Lunar Landing Trajectory and Abort Trajectory Integrated Optimization Design

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BACKGROUND and PURPOSE: Manned lunar landing trajectory and abort trajectory design has always been a hot issue in the study of manned deep space exploration. There are mainly two types of manned lunar trajectory, i.e. free return trajectory and hybrid trajectory. The free return trajectory will enable the spacecraft to return to the earth safely after moving around the moon when there is no braking at perilune, therefore it is able to stop the spacecraft's return when it has faults. The deficiency is that its lunar surface area accessible is confined near the equator and it has no automatic return ability after completion of braking at perilune. But the hybrid trajectory consists of free return trajectory and non-free return trajectory, which, in theory, has no limitation in access to lunar surface, therefore it has been widely studied and applied. But only its free return trajectory has automatic return ability and other flight segments have no such ability.

Although the aim of manned lunar landing is to send astronauts to the lunar surface to carry out relevant scientific exploration, the safety of astronauts is still a top priority. In-depth study is required on how to protect lives and safety of astronauts and how to effectively abort task and safely send astronauts back to the earth in the event of any fault or danger. Therefore, the manned lunar landing trajectory design shall incorporate the design of abort trajectory for the spacecraft return to the earth after faults occur to obtain the optimal trajectory for emergency lifesaving.

This article is based on Apollo research and aims at design of manned lunar landing trajectory (free return trajectory and hybrid trajectory); with consideration of abort and return after the spacecraft has faults and through application of the hybrid optimization method based on particle swarm optimization (PSO) and sequential quadratic programming (SQP), this article obtains the lunar landing trajectory that meet abort requirements and is optimal in energy consumption, so as to effectively protect lives and safety of astronauts and provide some references for manned lunar trajectory design.

METHODS: To obtain the manned lunar landing trajectory that meets abort requirements, is optimal in energy consumption and is closer to the project's actual situation, this article puts forward an optimized integrated manned lunar landing trajectory-abort trajectory design method under perturbation. In order to accelerate the convergence speed, an unperturbed solution is taken as the initial value of its perturbation. Therefore, this article first introduces unperturbed models of manned lunar landing trajectory and abort trajectory before giving their perturbation models and analyzes main constraints; on this basis, this article puts forward the hybrid optimization method based on PSO and SQP and uses the method in simulation to verify the correctness and effectiveness of the method.

The second part, without considering perturbation, is based on the patched conic approximation to introduce the initial trajectory design and characteristic analysis. First, it makes design analysis of task trajectories (free return trajectory, hybrid trajectory); secondly, according to the spacecraft's location and flight mode when it aborts maneuver, it makes design analysis of abort trajectory by three modes, i.e. direct abort, abort around the moon and abort after perilune.

The third part gives a more detailed perturbation model. It includes a trajectory calculation model with integrated design and constraints analysis. In the trajectory calculation model with integrated design, it mainly considers non-spherical perturbation of the earth, sun gravitational perturbation, lunar gravitational perturbation and solar radiation pressure perturbation effects. Then it analyzes various constraints to be met at four stages, i.e. earth-moon transfer maneuver, hybrid maneuver, braking maneuver at perilune and abort maneuver, mainly including flight time, perilune distance, perilune trajectory inclination, return trajectory inclination, reentry flight path angle and visibility to ground observatory.

Based on the above modeling, the fourth part puts forward an integrated optimization algorithm based on the hybrid method. First, with energy consumption as an indicatory of the global optimized design, it gives an integrated design model with global optimization. Secondly, it uses SQP to solve the aforementioned nonlinear optimization with constraints. Although the SQP algorithm has global convergence while maintaining partial convergence for at least one time, but it is sensitive to initial value and demanding on initial point. To obtain the best global solution, optimization is made in two steps: (1) first optimize design under no perturbation and use the PSO algorithm to make global search to obtain a solution of global convergence; (2) use the optimal solution obtained using the PSO algorithm as the initial value of SQP to obtain the optimal solution under perturbation.

Finally, the correctness and effectiveness of the proposed algorithms is verified by comparing simulation under different circumstances.

RESULTS: By calculating the launch window, the initial simulation is determined. And given the fact that only one abort can be made during a manned lunar landing task and braking at perilune is key to lunar landing and is the stage where the spacecraft's main engine has worked for a long time and is prone to faults, this article takes the abort trajectory after passing the perilune as optimization object. First, it makes a comparative analysis of manned lunar landing perturbed trajectory-abort trajectory and manned lunar landing unperturbed trajectory-abort trajectory. Secondly, it makes a comparative analysis of integrated design and independent design; the integrated design is the design method put forward herein while the independent design doesn't consider abort in task trajectory design. Through comparative analysis, it can be concluded that the design considering perturbation is closer to the project's actual situation and the integrated optimization design can save velocity increment and thus improve emergency rescue capability for a higher safety, which also illustrates correctness and validity of the algorithm.

CONCLUSIONS: The results of comparative analysis of manned lunar landing perturbed trajectory-abort trajectory and manned lunar landing unperturbed trajectory-abort trajectory show that: unperturbed solution has characteristics of simple calculation, fast solving, etc. and can reflect general characteristics of trajectory to still have great application value; perturbed solution has complex calculation and slow solving, but it is closer to the project's actual situation. And the results of the comparative analysis of integrated design and independent design show that: energy required by the task trajectory obtained by the integrated optimization design is consistent with the optimal value obtained without considering abort; however, the integrated optimization design's results can save velocity increment for abort maneuver, which is equivalent to increase the capability of emergency rescue. Furthermore, the purpose of the integrated optimization design lies not only in the optimization of energy but also introduction of abort constraints into task trajectory design, which is required for safety of manned trajectory. Therefore the trajectory obtained from the integrated design has higher safety.