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Review Article

Prospects for the Future Development of China's Space Transportation System

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At present, the world has developed to a new stage of large-scale access to space, which has put forward higher requirements for the development of space transportation. Facing the historical mission of building a space power, focusing on the construction of the China's space transportation system, this paper studied the development situation of the space transportation system in the world, summarized the development status of the China's space transportation, combined with future development requirements, and put forward prospects for the future development of the China's space transportation system.

1. Introduction

As the support and foundation for a country to carry out space activities, the space transportation system is an important symbol of its comprehensive national power [1]. After more than 60 years of development, especially with the applications of the new generation of launch vehicles represented by Long March 5 (see Figure 1), China's Long March series of launch vehicles have formed a complete product series, laying a solid foundation for the steady implementation of China's major projects such as Manned Spaceflight, Lunar Exploration, and Mars Exploration, and making remarkable achievements in rows. China attaches great importance to the development of China's aerospace industry and has put forward the strategic goal of "developing the space industry and building a space power".

Currently, the world spacefield has entered a new phase represented by large-scale internet constellation construction, space resources exploitation, manned lunar exploration, and large-scale deep space exploration [2]. Moreover, the demands for access to space are growing rapidly, which put forward higher requirements on space transportation systems. At the same time, with the development of new technologies such as artificial intelligence, recovery, new power, and materials, space transportation systems are also in a period with great opportunity for technological development.

Standing at a new historical point and facing the historical mission of building a space power, this paper presents the future development prospects of China's space transportation system (including expendable and recoverable launch vehicles and orbital transfer spacecraft) from the analysis of the development trend of space transportation systems in the world and development requirements of China.

2. The Development Achievements of China's Space Transportation System

China's space transportation system has made significant achievements that attract worldwide attention, realizing the leap from normal propulsion to cryogenic propulsion, from tandem to strap-on launch vehicle, from launching a single satellite to multiple satellites, from launching satellites to manned spacecraft, and from near-Earth orbit missions to deep space exploration, which has strongly promoted the development of national economy, science, technology, and national defense construction. In recent years, under the guidance of the goal of building a space power, China's space transportation system has made new achievements in products, technologies, and management.

In terms of products, a relatively complete product system of space transportation has been built. In the aspect of expendable launch vehicles, new generation launch vehicles such as LM-5, LM-6, and LM-7 have started to be applied for launch service, supporting the implementation of major projects and have placed China among top space powers (see Figure 2). In the aspect of operationally responsiveness

Figure 1: The LM-5 new generation launch vehicle.

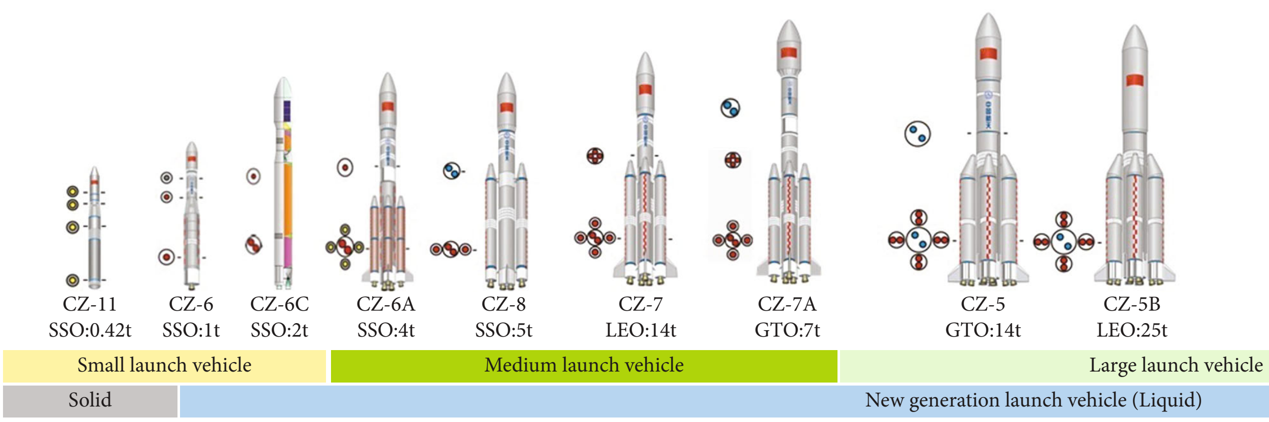
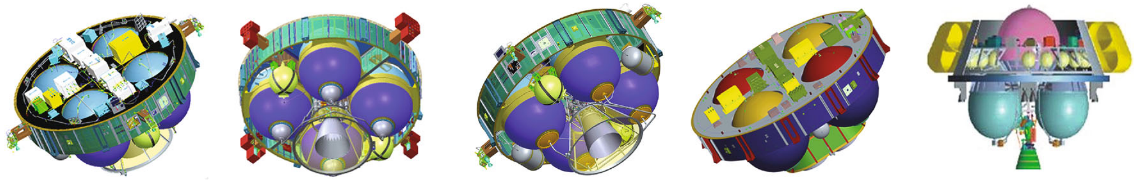


