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Technical advancements and significance of circumlunar return and reentry spacecraft

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As one of the vital steps in the 3rd phase of China's lunar exploration program (CLEP), the circumlunar return and reentry spacecraft, developed by China Academy of Space Technology (CAST), is used to demonstrate the key technologies of hyper-speed return and reentry spacecraft. The system configuration and flight process are presented in this paper, as well as the analysis of mission characteristics, the key technologies and the technical advancement during the R&D progress. The significance of circumlunar return and reentry spacecraft is given at the end.

circumlunar return, skip reentry, technical advancement, China's lunar exploration program (CLEP)

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1 Introduction

The unmanned sampling and return is the target of the 3rd phase of China's "three-step" Lunar Exploration Program, i.e. the "orbiting, landing and returning" strategic plan [1]. As one of the vital steps in the 3rd phase, the circumlunar return and reentry mission has been implemented ever since the year of 2011, for the demonstration of the key technologies of circumlunar return and reentry spacecraft, which is necessary for the 3rd phase of China's lunar exploration program (CLEP).

The circumlunar return and reentry spacecraft was launched on 24th, October, 2014 (BJT). After about 196 hours' flight, the reentry capsule landed safely at Siziwangqi in Inner Mongolia of China at 6:42 of 1st, November (BJT) and was recovered and delivered to Beijing on the same day. The mission was completed successfully.

The mission is designed to simulate the flight and reentry conditions of Chang'E V Probe and verify key technologies of semi-ballistic skip reentry, which demonstrates the feasibility and validity of return technology. It lays foundation for the implementation of the unmanned lunar sampling and return mission.

The major concerns for China circumlunar return and reentry mission are listed as below.

(1) Demonstrate hyper-speed semi-ballistic skip reentry technologies, including the circumlunar free return trajectory design, aerodynamic design and verification, thermal protection, guidance, navigation and control (GNC), light-weight and minimized recovery system, etc.

(2) Develop and launch the circumlunar return and reentry spacecraft.

(3) Complete the in-orbit flight control and new-tech experiments, the reentry and landing of the reentry capsule in the designated region.

(4) Collect flight data of aerodynamics, thermal protection, GNC, etc. for the follow-up mission.

(5) Verify the reentry flight process and operation pro-

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cedure and the interface between the spacecraft and ground system.

2 Mission profile

The spacecraft consists of a service module and a reentry capsule. There are 11 subsystems, such as structure, mechanics, thermal control, power supply and distribution, on-board data handling, TT&C, antenna, GNC, propulsion, recovery and parameter measurement, as well as some experimental equipment. The spacecraft's configuration in launch vehicle fairing is shown in Figure 1. The solar panel is deployed after separation with launch vehicle; which is shown in Figure 2.

The service module provides function of the structural sustainer, power supply and distribution, TT&C communication, attitudes and orbit control for the whole spacecraft. The module also performs flight new-tech experiments. It also carries on extended experiments after separation with the reentry capsule.

The reentry capsule receives commands from the service module, transmits telemetry data to the module, and completes the inertial measurement units (IMUs) calibration before reentry. Once separated, the reentry capsule reenters Earth's atmosphere and lands in the designated region for the sake of search and recovery after a semi-ballistic skip reentry.

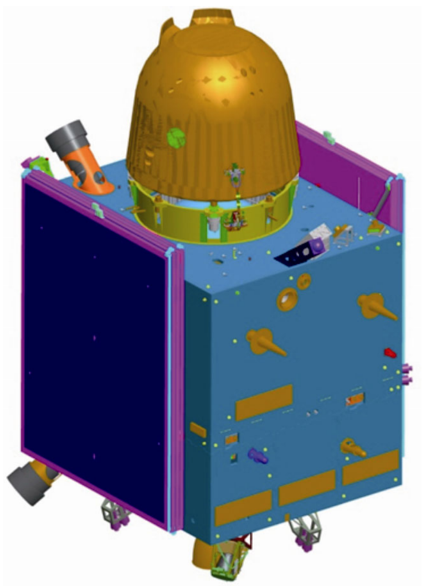

Figure 1 Spacecraft configuration in launch vehicle fairing.

