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SUPER ENGINEERING

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Management innovation of Chang’e-5 project

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1 Overview of Chang’e-5 project

As the final step of the “three-step” development strategy (i.e., orbiting, landing and sample returning) of the Chinese Lunar Exploration Program, the Chang’e-5 project aims to achieve moon surface sampling and retrieving for the first time in China. It was initiated with the approval of the State Council in January 2011. Through nearly a decade of conceptual design, prototype development and flight model development, the Long March 5 launch vehicle and a totally new probe composed of a lander, an ascender, an orbiter and a re-entry capsule, have been developed. Ground-based facilities such as the comprehensive test site for landing and take-off, the sampling and sealing ground test facilities, the Argentina 35 m deep-space station, the re-entry radar, and the lunar sample laboratory, have been constructed. Hence, China has the ability to fulfill the lunar sample return mission (Pei et al., 2015).

At 4:30 am on November 17, 2020, the Long March 5 Y5 rocket successfully launched the Chang’e-5 probe. At 23:11 on December 1, the combination of the Chang’e-5 lander and ascender landed on the lunar surface. In the following 48 hours, a total of 1731 g of samples were collected through drilling by drilling rig and scoop sampling by mechanical arm. At 1:59 am on December 17, the Chang’e-5 re-entry capsule landed, with lunar samples, on Siziwang Banner, Inner Mongolia. It is the first time after 44 years that human beings have retrieved soil and rock samples from the moon. The entire mission lasted 23 days, with 11 flight stages, six separations and one docking, as shown in Fig. 1.

2 Management innovation of Chang’e-5 project

The Chang’e-5 project represents China’s most complex and most difficult aerospace system engineering. Many key links, from landing on the lunar surface to re-entry into the earth, have all been implemented for the first time in China. Key technologies breakthroughs and explorations on plenty of unknown technologies have been made. Also, the complexities in engineering system composition, flight process, product structure and interface relationships, as well as synergistic relationship between space and earth, bring great risks to the successful achievement of the project goals. To organize and implement this huge, complex aerospace project, it is necessary to make innovations in technologies, schedules, qualities, and facilities construction management measures and establish a aerospace engineering management system adaptive to the high-complexity feature, based on the management models of the traditional aerospace system engineering and the lunar exploration program stages I and II (Wang, 2006; Luan, 2010; Guo, 2011; Luan et al., 2016; Zhang et al., 2017).

2.1 System fusion management methodology

System fusion management means integration of various factors into one unit while reducing system complexity at each stage within the life cycle of a complex engineering system, so that the project can evolve according to the expected design and finally achieve its goals (Mai et al., 2021). In view of the high complexity of the Chang’e-5 project, with the overall objective as orientation and system fusion management as the concept, the project was divided into three levels (general department, five systems and stand-alone products) and four phases (conceptual design, prototype development, flight model development

