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MULTI-HOMOTOPIC OPTIMIZATION METHOD FOR WARM-START MULTI-REVOLUTION TRAJECTORIES IN LOW THRUST SPACECRAFT

Abstract

In recent years, low-thrust propulsion has attracted much attention of space agencies and scientists for its high efficiency. It has been successfully applied to a series of missions, i.e., Hayabusa, Dawn, and BepiColombo. However, the trajectory of low thrust spacecraft is not analytically integrable, and multiple revolutions are needed for deep-space or Earth-center missions, resulting in challenges in the trajectory preliminary design and optimization. The optimization methods are mainly categorized as direct methods and indirect methods, where initial guesses are usually needed. In the indirect method, the original optimal control problem is converted into a two-point boundary-value problem based on the calculus of variations or Pontryagin's maximum principle. This work focuses on providing an analytical initial guess for the indirect method and solving the fuel-optimal multi-revolution trajectory in low-thrust spacecraft with a multi-homotopic optimization method.

Traditionally, the fuel-optimal control problems of low-thrust trajectories are connected with energy-optimal control problem to increase the convergence reliability of indirect methods. However, for low-thrust multi-revolution problems, it is still hard to achieve fast and reliable generation of energy-optimal trajectories due to the strong nonlinearity. In this study, a multi-homotopic method is presented for solving the fuel-optimal low-thrust warm-start multi-revolution trajectories, wherein an analytical initial guesses supplying strategy is proposed to start the solving, and the obtained algorithm enjoys fast and guaranteed convergence performance. Firstly, the energy-optimal control problem is transformed into a true longitude-dependent energy-optimal control problem based on a Sundman transformation technique, and the equivalent relations of costates before and after the transformation are derived analytically. Then, through a homotopy to the final time constraint, the true longitude-dependent energy-optimal control problem is further linked to a time-free energy-optimal control problem. Finally, a smoothing technique is proposed to connect the time-free energy-optimal control problem with a linearized time-free energy-optimal control problem, of which the solution can be obtained analytically. Based on these techniques, a multi-homotopic algorithm is developed to achieve fast and reliable generations of warm-start multi-revolution fuel-optimal trajectories. Numerical results of a rendezvous problem from the Earth to the asteroid Dionysus and an Earth-orbit transfer from geostationary transfer orbit to geostationary orbit are presented to substantiate the efficiency of the proposed multi-homotopic optimization method.