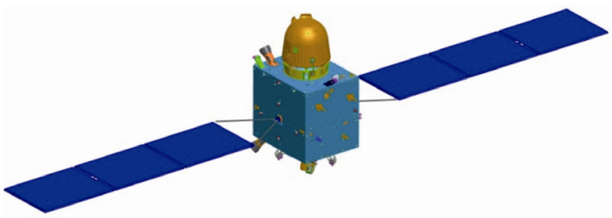

Figure 2 Spacecraft configuration after separation with launch vehicle.

The flight profile of the spacecraft includes 12 phases, as shown in Figure 3. The skip reentry process of the capsule is shown in Figure 4. The total time from launch to landing of the reentry capsule is about 196 hours.

3 Mission analysis

Compared with the near-earth reentry spacecraft, the circumlunar return and reentry spacecraft has more design constraints and technical challenges, and key technologies such as the aerodynamics, thermal protection, reentry GNC, etc. Meanwhile, it also applies multiple new technologies and is required to accomplish the extended experiment.

3.1 Aerodynamics

The aerodynamic and aerothermodynamic data are the basis for the thermal protection and reentry GNC design of the reentry capsule. The accuracy of aerodynamics is crucial for the safety and reliability of the thermal protection and the reentry GNC control. The reentry speed of the capsule is approximately 40 Mach and needs to fly in the Earth atmosphere for long time, which has serious impact on the aerodynamic and aerothermodynamic properties of the capsule because of the ambient flow field gas catalyst, chemical reaction, high temperature radiation, plasma blackout, flow slip, rarefied gas molecule collision, etc. [2–4]. Besides, during the reentry process, the shape deformation caused by the ablation may change its aerodynamics. The capsule also has lower flight stability because of its small size. Therefore the high accuracy on aerodynamics of the reentry spacecraft is necessary.

3.2 Thermal protection

Because of the high reentry speed, the aerothermal condition is severe for the capsule with the peak heat flux up to 5.2 MW/m^2, the integrated heat load up to 715 MJ/m^2 and the total heating time up to 20 min. Meanwhile the twice ablation impact after skip on the thermal protection structure should be considered [4]. The conventional thermal protection material and structure cannot meet the thermal protection and weight requirements. The new thermal protection material and structure are indispensable.

3.3 GNC

A spacecraft returning from Moon is continuously accelerated by Earth's gravity. Upon the edge of Earth's atmosphere, the speed of the reentry capsule rises up as high as

