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MODEL PREDICTIVE STATIC PROGRAMMING FOR BANG-OFF-BANG LOW-THRUST NEIGHBORING CONTROL LAW DESIGN

Abstract

In recent decades, highly efficient propulsion systems, such as electric propulsion and solar sails, have made low-thrust engine an alternative to enable more ambitious space missions, simultaneously, reducing the fuel consumption. Extensive work has focused on high-fidelity modeling and open-loop optimal low-thrust trajectory design, solved by direct or indirect methods. However, in real-world deep-space flight, disturbances such as solar radiation pressure, irregular gravitational field, outgassing etc, deviate the spacecraft off the reference trajectory, which requires a closed-loop control compensation. In this paper, Model Predictive Static Programming (MPSP), an optimal control design technique that combines the philosophy of model predictive control and approximate dynamical programming, is presented as a suboptimal neighboring control law that corrects deviations by adapting the bang-off-bang reference trajectory on-line. Firstly, the fuel-optimal low-thrust problem is established in the Cartesian framework, where bang-off-bang control is formulated based on Pontryagin minimum principle (PMP). The reference solution solved by indirect method off-line is stored on board. Secondly, inspired by the natural feedback controller formulation given by PMP, the related unconstrained costate variables are witnessed as the new control variable in MPSP design. In order to ensure the continuation of switching function at switching points, dynamical equations are argued by costate dynamics related to the mass. Thirdly, the sensitivity matrix (SM) is recursively calculated using analytical derivation, where SM at switching points is compensated based on calculation of variations. Since the discontinuity of SM would result in discontinuity of discrete thrust angle sequence, the control history is further represented by the combination of Cheybshev basis functions. The corresponding weights are initialized based on reference trajectory using least square method, and updated using Newton downhill method. The MPSP technique is applied to bang-off-bang control successfully for the first time in literature, while remaining the simplicity and highly computational efficiency of original MPSP technique. Unlike backward sweep method, the proposed method is not restricted by the bang-off-bang sequence given by reference trajectory, and thus has stronger robustness. An interplanetary Cubesats mission to an asteroid is used to assess the effectiveness and efficiency of the proposed method.