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A GRAPH-AIDED DESIGN FRAMEWORK OF LOW-ENERGY TRANSFERS

Abstract

This paper proposes a framework for efficiently designing low-energy transfers in the multi-body gravitational environment. The novelty of the framework is fourfold. Firstly, a database of trajectories emanating from zero-velocity states in a rotating reference frame is generated. Zero-velocity states correspond to apsides with respect to two bodies and thus include those perturbed in a most significant manner, which can induce low-energy transfers. Secondly, flight time and delta-v for patching all the pairs of the trajectories are organized as a directed graph. Each graph node represents a zero-velocity-bouncing trajectory patched by an edge, whose weight reflects the corresponding flight time. Various tolerances of delta-v are applied to determine the connectivity between the graph nodes that affects the diversity of solutions. Thirdly, design processes are grouped into preceding and mission-specific ones. The former includes the database generation and the graph creation that are separable from a specific mission analysis. The latter includes the addition of graph nodes and edges corresponding to boundary arcs of a specific mission, a path planning via the Dijkstra's algorithm generating initial guess solutions for an end-to-end trajectory, and the optimization. The separation of the processes drastically reduces the computational burden of a mission analysis. Fourthly, a doubly regularized optimizer is newly developed to compute fuel-optimal multi-impulse solutions. The Kustaanheimo-Stiefel and Sundman transformations are applied to remove the notorious singularity in the fuel minimization problem and relax the uneven distribution of shooting nodes, respectively.

The method has been applied to study Earth-to-Moon low-energy transfers adopting the boundary conditions based on the SMART-1 mission. The computational time in the preceding processes was 6 hours with 2 million initial seeds on zero-velocity states and that in the mission-specific processes was 30 minutes including the optimization of three representative solutions. Distinct families of initial guess solutions were observed in an orderly manner in terms of the orbital resonance with the Moon. The optimal solutions resulted in multi-revolutional transfers leveraging high-altitude lunar flybys that increase the perigee altitude and crank the inclination in a fuel-efficient manner.

In conclusion, our strategy has reduced a complicated search for low-energy transfer to a simple graph search. The limited number of design variables for the zero-velocity states has kept the database a manageable size and enabled the graph-aided efficient search. Together with the separation of the preceding and mission-specific processes and the doubly regularized optimizer, we have developed an efficient framework for designing low-energy transfers.