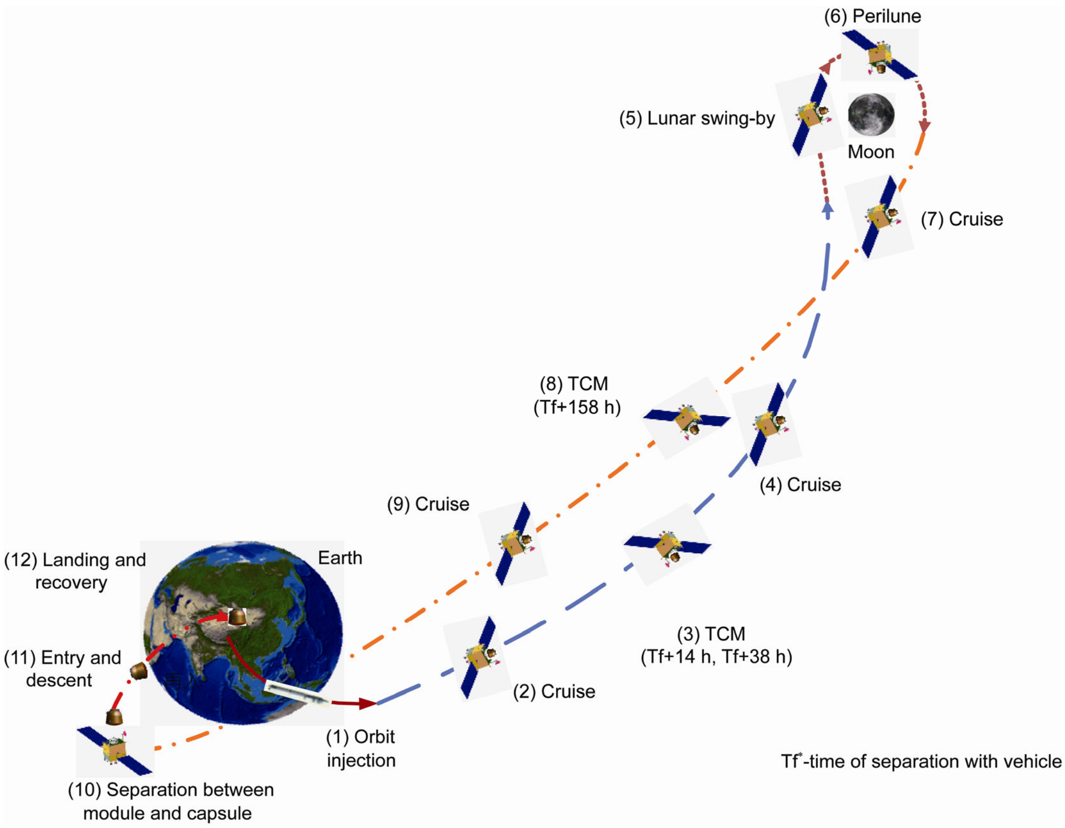

Figure 3 Mission profile.

