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Technological advancements and promotion roles of Chang'e-3 lunar probe mission

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The mission objective of Chang'e-3 lunar probe is to achieve our first soft-landing and roving exploration on celestial bodies beyond Earth. On the basis of analyzing technological characteristics in the probe development, key technology breakthroughs and technological promoting roles of Chang'e-3 are both described.

Chang'e-3, probe, technological advancement, technological promotion

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1 Introduction

As part of the major special projects of our National Medium- and Long-Term Program for Science and Technology Development, the Chinese Lunar Exploration Program has been divided into three main operational phases, which are "orbiting, landing and sample returning". In the second phase of the lunar exploration program, Chang'e-3 lunar probe will be used to achieve the mission objective of our nation's first soft-landing and roving exploration on celestial body beyond Earth, a new milestone in the development of our space technology. Lunar soft-landing and roving exploration is a whole new field in our nation's space activities, involving the probe, launch vehicle, launch site, measurement and control, ground application and other systems. We must make breakthroughs in the following techonolies:

– lunar soft-landing technology;
– lunar surface exploring technology;
– lunar-night survival technology;
– telemetry; tracking & control (TT&C) technology;
– integrated electronic technology;
– lunar science and instrument technology;
– other system-level key technologies.

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The scientific objectives of Chang'e-3 mainly includes lunar surface topography and geology survey, lunar surface material composition and resource survey, Sun-Earth-Moon space environment detection and lunar-based astronomical observation [1].

From the perspective of space technology advancements and promoting roles, lunar soft-landing and exploring are of great significance, and the engineering technical objectives could be summarized as follows [2].

1) Breaking through lunar soft-landing, lunar exploration technology and other related technologies, which include the Earth-Moon transfer flight orbit technology, lunar soft-landing technology, lunar exploration technology, teleoperation technology, TT&C technology, thermal control and power technology under the special environment on lunar surface and so on.

2) Developing and launching lunar probes. According to the mission needs, the probe system comprises a lunar landing vehicle and a lunar surface exploring vehicle, along with some relevant scientific instruments.

3) Building up lunar exploration space engineering fundamental systems. These include developing lunar soft-landing vehicle and lunar surface exploring vehicle, building up deep space TT&C network, improving ground application and data handling systems, and reconstructing the

launch vehicle and launch site, all of which form a body of supporting lunar exploration engineering systems.

2 Overview of Chang'e-3 probe

Chang'e-3 probe will fly through the Earth-Moon transfer phase, circumlunar phase and powered descent phase, then perform a soft landing on the predetermined area on the lunar surface, followed by the Lander to conduct in-situ exploration and the Rover to conduct roving exploration; all the exploration data will be sent back to the ground. Chang'e-3 probe is a brand new spacecraft, the mission of which is the first time for our nation to conduct in-situ and roving exploration on celestial bodies beyond Earth. The flight profile of Chang'e-3 mission is shown in Figure 1, and the soft-landing process is shown in Figure 2.

Chang'e-3 lunar probe consists of two parts: lunar soft-landing vehicle (known as "Lander") and lunar surface exploring vehicle (known as "Rover"), as shown in Figure 3. The Lander incorporates 11 subsystems such as the propulsion and landing cushion subsystems; during the lunar days, with the support of power supply, thermal control, TT&C and communications, lunar-based optical telescopes,

