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OPTIMAL LOW-THRUST EARTH-MOON ORBIT TRANSFERS VIA MULTIPLE-ARC FORMULATION AND IMPLICIT COSTATE TRANSFORMATION

Abstract

In the scientific literature, several contributions are devoted to investigating optimal low-thrust trajectories about a single attracting body, using indirect numerical methods. This work focuses on minimum-time low-thrust orbit transfers from a prescribed low Earth orbit to different, specified low lunar orbits. The well-established indirect formulation of minimum-time orbit transfers is extended to a multibody dynamical framework, with initial and final orbits around two distinct primaries. To do this, different representations, useful for describing orbit dynamics, are introduced, i.e. modified equinoctial elements (MEE) and Cartesian coordinates. Use of two sets of MEE, relative to either Earth or Moon, allows simple writing of the boundary conditions about the two celestial bodies, but requires the formulation of a multiple-arc trajectory optimization problem, including two legs: (a) geocentric leg and (b) selenocentric leg. Moreover, the use of MEE was proven to mitigate the hypersensitivity issues in detecting the initial adjoint variables, which is the major difficulty when indirect techniques are employed. Both MEE representations are equivalent (and thus coexist) along the entire transfer path. In the numerical solution process, the transition between the two MEE representations uses Cartesian coordinates, which play the role of intermediate, matching variables. The multiple-arc formulation at hand leads to identifying a set of additional necessary conditions for optimality, at the transition between the two legs. This research proves that a closed-form solution to these intermediate conditions exists, leveraging implicit costate transformation. As a result, the parameter set for an indirect algorithm retains the reduced size of the typical set associated with a single-arc optimization problem. The indirect heuristic technique, based on the joint use of the necessary conditions and a heuristic algorithm (i.e., differential evolution in this study) is proposed as the numerical solution method, together with the definition of a stratified fitness function, aimed at facilitating convergence. The minimum-time trajectory of interest is sought in a high-fidelity dynamical framework, with the use of planetary ephemeris and the inclusion of the simultaneous gravitational action of Sun, Earth, and Moon, along the entire transfer path. The numerical results unequivocally prove that the approach developed in this research is effective for determining minimum-time low-thrust Earth-Moon orbit transfers. Furthermore, in the context of the multiple-arc formulation, a set of general matching conditions is derived for the costate, with potential use in a variety of cases of practical interest, e.g. orbit transfers of space vehicles equipped with multiple propulsion systems.