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Challenges and Countermeasures for Commercial Space Management

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Abstract: *Against the backdrop of the booming global aerospace industry, China's commercial aerospace sector has also made significant progress. This article deeply and comprehensively analyzes the current situation of commercial aerospace management in China, and clearly demonstrates the phased achievements made through a large amount of data and practical cases. At the same time, it also focuses on exploring the severe challenges and prominent issues faced in multiple key areas such as technological security, policy completeness, and sustainable development. In terms of technical security, how to ensure that core technologies are not stolen and respond to complex network attack threats; How do gaps and lagging policies and regulations hinder industry development in terms of policy completeness; At the level of sustainable development, issues such as rational utilization of resources and long-term market stability urgently need to be addressed. In response to these issues, this article conducts in-depth research and proposes a series of targeted and actionable response strategies, aiming to provide suggestions and recommendations for China's commercial aerospace to achieve high-quality development and successfully enter the world, and to help China's commercial aerospace occupy an important position on the international stage.*

Keywords: *Commercial Aerospace, Commercial Aerospace Management, Technological Safety, Green Aerospace*

1. Introduction

Globally, the commercial space industry is booming at an unprecedented pace. Since the 1990s, with advancements in technology and gradual policy liberalization, the commercial space industry has rapidly grown from its nascent state into a force to be reckoned with in the aerospace field. Today, the commercial space industry encompasses multiple segments, including satellite manufacturing; launch services, satellite applications, and construction of relevant basic facilities, forming a vast and complex industry chain.

In terms of market size, the commercial space industry is experiencing explosive growth. According to relevant data, over the past decade, the global commercial space market has been increasing at an annual rate exceeding 10%. In 2023 alone, revenues of the global commercial space industry surpassed USD 460 billion, and this figure is projected to exceed USD 700 billion by 2030. In the field of satellite launches, the proportion of commercial launches continues to rise, with more and more satellites being sent into space to meet diverse requirements such as communications, remote sensing, and navigation. In terms of satellite applications, communication satellites provide stable communication services globally, especially in remote areas and oceans where ground communications are difficult to cover; remote sensing satellites are widely applied in fields such as agricultural monitoring, weather forecasting, and resource exploration, providing important data support for various industries.

China's commercial space industry has also made remarkable progress. In recent years, the government has introduced a series of encouraging policies, creating a favorable policy environment for the development of the commercial space industry. Guided by these policies, a large amount of social capital has poured into the commercial space field, promoting the rapid development of the industry. In 2023, China's social capital investment in the aerospace field approached RMB 6 billion, with a total of 26 commercial launches completed throughout the year, accounting for nearly 40% of China's annual launches and achieving a 96% success rate. The construction of the Hainan International Commercial Space Launch Site is also steadily progressing, with the first launch pad officially completed and the second pad under accelerated construction. Each pad will have an annual launch

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capacity of 16. Numerous private aerospace enterprises have emerged like bamboo shoots after a spring rain, actively advancing in areas such as technological innovation and business model exploration, injecting new vitality into China's commercial space industry.[1]

Against this backdrop, conducting in-depth research on commercial space management is of utmost importance. Effective management helps optimize the allocation of commercial space resources and improve the overall efficiency of the industry. In the satellite manufacturing segment, scientific management allows for reasonable arrangement of R&D resources, accelerating the development of new satellites and enhancing their performance and quality; in the field of launch services, optimizing management processes can reduce launch preparation time, lower launch costs, and improve launch reliability. Reasonable management can mitigate the risks of commercial space activities. Space activities are inherently high-risk, with uncertainties in every stage from satellite design and manufacturing to launch and operation. Through a comprehensive risk management system, various risks can be effectively identified, assessed, and addressed, ensuring the smooth progress of projects. From a macro perspective, strengthening commercial space management plays a crucial role in safeguarding national security and promoting national economic development. In terms of national security, communication satellites, remote sensing monitoring, and other services provided by the commercial space industry can enhance the country's information acquisition and monitoring capabilities, providing strong support for national defense security; As far as the national economy is concerned, the development of the commercial space industry can drive the coordinated development of relevant industries such as electronic information, materials science, and mechanical manufacturing, promoting industrial structure upgrading and creating more economic growth points.