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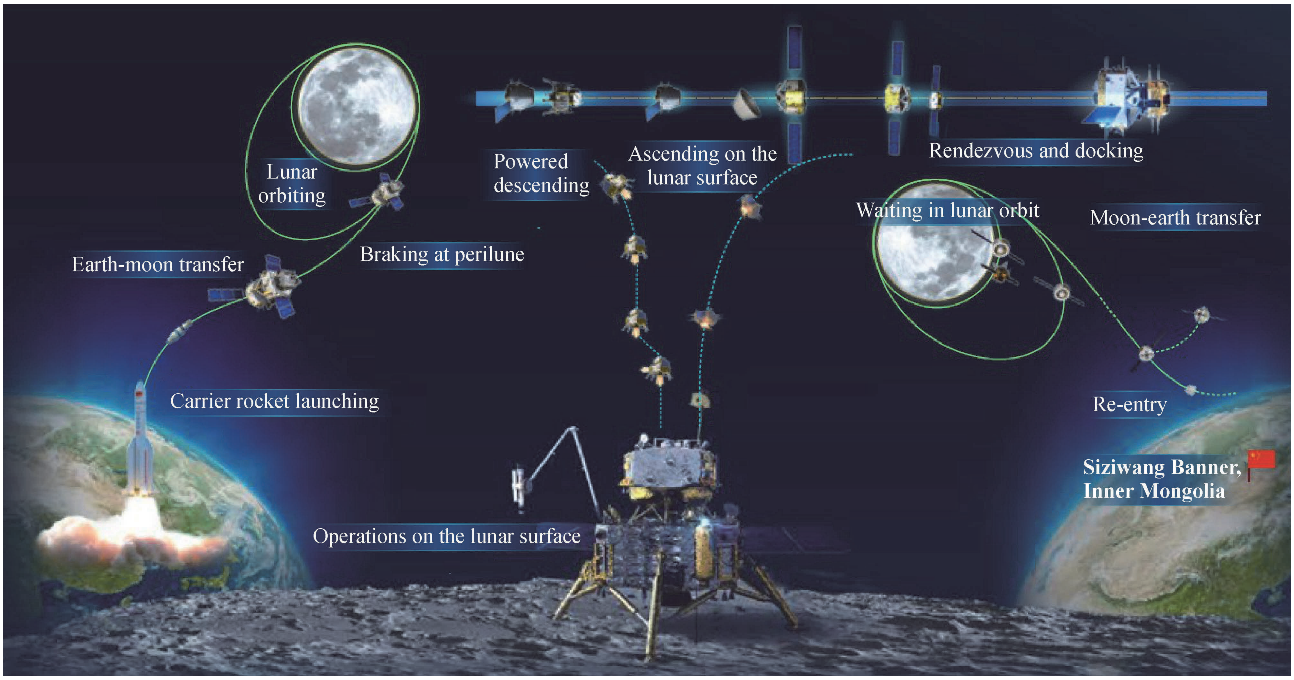

Fig. 1 The flight profile of the Chang'e-5 lunar mission.

and mission implementation), and a development procedure featuring full system, full cycle, full factors and full granularity has been prepared. Starting from this, the complexity degradation focusing on decomposition and the holistic synthesis focusing on integration have been carried out simultaneously during each phase of the whole life cycle of the project. A system fusion management methodology involving robust decision-making, panoramic analysis, risk reduction, integrated propulsion, etc., has been built. The technology system, management system, organization system, and facilities construction system have been integrated into a whole to solve the problems of non-cooperative behaviour and fragmentation within project management and ensure the multi-system, multi-factor, and multi-level integrated advancement of the project. The system fusion management methodology framework for the Chang'e-5 project is shown as Fig. 2.

Compared with traditional system engineering, project management methods and meta-synthesis methods, the characteristics of the system fusion management methods formed in the Chang'e-5 lunar mission are mainly reflected in the following three aspects: 1) parallel decomposition and integration, 2) integration and coordination of multiple management methods, and 3) combination of integrity management and complexity management.

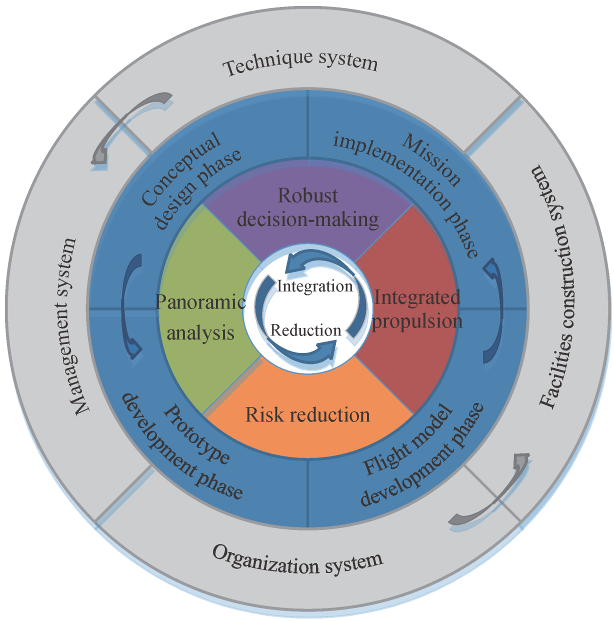

Fig. 2 The system fusion management methodology framework for the Chang'e-5 project.

