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STOCHASTIC CONTROL OF LAUNCH VEHICLE UPPER STAGE WITH CHANCE-CONSTRAINED SPLASH-DOWN

Abstract

Launch vehicle dynamics are subject to significant uncertainties due to dispersions of the propulsion system performance, random variations of the local environment, and hard-to-model external perturbations. Therefore, designing a guidance and control algorithm that can robustly ensure operation in such an uncertain scenario is essential for the system's in-flight autonomy. Besides safety requirements, the algorithm should also be optimal, e.g., in terms of propellant consumption, to maximize the mass-to-orbit, enhance the vehicle responsiveness in off-nominal conditions, and reduce the mission cost.

The optimal control of uncertain systems is traditionally an uneasy task, as a general approach to an uncertain optimal control problem (OCP) would involve solving a dynamic programming (DP) problem over arbitrary feedback control laws, which is computationally impractical for real-world applications due to the curse of dimensionality. Model predictive control (MPC) circumvents the formidable computational cost of DP by recursively solving onboard the deterministic OCP updated with real-time measurements. However, performing hardware is necessary onboard to attain sufficiently high update frequencies and guarantee robustness.

This paper presents a computationally efficient and robust algorithm, based on stochastic optimal control, for the guidance and control of the third stage of a VEGA-like launch vehicle. A major challenge of this application consists in safely ensuring that the spent stage falls in an uninhabited area, despite uncertainties on the propulsion system performance and the hard-to-model atmospheric return dynamics. Unlike MPC, stochastic optimal control explicitly accounts for probabilistic descriptions of uncertainties in the OCP to design a nominal trajectory and a control policy tailored to the considered characterization of the random processes.

Specifically, a two-step solution process is pursued. Starting from the optimal trajectory found in the deterministic scenario, we pose a covariance control problem to design a multiplicative feedback control policy that minimizes the dispersion of the spent stage splash-down point, while not altering the thrust level (hence, applicable to non-throttleable solid rocket motors). Then, a stochastic OCP with a chance-constrained splash-down is solved to update the nominal path and the feedforward control signal based on the previously attained feedback policy. In either step, introducing a convenient change of variables and a lossless constraint relaxation allows casting the upper stage stochastic OCPs as convex optimization problems, thus solvable with low computational complexity. Numerical results assess the robustness and performance of the proposed algorithm through extensive Monte Carlo campaigns and compare the stochastic control approach with an MPC-based algorithm.