Robust Differential Dynamic Programming for Low-Thrust Trajectory Design: Approach with Robust Model Predictive Control Technique

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The low-thrust propulsion is a key technology for space exploration because of its high specific impulse, and several low-thrust trajectory design methods have been developed. The most numerically stable methods use Differential Dynamic Programming [1]. Although low-thrust trajectory design methods are implemented on deterministic systems, in actual spacecraft operations, the trajectories are perturbed by disturbances including un-modeled accelerations, guidance/navigation errors, and *missed-thrust* (i.e. the contingent coasting period due to operational troubles, such as safe-mode operations).To account for model and execution errors, mission designers heuristically add margins - for example, introducing *duty cycle*, which reduce the thrust magnitude and *forced coast periods*. These conventional methods are time-consuming, done by hand by experts, and lead to conservative margins.

This paper introduces a new method to compute nominal trajectories, taking into account disturbances. The method is based on Stochastic Differential Dynamic Programming (SDDP), which computes the stochastic optimal control solving a second-order expansion of Bellman equation, and Robust Model Predictive Control technique, such as constraint tightening approach [2] and disturbance invariant tube [3], as shown in Fig.1. The idea is tightening the state and control constraints on the nominal trajectory to improve the robustness, and retaining the margins for future re-computation of the trajectory. We propose a modified version of SDDP by using the constraint tightening techniques. The expected value in the Bellman equation is computed with the Unscented Transform method, which is easy to implement to trajectory design problems.

Finally, we present numerical examples where the solutions of the proposed method are more robust to disturbances and require less penalties than those computed with traditional approaches, when uncertainties are introduced.

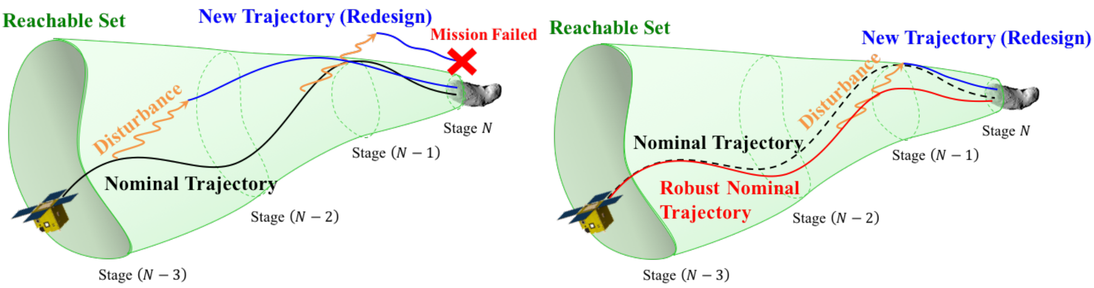

Fig. 1. Constraint tightening approach: conventional nominal trajectory (left) and robust nominal trajectory (right).

References

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