2.2 Robust decision-making method for key technical schemes

Aimed at establishing a robust decision-making system, robust decision-making method refers to the process of establishing a group-based decision-making organization system and a decision consultation mechanism, carrying out multi-factor, multi-objective, and multi-constraint scheme evaluations, and finally forming robust technical and implementation schemes. In view of the big technical difficulties, multiple optional schemes, multiple decision-makers and multiple development projects of Chang'e-5 project, a decision-making system for key technical schemes that involve multiple factors, multiple objectives and multiple constraints has been established to improve the overall robustness of the decision-making of the project technical schemes.

The decision-making organization system of Chang'e-5 project includes the leading group/mission headquarters, general department, system development organizations and engineering expert teams. Different types of participants play different functions in project decision-making. Each system development organization studies the corresponding system technical schemes according to the goals proposed by the general department. The general department carries out comprehensive design of each system technical scheme to form the overall technical scheme. The expert group participates in the whole process of the formulation and decision-making of the schemes, providing decision support for each systems and the general department. In the multi-scheme evaluation process, various uncertain factors such as technological breakthrough, earth-moon environment, and international cooperation, and multiple constraints such as China's aerospace technology capabilities and facilities construction capabilities, were taken into account. The group-based decision-making organization system and non-structured modeling method were adopted to analyze and compare different schemes, through which technical and implementation schemes with higher robustness and better performance were selected (Mai et al., 2018). The robust decision-making framework for the Chang'e-5 project is shown in Fig. 3.

During the process of scheme demonstration, a wide range of schemes from multiple development organizations were compared, with an attempt to achieving better performance and lower costs in a competitive environment. The key links affecting the success of the mission were sorted out, forming 39 key technologies for nine links (i.e., rocket launching, soft landing on the lunar surface, lunar surface sampling and sealing, take-off on the lunar surface, rendezvous and docking, sample transfer, re-entry, landing and recovery, and sample unsealing/processing and storage). Six batches of researches that focused on 23 topics were conducted on major challenges, risks, divergences and disruptive issues, such as whether to choose skip re-entry, whether to conduct rendezvous and docking in the lunar orbit, selection of two sampling methods, etc. After taking into account technical risks, schedule, funds and other factors, the final decision was made to reduce one re-entry flight test to optimize the mission scheme (Wang et al., 2021).

2.3 Panoramic analysis method of complex aerospace engineering

The panoramic analysis of complex aerospace engineering is conducted as follows. According to the possible states of each system, in the time dimension, flight stages and the time span of each stage are classified in detail; in the technical dimension, the actions, positions and attitudes of the spacecraft and its components systems in each flight stage, and various tasks to be executed and constraints to be met during stage transitions, are comprehensively analyzed; in the management dimension, management plans on schedule, quality, funds, etc., are formulated in a scientific way; and in the organization dimension, technical and management work is allocated to specific responsible unit and person in charge. Also, the restriction and support relationships among technology, management and organization systems in each flight stage are vertically determined, and the connection and development relationships