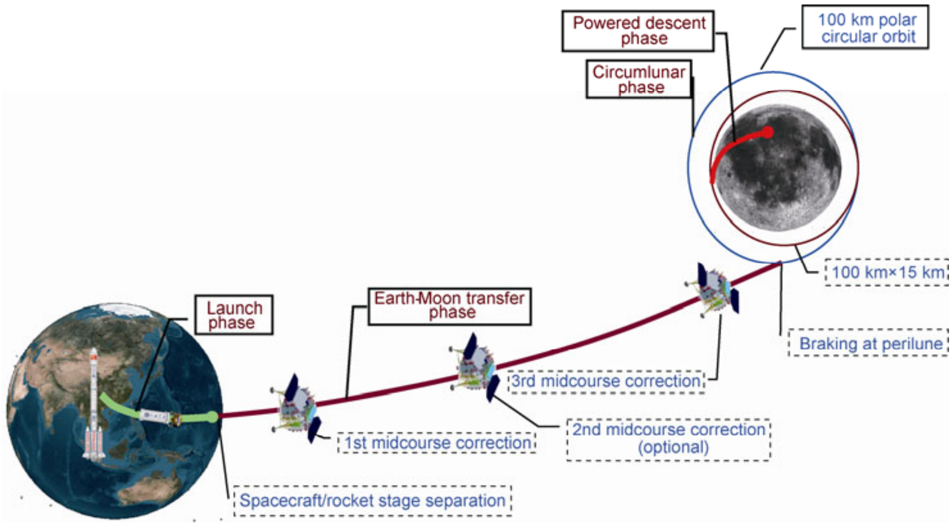

Figure 1 Flight profile of Chang'e-3 mission.

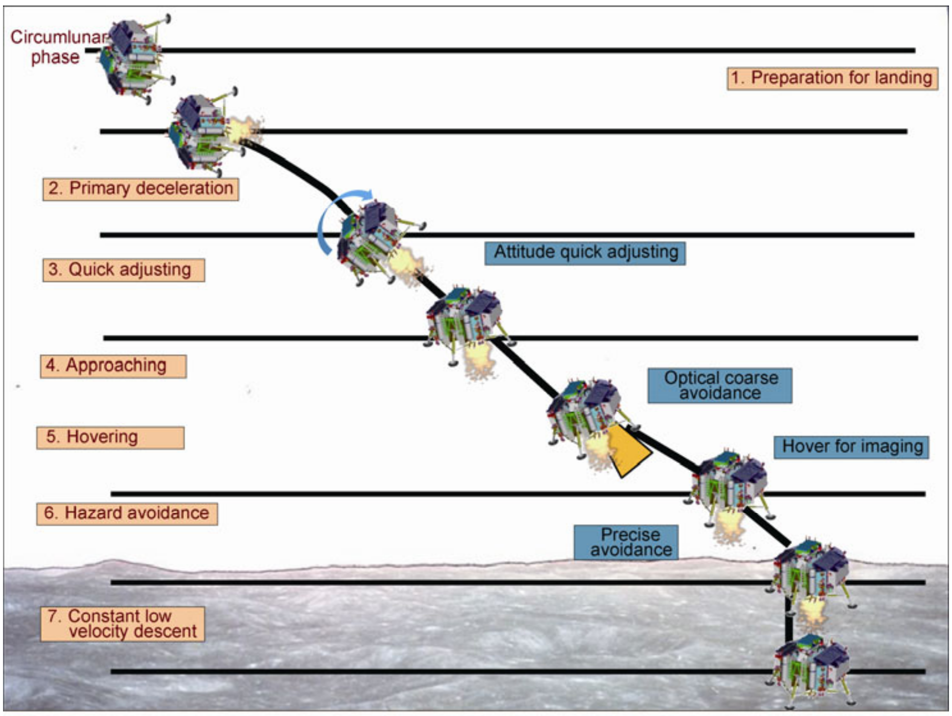

Figure 2 The soft landing process of Chang'e-3 probe.

