Paper ID: 87184
student

IAF ASTRODYNAMICS SYMPOSIUM (C1)
Interactive Presentations - IAF ASTRODYNAMICS SYMPOSIUM (IP)

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OPTIMAL LOW-THRUST TRAJECTORY APPROXIMATION VIA SINGULAR PERTURBATION THEORY

Abstract

The objective of the work is to derive a semi-analytical approximation heuristic for optimal low-thrust transfer trajectories. The approach is based on previous results of the application of singular perturbation theory. A perturbation expansion allows one to analytically determine an approximation for the evolution of orbit parameters as a function of the angular travel for the planar case. Such an expansion has been used in a previous work for i) evaluating the constant tangential thrust required to reach a desired final position, without a constraint on time, and ii) determining a trajectory, made of two low-thrust arcs, in order to match both final position and time of flight, thus providing an approximate solution for the low-thrust Lambert problem.

The present work aims at comparing the solution derived from this analytical approximation, based on perturbation theory, with an optimal trajectory obtained from the numerical solution of an optimal control problem. The solver adopted for this study is the DMG tool (https://github.com/uc3m-aerospace/DMG.git). The role of the approximated trajectory as a potential initial guess for the solver is analyzed, aimed at increasing solution capability and convergence speed toward the optimal solution. The approximation is also expected to preliminary asses feasibility of the transfers and estimate fuel consumption.

The characteristics of the trajectories are analyzed in order to better understand capabilities and limits of the approximate perturbative models. At the same time, a heuristic is proposed, based on minimum thrust required to perform the transfer and on the difference between the final desired state and the actual one. The heuristic provides a correction to be applied to the approximate solution in order to improve quality of the preliminary estimates of transfer trajectory and fuel cost. Performance of the heuristic are analyzed both for flyby and full rendezvous problems to assess its accuracy, efficiency and effectiveness. Different test cases are considered, starting from the simple circular planar motion. The problem is then extended to eccentric orbits. Finally, transfers with change of inclination are also dealt with. Even if the analytical models derived are based on small eccentricity and planar motion hypotheses, the accuracy of the heuristic is demonstrated also in this last scenario, for small changes of inclination. Numerical results of the tests conducted are reported to identify those cases in which the approximation remains acceptable, highlighting those where, conversely, accuracy is rapidly lost.