attitude control of manned and cargo spacecraft Soyuz MS and Progress MS. *J Comput Syst Sci Int*. 2017;56:886–895.
36. Barmin I, Bryukhanov N, Egorov A, Filatov I, Markov A, Senchenkov A, Tsvetkov V. Using the progress transport spacecraft 568 in structure of the international space station for realization of scientific experiments under microgravity conditions. *Acta Astronaut*. 2002;51(1–9):255–259.
37. Barmin IV, Egorov AV, Senchenkov A, Filatov IG, Bryukhanov N, Tsvetkov V. Utilisation of the 'Progress' Transport spacecraft as an element of the International Space Station for experiments under microgravity conditions. Paper presented at: Proceedings, first International Symposium on Microgravity Research & Applications in Physical Sciences and Biotechnology; 2000 Sep 10–15; Sorrento, Italy.
38. Ferkul P, Olson S, Urban DL, Ruff GA, Jomaas G. Results of large-scale spacecraft flammability tests. Paper presented at: Proceedings of the 47th International Conference on Environmental Systems, 2017 July 16-20, Charleston, South Carolina.
39. Ohkawa Y, Kawamoto S, Okumura T, Iki K, Horikawa Y, Kawashima K, Miura Y, Takai M, Washiya M, Kawasaki O, et al. Preparation for an on-orbit demonstration of an electrodynamic tether on the H-II transfer vehicle. *Trans Jpn Soc Aeronaut Space Sci Aerosp Technol Jpn*. 2016;14(sts30):Pb_1–Pb_6.
40. Ohkawa Y, Okumura T, Horikawa Y, Miura Y, Kawamoto S, Inoue K. Field emission cathodes for an electrodynamic tether experiment on the H-II transfer vehicle. *Trans Jpn Soc Aeronaut Space Aerosp Technol Jpn*. 2018;16:63–68.
41. Ohkawa Y, Okumura T, Kawamoto S, Kobayashi Y. Charging behavior of the H-II transfer vehicle by active electron emission. Paper presented at: IEEE Transactions on Plasma Science; 2019;47(8):3852–3857.
42. Koyari Y, Sasaki H, Suzuki Y, Yamanaka K, Dai A. Imada T. HTV Vehicle design and its first flight result. Paper presented at: International Conference of Pacific-Basin Societies; 2010;Montreal(CA).
43. Suzuki Y, Imada T. Concept and technology of HTV-R: An advanced type of H-II transfer vehicle. *Trans Jpn Soc Aeronaut Space Sci Aerosp Technol Jpn*. 2012;10:Tg_9–Tg_18.
44. Yo A, Sk A, To B, Ki B, Ho B, Ki C, Tu D, Dt E. Review of KITE—Electrodynamic tether experiment on the H-II transfer vehicle. *Acta Astronaut*. 2020;177:750–758.
45. Adams, J.H.; JR.; Young, R.M.; Olinto, A. JEM-EUSO design for accommodation on the SpaceX Dragon Spacecraft. Paper presented at: Proceedings of the 33rd International Cosmic Ray Conference; 2013 July 2–9; Rio de Janeiro, Brazil.
46. Hernandez B, Prina M, Piatrovich S. SpaceX Dragon Air Circulation System. Paper presented at: Proceedings of the 41st International Conference on Environmental Systems, 2011 July 17—21; Portland, OR.
47. Peek KE. *On-orbit spacecraft for lease: Uses for Cygnus after ISS resupply missions are complete*; AIAA SPACE 2015 Conference and Exposition; 31 Aug-2 Sep 2015;Pasadena, California.