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INDIRECT OPTIMIZATION OF LOW-THRUST EARTH-MOON TRANSFERS IN THE SUN-EARTH-MOON SYSTEM

Abstract

In recent years, the problem of designing low-fuel Earth-Moon transfers has attracted great interest from the astrodynamics community. The most effective approach consists both in considering a high specific impulse low-thrust spacecraft and in exploiting the dynamics properties of the Sun-Earth-Moon system. The aim is to benefit from the invariant manifolds of the two underlying Sun-Earth and Earth-Moon Circular Restricted Three-Body Problems (CR3BPs) to decrease the fuel expenditure leading to so-called low-energy transfers. Some authors built sub-optimal trajectories by connecting low-thrust arcs computed in the two coupled Sun-Earth and Earth-Moon CR3BPs. More recently, a minimum-fuel optimal control problem has been stated by considering the dynamics of the Planar Bicircular Restricted Four-Body Problem (PBR4BP). This optimal control problem has been solved by means of a direct method based on a discretization of the state and control variables. The main drawback in using direct methods here is due to the unstable nature of the PBR4BP. More precisely, this instability requires the use of a very fine time grid and thus the solution of a huge mathematical programming problem to achieve accurate and, above all, reproducible results. In this work, it will be shown for the first time how indirect methods based on Pontryagin's Maximum Principle (PMP) can be successfully applied to the same optimal control problem. First, the standard numerical difficulties related to the solution of minimum-fuel problems by means of indirect shooting methods will be recalled. Then, for the problem under consideration, additional specific difficulties arising from the huge sensitivity of the state and costate equations will be detailed. To overcome these difficulties, a new robust indirect approach will be presented in this work. Instead of using a standard shooting method, based on a Newton-like scheme, a derivative-free algorithm will be used to find the zero of the shooting function. Numerical results will be provided demonstrating the efficiency of the developed approach. First, different families of locally optimal medium-duration trajectories will be presented. Finally, long-duration low-energy trajectories will be shown exploiting the counterparts in the PBR4BP of manifolds defined in both Sun-Earth and Earth-Moon CR3BPs. In conclusion, this work proposes a new numerical method for the computation of minimum-fuel low-thrust Earth-Moon transfers in the PBR4BP framework. This method is based on the PMP and thus ensures local optimality. In addition, it addresses the numerical challenges related to the sensitivity of the problem by using a derivative-free shooting method.