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CHANG'E-5T1 extended mission: The first lunar libration point flight via a lunar swing-by

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Abstract

This paper introduces the extended mission of the Chinese circumlunar return and reentry test (i.e., the CHANG'E-5T1 mission), the first Chinese flight in the Earth–Moon libration orbit and the first spacecraft to reach the Earth–Moon libration orbit via a lunar swing-by. The extended mission utilized the remaining propellant from the CHANG'E-5T1 mission. Based on the normal trajectory and satellite state at the end of the CHANG'E-5T1 mission, a lunar return and a flight in the lunar libration orbit were determined to be the flight goals of the extended mission. Two schemes were then proposed for the CHANG'E-5T1 extended mission, including a possible Earth–Moon libration orbit. The methodology for the trajectory design and maneuvering included the direct libration-point orbit transfer and injection method, which is characterized by a reduced calculation burden compared with the prevalent invariant manifold method. The scenarios were compared in terms of flight time, control energy and number of maneuvers, flight distance, and achieved flight goals. The comparison indicated that the scheme, including the Earth–Moon L2 point and return to the Moon, was preferred for the CHANG'E-5T1 extended mission. Furthermore, the actual flight parameters of the CHANG'E-5T1 extended mission are also presented to validate the selected scheme.

Keywords: CHANG'E-5T1 mission; Extended mission; Lunar swing-by; Flight scheme; Trajectory design; Libration point

1. Introduction

The Chinese lunar exploration program consists of three major operational phases: lunar orbiting, soft landing and rover operation, and sample return. Each phase serves as the basis for the implementation of the next one. The first two phases were completed by the CHANG'E-1, CHANG'E-2, and CHANG'E-3 probes. CHANG'E-1 earned China membership among the nations that have conducted lunar exploration (Ouyang et al., 2010; Ping et al., 2011), and CHANG'E-2 completed a number of additional innovative exploration activities (Liu et al., 2014a,b; Qiao et al., 2013; Wu et al., 2012), including the CHANG'E-2 extended mission to the Sun-Earth libration orbit and the CHANG'E-2 flyby of the Toutatis asteroid. CHANG'E-3 completed a successful unmanned lunar soft landing and rover mission in December 2013 (Sun et al., 2014; Wu et al., 2014). The third phase began with the Chinese circumlunar return and reentry test in the second half of 2014. This test is termed the CHANG'E-5T1 mission; the objective of the mission was to perform essential technological tests for the future CHANG'E-5 mission.

The CHANG'E-5T1 spacecraft is composed of a service module and a reentry module. As some propellant was to

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remain in the service module after the mission, it was essential and valuable to design an extended mission for CHANG'E-5T1 that would utilize the remaining propellant.

Based on the normal trajectory and satellite status at the end of the CHANG'E-5T1 mission, this paper first analyzes and determines the feasible flight goals for the extended mission, proposing two possible scenarios and the corresponding trajectories. The merits and drawbacks of both plans are presented in terms of flight time, control energy, number of maneuvers, flight distance and achieved flight goals. Based on these results, the scenario including an Earth–Moon libration (EML) orbit and a return to the Moon was selected for the CHANG'E-5T1 extended mission.

The design presented in this paper was successfully implemented for the CHANG'E-5T1 extended mission; therefore, the research findings are expected to serve as a reference for future libration-point and lunar missions.

2. Determination of flight goals

The CHANG'E-5T1 trajectory was a free-return trajectory, encompassing the launch phase, the cislunar transfer phase, the lunar swing-by phase, the lunar return phase, the separation of the service and reentry modules, the reentry and the soft landing. As indicated by the CHANG'E-5T1 mission design as well as the propellant budget and costs, the remaining fuel could provide a velocity increment of up to 1.4 km/s after the completion of the designated mission. This capacity enabled the design of an extended mission for CHANG'E-5T1.

Based on previous deep-space exploration missions and relevant research findings, the potential flight goals of the CHANG'E-5T1 extended mission could include planets and their moons, comets, asteroids and libration points. However, the service module antenna has an effective distance of only 30 million kilometers, which renders the exploration of planets, asteroids and comets impossible and limits the potential practical flight objectives to the Sun–Earth and Earth–Moon regions of space and their corresponding libration points.

As a result, a lunar return and the EML point were selected as the primary flight goals based on the following considerations: First, Phase III of the Chinese lunar exploration program is aimed at achieving automatic lunar sampling and return. Several new technologies are required for lunar ascent, rendezvous and docking. The extended mission offers a highly valuable opportunity to test these new technologies while guiding the service module to the Moon. Second, the EML points are of essential interest for future lunar exploration because they will not only provide vital support for navigation and communication relay throughout the entire cislunar space (especially behind the Moon) but also function as the transfer terminals for future automatic sample returns and deep-space explorations (Lo, 2002; Lo and Chung, 2002). However, the EML orbit has a weak stability and is difficult to control; thus far, only the Artemis mission has performed a flight around the collinear EML points (Angelopoulos, 2011; Folta et al., 2011). With these points included in the extended mission, the necessary tests of certain key flight technologies for the future exploitation of the EML points could be performed. Finally, the Sun–Earth libration points were excluded from the flight goals of the extended mission because CHANG'E-2 explored the Sun–Earth L2 point in 2011.

As a result, two scenarios were designed for the CHANG'E-5T1 extended mission based on the identified flight goals, i.e., the EML point and a lunar return. One scheme involved guiding the spacecraft to directly return to the Moon. The other scheme was to direct the flight of the spacecraft to the Earth–Moon L2 (EML2) point via a lunar swing-by, an innovative mode of transfer to the lunar libration orbit. After completing the flight to the EML2 point, the spacecraft would be maneuvered to return to the Moon. The preferred scenario was selected for the actual CHANG'E-5T1 extended mission based on comparisons of the flight goals, flight times, flight distances, amounts of required energy and numbers of maneuvers.

3. Mission and trajectory design

After the separation and avoidance maneuver, the orbit of the CHANG'E-5T1 service module was a hyper-eccentric ellipse with an eccentricity of 0.98 and a semi-major axis of 361,081 km. The service module was expected to fly as far as 690,000 km and then return to the Earth if no maneuver was performed. Table 1 shows the orbital parameters of the CHANG'E-5T1 service module and other dynamics parameters employed in the mission and trajectory designs presented below, where SRP is used as an abbreviation for solar radiation pressure and atmospheric drag is considered only when the satellite returns to the vicinity of the Earth.

3.1. Scheme A

Scheme A has the flight goal of a direct lunar return, in which the service module is controlled to return directly to the Moon and injected into a circular orbit. The purpose of such a flight would be to test certain key technologies for rendezvous and docking required in the third phase of the Chinese lunar exploration program.

3.1.1. Methodology

Scheme A and the corresponding trajectory are illustrated in Fig. 1.

The objective of the trajectory design in Scheme A is to achieve the corresponding maneuvers and trajectory such that the service module arrives at the Moon at t_{11} or t_{12} with the desired terminal state. The trajectory design adopts the classical intercept-trajectory design method to achieve an initial transfer trajectory to arrive at the Moon,