Doctoral Dissertation
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Low-Thrust Optimal Escape Trajectories from Lagrangian Points and Quasi-Periodic Orbits in a High-Fidelity Model

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Abstract

This thesis focuses on analyzing escape trajectories that use electric propulsion and depart from a Lagrangian point. Electric propulsion is a key technology for the exploration of the solar system due to the low propellant consumption, and the exploitation of Lagrangian points has become of great interest. Among the infinite possible trajectories for a specific mission, historically, those at minimum propellant request, in compliance with the other boundary conditions, have been identified as essential for maximizing the scientific return and minimizing the correlated costs. Namely, bringing less propellant on board, and thus being more efficient, means having more space available for the payload, which increases the scientific return to the same mission; at the same time, larger spacecraft structures are avoided to accommodate the extra-required space.

For this purpose, this thesis researches optimal space trajectories using electric propulsion in a higher fidelity model, aiming to minimize the propellant requests. The electric propulsion trajectory optimization is carried out with an indirect method based on the theory of optimal control and transforms the propellant minimization problem into a multipoint boundary value problem, solved with an iterative single-shooting procedure based on Newton's method. The problem considered here is a specific subclass of optimal control problems with discontinuous control law, named *bang-bang*. Techniques to address numerical issues and find proper tentative solutions, and an automated tool built over the user experience to autonomously generate tentative solutions, are explored. Issues regarding the handling of thrust discontinuities are also addressed, whereas the delicacy of the indirect method is tackled with specifically tailored strategies, such as the definition of an *a priori* thrust structure; the application of the

Pontryagin's Maximum Principle allows to change a suboptimal solution when the thrust structure violates it in some arcs.

The dynamic model includes 4-body gravitation (spacecraft subject to the gravitational pull of the Earth, Moon, and Sun) and uses JPL's ephemerides to retrieve the gravitational bodies' states over time. The solar radiation pressure, a spherical harmonic model for the Earth, and the lunisolar gravitational effect are all included as additional perturbative effects. The delicate gravitational interaction between the Sun, Earth, and Moon dictates the dynamics in the neighborhood of the departure point, namely the Lagrangian point L_2 around the Sun-Earth and Earth-Moon binary systems. The proposed research aims to identify optimal trajectories among the suboptimal ones in such a complex gravitational interdependency and seeks to provide a structured methodology to differentiate one from the others. Escape trajectories from Lagrangian points in both the Sun-Earth and Earth-Moon systems are the focus of this work. They are analyzed in detail in two different nuances; first, simple escape trajectories with a fixed time to escape and free terminal energy are sought, and then more complex escape trajectories with bounded terminal energy conditions are optimized. These solutions represent a starting point for both the transition into high-fidelity escape trajectories from quasi-periodic orbits (e.g., the Lyapunov orbits considered in this thesis) and for the analysis of interplanetary transfers (e.g., to Near-Earth Asteroids), and the effect that escape conditions have on their overall propellant consumption.