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OPTIMIZED LONG-TERM STABILITY AND TRANSFER TRAJECTORY DESIGN IN THE SATURN-TITAN SYSTEM

Abstract

Titan, Saturn's largest moon, is a high-priority target for planetary exploration due to its dense nitrogen-rich atmosphere, hydrocarbon lakes, and potential subsurface ocean, making it a key location for investigating prebiotic chemistry and extraterrestrial habitability. Future missions, such as orbiters, landers, and sample return concepts, will require long-duration orbital stability and efficient transfer strategies to maximize science return and minimize propellant consumption. However, the Saturn-Titan system presents a complex and highly perturbed dynamical environment, where various effects, including Saturn's oblateness, solar tides, and the distributed mass effects of Saturn's rings that significantly influence orbital stability and long-term trajectory evolution. Understanding these perturbative influences is crucial for designing sustainable mission and systems that optimize station-keeping, inter-moon transfers, and low-energy capture mechanisms.

This study develops a high-fidelity numerical optimization framework to systematically evaluate orbital stability and optimal transfer trajectories in the Saturn-Titan system. Using Multi-Objective Genetic Algorithms (MOGA), we explore trade-offs between station-keeping fuel consumption, observational coverage, and long-term stability, while SNOPT-based low-thrust optimization is applied to design fuel-efficient inter-moon transfer trajectories. To ensure that selected orbits remain dynamically stable over extended periods, chaos-sensitive trajectory selection techniques, such as Fast Lyapunov Indicators (FLI) and Recurrence Quantification Analysis (RQA), are used to distinguish between quasi-periodic, resonant, and chaotic regimes. Additionally, perturbation-driven orbit correction strategies are implemented to minimize cumulative ΔV costs in regions where gravitational perturbations are dominant, ensuring that orbits remain stable without excessive station-keeping maneuvers.

Results demonstrate the existence of previously unidentified quasi-stable orbital corridors, which facilitate low-energy transfers between Titan and Saturn-bound orbits, reducing fuel requirements for extended-duration missions. Additionally, Saturn's rings introduce unexpected secular drifts, influencing the feasibility of DRO-based staging orbits for interplanetary gateway missions. These findings contribute to the future mission planning strategies for planetary orbiters and deep-space exploration systems in complex gravitational environments. The proposed approach is applicable not only to Titan exploration but also to future planetary missions requiring precise orbit stability assessment and fuel-efficient transfer design.