Paper ID: 81933
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IAF ASTRODYNAMICS SYMPOSIUM (C1)
Interactive Presentations - IAF ASTRODYNAMICS SYMPOSIUM (IPB)

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ROBUST TRAJECTORY DESIGN OF IMPULSIVE MULTI-FLYBY TRAJECTORIES WITH CHANCE-CONSTRAINT FORMULATION

Abstract

In interplanetary missions, spacecraft encounter a multitude of stochastic disturbances and dynamical uncertainties, complicating the task of maintaining their intended trajectories. Gravity assists, while invaluable for propellant-free maneuvers, introduce significant uncertainty due to close passages with massive bodies, amplifying dynamic perturbations. Depending solely on precise navigation to mitigate state dispersion during critical mission phases may prove inadequate for ensuring robustness. This concern is particularly relevant for future satellite generations, as the anticipated adoption of low-cost operations could limit communication capabilities, especially for deep space missions.

A common and conventional strategy to enhance trajectory robustness and mitigate the risk of failure involves allocating additional propellant reserves after computing a nominal control policy that minimizes specific performance metrics. These reserves are designated for correction maneuvers, aimed at offsetting trajectory deviations. However, this straightforward solution often relies on iterative and time-consuming procedures to ensure an adequate level of robustness, resulting in the definition of sub-optimal control strategies and overly conservative margins. A more efficient approach to handle this issue is to directly incorporate expected uncertainties into the optimization process. This tailored strategy allows for the derivation of the most effective control for the specific scenario.

This manuscript proposes a systematic approach for designing a robust nominal trajectory involving flybys and an associated closed-loop control law to address these challenges. Quantitative information regarding uncertainties and stochastic navigation errors are directly incorporated in system dynamics and thus into the optimization process. Specifically, the aim is to seek a linear feedback control law that steers the probability distribution of the spacecraft state towards a target distribution at a predefined final time, incorporating the perturbing effects of flybys along the trajectory by estimating the evolution of state dispersion during close passages to selected celestial bodies. Given the stochastic nature inherent in robust optimization, a chance-constraint formulation is adopted for both the cost function and the constraints on maneuver magnitude.

The algorithm's effectiveness is assessed through a conceptual mission scenario devised by JAXA, which involves asteroid flyby cycler trajectories. These trajectories consist of orbits that alternate between flybys of the Earth and asteroids. In this setting, a constellation of micro spacecraft is deployed in an Earth-resonant orbit. The primary objective of the mission is to leverage Earth gravity assists to efficiently rendezvous with potentially hazardous asteroids upon detecting close passages near Earth.