Figure 2: The new generation of LM series launch vehicles.

space, LM-11 has achieved a breakthrough in the Long March series of solid launch vehicles, with operationally responsive launch capability and launch preparation time of less than 24 hours. In addition, it achieved China's first sea launch, providing a new launch mode for China's entry into space. In the aspect of space transportation, two generations of orbital transfer transportation systems have been developed, which realized the leap from solid to liquid for the upper stage, and the "Yuan Zheng (YZ)" series upper stage family has been formed (see Figure 3), which played an important role in the global network construction of the BeiDou project. At present, China is continuing to carry out technical research on the new generation of manned launch vehicles, heavy launch vehicles, and cryogenic upper stages.

In terms of technological innovations, significant progress has been made in key technologies such as reusability and high specific impulse propulsion. Many breakthroughs have been made in reusable technology, such as the landing zone control with lattice, vertical takeoff and horizontal landing (VTHL), and horizontal takeoff and landing. In the aspect of propulsion, a series of important engines are being developed, including the 4800 kN high-pressure staged combustion cycle LOX-Kerosene engine, the complete assembly of the 2200 kN high-pressure staged combustion cycle LOX-LH2 engine, the 4.5 m diameter 500 t level large-thrust solid engine, and the 3.2 m



YZ-1 YZ-1A YZ-1S YZ-2 YZ-3

Figure 3: The configuration spectrum of YZ series upper stages.

diameter 3-stage large-thrust solid engine. The new generation of launch vehicles fully adopts the redundant design of control system based on 1553B bus. The 5 m-diameter launch vehicle structure has made significant achievements in the design, production, and manufacturing technologies. The application of Ka-band space-based measurement and control effectively supports the continuous improvement of rocket performance. Meanwhile, China is continuing to actively promote the research of smart launch vehicle technology to further enhance the comprehensive capability of space transportation system through intelligent technologies [3–7].

In terms of management improvement, substantial progress has been made in industrialization and commercialization. The launch vehicle batch-production project has been implemented, with products organized in batches for procurement, production and acceptance, and multiple rounds delivered for tests and launches on a rolling basis. The average annual launch times of Long March series launch vehicles have increased from 2-3 in the first three decades to 30-40 at present, and the launching success rate has also steadily increased. Particularly, the number of launches became the first of the world in 2018 and in 2019. Commercial spaceflights are booming. The number of the aerospace company is growing rapidly, and the fields involved the whole industry chain of launch vehicles. Several commercial companies have launched new launch vehicles for the commercial market and become a new growth point for the future development of space transportation systems [8].

3. The Development Tend of Foreign Space Transportation System

Recent years, with the increase in demand for large-scale access to space missions, the world's major space nations are continuing to develop reliable, low-cost, and efficient space transportation systems, and the capabilities and connotations of space transportation systems are changing.

Focusing on long-term development objectives, the world's major space nations are carrying out the development of next-generation launch vehicles, such as the Vulcan and New Glenn launch vehicles in the United States, the Ariane 6 launch vehicle in Europe, the Soyuz 5 launch vehicle in Russia, the H-3 launch vehicle in Japan, etc. They all pay attention to the optimization of the launch vehicle spectrum, while to achieving more prominent task adaptability and cost-effectiveness.

