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Author: Ms. Chiara Pozzi
Khalifa University of Science and Technology (KUST), United Arab Emirates

Dr. Mauro Pontani
Sapienza University of Rome, Italy
Mr. Alessandro Beolchi
Khalifa University of Science and Technology (KUST), United Arab Emirates
Dr. Elena Fantino
Khalifa University of Science and Technology (KUST), United Arab Emirates

OPTIMAL LOW-THRUST ORBIT TRANSFERS CONNECTING EARTH, MOON, AND GATEWAY

Abstract

Gateway will represent a primary logistic infrastructure in cislunar space, useful for Earth-Moon transportation, the Artemis program, and deep space exploration. The identification of efficient orbit transfers capable of connecting Earth, Moon, and Gateway paves the way for enabling refurbishment, servicing, and utilization of this orbiting platform. This study is devoted to determining minimum-time low-thrust orbit transfers able to connect both Earth and Moon to Gateway, which is placed in a lunar near-rectilinear halo orbit. First, two-way transfers from Gateway to a specified lunar orbit are determined, using the indirect heuristic method, which employs the necessary conditions for optimality and a heuristic algorithm. Modified equinoctial elements (MEE) are used for orbit propagations. In particular, orbit transfers that connect Earth and Gateway involve two major attracting bodies, and the optimal control problem is to be formulated and solved in a multibody dynamical framework. Unlike most previous contributions focused on indirect approaches applied to optimal low-thrust trajectories, this research extends the indirect formulation of minimum-time orbit transfers to a multibody mission scenario, with terminal orbits around two distinct primaries. Three different representations for the spacecraft state are employed, i.e. (i) MEE relative to Earth, (ii) Cartesian coordinates, and (iii) MEE relative to Moon, and a multi-arc trajectory optimization problem is formulated, including two legs: (a) geocentric leg and (b) selenocentric leg. While MEE were shown to mitigate hypersensitivity issues in finding the corresponding initial adjoint variables, which are needed in an indirect solution approach, Cartesian coordinates are useful as intermediate variables, to step from Earth MEE to lunar MEE (and viceversa). Multi-arc optimal control problems are associated with several additional corner conditions, at the transition between the two legs. This study derives a closed-form solution to these corner conditions, using 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 and the indirect heuristic technique can be applied again. Low-thrust orbit dynamics is propagated 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 paths, in all cases. The numerical results unequivocally prove that the methodology developed in this research is effective for determining minimum-time low-thrust orbit transfers connecting Earth, Moon, and Gateway.