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Title

A Dual-Based Linear Programming formulation of Optimal Control: Fuel-Optimal Rendezvous Guidance and Boresight Pointing Applications

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Abstract

Optimal control problems are natural and intrinsically valuable to astrodynamics and general mission design of aerospace vehicles, in which tight performance constraints exist. Along this line, fuel-optimal performance is of vital interest, as carrying additional fuel is contrary to payload capacity. The design of fuel-optimal state trajectories is a major challenge is space dynamics for which no closed solution can a-priori be found.

Despite the vast literature on the topic, Optimal Control Theory still poses untackled problematics, especially with regards to Real Time Optimal Control onboard legacy systems. The design of optimal control laws is constrained by the need to solve complex nonlinear programming problems associated to a Hamiltonian Minimization Condition, either in the form of Pontryagin's Maximum Principle or the complementary Hamilton-Jacobi-Bellman PDE equation. General, standard optimal control problem solvers focus on the former, by either solving the primal or dual formulation of the problem of interest. For the first method, the so-called direct approach, discretization of the state-control pair allows to render the infinite-dimensional function problem into a finite nonlinear programming problem (NLP). However, despite being easier to solve, it does not provide information on the co-states trajectory, which is necessary to verify optimality. Solving the dual problem is known as the indirect method and still requires of discretization; moreover, due to its symplectic Hamiltonian structure, the problem is highly sensitive on the initial co-state guess. Nonetheless, both formulations require of general NLP techniques to solve the optimal control problem, which may not always be available, especially on low-cost, legacy systems, such as those arising in the spirit of the NewSpace Era. Therefore, the reduction of such computational burden is always a desirable goal.

This work exploits two novelties to formulate fuel-optimal control problems: first, modern optimization techniques, such as Alternating Direction Method of Multiplier and Model Predictive Control, are used to close the gap between L1 and L2 optimization in classical astrodynamics problems, allowing to establish a cost mapping principle between fuel-optimal and quadratic-cost problems; second, this latter L2 optimization is solved exploiting its dual-problem multi-stage formulation, for which a close-form solution exists [2]. The combination of these two techniques allows to render general NLP fuel-optimal problems solvable by Linear Programming techniques. The low footprint of the proposed algorithms makes it a solid candidate for real-time, embedded applications, providing sub-optimal solutions at nearly

null expenses. Moreover, connections between the novel algorithm and classical Primer Vector Theory and Dynamic Programming are also studied. Finally, the performance of this novel algorithm is validated against Optimal Control pseudospectral collocation.

The proposed algorithm is applied to several consensus rendezvous and orbital transfer test cases in both the Keplerian and the Circular Restricted Three-Body Problems [2]. Comparison against classical rendezvous trajectory planning algorithms is addressed to objectively assess the performance of the novel technique. Additionally, the same methodology is applied to the design of rest-to-rest attitude slews. Finally, conclusions are presented and further open lines of research and steps ahead discussed.

References

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