At the same time, heavy launch vehicles are developed for future manned lunar exploration, manned Mars exploration, and other significant space missions. The United States released the "Artemis" plan, which planned to return to the Moon with astronauts in 2024 and had long-term stationing capability after 2028. It also invested in the construction of the lunar orbiting space station "Deep Space Gate" and announced the implementation of manned Mars exploration in the 2030s [9–13]. The Russian National Space Group successively proposed the heavy launch vehicle program "Yenisei," which is scheduled to make its first flight in 2028 with a LEO capacity of 70 tons or more. SpaceX company is also progressing the development of the "Super Heavy-Starship," which can reach more than 100 tons of LEO capacity.

Reusable technology has become an important technical development direction for space transportation systems. The vertical takeoff and vertical landing (VTVL) recovery technology of SpaceX's Falcon-9 launch vehicle becomes more practiced and has achieved the first stage recycling dozens of times, and single module has succeeded in reusing up to nine times. ESA plans to adopt reusable technology on the next-generation Ariane launch vehicle and continues to develop the "Prometheus" engine and the "Semis" VTVL prototype, while the U.K. continues to work on the technology of the combination power "Sabre" engine and "Skylon" space shuttle. Japan and India plan to carry out experimental verifications of reusable technologies too [3–5].

With regard to the upper stage, ACES' upper stage is developing for the Vulcan launch vehicle of the United States by applying new technologies such as advanced cryogenic propellant evaporation control and Integrated Vehicle Fluids (IVF) to extend its in-orbit service time to several weeks. With the in-orbit refueling technology, it can significantly expand the existing design concepts and application modes of space transportation systems [14–17]. In addition, the MiTEx upper stage with normal propellants, developed in the United States, is powered by solar cells and has the ability to work in orbit for a long time [18, 19].

The rapid progress of artificial intelligence technologies has brought new momentum to the development of the aerospace field and has become an important research direction. It leads to continuous breakthroughs in technologies such as full life-cycle digital management, virtual design based on digital prototypes, rapid production and manufacturing, intelligent flight, and autonomous return control [6]. Space powers are also continuously developing Al-Li alloys and lightweight composites to improve the structural efficiency. The development of materials also promotes the upgrade of the structure products in launch vehicles. The performance of launch vehicles engines improves continuously. Space powers are developing high-performance LOX-Kerosene, LOX-LH_2, and LOX-CH_4 engine technologies to increase the launch efficiency. The Merlin-1D LOX-Kerosene engine of SpaceX has the thrust-to-weight ratio of up to 185. The RL-10B LOX-LH2 engine has the vacuum-specific impulse ups to 465 s. The Raptor LOX-CH4 engine has the vacuum-specific impulse of more than 370 s. All the three above engines have thrust depth adjustment capability.

The development tends can be summarized in the following:

(1) Upgrading and optimizing the launch vehicle spectrum and improving the cost-effectiveness by developing next-generation launch vehicles

(2) Increasing enter-space capabilities and supporting the implementation of manned deep space exploration missions by developing heavy launch vehicles

(3) Reducing the cost of entering space and improving market competitiveness by developing reusable technologies

(4) Expanding the upper stage application area to satisfy the demands for space transportation and space exploration missions by enhancing the orbital transfer capability and developing long-duration in-orbit technology

(5) Improving the reliability and efficiency of launch vehicles by applying new technologies such as intelligent design, lightweight structural design, and high-performance engines

4. Analysis of Development Demands

From 2021, China has already started the construction of a manned space station and faces the follow-up maintenance and operation management. Such missions as large-scale Internet Constellations (Chinese Starlink), In-orbit Service and Maintenance, Manned Lunar Exploration, large-scale Deep-space Exploration, large-scale Space Solar Power Station, and Manned Mars Exploration put forward higher requirements for China's space transportation system. At the same time, there is still a certain gap between China and other space powers in terms of reliability, launch efficiency, mission adaptability, launch cycle, and other core indicators of launch vehicle performance. There is also further improvement in terms of production capacity, test-launch mode, and launching interval. It is necessary to further benchmark the goal of Space Power and catch up with and surpass the world-class level.