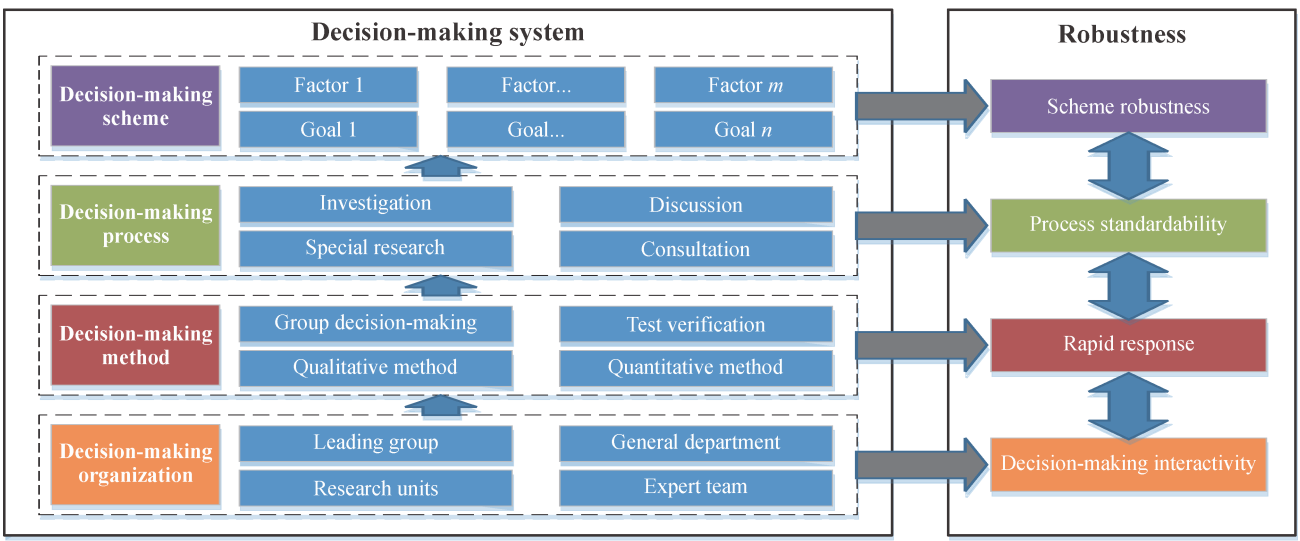

Fig. 3 The robust decision-making framework for the Chang'e-5 project.

among those systems between each flight stage are horizontally determined, so as to form a panoramic view of the engineering. The panoramic analysis method framework for the Chang'e-5 project is shown in Fig. 4. In response to multiple flight actions, large differences between space and earth environments, strong correlation among systems and other issues of the Chang'e-5 lunar mission, the panoramic analysis method for complex aerospace project, with technology, management and other factors as scenario objects, was proposed to form a whole-process mission guarantee chain, thus realizing a high degree of collaboration during the overall life-cycle.

In engineering practice, with the goal of automatically collect and return samples from the lunar surface and guided by the integrated space-earth design, the analysis and research of the whole-process mission guarantee chain were conducted based on the development and test results of the products and facilities of each system during the prototype development phase (Wang et al., 2021). With the whole process of the project as the main thread, the research focuses on overall tasks and tasks across systems, departments and organizations, and attaches great importance to disruptive and significant issues. The ballistic-orbit splicing, iterative determination of the timing of lunar descent and landing, strategic analysis on whether to delay the take-off on the lunar surface, avoidance of collision risk during the rendezvous and docking, collaborative analysis and command optimization of the space-earth system and other tasks were completed. Therefore, the research ensured technical disclosure, quality control and system coordination to finally determine the flight model development phase.

Good results have been achieved using this method: 1) the multi-dimensional decomposition of the project tasks facilitates the overall control of the complex project; 2) the panoramic collaboration among systems of the project contributes to the formation of a consistent inter-system interface relationship; 3) the clear division of responsibilities for each organization involved in the project is conducive to the formation of a coordinated, matched engineering task chain; and 4) the early exposure of engineering risks and problems helps their resolution in a low-cost, high-efficient way.

2.4 Mission risk reduction method

Risk reduction refers to the adoption of several methods to reduce engineering risks at different levels and dimensions and improve the overall quality and reliability of the project, in response to key links and their possible risks during different project phases. In consideration of the Chang'e-5 project's low technological maturity, high mission complexity, close connectivity between flight links and other characteristics, a mission risk reduction method was proposed; a risk reduction procedure verified at multiple stages and levels was formulated; and a risk reduction strategy of space-earth mapping between the flight process and ground physical simulation was established. All of these have effectively reduced the overall engineering risks.

