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ANALYTICAL DESIGN OF LOW-THRUST V-INFINITY LEVERAGING

Abstract

Deep-space exploration missions increasingly utilize low-thrust propulsion and gravity assists to achieve ambitious scientific objectives. Efficient capture at the target celestial body, often requiring significant reductions in hyperbolic excess velocity (v_∞), is a crucial aspect of these missions. The challenges and importance of optimizing these maneuvers are highlighted by missions like BepiColombo, which aims for capture at Mercury. Traditional methods, often relying on impulsive maneuvers or multiple gravity assists, can be time-consuming or limit mission flexibility. Therefore, the development of v-infinity leveraging (VIL) strategies, combining the effects of low-thrust propulsion and gravity assists, is of great importance. While some research has focused on the numerical optimization of VIL, a comprehensive analytical understanding of optimal low-thrust VIL strategies remains an open area.

A novel analytical approach to designing optimal low-thrust VIL strategies for interplanetary missions is presented in this paper. The main contribution is two-fold. First, an analytical expression for the optimal thrust direction, which maximizes the instantaneous rate of change of v_∞, is derived. This is achieved by formulating the problem as an optimal control problem using modified equinoctial orbital elements and assuming negligible changes in orbital elements within one orbital period. A direct relationship between maneuver efficiency and radial distance is established, revealing a symmetric structure in the optimal thrust arc switching points. This symmetry implies that optimal thrusting is performed at locations mirrored around the major axis of the orbit. Second, based on the analytical efficiency expression, optimal, analytical control strategies for low-thrust VIL are proposed. Three thrusting strategies (full-orbit, dual-arc, single-arc) tailored to mission requirements are enabled by this discovery, offering flexibility in balancing mission duration, propellant consumption, and Δv_∞ requirements. For continuous thrusting, an averaged orbital elements dynamics model is further developed, providing an efficient tool for the rapid estimation of multi-revolution trajectory evolution. Physical Symbolic Optimization (PhySO) is employed to incorporate higher-order effects and improve accuracy.

The design of more fuel-efficient interplanetary trajectories is enabled by this analytical framework, providing a fundamental insight into the interplay between thrust direction, orbital position, and maneuver efficiency. The results of this work contribute to the advancement of low-thrust trajectory optimization techniques, facilitating the development of future deep-space missions with enhanced capabilities and reduced propellant consumption.