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A POLYNOMIAL-BASED DIFFERENTIAL DYNAMIC PROGRAMMING OPTIMISATION METHOD FOR SPACE TRAJECTORY DESIGN

Abstract

Differential Dynamic Programming (DDP) is a powerful optimisation technique for the design of space trajectories, renowned for its robustness to suboptimal or infeasible starting points, and adaptability in tackling diverse challenges in astrodynamics, such as large-scale problems.

DDP relies on Bellman's optimality principle and consists in computing the quadratic approximations of cost functions to iteratively refine design variables, embodying a robust framework for optimisation. Incorporating Taylor Differential Algebra (DA) methods can significantly enhance DDP's efficiency. These methods consist of employing Taylor polynomials to map functions over continuous sets, facilitating cost-effective evaluation of function values within a specified convergence radius thanks to inexpensive polynomial evaluations. Additionally, the derivatives of the functions, assuming sufficient differentiability, can be obtained with limited effort.

Expanding upon these fundamental concepts, the authors present DA-based enhancements to DDP, implemented in the DA-enhanced DDP (DADDy) solver, which integrates nonlinear constraint enforcement using an Augmented Lagrangian approach. After finding an initial optimal solution, the solver performs a "solution polishing" phase via a projected Newton method to validate constraints up to machine precision.

This methodology is applied to various fuel-optimal low-thrust test cases. Among them, an Earth to Mars and GTO to GEO transfers in the two-body problem, or Halo L1 to Halo L2, Distant Retrograde Orbit (DRO) to DRO, and Near-Rectilinear Halo Orbit (NRHO) to DRO transfers in the complex dynamics of the circular restricted three-body problem were performed. Initial computations yield very regular minimum-energy solutions for each test case, allowing to warm-start the iterative determination of the minimum-fuel solutions. Results show that the DADDy solver delivers solutions comparable to traditional DDP while dividing runtimes by at least 3.

The authors developed and validated a new trajectory design tool against various astrodynamic problems. The solver is based on DDP and enhanced using DA techniques, and results show that runtimes are dramatically reduced without loss of robustness compared to regular DDP.