2. Challenges Faced by Commercial Space Management

2.1 Technological Risks and Safety Challenges

2.1.1 Technological reliability dilemma

Commercial space activities highly rely on complex and advanced technological systems; however, technological reliability issues have always been a "sword of Damocles" hanging over the industry. In the field of rocket launches, technological failures can lead to extremely serious consequences. On December 27, 2024, during the execution of a launch mission, the Kinetica-1 Y6 Launch Vehicle experienced normal flight in the first and second stages, but approximately 3 seconds after the third-stage engine ignition, the attitude became unstable, and the onboard autonomous safety control system initiated self-destruction. This launch failure not only resulted in the inability of the 11 satellites onboard to enter their intended orbits, causing satellite operators to face huge economic losses, but also severely damaged the reputation of CAS Space, affecting its subsequent commercial collaborations and project progress. The Japanese commercial space company "Space One" also suffered a setback during the launch of a small solid-fuel rocket on December 18, 2023. The rocket encountered problems shortly after liftoff, resulting in launch failure. This incident dealt a heavy blow to the development of Japan's commercial space industry and greatly impacted investors' confidence in it.[2]

These cases fully demonstrate that insufficient reliability of key technological components such as rocket engines, flight control systems, and navigation systems can lead to rocket launch failures, causing incalculable economic losses and reputational damage. In satellite manufacturing, technological reliability issues cannot be overlooked either. Satellites need to operate stably in space for extended periods, facing numerous challenges such as extreme temperature changes, radiation environments, and micrometeoroid impacts. Electronic components of satellites may malfunction due to radiation, causing partial failure of satellite functions; if the satellite's power system experiences problems, such as decreased performance of solar panels, it will affect the satellite's power supply and jeopardize its normal operation. According to statistics, approximately 10%-15% of satellites retire prematurely within their design lifespan due to technological failures, not only wasting a large amount of resources but also reducing the investment return rate of the commercial space industry.

2.1.2 Imperfect safety assurance system

Currently, the safety assurance system of the commercial space industry still has many deficiencies, making it difficult to fully meet the requirements of the industry's rapid development. In terms of safety standards, although there are some general international spaces safety standards, these standards are often broad and lack detailed regulations tailored to the specific requirements and characteristics of the commercial space industry. Safety standards also vary among different countries and regions, which

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brings many inconveniences to the development of cross-border commercial space projects.[3] For example, countries have different standards for setting the safe distance for satellite launches, causing uncertainties for satellite launch sites in planning and operations, increasing safety risks.

There are also loopholes in the supervision system of the commercial space industry. The commercial space industry involves multiple departments and fields, including aerospace, communications, and transportation, yet currently, there is a lack of a unified and efficient supervision coordination mechanism. This leads to unclear responsibilities and buck-passing phenomena in the actual supervision process, making it impossible to conduct comprehensive and effective supervision of commercial space activities. The qualification review and daily supervision of commercial space enterprises are not strict enough, and some enterprises with insufficient technological capabilities and safety management abilities may enter the market, increasing the hidden dangers of safety accidents. In the satellite operation stage, the management of satellite orbits is not refined enough. With the large-scale deployment of low-Earth-orbit satellite constellations, the risk of collisions between satellites is increasing. According to predictions by the European Space Agency, by 2030, the quantity of space debris in Earth's orbit will increase by 50%, posing a serious threat to the safe operation of satellites.

2.2 Legal and Policy Dilemma

2.2.1 Lagging domestic regulations

In China, the lagging issue of commercial space regulations has become increasingly prominent, significantly constraining the healthy development of the industry. From the perspective of market access, current regulations are inadequate in many aspects. Relevant regulations lack clear, quantified, and operational standards for reviewing the qualifications of commercial space enterprises. This makes it difficult for enterprises to accurately determine whether they meet the requirements when applying for access, resulting in an uncertain application process and increasing the time and cost for enterprises. In some emerging commercial space fields, such as the construction of satellite internet constellations, due to the lack of targeted access regulations, enterprises face numerous policy obstacles in project planning and advancement, unable to carry out relevant businesses in a timely manner.[4]