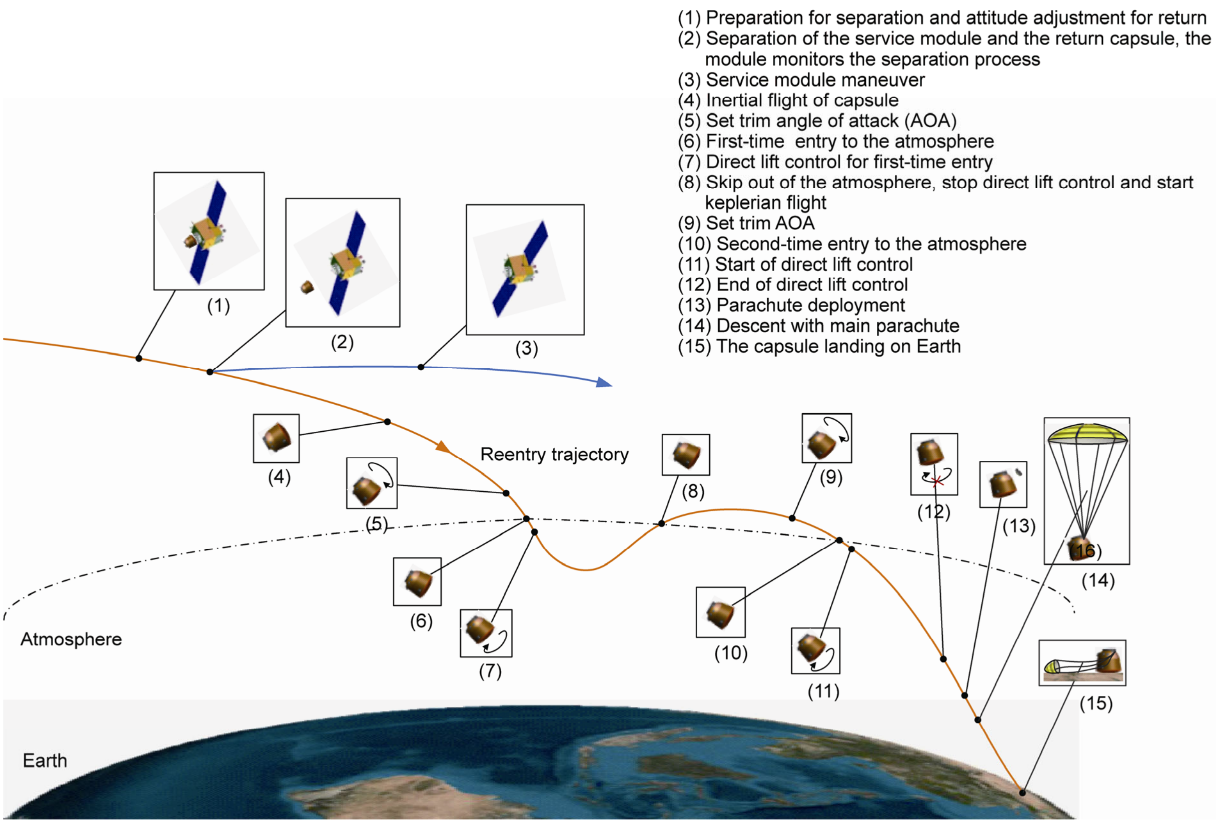

Figure 4 Reentry flight process of reentry capsule.

the escape velocity. It is physically intrinsic that the atmospheric reentry trajectory becomes unstable with such a high speed. This unstable nature leads to an extreme sensitivity of the landing point to the disturbances either from atmosphere or from the vehicle itself [5,6]. The reentry capsule is in the scale of hundreds of kilograms that decrease the ballistic coefficient to a much smaller one compared with the USSR Zond and US's Apollo Command Module. This leads to a larger divergence trend in the trajectory footprint. Besides, the low lift-to-drag ratio limits the aerodynamic control capability of the GNC system. To satisfy all those design constraints while steering the reentry capsule to the aiming target of ±30 km×(±20 km) with the down range of 5600–7100 km is a great challenge to the GNC system.

3.4 Miniaturization of equipment

In order to pave the way for the further successful implementation on the third phase of Lunar Exploration Program, strict constraints on the capsule's weight, size and power consumption are made (weight less than 335 kg, size less than Φ1258 mm×1236 mm, power consumption less than 200 W). Compared to ballistic reentry capsule, the semi-ballistic reentry capsule has more complex system configuration, more strict constraints, higher accuracy requirement and more difficulties on assembly design. The conventional design cannot meet the requirements of light weight and small size. Under this circumstance, it is indispensable to optimize the system in the aspect of composition, flight strategy, weight and power consumption of equipment as well as configuration and assembly method. At the same time, miniaturized equipment is developed to meet the requirements mentioned above, such as the S band responder, on-board computer, parachute and IMUs.

3.5 Strict constraints on launch and recovery

Because of system engineering constraints, the spacecraft was launched towards southeast in Xichang Satellite Launch Centre with the injection trajectory inclination of 28.5°. With semi-ballistic skip approach, the spacecraft raised its trajectory to reenter the Earth and landed at Siziwangqi in Inner Mongolia of China with the trajectory inclination of about 45° under the earth-fixed coordinate system. The inclination angle shift between the launch and reentry trajectory was approximately 73°, thus the spacecraft had to change its trajectory inclination significantly [7].

3.6 Precise control of reentry trajectory

The capsule reentered the earth's atmosphere at near escape velocity, which strictly limited the reentry corridor [8,9]. Constrained by the reentry range, aerodynamic overload, aerothermal conditions, landing accuracy and so on, the reentry corridor was set as –5.8°±0.2°, while the inertial reentry speed was about 11 km/s and the down range was 5600–7100 km. In order to make sure that the capsule entered the reentry corridor precisely, the accuracy of trajectory control was mandatory.

3.7 Multiple working modes for thermal control

Some equipment is powered off inside the capsule which is cold during the Earth to Moon transfer or *vice versa*, thus heat preservation is required. Immediate heat emission is required for equipment with high power consumption such as IMUs when they are calibrated. The heat shield bears over heat load by aerothermodynamics during reentry. Those different requirements of thermal control challenge the design strategy, meaning that the conventional thermal control method [10], such as blankets, insulator and electrical heater cannot meet the mission's requirements at the same time.