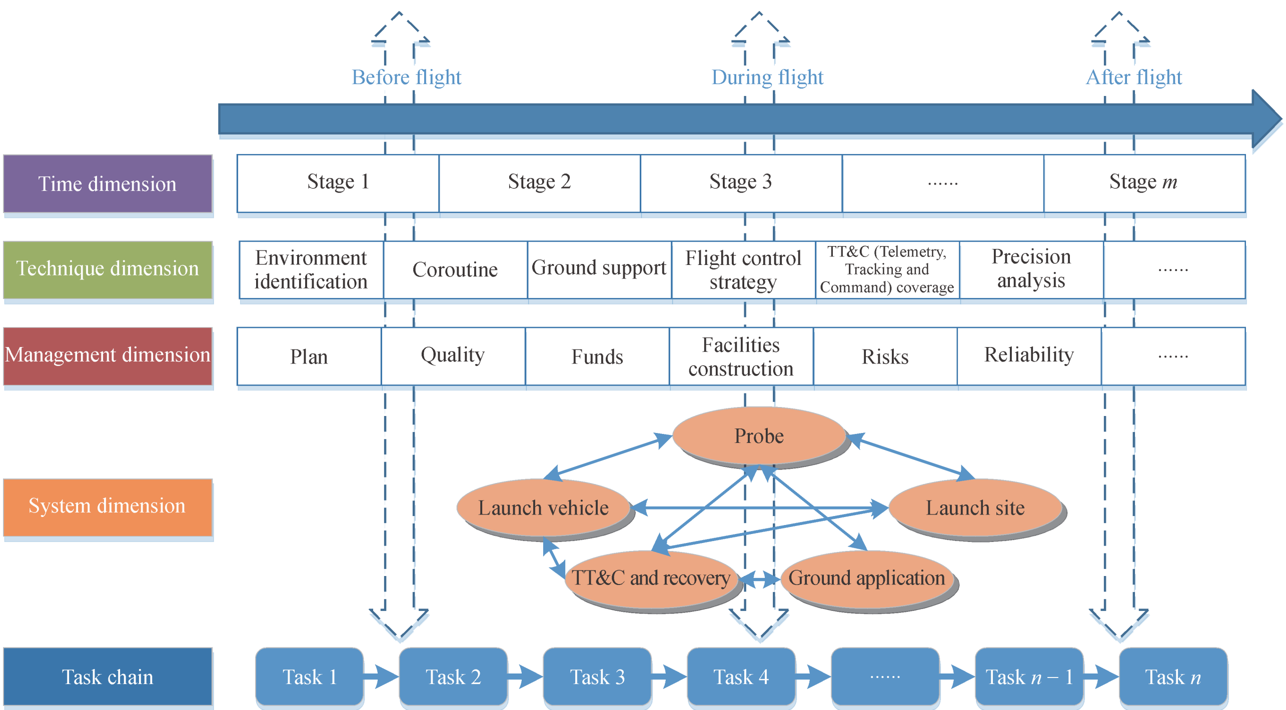

Fig. 4 The panoramic analysis method framework for the Chang'e-5 project.

In the Chang'e-5 project, the risk management process was closely integrated with tasks in different project phases and the risks were continuously reduced level by level, dimension by dimension and phase by phase, thus ensuring the fault-free operation of 11 stages of the flight process. In the time dimension, the risk reduction and the main tasks during each phase were combined, evidencing differential risk management. In the system dimension, during each phase, the multi-level and verification-oriented risk reduction was conducted on bottom-level components and raw materials, then gradually upwards to the systems and the overall project. In the organization dimension, a whole-process expert support system that includes an advisory expert team from mission headquarter, four professional expert teams, five independent evaluation expert teams, a quality expert team, a software expert team and a flight control expert team was formed to participate in the guidance and control of risk reduction at different phases and levels (Wang et al., 2021). In the method dimension, redundant fault-tolerant design, failure models and effect analysis (FMEA), simulation and other risk analysis and management technologies were adopted to support the above-mentioned risk reduction. The risk reduction method framework for the Chang'e-5 project is shown in Fig. 5.