In terms of equity protection, domestic regulations also fall short. The commercial space industry involves a large amount of intellectual property, such as satellite manufacturing technology and aerospace software algorithms, but existing intellectual property protection regulations are inadequate in adapting to the characteristics of the commercial space industry. For intellectual property infringement unique to the aerospace field, there is a lack of clear definitions and effective punishment measures, making it difficult for enterprises' innovation achievements to receive full legal protection and weakening their enthusiasm for investing in research and development. In the collaboration process of commercial space projects, the handling of contractual disputes also faces the issue of imperfect regulations.[5] Aerospace project contracts are usually complex and long-term, involving multiple interests and numerous technological details, but current regulations lack specific provisions and guidance for handling such contractual disputes, resulting in a lengthy and uncertain dispute resolution process and increasing commercial risks for enterprises.

2.2.2 International legal conflicts

With the increasing trend of globalization in commercial space activities, cross-border commercial space activities face severe challenges of international legal differences and conflicts. Different countries and regions have formulated their own unique commercial space laws and supervision policies based on their political, economic, and security considerations. In terms of satellite frequency and orbital resource allocation, although there are certain international rules and procedures, there are significant differences among countries in the actual implementation process. The International Telecommunication Union (ITU) is responsible for managing the allocation of satellite frequency and orbital resources, but due to complex application procedures and limited resources, competition among countries is fierce. Some countries may adopt certain measures that do not comply with international rules in order to seize resources, leading to constant international disputes. In terms of cross-border transmission of satellite data, there are huge differences in privacy protection and data security regulations among countries. Some countries have strict restrictions on data export, requiring data to be stored within their borders or undergo rigorous approval procedures for cross-border transmission, while other countries are relatively lenient. This poses complex legal compliance issues for commercial space enterprises when providing global satellite data services.[6]

International law is not yet fully developed in some areas of the commercial space field, with many

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ambiguities. For example, there is currently no unified and clear international legal framework for the development and utilization of space resources. Although the Outer Space Treaty stipulates that outer space cannot be appropriated, it lacks specific regulations on the ownership and development rights of space resources. This leads to different understandings and practices among countries regarding the development of space resources in commercial space activities, easily triggering international disputes. Commercial space enterprises face enormous legal risks when conducting cross-border business and need to invest significant resources to comply with the legal requirements of different countries, which to some extent hinders the internationalization process of commercial space development.

2.3 Sustainable Development and Environmental Issues

2.3.1 Space debris and orbital resource occupation

As commercial space ventures become more common, the amount of debris in orbit is rising swiftly, seriously occupying orbital resources and becoming a key bottleneck restricting the sustainable development of the commercial space industry. Space debris, including abandoned satellites, rocket remnants, and various fragments, orbits at extremely high speeds, posing an immeasurable safety threat to the normal operation of spacecraft, like "space bullets". According to statistics from the European Space Agency, as of 2024, the quantity of space debris larger than 10 cm in diameter in Earth's orbit has exceeded 34,000, while debris between 1-10 cm in diameter amounts to millions. The presence of this space debris greatly increases the risk of spacecraft collisions. In the event of a collision, not only will the spacecraft be damaged, but more fragments will be generated, further exacerbating the harm of space debris and forming a vicious cycle.[7]

In geostationary orbit, the orbital resource is extremely limited and has important strategic value, yet the accumulation of space debris is posing an increasingly severe challenge to this orbit. Geostationary orbit is located approximately 36,000 km above the equator and can provide stable services for satellite communications, weather monitoring, and more. However, due to the existence of space debris, available orbital positions are gradually decreasing, making it increasingly difficult to deploy new satellites. Some space debris has an orbital lifespan of several decades or even a century, occupying orbital resources for a long time and imposing many restrictions on commercial space enterprises when planning satellite launches and orbital deployments. It is predicted that if effective measures are not taken to reduce space debris, by 2050, the available space in geostationary orbit will decrease by more than 50%, which will have a tremendous impact on fields such as global communications and weather forecasting.