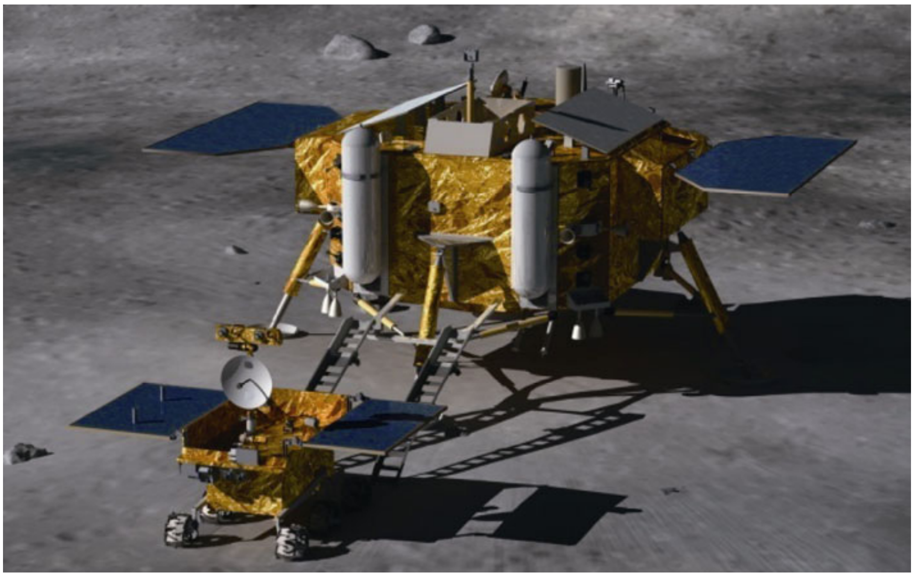

Figure 3 Chang'e-3 probe.

extreme ultraviolet cameras and terrain cameras are used to conduct scientific exploration tasks. The Rover incorporates 9 subsystems, such as the locomotion subsystem; during the lunar days, with the support of power supply, thermal control, TT&C and communications, roving exploration on the lunar surface will be achieved; lunar radars, infrared spectrometers, panoramic cameras and particle excitation X-ray spectrometers are used to conduct scientific exploration tasks. During the lunar nights, the Lander and the Rover will go into the lunar-night sleep mode, and by use of radioisotope heater units (RHU) and two-phase fluid loops, lunar-night survival will be achieved. The structure of Chang'e-3 probe is shown in Figure 4.

3 Chang'e-3 probe mission features analysis

Chang'e-3 probe mission, involving cross-disciplinary technologies and multiple design constraints in comparison with Chang'e-1 and Chang'e-2 missions, is designed with the following mission features:

1) Uncertainties of the lunar surface environment. Base on the analysis of Chang'e-1 and Chang'e-2 probing results, as well as investigation of foreign data, understandings of the lunar surface environment are formed, especially around the landing site, including the lunar surface landforms, heat flow and temperature, space particle radiation environment and so on. Studies on landing impact, engine plume and other induced environment also have definite conclusions. But since there are uncertainties in the distribution of landing points, details of the lunar surface landforms, influence of the lunar dust and other factors, the probe design has to be with a certain environmental adaptability margin.

2) Braking during landing. There is no atmosphere above the lunar surface, so any probe is unable to achieve a soft landing by means of aerodynamic deceleration. The

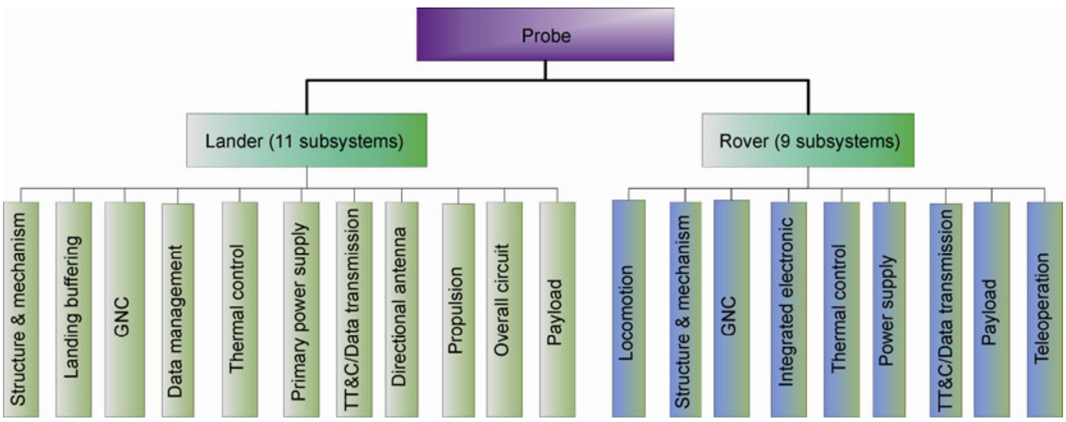

Figure 4 Structure of Chang'e-3 probe.

probe has to reduce its speed by about 1.7 km/s via its own propulsion subsystem. During this course, the attitude should be precisely adjusted so as to ensure the normal relative velocity between the probe and the lunar surface is reduced to less than 3.8 m/s, and landing on the predetermined site. To keep the landing process controllable, the thrust of the probe is required to be throttleable. All those aforementioned have put forward higher requirements on the propulsion subsystem design.