In the conceptual design phase, special research, test matrix analysis, technical difficulty decomposition, important stand-alone product competition and selection, key technological breakthrough test verification, and other methods were adopted, and simulation, fault tree analysis (FTA), probabilistic risk assessment (PRA) and other risk analysis techniques were used, to identify the risk links that are the most innovative, with least practical experience and most influential on the flight process, such as semi-ballistic skip re-entry and lunar take-off. A risk control scheme of reducing risks by verification at multiple phases and levels was proposed. Therefore, scheme risks were continuously reduced. In the prototype development phase, systematic test verification represented by special tests like comprehensive landing and take-off test, test of rendezvous, docking and sample transfer and re-entry flight test were carried out. In-depth special research and whole-process task chain analysis were further performed to continuously reduce design risks. In the flight model development phase, technical status changes were strictly controlled. Systematic test verification, ranging from stand-alone product test to 1:1 flight simulation, was conducted. Independent third-party evaluation was organized on five risk areas, and failure contingency plans were formulated and drilled sufficiently, continuously reducing integration risks (Wang

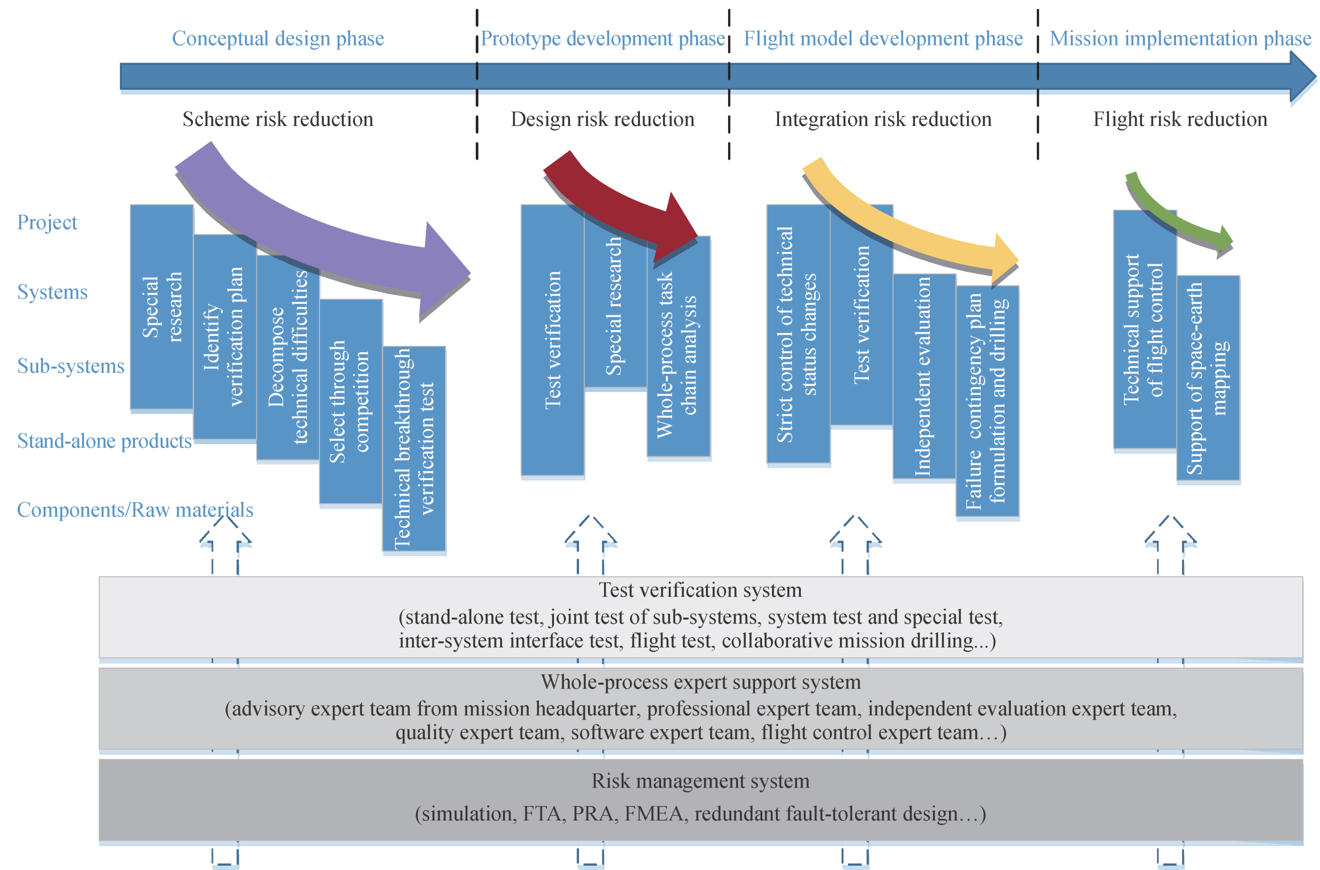

Fig. 5 Risk reduction method framework for the Chang'e-5 project.

et al., 2021). In the mission implementation phase, through technical support from flight control experts, support of the space-earth mapping between flight control and ground physical simulation and other means, flight risks were continuously reduced.

2.5 Integrated propulsion method of engineering systems