2.3.2 Balancing environmental requirements and costs

In commercial space activities, there is a complex contradiction between meeting increasingly stringent environmental requirements and controlling costs, posing a huge challenge for enterprises. As international society pays more attention to environmental protection, the commercial space field also faces increasingly strict environmental regulations and standards. In the rocket launch process, the combustion of rocket fuel produces a large amount of exhaust gas, including pollutants such as nitrogen oxides and sulfur oxides, causing pollution to the atmospheric environment. To reduce the emission of these pollutants, enterprises need to adopt more environmentally friendly fuels or install exhaust gas purification equipment. However, these environmental measures often require substantial financial investment.[8] Adopting new environmentally friendly fuels may require redesigning and developing rocket engines, involving a large amount of human, material, and financial resources; installing exhaust gas purification equipment will also increase the weight and complexity of rockets, thereby increasing launch costs.

The manufacturing and operation processes of satellites also face the issue of balancing environmental requirements and costs. In the satellite manufacturing process, using environmentally friendly materials and processes can reduce the impact on the environment, but environmentally friendly materials are usually more expensive, and production processes may be more complex, leading to a significant increase in satellite manufacturing costs. In the satellite operation stage, to ensure that satellites do not become space debris after the end of their lifespan, enterprises need to take effective de-orbiting measures, such as using propellants to push satellites out of orbit and burn them up in the atmosphere. This requires equipping satellites with additional propellants and control systems, increasing the weight and cost of satellites. For commercial space enterprises, how to effectively control costs while meeting environmental requirements and maintaining enterprises' profitability and market competitiveness, is an urgent problem to be solved.

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3. Optimization Strategies for Commercial Space Management

3.1 Synergy between Technological Innovation and Safety Management

3.1.1 Increasing investment in technology research and development

Increasing investment in technology research and development is a key driving force for promoting the coordinated development of technological innovation and safety management in the commercial space industry. The government plays a crucial guiding role in this process and can formulate a series of targeted policy measures to inject strong impetus into the research and development of commercial space technology. Establishing special scientific research funds is one of the most effective means. For example, the "Special Fund for Technological Innovation in Commercial Space" can be set up, with the government allocating hundreds of millions of RMB from the annual fiscal budget specifically to support key technology research and development projects in the commercial space field, such as new rocket engine technology and high-precision satellite attitude and orbit control technology. The government can also introduce tax incentive policies to provide a certain percentage of tax reductions and exemptions for research and development investments made by commercial space enterprises. Funds invested by enterprises in research and development are eligible for a 150% pre-tax deduction, which will effectively reduce the tax burden on enterprises and encourage them to increase research and development investments.[9] Through government guidance, the enthusiasm of commercial space enterprises to increase research and development investments can be stimulated, prompting enterprises to invest more funds in technological innovation.

Commercial space enterprises themselves should also deeply recognize the importance of technology research and development investment and make it a core strategy for enterprise development. Enterprises can set aside a certain percentage of funds from their business revenue to establish a dedicated research and development fund. Powerful commercial space enterprises can allocate 10%-15% of their annual business revenue to research and development funds to ensure the stability and sustainability of research and development investments. In terms of fund allocation, enterprises should focus on key fields such as reusable rocket technology and satellite safety protection technology. In the research and development of reusable rocket technology, increase investment in technologies such as reusable design of rocket engines and precise control of rocket landing to improve the reusability of rockets and reduce launch costs. In the research and development of satellite safety protection technology, invest funds to study satellite anti-radiation materials, satellite collision warning systems, etc., to enhance the safety and reliability of satellites in space. Through continuous research and development investment, enterprises can constantly improve their technological level and core competitiveness.

3.1.2 Establishing safety standards and supervision systems

Establishing unified and comprehensive safety standards and supervision systems is an important guarantee for ensuring the safe operation of commercial space activities. In terms of formulating safety standards, advanced international experience should be fully drawn upon, and based on the actual situation of China's commercial space development, safety standards with scientific, practical, and operational characteristics should be formulated. In terms of satellite launch safety standards, clear regulations should be made regarding the requirements for the selection of rocket launch sites, safety design standards for launch facilities, standards for launch operation procedures, etc. Rocket launch sites should be far away from densely populated areas and have good geological and meteorological conditions; launch facilities should have complete safety protection measures such as fire prevention, explosion prevention, and lightning protection; launch operation procedures should be strictly carried out in accordance with standardized procedures to ensure the safety and reliability of the launch process. For satellite operation safety standards, standards for satellite orbit management and emergency response to satellite failures should be formulated. The operation rules for satellites in orbit should be clarified to avoid collisions between satellites; and the emergency response process for satellite failures should be regulated to ensure that satellites can promptly resume normal operation or take safe de-orbiting measures.[10]

