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ROBUST TRAJECTORY DESIGN AND CONTROLLABLE SET METHODS

Abstract

This paper presents methods for the computation of controllable sets and introduces the use of a controllable set framework to study the robustness of trajectories to missed thrust events (MTEs). An MTE occurs when an anomaly causes loss of thrust capability, leading the spacecraft to deviate from its nominal trajectory. Without robust trajectory design, such losses jeopardize mission objectives, especially when flight paths leverage encounters with celestial bodies. The aerospace industry lacks a framework to design for robustness that does not require the brute force simulation of MTEs. A controllable set framework is used to study the robustness of existing sub-optimal design techniques, such as duty-cycle methods, where thrust magnitude is reserved for use post-MTE. Using controllable sets to study robustness has the potential to change how we view the problem of robust trajectory design.

Controllable sets characterize the initial conditions of a system, which delineate an envelope in which a spacecraft must reside to have the ability to reach a target orbit or state. The controllable set spans initial conditions of both position and velocity, making it an object in 6-dimensional phase space relative to the target end state. To compute the controllable set, a direction vector is used to specify which components of the state to maximize, since the maximum position and velocity solutions do not coincide. In this work, controllable sets are computed using indirect methods by applying classical optimal control results to a maximum state optimization problem. Three different methods for computing the controllable set are presented and the advantages and drawbacks of each method are explored. These reachability results have implications for robust trajectory design considering MTEs. Spacecraft on the boundary of the controllable set have no margin for missed thrust, thus the controllable set can be used as the starting point for designing flight paths which do not encroach on this boundary. Trajectories designed using duty-cycle methods are studied to understand how lowering the thrust changes the shape and size of the controllable set. MTEs are simulated to explore how recovery trajectories behave with and without applying duty-cycle methods.