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# LYAPUNOV-BASED LOW-ENERGY LOW-THRUST TRANSFERS TO THE MOON

**Abstract**

In recent years, the problem of designing low-energy low-thrust Earth-Moon transfers has attracted great interest from the astrodynamics community. For example, indirect optimal control has been applied recently by the authors to compute minimum-fuel Earth-Moon trajectories in the Planar Bicircular Restricted Four-Body Problem [1]. This work revealed different families of locally optimal low-thrust trajectories exploiting the manifolds of the two underlying Sun-Earth and Earth-Moon Planar Circular Restricted Three-Body Problems (PCR3BPs). In this paper, it will be shown how Lyapunov-based control can be used to build robust low-fuel low-thrust transfers to the Moon in the three-dimensional full ephemeris model incorporating gravity from the planets of the solar system and a solar radiation pressure acceleration based on a sample spacecraft area and mass. In the first step, a departure velocity increment to be provided by the launcher will be computed. This initial impulse will put the spacecraft on the counterpart in the full ephemeris model of a stable invariant manifold defined in the Sun-Earth CR3BP. Then, after a coast arc, a closed-loop thrust law will be applied to bring the spacecraft to the final lunar orbit. This control law will be based on Lyapunov control theory. More precisely, a control-Lyapunov function will be defined as the weighted quadratic distance between the first five equinoctial orbital parameters of the spacecraft in a Moon-centered reference frame and those defining the final lunar orbit. The control will be computed in such a way so as to make the time derivative of the control-Lyapunov function as negative as possible. Then, it will be seen that unlike in the case of an open loop control, concentrating the thrust in the vicinity of the perilune and the apolune increases the convergence time of the guidance, but without reducing the fuel consumption. This is due to the uncontrolled effect of the perturbations incurred during the coast arcs. Finally, the robustness of the guidance law against thrust errors and unexpected engine shutdown events will be demonstrated. In conclusion, this work proposes a new approach for the design of low-fuel low-thrust Earth-Moon transfers in the full ephemeris model. The resulting strategy benefits from the counterparts of invariant manifolds to decrease the fuel expenditure while yielding robust transfers thanks to the use of Lyapunov control techniques.

References

[1] D. Pérez-Palau and R. Epenoy, "Fuel Optimization for Low-thrust Earth-Moon Transfer via Indirect Optimal Control", *Celestial Mechanics and Dynamical Astronomy* (2018) 130:21. https://doi.org/10.1007/s10569-017-9808-2.