To ensure the effective implementation of safety standards, supervision must be strengthened, and a sound supervision mechanism must be established. It is imperative to establish a dedicated commercial space supervision institution, which should have independent law enforcement power and supervision capabilities, and be responsible for comprehensive and in-depth supervision of commercial space activities. The supervision institution should strengthen the qualification review of commercial space

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enterprises, strictly reviewing the technological strength, safety management capabilities, and financial status of enterprises to ensure that only enterprises meeting the joint venture qualification requirements can enter the commercial space market. This study strengthens the supervision of the whole process of commercial space projects, from project planning and design, construction and implementation to operation and maintenance, to strict supervision and inspection. In the project planning and design phase, it reviews the project safety design plan to meet the safety standards. During the construction implementation phase, it supervises whether the enterprise carries out construction and equipment installation in accordance with safety standards. In the operation and maintenance stage, it regularly check the implementation of the enterprise security management system and equipment operating status, and timely discover and eliminate security risks. A reporting and reward mechanism should also be established to encourage the public to report unsafe behaviors in commercial space activities, with material rewards given for verified reports, creating an atmosphere of safety supervision participated by the whole society.

3.2 Improving the Legal and Policy Ecosystem

3.2.1 Revising domestic regulations

Revising domestic regulations is an important cornerstone for improving the legal and policy ecosystem of the commercial space industry and plays an irreplaceable key role in promoting the healthy and orderly development of the commercial space industry. In terms of market access, a clearer, more reasonable, and forward-looking regulatory system should be constructed. The qualification review standards for commercial space enterprises should be further refined, and detailed and quantified assessment rules should be formulated based on multi-dimensional indicators such as enterprises' technological strength, funding scale, talent reserve, and management level. For enterprises applying to engage in satellite manufacturing, the technological capabilities and relevant experience required in areas such as satellite overall design, electronic component research and development, and manufacturing processes, should be clarified; for enterprises providing launch services, the technological specifications of their launch vehicles, safety standards for launch sites, and professional qualifications of launch operation teams should be regulated. Efforts need to be made to establish a risk assessment mechanism to comprehensively assess the technological risks, safety risks, market risks, etc. that enterprises may face in the project implementation process, ensuring that only enterprises with the corresponding risk response capabilities can enter the market. Through these measures, the scientific nature and transparency of market access can be improved and the access costs and uncertainties for enterprises be reduced.

In terms of property rights protection, relevant regulations need to be further improved to strengthen the protection of intellectual property in the commercial space industry. In view of the unique technological characteristics and innovation achievements of the aerospace field, the ownership and protection scope of intellectual property should be clarified. For core intellectual property such as satellite manufacturing technology, aerospace software algorithms, and new material applications, special protection clauses should be formulated and the crackdown on infringement activities should be strengthened. Compensation standards for infringement should be increased to fully compensate right holders for their losses and act as a strong deterrent against infringement. Additionally, efforts should be made to establish a fast and efficient mechanism for resolving intellectual property disputes, to establish a special court for intellectual property in commercial space, to staff it with professional judges and technology advisors, and to improve the efficiency and fairness of dispute resolution. It is also recommended to strengthen the management and service of intellectual property, establish and improve intellectual property information platforms, provide enterprises with one-stop services such as intellectual property inquiry, assessment, and transaction, and promote the reasonable flow and effective utilization of intellectual property.[11]

3.2.2 Participating in the formulation of international rules

Actively participating in the formulation of international rules is a key measure for China to safeguard national interests and enhance its international voice in the commercial space field. In international collaboration, China should fully leverage its technological advantages and market potential in the commercial space field, strengthen exchanges and collaboration with other countries, and jointly explore the formulation of international rules that align with the interests of all countries. In terms of satellite frequency and orbital resource allocation, China should actively participate in relevant meetings and consultations of the International Telecommunication Union (ITU), put forward reasonable allocation plans and suggestions, and strive for a larger share of resources, so as to promote

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the establishment of a fair, transparent, and efficient resource allocation mechanism to avoid excessive concentration and waste of resources. It should also strengthen collaboration with other countries in satellite frequency coordination and orbit management, and through technological means and negotiation mechanisms, reduce the interference and collision risks between satellites.