3.8 Multiple targets on flight mission

The top goal is to realize the return and reentry of the capsule as well as the verification of key technologies and the interface matching. Secondly, it needs to take advantage of this opportunity to validate new technology and complete the orbital experiment. In this mission, the optimization of the system composition and flight profile is required to achieve multiple targets in one mission.

4 Technical advancements of circumlunar return and reentry spacecraft

The circumlunar return and reentry spacecraft, especially its reentry capsule, is a brand new spacecraft for China. During the system development phase, it set the high-speed return and reentry from Moon to Earth as the top goal, made comprehensive breakthrough on key technology of hyper-speed reentry by independent technical innovation and system optimization and completed the spacecraft development and ground test. It also obtained the experiment data and recovery data during flight and carried on new-tech and extended experiments of the service module.

The technical advancements of the spacecraft are summarized in the following aspects.

4.1 Multi-target and multi-mission system design

The dual platform and parallel operation system have been designed and realized, i.e. The dual platform has both united and independent operation, which is the basis to accomplish the reentry mission and is capable of implementing new-tech experiments and extended experiments. The advancements are reflected in the following five aspects.

(1) The parallel operation system of the service module and the reentry capsule is demonstrated. According to the

mission requirements, the function of the service module and reentry capsule is designed. The interface is designed to make the spacecraft operate during joint flight and the module and capsule work independently after separation.

(2) The difficulty in information transmission of hetero generous data system between the service module and the reentry capsule is resolved, as well as the information transmission between the spacecraft and ground by data bus of variable framework and data fusion. A highly reliable data handling system of mutual support and parallel operation is realized.

(3) The influence factor model of mechanical stress, thermal stress and assembling stress is set up to deal with the coupling problem of the light weight of capsule and the resistance force when the reentry capsule is separated from the service module. The reliable separation of the service module and the reentry capsule is realized.

(4) A safety evaluation of multiple factors is implemented and an all-regional trajectory optimization algorithm is realized by taking advantage of the trajectory control capability of the service module; the separation point of the service module and the reentry capsule is set to 5000 km above the earth surface; the maneuver strategy of the service module is optimized to achieve enough safety distance from service module to reentry capsule, and adequate maneuver time before the service module reaches perigee. The service module returns to Moon and performs extended experiment.

(5) The hyper-speed reentry mission is completed and the 5 new technologies and extended experiment are verified. The system of high-reliable fault isolation, multi-origin data fusion, data transmission at variable bit-rate, etc. is successfully demonstrated. The platform is utilized to realize the multi-target and multi-mission exploration.

4.2 Circumlunar free return trajectory design

The circumlunar free return trajectory with the energy optimization and the largest inclination change is designed, and is regarded as the precursor for further fly-by trajectory design in deep space exploration. The advancements are summarized in the following three aspects [11,12].

(1) The free return trajectory under the constraints of launch and recovery is innovatively realized by using the lunar gravity to change the inclination. The requirements of launch at Xichang and recovery at Siziwangqi are met without any large orbit maneuver. This is the first time for China to apply such orbit design.

(2) Three-body pseudo state theory and fast solution to the free return trajectory by using flight-path-angle-constrained Lambert problem are applied; the problem of orbit dynamic sensitivity and the convergence difficulty of regular differential correction algorithm is resolved by using the bi-directionally patched differential correction numerical algorithm.

(3) By comprehensive consideration about the constraints of free return trajectory due to the launch condition, launch time, down range of reentry and sunlight condition etc., mathematical model is set up for searching launch opportunity with multiple constraints. The free return trajectory design with multiple constraints and energy optimization is resolved by using intelligent algorithm such as the differential evolution

4.3 Aerodynamic design

The aerodynamic design of China first small skip reentry capsule at hyper speed is verified by successful reentry and landing. The experiment data for thermal protection and reentry GNC of the capsule is acquired, which distinctly upgrades the understandings on the physical and chemical interact mechanism of hyper-speed capsule in the rarefied gas condition. The advancements are mainly summarized in the following six aspects.