To sum up, there are three main requirements for China's space transportation system.

(1) The coverage and comprehensiveness of the launch capacity, launch modes, and applications of China's space transportation system need to be further improved

(2) The comprehensive performance (such as launch period and cost) of China's space transportation system needs to be further improved

(3) The development, launch, and quality control capabilities of China's space transportation system needs to be further improved

5. Future Development Prospects

Aiming at the goal of building China into a space power nation, China will build a world-class level space transportation system based on China's development foundation. It is required to form a complete series of the new generation launch vehicle family, implement performance enhancement, commercial development, and digital transformation, apply reusable, intelligent technical means, add new functions, incorporate new elements, and realize the important transformation of China space transportation system from "perfection" to "strength", covers from "expendable" to "recovery," from "automation" to "artificial intelligence," from "task-driven" to "design demand-based" transformation.

5.1. Build a World-Class Level Product System

(1) Develop the new high-orbit launch vehicle by applying common modules and promote the development of a new generation of manned launch vehicle and heavy launch vehicle in 5 to 10 years, realize comprehensive upgrades, and fully form the capabilities of the new generation of launch vehicle

In response to the continuous increase in space capacity, and fill the gaps, China needs to promote the development of the new generation manned launch vehicle and heavy launch vehicle, and the replacement of the normal launch vehicles by the new-generation launch vehicles.

The first is to develop the new high-orbit launch vehicle with common modules to satisfy the requirement of GTO capacity more than 7 tons and to support the implementation of manned lunar exploration missions, which is required to achieve the first flight of a new generation of manned launch vehicles by 2025. Through advanced layout, strategic planning, and step-by-step implementation of the strategy of task priority, carry out the replacement of conventional propellant launch vehicles in service, making the new generation of launch vehicles become the main force into space.

The second is to support the implementation of major tasks such as the construction of a manned lunar base, and it is required to achieve the first flight of a heavy launch vehicle by 2030. The capability of the new generation launch vehicle is fully formed, and the upgrade of conventional toxic propellant launch vehicle has been fully completed.

(2) Continue to advance the technical research and test verification of the reusable space transportation system, accelerate the process of engineering application, and realize the flight transportation

Reusable launch vehicle is an important development direction of space transportation technology, and a quick, economically effective way to enter space. At present, China is actively advancing the deepening demonstration, key technical research, and flight test missions of the reusable of space transportation systems. The engines in recovery launch vehicle should be reused after simple treatments and the structures of the recovery launch vehicle are designed to consider more factors such as fatigue.

The first is to realize the recovery of the first stage of the launch vehicle by 2025. The key technologies for horizontal landing will be initially verified in 2021, and horizontal and vertical landing technologies will be further verified by 2025, which will initially form the ability to quickly and economically enter space.

The second is to achieve complete reuse of launch vehicles by 2035. The number of repeated use reaches 10-50 times, forming the basic ability to quickly respond to entering the space and returning on demand.

The third is to establish a full flight-based space transportation capability by 2045. The repeated use of space transportation system technology is continuously upgraded, new technologies such as intelligent configuration, new materials, and combined power are widely used, and single-stage orbit technology has achieved breakthroughs.

(3) Vigorously develop high-performance space transportation technology, achieve a substantial increase in China space transfer and transportation capacity, and gain the initiative in the future competition of large-scale space resource development and utilization

The development and utilization of large-scale space resources (such as SSPS) have become a reality. China will vigorously develop efficient and environmentally friendly cryogenic space transportation systems and new power space transportation systems represented by high-power electric propulsion and nuclear power and gradually increase large-scale and multiple orbital changes. The ability and long-term on-orbit ability expand the application fields of high-performance space transportation systems; promote the research and engineering practice of upper-level orbital applications to realize the redevelopment of the ability to enter space. The high-performance space transportation system adopts design ideas with modularization, integration, integrated, and intelligence.

The first is to have long-term on-orbit, multiton round-trip transportation capacity by 2025. Key technologies such as cryogenic propellant evaporation control in orbit achieve breakthroughs, and the long-term in-orbit flight test verification (more than a week) of the cryogenic space transportation system will be completed.