In the formulation of rules for the development and utilization of space resources, China should actively participate in discussions and research in the international community and put forward concepts and plans with Chinese characteristics. It should uphold the principle of peaceful utilization of space resources and emphasize that the development of space resources should serve the common interests of all mankind; promote the establishment of an international collaboration mechanism for the development of space resources, encourage countries to collaborate in space resource development projects, and achieve resource sharing and mutual benefit; and strengthen the research, development, and innovation of space resource development technology, improve its own technological level and competitiveness in the field of space resource development, and strive for more say in the formulation of international rules. Through active participation in the formulation of international rules, China can better safeguard its national interests in the commercial space field, promote the internationalized development of the commercial space industry, and make greater contributions to the prosperity of the global commercial space industry.

3.3 Promoting Sustainable Development and Environmental Protection Initiatives

3.3.1 Research and development of space debris removal technology

The research and development of space debris removal technology is urgently needed, as it is a core measure to solve the problem of space debris proliferation and ensure the sustainable development of commercial space. Currently, various countries have made a series of explorations in this field, and many innovative technologies have emerged. The "laser broom" technology is one of them, which uses the light pressure generated by lasers to precisely push away small debris or vaporize space debris through heat. This technology is particularly suitable for cleaning up space debris with diameters between 1 and 10 cm, providing an effective means to remove this type of debris that is large in quantity and more harmful. Japan's "Space Debris Removal Satellite" adopts a different approach, releasing robotic arms or tethers to capture abandoned satellites and larger space debris. The robotic arms, like flexible "giant hands in space," can accurately grab the target debris, while the tethers can be used to wrap and secure the debris, dragging it away from its current orbit and into a safe area to avoid posing a threat to normally operating spacecraft.

The "Space Harpoon" proposal put forward by the European Space Agency is highly innovative, precisely shattering larger space debris by launching specially made "harpoons," breaking it down into smaller fragments that will then naturally burn up in the Earth's atmosphere. This method can effectively reduce the quantity of large space debris and lower its threat to orbital safety. The "magnetic adsorption" technology utilizes magnetic materials to adsorb and capture space debris containing magnetizable substances such as iron and nickel. By installing magnetic adsorption devices on spacecraft, when approaching the target debris, the magnetic adsorption device activates and firmly adsorbs the debris, enabling the cleanup of specific types of space debris.

To accelerate the research and development process of space debris removal technology, governments of various countries should increase financial investment, establish special research funds, and encourage scientific research institutions and enterprises to actively participate. The United States government invests hundreds of millions of dollars each year in the research of space debris removal technology, supporting the development of multiple scientific research projects. International collaboration should also be strengthened to promote exchanges and cooperation among countries in technology research and development, data sharing, project collaboration, and other aspects. The European Space Agency jointly carries out space debris removal projects with multiple countries, sharing research results and accelerating technological breakthroughs. Through international collaboration and integration of global resources, the research and development efficiency of space debris removal technology can be effectively improved, creating a safer space environment for the sustainable development of commercial space.

3.3.2 Promoting the concept of green space

In commercial space activities, vigorously advocating the concept of environmental protection is crucial, requiring comprehensive and in-depth work at multiple levels. In terms of rocket fuel selection, more environmentally friendly fuel types should be actively explored and widely adopted. Traditional

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rocket fuels produce large amounts of pollutants such as nitrogen oxides and sulfur oxides during combustion, causing serious pollution to the atmospheric environment. New environmentally friendly fuels, such as liquid hydrogen and liquid oxygen fuels, only produce water after combustion, causing almost no pollution to the environment. In addition, significant progress has also been made in the research, development and application of some fuels based on clean energy such as methane. These fuels not only have superior environmental performance but also have higher energy density, providing powerful thrust for rockets and meeting the requirements of commercial space launches.