(1) An aerodynamic configuration is designed for the small capsule to bear the severe conditions during semi-ballistic skip reentry. A method for centre-of-gravity box based on time-variant estimation is proposed. Therefore the centre-of-gravity is varied to meet the aerodynamic needs during all the stages of reentry [13].

(2) A method of calculating the 6-DoF (degree of freedom) aerodynamic coefficients variation is proposed, which is suitable for the centre-of-gravity offset and shape deformation of the reentry capsule. The aerodynamic coefficients variation is predicted for the capsule. The flight results indicate that the prediction accuracy of the lift-drag coefficient within main guidance region is less than 8%.

(3) The connection between the wall model and transition flow characteristics is determined. And a systematic, high efficiency and precise algorithm is developed for the aerodynamic data prediction of the transition flow region.

(4) A precise aerodynamic and aerothermodynamics simulation model for chemical reaction is set up. A shock-aligned mesh adaptive technology is used. Also, a precise predicting technology of real-gas effect aerodynamic and aerothermodynamic is developed.

(5) A film platinum resistance sensor with firm adhesion and strong thermo-stability is developed, which effectively resolves the problem of big measurement error due to the strong erosion and high heat flux on the windward of the big blunt body. Thus the accuracy of the capsule's thermal flux measurement is improved.

(6) A high-accuracy force-measurement experimental technology for short blunt body shape is developed with significant improvement on the measurement accuracy of the capsule's 6-DoF aerodynamic forces in 6-DoF during hypersonic wind tunnel tests.

4.4 Thermal protection design

The technical problem of thermal protection during the hyper-speed return and reentry process from Moon to Earth is resolved, various new thermal protection materials and structures are developed, the weight of the capsule's thermal protection structure is reduced, the safety during the reentry process is guaranteed and the understanding of the thermal protection mechanism is deepened. The advancements are summarized in the following four aspects [14].

(1) Seven new kinds of light-weight thermal protection material are developed, with the density of carbon-silicon composite material reinforced by honeycomb matrix as low as 0.50 g/cm^3, and the density of material reinforced with the mixed continuous fiber as low as 1.0 g/cm^3. Meanwhile the ablation and heat insulating performance is strengthened obviously. This work promotes the development of the composite material in China.

(2) Various kinds of materials with different thickness are used in different positions, and the light-weight composite-material heat shield with axis offset is designed; the problem of decreasing the weight of the capsule's thermal protection system is resolved; the demand on thermal protection design with high heating flux, long heating time and large heat load is satisfied; and the weight reduction of the whole spacecraft is accomplished.

(3) A design method with gradient distribution of material density is proposed and the overall-orbit dynamic matching of the ablation speed of the adjacent material is developed and used; the ablation matching problem of the various thermal protection materials on the surface of the reentry spacecraft is solved; the structure of the corner ring strengthened by continuous fiber is designed; the anti-eroding problem of the corner ring under circumstances of high heat flux density and strong airflow is resolved; and the requirements of capsule's aerodynamic shape are met by smoothening the reentry spacecraft's shape under ablation

(4) The simulation method for overall ablation speed based on carbon-silicon volume weights is proposed; the ablation simulation problem with the physical and chemical reaction of carbon oxidation and silicon loss is resolved; the ablation model of the carbon-silicon composite material with high-enthalpy heating is set up; the coupling analysis method of ablation and heat transfer is applied; the adaptability of thermal protection material in random carbon-silicon ratio is well performed; the precise prediction and evaluation method of the ablation capability of the new thermal protection material is validated. The difference in heat ablation recession between the predictions and measurement after the recovery of the capsule is less than 4 mm.