The second is to have a larger-scale high- and low-orbit reusable transportation and space-based launch capabilities by 2035. Key technologies such as low-temperature propellant on-orbit refueling achieve breakthroughs, and on-orbit refueling, maintenance, and modular replacement will be realized.

The third is to form a series of space transportation system products by 2045. Small nuclear-powered engine technology for nuclear thermal power engine with high-reliability and high-safety achieves breakthrough, and the on-orbit flight verification of nuclear propulsion and other new power space transportation systems will be completed.

5.2. Build a World-Class Level Technology System

(1) By changing design concepts, innovating the standard system, improving basic understanding, and breaking through common technologies, the overall performance of China aerospace transportation system can be improved, and it can catch up with the world-class level

The new generation of launch vehicle represented by the LM-5 embodies the highest level of China's current launch vehicle, and its comprehensive performance indicators such as capacity, efficiency, and reliability have reached the forefront of the world. To meet the needs of building a world-class level space transportation system and to improve the overall performance of China launch vehicle as a whole, it is necessary to carry out special research on design concepts, design standard systems, basic issues, and common bottleneck technologies, and increase advanced design technologies, new material (such as Al-Li alloy and composite materials) and new technology research and application.

The first is to raise the comprehensive performance of China's space transportation system to the world-class level by 2025. Preliminarily build an advanced design standard system, grasp a batch of common basic problems and bottleneck technologies in advance, upgrade the design method and concept, and achieve a substantial increase in the design and development level of China launch vehicle.

The second is to lead the comprehensive performance of China's space transportation system to surpass the world-class level by 2035. Comprehensively build an advanced design standard system, fully grasp relevant common basic problems and bottleneck technologies, and further enhance the original innovation capabilities.

(2) Realize breakthroughs in fault diagnosis and fault-tolerant reconstruction technology and engineering applications, combined with the development of a new generation of the manned launch vehicle to move toward a smart space transportation system

"Aerospace+artificial intelligence" is an important direction for the development of the aerospace transportation system in the future, and the rapid progress of intelligent technology has brought new momentum to the development of the aerospace field. At present, China is actively exploring the technology of intelligently empowering aerospace transportation systems and is striding forward to the goal of fully realizing intelligent design and manufacturing, building intelligent rockets, and building intelligent management.

The first is to greatly improve the reliability and flight success rate of launch vehicles by 2025. Realize the fault tolerance and mission reconfiguration capabilities of the existing launch vehicle against typical failures and the unattended test launch of the cryogenic liquid launch vehicle by applying the automatic docking technology.

The second is to achieve the "preparation-ignition-flight-into orbit" all-up smart design with information fusion and artificial intelligence to satisfy the requirements of more reliability and safety for the next generation smart launch vehicle. Comprehensively build an intelligent aerospace transportation system ecosystem including development and verification, production and manufacturing, testing and launch, and flight and evaluation.

(3) Continuously improve China aerospace propulsion technology capabilities and levels, improve the performance level of active engines, develop new propulsion technologies, and vigorously support the rapid development of China aerospace transportation system

The power system is an important support for the space transportation system, and its capability level has an important impact on the overall performance of the aerospace transportation system. At present, China's aerospace propulsion technology capabilities and levels need to be continuously improved.

The first is to improve the performance of in-service engines by 2025. In view of China's current rocket engines, continuous improvements and enhancements have been implemented in key performance indicators such as specific impulse, thrust-to-weight ratio, and thrust adjustment capability. Moreover, it is also required to solve the key problems such as engine multi-ignition and the low-starting pressure on the turbine inlet for engine restart. These will strongly support the overall performance of China's new generation of launch vehicles constantly.

The second is to apply new high-thrust (round 500 t) and reusable engines by 2035. Carry out the development of high-thrust liquid oxygen kerosene, liquid oxygen liquid hydrogen engines, and high-thrust solid engines; continuously promote the development of reusable liquid oxygen hydrocarbon engines and combined power technologies; and support the rapid development of heavy launch vehicles and reusable vehicles.

The third is to break through the advanced propulsive technology and make applications in launch vehicles before 2045. Continue to carry out research on new power technologies such as high-power electric propulsion, detonation propulsion, and nuclear propulsion to revolutionize the ability of the space transportation system to lay a solid foundation for the development and utilization of large-scale space resources in the future and manned exploration in farther space.

