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LOW-THRUST TRAJECTORY DESIGN WITH POWER CONSTRAINTS AND ATTITUDE DYNAMICS INTEGRATION

Abstract

Efficient low-thrust trajectory design is a critical element of space mission design of small satellites equipped with electric propulsion. The Q-Law—a Lyapunov-based feedback control law— constitutes a popular way to design near-optimal maneuvers, owing to its use of analytic expressions for the maximum rates of change of orbital elements and the desired element adjustments. Traditional Q-Law-based maneuver planning solutions, with parameters often optimized using metaheuristic algorithms, usually solve for constant Q-Law parameters throughout the maneuver. Moreover, most studies either assume unlimited power for thrusting or restrict thrusting strictly to sunlight periods, ignoring the possibility of using stored energy to enable efficient thrusting during eclipse phases and assuming no power constraints during the thrusting arcs. Therefore, without modeling electric power generation and storage, these common assumptions might impose tighter operational and platform constraints, although they also simplify or avoid attitude modeling. However, since power generation depends on attitude, a realistic representation of power constraints requires modeling the full attitude of the spacecraft (rather than just specifying a thrusting vector) and potentially modeling the Attitude Determination and Control Systems (ADCS) as well. In this study, we present a simulation-based approach that fully models power generation and consumption to capture the inherent electrical constraints of spacecraft relying on low-thrust propulsion systems. By leveraging Reinforcement Learning (RL) to dynamically adjust Q-law parameters, our method supports decision-making based on the spacecraft's current state and available power. Furthermore, we incorporate an efficient ADCS modeling approach that addresses misalignment issues during transient phases. This approach is activated only when needed, thereby conserving computational resources while ensuring that power generation is closely linked to precise attitude control. Beyond trajectory optimization, our approach significantly improves power efficiency by integrating power management into the guidance system. During low-battery conditions, the spacecraft temporarily shifts focus, realigning its solar panels to maximize energy absorption and quickly restore its power reserves. Once sufficient energy is available, the RL-enhanced Q-law seamlessly resumes trajectory guidance, steering the spacecraft toward its target orbit. We validate the effectiveness of this integrated strategy in a Geostationary Transfer Orbit (GTO) to Geostationary Orbit (GEO) mission. By combining trajectory control with power management and the ADCS module, our method represents a more realistic approach than conventional techniques and allows for the discovery of more efficient solutions in power- and attitude-constrained scenarios.