The integrated propulsion method of engineering systems refers to forming a fully-closed integrated engineering system with collaborative advancement and dynamic response, through the strong real-time correlation among technique, management, organization and facilities construction systems with the aid of information flow, material flow and capital flow. In response to the Chang'e-5 project's characteristics like high quality requirements, high facilities construction requirements, and complex organization and coordination tasks, an integrated engineering propulsion method was proposed. Mechanisms such as closed-loop quality management that deeply integrates with the engineering product development process, concurrent construction of facilities, refined funds control and multi-level progress control were established. Therefore, the collaborative and orderly advancement of engineering systems are enabled. The integrated propulsion method framework for the Chang'e-5 project is shown in Fig. 6.

In the Chang'e-5 project, an integrated management line based on the system of "chief commander and chief designer" and the general department was established to fully integrate information, materials and funds in all management fields, realizing coordinated and orderly engineering system advancement. The general department is composed of technical and management personnel who are familiar with various aspects of professional engineering knowledge and led by experts with broad scope of knowledge (i.e., chief designer and chief commander), which is a necessary technical control and leading management unit in the entire project development (Qian et al., 1982). As a general design department with expanded connotations and a key organizational link for integrated propulsion, this department conducts integrated management of technology, schedule, quality, facilities construction, funds and other elements, fully integrates administrative and technical decision-makings, and exerts the overall role in actively coordinating resources such as scientific research, product transportation, epidemic prevention and control, safety management and control, public announcement, mission support, emergency rescue, etc.

In terms of technique management, the overall coordination meeting, chief designer meeting, special coordination meeting, product-level working group meeting, etc., were held to promptly coordinate issues, make decisions