In the satellite manufacturing process, environmentally friendly materials should be prioritized to minimize potential harm to the environment. Environmentally friendly materials have lower energy consumption during the production process, and when the satellite's service life ends, they can be more easily recycled or naturally degraded. In the selection of satellite structural materials, degradable composite materials can be adopted. When the satellite completes its mission, these materials can gradually decompose under certain conditions, reducing the generation of space debris. In the selection of satellite surface coating materials, non-polluting and recyclable materials should be chosen to prevent coatings from peeling off and forming debris in space.

Commercial space enterprises should strengthen environmental protection education for employees and raise their environmental awareness. Through regularly organizing environmental protection training, launching environmental protection publicity activities, and other methods, employees can deeply understand the importance of green space and consciously put environmental protection into practice in their daily work. In the project planning and decision-making process, enterprises should incorporate environmental factors into the scope of consideration and prioritize solutions with less impact on the environment. In the selection of satellite orbits, densely debris-populated areas should be avoided to reduce the risk of collisions between satellites and space debris, which also helps lower the probability of space debris generation.

4. Conclusion and Outlook

This study comprehensively dissects the field of commercial space management, revealing the challenges it faces and corresponding countermeasures. In terms of technological risks and safety challenges, the reliability of technology in commercial space is a prominent issue, with frequent technological failures in rocket launches and satellite manufacturing, seriously affecting project progress and economic benefits; the safety assurance system is imperfect, safety standards are not unified, and there are loopholes in the supervision system, increasing safety hazards in space activities. Legal and policy dilemmas are significant, with lagging domestic regulations, ambiguous market access standards, and insufficient equity protection; international legal conflicts are frequent, with rule differences and imperfections in satellite frequency and orbital resource allocation, cross-border data transmission, and other aspects, restricting the internationalized development of commercial space.

Looking to the future, there are still many highly promising research directions in the field of commercial space management that are worth exploring in depth. In terms of technological innovation, with the rapid development of cutting-edge technologies such as artificial intelligence and quantum technology, their deep integration with commercial space will become a research hotspot. Artificial intelligence has enormous application potential in satellite autonomous control, fault diagnosis, and mission planning. By developing advanced artificial intelligence algorithms, satellites can autonomously adjust their operation strategies based on real-time monitoring data for more efficient mission execution, while promptly detecting and diagnosing potential faults and taking preventive measures in advance, improving the reliability and service life of satellites. The application of quantum communication technology is expected to bring revolutionary changes to commercial space communications, with its ultra-strong confidentiality and anti-interference capabilities, providing safer and more stable communication links for satellite communications and meeting the high requirements for communications security in sectors such as military and finance. Future research can focus on the expansion of application scenarios, technology integration, and optimization of these new technologies in commercial space, promoting the leapfrog development of commercial space technology.

In the field of sustainable development, with the increasingly severe problem of space debris and the continuous improvement of environmental awareness, research on the sustainable development model of the entire life cycle of commercial space is urgently needed. This includes fully considering the application of recyclable and degradable materials from the design and manufacturing stages of satellites to reduce the impact of decommissioned satellites on the space environment; developing more

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environmentally friendly propellants and launch technologies in the launch stage to reduce pollutant emissions during the launch process; exploring efficient space debris removal technologies and methods for optimizing the utilization of orbital resources in the satellite operation stage. Future research can be dedicated to constructing a complete set of sustainable development evaluation indicator systems for commercial space, conducting comprehensive and scientific assessments of the sustainability of commercial space projects, and providing a basis for decision-making by enterprises and governments.

In terms of international collaboration and rule formulation, with the increasing trend of internationalization in commercial space, how to coordinate the interests of various countries on the international stage and establish a fair, reasonable, and effective international collaboration mechanism and rule system will be an important direction for future research. Research can focus on optimizing international satellite frequency and orbital resource allocation mechanisms, innovating international collaboration models for the development and utilization of space resources, improving international dispute resolution mechanisms for commercial space, and other aspects. By deeply analyzing the interests, demands and policy orientations of various countries in the field of commercial space, feasible and forward-looking solutions can be proposed to promote the healthy and orderly development of international commercial space collaboration and enhance China's voice and influence in the international commercial space field.

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