3) Autonomous navigation control for landing. The powered descent phase in the lunar soft-landing process will not be a long period of time (appr. 700 s), with a larger ΔV (1.7 km/s), so the implementation of guidance, navigation & control could not be dependent on ground stations; therefore, the probe has to act this function on its own by use of distance-to-Moon and velocity-to-Moon measurement sensors and terrain recognition sensors. Because of the complicated terrain on the lunar surface, in order to keep the probe operating on the surface without turnover and subsiding, the GNC subsystem calls for certain abilities of terrain recognition and autonomous obstacle avoidance.

4) Landing impact cushion. At touchdown on the lunar surface, the impact will generate large impact loads on the surface, so the appropriate landing cushion system must be designed to absorb the impact loads, keep operating on the surface without turnover and subsiding, and provide firm support for the probe.

5) Lunar surface thermal control and protection. The lighting conditions and day/night external heat flow change a lot on the lunar surface. For lunar days, the probe will face thermal dissipation at elevated temperature; for lunar nights, it will face the difficulty of keeping the temperature of its instruments in the case of no solar energy available.

6) Surface locomotion. The lunar surface the Rover will be operating on is covered with lunar regolith layers of variable thickness, and there are lunar craters and rocks of unequal sizes. The physical and mechanical properties of them, as well as the lunar terrains, will be all directly related to the locomotion performance of the Rover. Determining the configuration parameters of the locomotion subsystem, performing locomotion performance tests on the ground assuring lunar surface locomotion capacity of the Rover, are the problem must be solved during the general design.

7) Autonomous navigation and teleoperation control during surface exploring. Roving exploration requires the Rover to safely travel on the lunar surface and reach a designated position. Therefore it is necessary to overcome such technical difficulties as lunar surface environmental perception, obstacle recognition, local path planning, and multi-wheel coordinated motion control, among others. Unlike the on-orbit TT&C operating mode of the previous spacecraft, the Rover's operating on the lunar surface is a process of probe-ground information interaction and ground continuous support, thus developing ground mission support and teleoperation systems required for roving should also be resolved.

8) Ground test method and technology. For the purpose of getting the system fully tested and demonstrated on the ground, in addition to the typical space environment simulation and mechanical environment simulation for the launch phase, the lunar surface specific environment simulation techniques are also needed. The focuses are the low-gravity of 1/6 g simulation conducted in various system test, fluid loops and mechanism performance testing, soft-landing impact test, simulant lunar regolith in the lunar surface locomotion testing, light environment simulation, lunar dust environment simulation in mechanism and other performance testing, simulation of lunar-night storage environment for extravehicular equipment and so on.

4 Chang'e-3 probe technogical advancements analysis

Chang'e-3 probe is a totally new spacecraft, and its overall development concept is: aiming at the highest development level in the world, and identifying the functionality and performance of the probe from a high staring point; fully inheriting and utilizing the proven space technologies developed over decades; focusing on new problems encountered in the new field, completely independently carrying out original and integrated technical innovations, breaking through the core key technologies in the processes of soft-landing and roving on the lunar surface. Through extensive design analyses, researches of key technologies and ground verification test, the key technologies have been basically broken through.

4.1 Multidisciplinary general design optimization

The main concepts in the optimization design are reflected as follows.

1) Applying the methodology of system theory and systems engineering to realize integrated design for the probe system functionality optimization. Models for the lunar gravitational field, lunar infrared, lunar surface landforms, physical characteristics of lunar regolith, lunar dust, lunar surface electromagnetic wave transmission, and engine plume flow field, built up design and analysis platforms for system simulation have been fully established, based on which system design, simulation and verification are completed.

2) Bold attempts have been made in system integration design by electronic devices integrated design through integrating the system power distribution management, mechanism control, temperature control, initiating device management, autonomy management, TT&C, data multiplexing and other functions into the data management subsystem and integrated electronic subsystem.

3) Through function multiplex of the masts, heterogeneous backup between navigation cameras and panoramic

cameras, heterogeneous backup between probe-ground and inter-probe TT&C data transmission channels and other optimized design schemes, hardware configurations are simplified, with the system reliability improved.

