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GRAVITY-ASSIST FUEL-OPTIMAL LOW-THRUST TRAJECTORY DESIGN USING HYBRID OPTIMIZATION TECHNIQUES

Abstract

Low-thrust propulsion technology and planetary gravity-assist maneuvers make a promising combination for deep space explorations. With the evolution that has taken place in both indirect and direct optimization methods that are typically used for solving optimal control problems, hybrid optimization methods have proved to be an excellent choice to exploit the advantages and alleviate the drawbacks of both the methodologies. For fuel-optimal trajectories, smoothing with traditional techniques like quadratic, logarithmic and extended logarithmic have been employed with homotopy to relax the non-smoothness arising due to bang-bang control structures. We employ a recently introduced hyperbolic tangent smoothing (HTS) method to design low-thrust interplanetary trajectories with gravity-assist opportunities. The HTS method is particularly promising since 1) the derivation of the first-order necessary conditions remains intact, 2) it removes the need for switch detections, and 3) control input is approximated by a continuously differentiable function with its immediate implications. The last item is particularly helpful in twofold: 1) it is possible to use variable step-size integration schemes to speed-up numerical simulations, and 2) analytic sensitivity calculations become significantly easier. Moreover, due to control smoothing, it is significantly easier to enhance convergence performance of solvers that rely on Newton and/or Quasi-Newton update iterative schemes by high-accuracy sensitivity information such as those obtained through the State Transition Matrix (STM) method. In this setting, implementation of the STM method is facilitated due to the fact that the entire trajectory is smooth and the control is infinitely differentiable. Thus, there is no need to construct an additional transition matrix to patch the discontinuities in STM when solving non-smooth trajectories with analytical sensitivities. Gravity-assist maneuvers lead to multiple-point boundary-value problems (MPBVPs), and to solve them, we use a two-level hybrid optimization method. At the first level, a particle swarm optimization (PSO) method is used to perform a global search over the unknown parameters of an easy-to-solve problem, namely, a problem with smoother control input. The second level uses the solution of the first level to perform an accurate on-parameter homotopy to obtain fuel-optimal solution with faster convergence and with minimal numerical difficulties while taking advantage of the HTS and STM methods. Utility of this method is demonstrated through interplanetary low-thrust trajectories with single gravity assist like Earth to Jupiter via Mars and Earth to Jupiter via Earth.