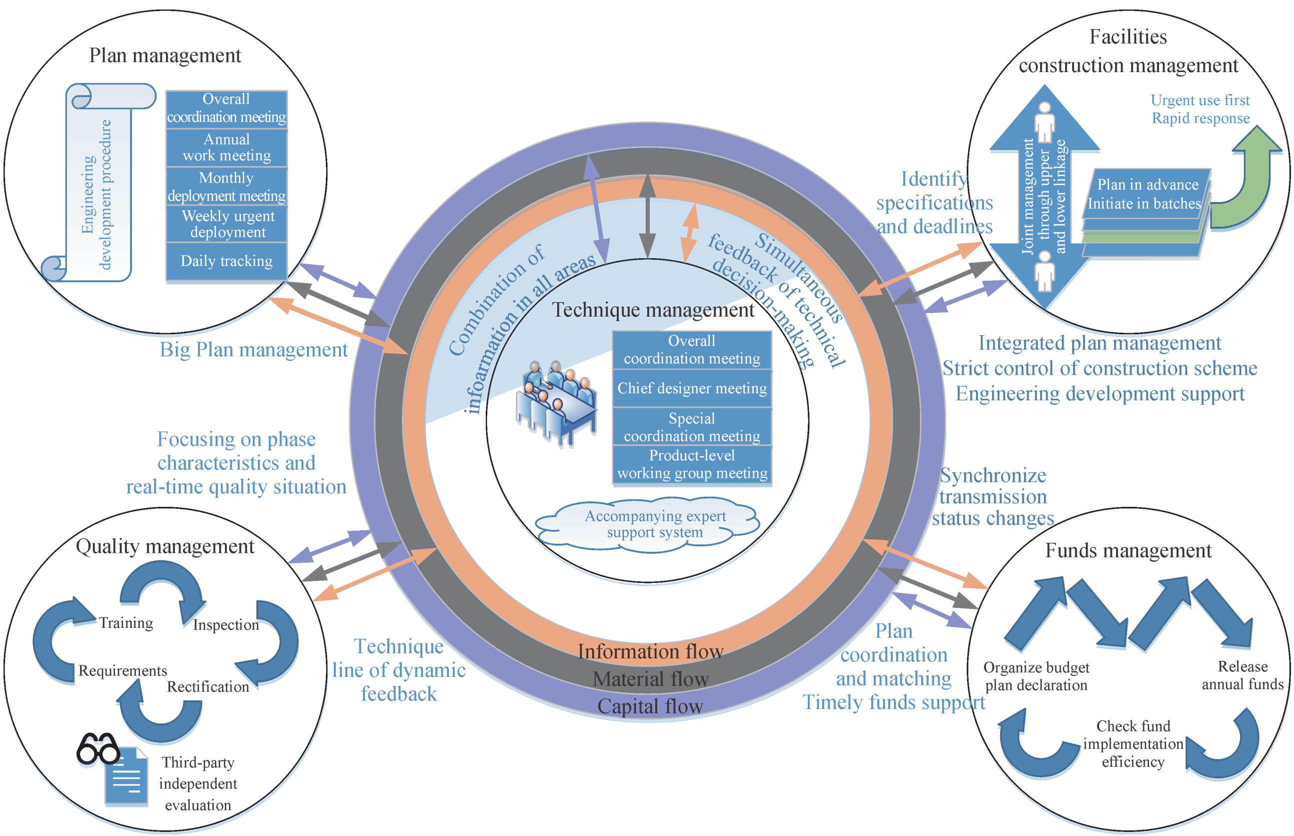

Fig. 6 The integrated propulsion method framework for the Chang'e-5 project.

and control technical status, synchronously feeding back related information to other domains. In terms of quality management, the whole process was planned and implemented in an integrated way, forming a closed-loop management model that covers five links to deeply integrate with the product development procedure. In terms of facilities construction management, schemes are strictly checked by the experts before construction. During the construction, through integrated deployment with project development, a whole-process coordination mechanism that links upper and lower levels for joint management and a rapid response mechanism of "urgent use first" were established, and a number of world-class development-oriented facility constructions were completed on schedule, meeting the urgent needs of engineering development. In terms of funds management, in close combination with project progress and annual work plans, surplus funds were comprehensively taken into account and annual budgets were formulated in a scientific way. The budget implementation efficiency was checked on a regular basis. Control was performed depending on situation and through the adoption of announcement, budget adjustment and other means to realize refined closed-loop management. In terms of plan management, based on the whole-process development procedure and phase transition guidelines, the monitoring, analysis and rectification of plans that integrate multiple levels and factors were conducted through overall coordination meeting, annul work meeting, monthly deployment meeting, weekly urgent deployment, daily tracking and other means, to ensure the consistency of the progress of all systems and domains with the overall engineering requirements.

3 Conclusions

The Chang'e-5 project, as a major engineering accomplishment, marks a big step forward for China Aerospace, featured with high complexity, high integrity, close coordination, accurate integrated propulsion, etc., in terms of organization and implementation. The system fusion management methodology explored and established in the Chang'e-5 project has effectively improved the overall robustness of engineering decision-making, reduced engineering risks, solved the problems of non-cooperative behaviour and fragmentation within complex system engineering management, and ensured the integrated and orderly advancement of engineering systems, achieving the goal of "no performance decreasing, no schedule delay and no over budget", and realizing a high degree of collaboration of mission processes. This methodology has provided strong support for the complete success of the Chang'e-5 lunar mission, and also references for the organization and implementation of major engineering projects in aerospace and other fields.

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