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# ROBUST TRAJECTORY OPTIMIZATION WITH ORTHOGONAL COLLOCATION METHODS FOR ASCENDING ROCKET STAGES IN EARLY PHASES OF MISSION DESIGN

**Abstract**

This paper presents CONORA (Collocated Orthogonal coNtrol Optimization for Rocketry Applications), a robust trajectory optimization software utilizing orthogonal collocation methods for ascending rocket stages, targeting applications in early phases of mission design.

The proposed methodology leverages orthogonal collocation techniques, preferred over other available options for their robustness to poorly defined initial guesses. This robustness is particularly crucial considering the inherent complexity in computing initial guesses for launch trajectories, where dynamic variables such as atmospheric conditions, thrust variations, and gravitational influences pose significant challenges. This, together with low amount of available data about the ascent profile, often makes preliminary optimization considerably complex, extremely case-specific and, consequently, very time consuming.

The implemented software addresses the problem of maximizing the payload mass of a rocket by providing the required flexibility to adapt to any mission scenario disregarding of the celestial body, launch site, vehicle design and target orbit. Proper functionality is demonstrated by replicating existing missions. Ariane V ascending to GTO (Geosynchronous Transfer Orbit), Electron launch to SSO (Sun Synchronous Orbit), ALTO (Air Launch To Orbit) mission to LEO (Low Earth Orbit), Apollo XI Lunar Module ascent and Starship take-off to LMO (Low Mars Orbit) are the multifaceted mission scenarios selected to demonstrate the capabilities of CONORA, resulting in accurate injection into orbit and close estimation of optimized payload masses.

The obtained outcomes grow more valuable when considering the small number of inputs provided, the simplicity of the utilized physical model and the strong assumptions considered. Furthermore, these results were achieved using one of the most straightforward approaches for an initial guess: a stage-wise linear interpolation to bridge the launch and orbital injection conditions.

The whole software development process followed a V-model, from requirement definition, passing by the actual implementation, to thorough code testing of each CONORA's module. The requirements were meticulously crafted based on the definition of personae and user stories, ensuring a user-centric approach in the software development.

Additionally, the coding was carried out in Python, ideal for such complex computations, while testing was efficiently executed using pytest, a powerful testing framework that enabled comprehensive verification of the code. Sphinx-Needs was used to define an object-oriented requirements system. The work was performed under technical supervision by DLR (Deutsches Zentrum für Luft- und Raumfahr), at the Institute of Space Systems in Bremen, Germany, as the Master Thesis project of the Author.