4.5 Reentry GNC design

The GNC technical problem for the hyper-speed semi-ballistic skip reentry is resolved and the control strategy for high-accuracy reentry with light weight, small size and low lift-to-drag ratio after long range is verified. The down range is 6636 km and the parachute deployment point error is less than 509 m. The advancements are summarized as follows.

(1) A typical all-coefficient adaptive Double-Loop strategy is proposed, and a pre-biased project direction-based lateral guidance method is verified. The problem of inadequate maneuverability caused by low lift-to-drag ratio, instability caused by the hyper speed and fast error diffusion of control for the capsule is resolved. Finally the high-accuracy reentry is completed successfully.

(2) A real-time planning and evaluating method for skip reentry corridor is proposed based on the bank angle and the susceptibility optimization; the barriers of coupling control between longitudinal and lateral motion as well as the optimization of aiming point in reentry corridor are tackled down; the control performance is demonstrated and the reentry safety and the control precision of landing are guaranteed.

(3) A precise and prediction method, available for engineering is determined by using full numerical integration algorithm. An online estimation and compensation method for lift-drag ratio and atmospheric density is applied to tackle down the problem of the aerodynamics and environmental perturbations during the reentry phase. The 4-DoF aerodynamic model is set up and step-variable and priority-scheduling management method is proposed to resolve the calculation problem of on-board computer.

(4) A reliable combined-navigation system with high-accuracy IMU aiming regime and wide dynamic range based on self-evaluation is demonstrated; the problem of initial alignment and the lossless navigation accuracy is tackled down by systematic reconfiguration with wide dynamic range for the non-orthogonal and heterogeneity IMU independently.

4.6 Thermal control design and verification

The thermal control design for the small capsule which is based on the flexible adaptive "heat-switch mode" method is realized. The difficulties of heat preservation, dissipation and isolation in different modes are resolved. The centralized thermal management is realized to meet various equipment requirements of thermal condition. The advancements are summarized in the following three aspects.

(1) A high-efficiency thermal management system based on flexible adaptive "heat-switch mode" method is designed, which achieves the independent switch between the normal thermal control mode and the blocking mode. The contradiction of thermal preservation with low power and heat dissipation with high power during circumlunar flight as well as heat isolation during reentry is solved by thermal control subsystem.

(2) A non-orthogonal loop heat pipe (LHP) which can emit working substance ammonia before reentry is designed. It reduces the risk of ammonia explosion when heated by aerothermal effects during reentry. The stability of products is

verified by flight and it is promising for further application.

(3) The thermal control of inverse-constraints under long-term weak vacuum condition is demonstrated. The impact of different vacuum conditions on the heat-exchange characteristic of thermal composite material is tested in flight.

4.7 Reentry corridor control

A high-precision free return trajectory correction maneuver is implemented and the technical difficulty of narrow reentry corridor and high accuracy is resolved. The accuracy of trajectory control is better than 0.009 m/s and that of the reentry angle is better than 0.024°.

A synthetic TCM (trajectory correction maneuver) strategy is established based on full target parameters, bias parameter and reduced-order strategy. The full-parameter strategy aims at satisfying the requirements of altitude, inclination, reentry angle, and parachute deployment point by one maneuver. The bias parameter strategy takes account of separation speed of the module and capsule into correction strategy to eliminate the influence on reentry angle. The reduced-order strategy releases part of the aiming parameter and concentrates on the precision of reentry angle. The problem of aiming at multiple target parameters in one single correction and the sensitiveness of reentry angle to separation speed in circumlunar free return trajectory is resolved.

4.8 Design methods of light weight capsule

The light weight and highly-integrated reentry capsule is designed for better performance in semi-ballistic skip reentry. The total weight of the capsule is less than 335 kg, which requires both limited power consumption and precise assembly. The advancements are summarized in the following four aspects [15].

(1) To deal with the problem of the limited room inside the capsule and meanwhile to satisfy the miniaturization requirements of equipment, the systematic resource is reasonably allocated. In order to reduce the weight, multi-functional subsystems are used widely, and new materials and components are utilized, integrated components are used and the structure is simplified.

