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OPTIMAL LOW-THRUST ORBIT TRANSFERS WITH SHADOWING EFFECT USING A MULTIPLE-ARC FORMULATION

Abstract

In recent years, low-thrust electric propulsion has attracted an increasing interest by the scientific community, and already found application in a variety of mission scenarios. A major drawback of electric propulsion resides in the demanding requirement of electrical power to operate. As a result, in operational scenarios low-thrust propulsion is usually switched off when the satellite is eclipsed. This study addresses the problem of identifying the minimum-time low-thrust transfer between two specified orbits about a celestial body, assuming that low-thrust is unavailable when the space vehicle is eclipsed. The underlying optimization problem is very challenging, because the control (i.e. low-thrust) depends on the instantaneous dynamical state. Unlike previous studies on the same subject, this research does not use averaging techniques nor regularization to address the theoretical challenges related to the problem at hand. Instead, this is formulated as a multiple-arc optimization problem, including a sequence of light arcs and eclipse arcs. Modified equinoctial elements are employed to model orbit dynamics, because these were proven to mitigate the hypersensitivity issues that affect spherical and Cartesian coordinates, when orbit transfers require very long flight times. All the necessary conditions for optimality, referred to modified equinoctial elements, are derived, and include the Pontryagin minimum principle (in the light arcs), the Euler-Lagrange equations, and the multipoint necessary conditions, at the junction times between two arcs. The latter relations are combined, to yield the matching (jump) conditions for the costate variables between two consecutive arcs. All the multipoint conditions are shown be solvable sequentially in the numerical solution process. As a result, the parameter set for an indirect algorithm retains the size of the typical set associated with a single-arc optimization problem. The multiple-arc formulation can be applied when either a single celestial body or multiple celestial bodies (e.g., Earth and Moon) – in separate time intervals – shadow the spacecraft. Illustrative numerical examples prove that the multiple-arc formulation at hand is effective, and allows determining minimum-time low-thrust transfers, fulfilling all the orbit injection conditions and the necessary conditions for optimality, to a great accuracy.