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Trajectory Optimization for Autonomous Deep Space Missions

Authors : Anne Schattel, Mitja Echim, Christof Büskens

Abstract : Trajectory planning for deep space missions has become a recent topic of great interest. Flying to space objects like asteroids provides two main challenges. One is to find rare earth elements, the other to gain scientific knowledge of the origin of the world. Due to the enormous spatial distances such explorer missions have to be performed unmanned and autonomously. The mathematical field of optimization and optimal control can be used to realize autonomous missions while protecting recourses and making them safer. The resulting algorithms may be applied to other, earth-bound applications like e.g. deep sea navigation and autonomous driving as well. The project KaNaRiA ('Kognitionsbasierte, autonome Navigation am Beispiel des Ressourcenabbaus im All') investigates the possibilities of cognitive autonomous navigation on the example of an asteroid mining mission, including the cruise phase and approach as well as the asteroid rendezvous, landing and surface exploration. To verify and test all methods an interactive, real-time capable simulation using virtual reality is developed under KaNaRiA. This paper focuses on the specific challenge of the guidance during the cruise phase of the spacecraft, i.e. trajectory optimization and optimal control, including first solutions and results. In principle there exist two ways to solve optimal control problems (OCPs), the so called indirect and direct methods. The indirect methods are being studied since several decades and their usage needs advanced skills regarding optimal control theory. The main idea of direct approaches, also known as transcription techniques, is to transform the infinite-dimensional OCP into a finite-dimensional non-linear optimization problem (NLP) via discretization of states and controls. These direct methods are applied in this paper. The resulting high dimensional NLP with constraints can be solved efficiently by special NLP methods, e.g. sequential quadratic programming (SQP) or interior point methods (IP). The movement of the spacecraft due to gravitational influences of the sun and other planets, as well as the thrust commands, is described through ordinary differential equations (ODEs). The competitive mission aims like short flight times and low energy consumption are considered by using a multi-criteria objective function. The resulting non-linear high-dimensional optimization problems are solved by using the software package WORHP ('We Optimize Really Huge Problems'), a software routine combining SQP at an outer level and IP to solve underlying quadratic subproblems. An application-adapted model of impulsive thrusting, as well as a model of an electrically powered spacecraft propulsion system, is introduced. Different priorities and possibilities of a space mission regarding energy cost and flight time duration are investigated by choosing different weighting factors for the multi-criteria objective function. Varying mission trajectories are analyzed and compared, both aiming at different destination asteroids and using different propulsion systems. For the transcription, the robust method of full discretization is used. The results strengthen the need for trajectory optimization as a foundation for autonomous decision making during deep space missions. Simultaneously they show the enormous increase in possibilities for flight maneuvers by being able to consider different and opposite mission objectives.

Keywords : deep space navigation, guidance, multi-objective, non-linear optimization, optimal control, trajectory planning.
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