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Author: Dr. Richard Epenoy
Centre National d'Etudes Spatiales (CNES), France, Richard.Epenoy@cnes.fr

A NOVEL INDIRECT APPROACH FOR FUEL OPTIMIZATION OF LOW-THRUST TRAJECTORIES UNDER THRUST AND COAST DURATIONS CONSTRAINTS

Abstract

For many years now, electric propulsion has been widely used in space missions due to its high specific impulse and the related propellant mass saving. Today electric thrusters are developed for smaller and smaller satellites. However, the low electrical power available on board small satellites gives rise to bound constraints on the duration of thrust and coast arcs. Computing fuel-optimal trajectories under these constraints is a difficult issue that warrants further research in optimal control theory. Among direct methods [1], direct shooting methods that discretize the control variable can address the above constraints but only provide an approximate solution of the problem. Moreover, the control switching profile, i.e. the number and sequence of thrust and coast arcs, must be known a priori which never occurs in practice. If the assumed profile is incorrect, the discretized problem may have no solution or a suboptimal one. Regarding indirect methods [2], the constrained problem can be posed as a switched optimal control problem [3] whose optimality conditions are difficult to exploit unless the control switching profile is prespecified. In the latter case, the optimality conditions can be reduced to a huge system of nonlinear equations solved by multiple shooting [4]. In this work, we will show first how to write the constraints on the duration of thrust and coast arcs as a single nonsmooth bound constraint on the control norm depending on time and on a set of free parameters considered as additional state variables. Then, after regularizing the constraint, we will show how to convert the constrained problem into an equivalent unconstrained one. The latter will be solved efficiently through an indirect single shooting algorithm [2,5] with much less unknowns than in [4]. The great advantage of this approach is that it does not require any prior assumption on the control switching profile. Moreover, it has the ability to generate multiple suboptimal solutions in addition to the optimal one, thus offering more options for mission design. Finally, numerical results will be provided to illustrate the interest and efficiency of the proposed method. An electric small satellite rendezvous problem in circular orbit will be considered. The fuel-optimal control of the constrained problem as well as several suboptimal controls will be computed and analyzed, all of which exhibiting different numbers of thrust and coast arcs.

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