4) Probe design concepts, tools and methods in the general design process greatly promote the spacecraft general design level.

4.2 Guidance, navigation & control technology

As for GNC subsystem, many technical difficulties have been broken through in conceptual design and technical design. There are a large number of individual technical innovations and integrated innovations throughout the entire development process of the subsystem, and the advancements are mainly reflected as follows.

1) In terms of control concepts, the landing process is divided into 7 mission phases, applying constant-thrust fuel-suboptimum explicit guidance, quartic polynomial guidance and other guidance modes, completing the guidance law design for 7 mission phases; according to the main controlled object properties in current guidance phase, with the strong constraint of time and fuel, resolving landing guidance with priorities, and further achieving landing hovering, hazard avoidance and constant low-velocity descent to the lunar surface.

2) By means of multi-source information fusion technique, applying navigation scheme design of inertial navigation assisted by range and velocity measurement correction; independently developed obstacle-recognition algorithm based on optical imagery and 3D elevation data, relay obstacle-avoidance strategy based on optical imaging coarse avoidance and laser 3D imaging precise avoidance; PID+PWM attitude control algorithm based on 10 N+150 N thrusters joint control, to implement attitude control during landing. A variety of control methods and strategies for navigation, guidance, obstacle avoidance and attitude control are first applied in our nation, propelling the development of spacecraft guidance, navigation & control technology.

3) In terms of technical design, high-precision large-dynamic-range laser ranging technique and microwave range and velocity measurement technique are broken through for the first time; meanwhile, bringing non-cooperative targets measurement technique, by means of laser and microwave navigation sensors, into engineering application in the field of spaceflight, bringing along the development of laser and microwave measurement techniques.

4.3 Propulsion technology

Advancements in the propulsion technology are mainly reflected as follows.

1) A constant-pressure-fed unified-bipropellant system is adopted as the propulsion subsystem of the Lander. By use of system flow resistance matching technique, anti-oscillation and anti-spin techniques, pressure reducing regulation technique, a series of design challenges for the propulsion subsystem have been overcome, such as the system parallel balanced emissions, liquid anti-oscillation, and system stability in large-flow variable-condition and so on.

2) Addressed the weldless aluminum alloy liners forming of a large LD ratio, variable-thickness variable-profile membrane manufacturing, carbon fibre winding and other issues, developed high-pressure gas cylinders, metal diaphragm tanks and other products, enriched the spectrum of similar products.

3) To address the difficulty of landing deceleration, the first high-specific-impulse high-precision variable-thrust engine for the spacecraft in our nation is developed, which adopts the pintle-type flowrate regulating device, precisely controlling the flowrates of oxygen circuit, fuel circuit and cooling circuit, respectively. Continuously variable thrust is realized, with the thrust varying from 1500 N to 7500 N and a control precision of 7.5 N. The breakthroughs in high-ratio flowrate regulation, adaptive regulating injector, large-diameter thin-wall nozzle spinning and other techniques all played a leading role in the development of our liquid rocket engine and related technologies.

4.4 Landing cushion technology

Advancements in the landing cushion technology are mainly reflected as follows.

1) After the comprehensive comparison of the pros and cons of various configurations of landing cushion, considering the factors of minimizing mass of the system,and improving landing stability and facilitating the Rover to release, the “cantilever-type” configuration design is finally selected for the landing cushion.

2) The landing gear consists of primary struts, multi-functional secondary struts, single-functional secondary struts, footpads, hold-down-to-release mechanism, with corresponding primary & secondary bumpers inside the primary & secondary struts. Buffer elements mounted on interior of bumpers are used to absorb the impact energy.

3) Through the integrated design of main devices and auxiliary bumpers, the problem of hold-down-to-release and deploy-to-latch is solved.

4) By means of developing new normal-temperature superplastic materials, with an elongation of more than 70%, the challenge of tensile energy-absorption cushion is addressed, and then the development of materials science is propelled.

5) A suite of ground simulation analysis and ground demonstration methods for complicated mechanisms is summarized.

4.5 Thermal control technology

The spacecraft thermal control technology mainly features the four aspects of thermal design, thermal analysis, thermal control hardware and thermal tests. Advancements in the thermal control technology for Chang'e-3 are mainly reflected as follows.