(2) An overall design on thermal protection system, equipment configuration and mass centre trimming is realized. By precise modeling and the mass-property analysis and weight allocation, the mass centre's position is measured and determined efficiently and precisely, which greatly reduced the total weight of the spacecraft. The weight estimation error is less than 0.5 kg and the mass centre estimation error is less than 0.5 mm.

(3) An integrated design of engine installation support and lateral structure is demonstrated, which reinforces the structure and tackles down the problem of the room occupation of engine. The demand to flame out and on plume diversion is satisfied and the reliability is guaranteed.

(4) To optimize the configuration in the limited room inside the capsule, the dense configuration of a great many electronic equipments is realized. The centralized heat management is realized. Meanwhile the total length of harness is shortened as much as possible.

4.9 New technologies verification and extended experiment

Several new technologies were verified during circumlunar return. After being separated with the capsule, the service module carried on extended experiments. The achievements are summarized in the following five aspects [16].

(1) The autonomous navigation technology by weak signal of GNSS is verified. When the altitude of spacecraft is higher than 5000 km, even up to 70000 km, normal GNSS receiver cannot work. A designed GNSS receiver which can receive side lobe signal from far side of Earth is proved to be feasible. The positioning accuracy is better than 100 m while the accuracy of speed determination is better than 0.1 m/s. It is promising for further application.

(2) The on-board SoPC based on FPGA (SRAM) technology is verified. A miniaturized Control Central Unit is tested in flight to prove its reliability under space environment.

(3) A small and high-accuracy star tracking sensor (STS) is verified. It works perfectly near Earth. Further experiments will be executed near Moon.

(4) A small single camera with both wide and narrow FOV (Field Of View) is tested. Pictures of Earth, Moon and Earth-Moon were taken during flight.

(5) When service module is on the way back to Moon after separation with reentry capsule, it is inserted into the transfer orbit to Lunar Liberation Point 2 (LL2) with lunar swing by. The fuel needed is decreased significantly compared to the direct transfer from Earth to LL2. The service module entered Lissajous orbit around LL2 in late November 2014.

5 Significance

The circumlunar return and reentry spacecraft is of multiple constraints, various mission patterns, technological difficulties, great complexity and numerous new products. The complete success of this mission indicates that the key technologies of circumlunar return and reentry have been broken through in China. There are greater benefits to the society, the economy and the national defense. It will play a positive role in the development of aerospace technology and the related fields.

5.1 Lay foundation for future deep space exploration

The success of reentry and return flight indicates that the key technologies of deep space exploration are verified in China. The key technologies demonstrated in this mission can be directly applied to subsequent lunar sample and return mission, and lays foundation for manned lunar exploration in the future. China will take further steps to Mars, Venus and comets in the future. The key technologies such as aerodynamics, GNC, thermal protection and miniaturization design will provide technical supports for planetary entry and earth reentry missions, and promotes the continuous development of Chinese deep space exploration with greater achievements.

5.2 Promote the development in relative technology fields

The deep space exploration is an extremely complex systematic program with high integration of new high-end technologies. The numerous key technologies and scientific achievements obtained in this mission, such as the spacecraft system design, the trajectory design and control, the aerodynamics design, the new thermal protection material utilization and the experiment result of new technologies will support the development of space utilization and exploration, which effectively improves the spacecraft development capabilities of China and raise the overall level of aerospace technology. The achievements can also be applied in other fields and drive the development of the information science and technology, the computer science and technology, the control science and engineering, the optical engineering, new materials, etc. The independent innovation capability of China will be improved dramatically. It will benefit the society and economy significantly.

5.3 Strengthen capability of independently technological innovation

The innovative scientific and technological achievements with independent intellectual property right obtained in this mission will strengthen the capability of independently technological innovation of China. A group of professionals has been well trained in this mission, who will play important role in keeping China's superiority on frontier domains such as aerospace technology.

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