5.3. Establish a World-Class Level Organization and Production Mode

(1) Improve the launch vehicle development system, adopt large-scale production mode, realize mass production of launch vehicles, establish pulsating production line, and further improve production efficiency and quality

With the increasing demand of China's capability into space, higher requirements are put forward for the development and production capacity of space transportation system. Adopting large-scale production and advanced production technology, reducing cost, and improving efficiency and quality are the future development trend.

The first is to improve the construction of intelligent and digital general assembly and testing production line of launch vehicle, adopt test calibration, intelligent monitoring and other equipment, and form the technical capabilities of electronic general assembly documents, operation visualization, inspection digitization, etc., so as to realize accurate and rapid assembly and testing and improve production efficiency and production quality.

The second is to establish and improve the production management system of launch vehicle. It will adopt the large-scale production mode, realize the mass production of launch vehicle, reduce the cost, and improve the product quality. The pulsating production line will be established to meet the high-density demand for the launch vehicle production.

(2) Implement the concept of commercial development, follow the market rules, meet the needs of the commercial aerospace launch market, promote the industrialization development of aerospace transportation system, and comprehensively enhance the popular service experience of commercial aerospace

With the continuous development of space technology and the ever-expanding scale of the aerospace industry, commercial aerospace such as commercial launch vehicle, low-orbit Internet constellations, suborbital tourism, and commercial remote sensing has been rapidly promoted. The development of the commercial aerospace industry and the improvement of aerospace technology are of great significance to support the space power construction.

First of all, China should implement the concept of commercialization development, follow the market rules and provide users with systematic solutions. It has been also required to continuously improve the product and service system and promote the transformation of aerospace research and development model from pursuing scientific research results to satisfying market demands. Furthermore, the successful transformation of commercial aerospace should be promoted from technological success to equal emphasis on technology, market, and efficiency, so as to realize the organic connection of technology, market, and benefit.

Secondly, low-cost commercial launch vehicles represented by the SD (smart dragon) series, LM-11 series, and LM-8 need to be developed. To provide high-quality services for commercial payloads, high-quality products with "high cost-effectiveness, high reliability, fast performance, and fast launch" are required. Continuously, we need to explore a new test-launch management mode, implement a new business operation mode, improve comprehensive competitiveness, and meet the needs of the public.

(3) Fully implement a digital transformation, achieve collaborative and efficient development, standardized and precise management, data sharing and scientific

decision-making intelligence, then promote high-quality, high-efficiency, and high-benefit development

To accelerate the construction of a world-class level space transportation system, it is necessary to seize the great opportunities of digital transformation and use digital transformation as an important means to upgrade traditional energy and cultivate new development energy. It is also required to comprehensively promote the construction of digital aerospace and enhance core competitiveness and value creativity, then to promote high-quality, high-efficiency, and high-benefit development.

First of all, model and data-driven digital system of scientific research and production should be constructed to improve the level of launch vehicle development. The system engineering method based on model is adopted to improve the digital collaborative development environment of aerospace model products, strengthen the applications of virtual design and simulation verification, and improve the design efficiency.

Secondly, a digital management system with big experimental data applications as the core needs to be built to improve the level of strategic management and control. Based on advanced technologies such as cloud computing, big data, and artificial intelligence, a unified management and control platform is built to achieve centralized management and control the factors of human, financial, and material. It will comprehensively improve the level of strategic management and control by deepening the application of big data intelligent analysis, carrying out quantitative analysis, and predicting and early warning of management business based on big data.`.

6. Summary

Standing at a new historical node, facing the new requirements, opportunities, and challenges, we must have the courage to assume, seize opportunities, continue to innovate, and make breakthroughs. Based on China's national conditions and the strategic development needs, China aerospace plans to carry out the launch vehicle spectrum optimization, performance improvement, commercial development, and digital transformation, by adopting technical methods such as recovery and artificial intelligence, adding new functions and integrating new elements, to achieve the cross development of China's space transportation system, build a world-class level space transportation system, and support the space power construction.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this article.

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