1) Major advancements in thermal design are for lunar-night survival caused by long-duration sunless environment during lunar nights. For the first time, assisted by low gravity on the lunar surface, the extravehicular isotopic heat is led into the interior with the aid of two-phase fluid loops to keep the survival temperature range for the intravehicular equipment.

2) There are various kinds of extravehicular equipment on Chang'e-3 probe, whose thermal design requirements are more complex, including protection for thermal effect of conduction, radiation and plume caused by engine operating, as well as dealing with lunar-noon high temperature and lunar-night low temperature. The thermal design means mainly include multi-layer (types of common, mid-temperature and high-temperature) thermal insulation and heater active control. In addition, several radioisotope heater units are adopted to raise the temperature for storage conditions.

3) Except for the traditional thermal control hardware, for the first time in the world, gravity-assisted two-phase fluid loops are applied on Chang'e-3 probe to introduce radioisotope heater to solve the difficulty of lunar-night survival. Also, variable-conductance heat pipes and other thermal control hardware are used on the Lander to enrich the thermal control hardware products used in spacecraft. During modeling of the two-phase fluid loop, mathematical simulation analysis, dimensionless similarity analysis, updating mathematical models based on experiment data and other technical means are applied to accurately describe the heat-transfer capability of two-phase fluid under the conditions of varied slope angles, low-gravity of 1/6*g* and varied heat source power, and the capability is verified by ground demonstrations. In view of the ground testing for two-phase fluid loops, the low-gravity of 1/6*g* simulation method, lunar surface slope angle equivalent method, external heat-flow simulation method and switching method of operation modes under thermal testing conditions are studied for the verification of thermal design on the ground.

4) The system-level thermal balance tests comprise 3 test status of the Lander, the Rover or both. According to the control requirements for different phases of flying to the Moon, circumlunar, powered descent, operating on the lunar surface and lunar-night survival, steady-state & transient-state thermal balance tests are performed.

4.6 Locomotion technology

Advancements in the locomotion technology are mainly reflected as follows.

1) Through terrain mechanical modeling and analysis of the lunar surface conditions, the Rover locomotion performance evaluation approach is proposed. From the aspects of carrying capacity, power performance, steering capability, trafficability, stability, technology readiness and reliability, a comprehensive evaluation of the Rover locomotion performance is made.

2) As for wheels, the performance and lunar surface environmental adaptability of various wheel configurations are compared via testing, combined with the Rover traveling performance, such as power performance, trafficability, stability, and other analyses; finally elastic mesh wheels are selected.

3) Synthetically considering the requirements of lunar surface environmental adaptability and minimization of mass and size, brushless DC motors are applied. Because of the limited wheels motor power, and yet higher torque requirements needed for the Rover's obstacle-crossing and climbing ability, with a large reduction ratio of the reducer, so multi-stage planetary reducers are applied. Besides, driving control technique for brushless motors has also been improved.

4) As for the locomotion suspension, by means of simulations and demonstrations, mainly studying on "main- and sub-rocker-bogie suspension" and "obverse-reverse four-linkage suspension" [3], considering in terms of mass, six-wheeled main- and sub- rocker-bogie suspension is selected.

5) After balancing weight of main- and sub- rocker-bogie according to the wheels pressure distribution during traveling on the lunar surface, the suspended cable approach is adopted, making it a simulation for low-gravity of 1/6*g* and ground contact pressure.

4.7 Autonomous navigation and teleoperation control

Normally traveling on the natural terrain and environment and then safely reaching the preassigned working spots are major tasks of the Rover's navigation and control subsystem. Consequently, it has to possess the capabilities of recognizing hazards and obstacles, determining own attitude and position, identifying the target location, planning the path towards the target location, moving along the planned path, and detecting and avoiding obstacles in the environment.

1) The environmental detection technique is used for three-dimensional recovery of the surrounding natural environment of the Rover, for obstacle-recognition, and providing teleoperation on the ground, path planning and obstacle-avoidance with terrain information. Passive-vision environmental detection methods based on CCD cameras are mainly used to realize three-dimensional recovery and reconstruction of the lunar terrain with the stereo-vision matching algorithm as the core.

2) By applying stereo vision-based local autonomous obstacle-avoidance algorithm, autonomous local path planning is accomplished. By used of the surrounding information obtained by navigation cameras, three-dimensional recovery and information integration are achieved on the ground, and then ground path planning is completed.

3) There will be serious slippage and trackslip in the Rover's traveling on incompact sandy soil on the lunar sur-

face. In order to adapt the terrains, the load distributed to each wheel is varied; therefore, the coordinated motion control algorithm that coordinates the driving and steering of the wheels is studied for optimizing the drive efficiency and achieving the energy optimization control.

4) In the complicated natural environment of the lunar surface, there would be more difficulties with the positioning of the Rover than that of unmanned ground autonomous vehicles and mobile robots. Several positioning methods are developed, such as image matching positioning based on onboard vision system, dead reckoning based on odometers, and landmark feature matching method.

4.8 Ground testing technology

Compared with other typical spacecraft, Chang'e-3 probe has its own particularity. For this reason, during the design process, the system should be fully tested and demonstrated on the ground for the purpose of comparing overall concepts, analyzing key technical problems, getting them verified by technical approaches and so on.

Applying low-gravity simulation, lunar surface reflection properties simulation, simulant lunar soil preparation, planar rapid servo, and high-precision optical and laser measurement techniques, the landing hovering test field, infield and outfield test facilities for the Rover are established, besides, a series of test schemes and methods are summarized. Extensive experimental verification work has been carried out for Chang'e-3, including 6 system-level special tests: hovering, obstacle-avoiding, low-velocity descent test, for the purpose of verifying the ability of coordinated operating between the GNC and propulsion subsystem; landing stability test to examine the effect of landing velocity and attitude on the landing stability; landing impact test to verify the impact resistance performance of the Lander main structure in typical operating conditions; gangmouted surface testing for the purpose of testing the Rover locomotion performance in typical lunar terrains; infield test for the purpose of testing the Rover locomotion and navigation control performance; and, outfield test for the purpose of the Rover teleoperation program verification carried out in the desert regions of Northwest China [4].

4.9 Scientific exploration technology

Lunar radars, lunar-based optical telescopes, extreme ultraviolet cameras and other scientific instruments are developed for the first time to achieve lunar shallow structure profiling, long period observation of astronomical variable-source brightness, earth plasma detection and other scientific tasks.

5 Chang'e-3 probe technological promotion

The technical breakthroughs Chang'e-3 probe has made in lunar soft-landing and roving have laid a solid foundation for the smooth implementation of the second phase of our national lunar exploration program. The development of Chang'e-3 probe pushes the development of space and other related disciplines, the role of which could be summarized as the following three aspects.

1) Effectively promoted the development of space technology. Technological breakthroughs and technological achievements in the spacecraft overall design, subsystem design of guidance, navigation & control, propulsion, thermal control and others together improved spacecraft design level. Through tackling and developing a large number of new high-performance products, such as integrated electronics, light and small mechanisms, navigation sensors, variable-thrust engines, two-phase fluid loops and so on, the spacecraft general technology development is comprehensively promoted; the applications of new materials, processes and device promoted the development of space technology from the basic level.

2) Effectively promoted advancements in multi-disciplinary technologies. Lunar soft-landing and roving exploration is an integration of new and high technologies, viewed as the comprehensive reflection of mechanical, electronic, materials, information, manufacturing and many other technologies. The deepening and transformation of lunar exploration technology would benifit a wide range of fields, such as unmanned armored vehicles, medical care, domestic service, safety checks and automated operations in hazardous environments, promoting the development of our national economy from mechanical, electronics, information and other aspects.

3) Promoted our national capacity for sci-tech independent innovation. The second phase of the lunar exploration program, with Chang'e-3 mission as the core, is a large-scale complicated system engineering, whose realization will enable major breakthroughs in our nation's related technical fields, form extensive innovations with independent intellectual property rights, generally promote our national capacity for sci-tech independent innovation and core competence, thereby boost development of relevant industries. Furthermore, attracting and cultivating a large number of high-level talents of proper structure and excellent quality, standing at the frontier of worldwide science and technology, will provide strong support for our national talent innovation projects.

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