Asteroid Rendezvous Trajectory Optimization with Stochastic Convex Optimization Approach

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Abstract

The exploration of asteroids has been the focus of an increasing number of scientists and engineers in recent years and plenty of exploration missions have launched to study various asteroids. In addition, more missions are planned in the near future. Exploring and studying asteroids bring scientific discoveries about the formation process of our solar system and the origin of life, are essential for establishing planetary defense technologies, and provide opportunities for asteroid mining to access various types of materials.

For examining an asteroid, sending a spacecraft to a vicinity of it is essential since the size of the majority of asteroids are so small that the ground-based observations are not capable of revealing the details. Moreover, sending a spacecraft allows to perform a sample return mission for further analysis on the ground. Asteroid rendezvous (RDV) approach is a sequence of trajectory maneuvers which brings a spacecraft to a vicinity of an asteroid and keeps it there. Because of the limitation of the ground-based operation due to the communication delay and the low bit-rate communication capability due to less complex communication system, the spacecraft should be operated autonomously. However, the autonomous operation is still challenging due to the highly constrained optimization problems and the less powerful on-board computer (OBC).

In the real world, the spacecraft dynamics is affected by various uncertainties such as in asteroid ephemeris, in spacecraft system and dynamics, and in perturbations. Hence, the RDV trajectory optimization problem has to deal with these uncertain factors otherwise the spacecraft will deviate from the nominal trajectory and fail to reach the asteroid. In other words, the RDV trajectory optimization has to be robust against these uncertainties. However, it is not an easy task to autonomously compute robust Trajectory Correction Maneuvers (TCMs) while taking into account the future evolution of state uncertainty under highly perturbed, uncertain dynamics.

To address the challenge in autonomous trajectory optimization with complex optimization problem, this paper adapts convex optimization techniques to solve the complex trajectory optimization problem with less computational load. Convex optimization techniques have started to emerge to solve aerospace guidance and control in real-time. These techniques guarantee the global optimal solutions and have been already applied to the RDV optimization between two spacecrafts [1, 2] and asteroid landing optimization [3, 4].

We also develops the robust trajectory optimization to tackle the difficulty in the optimization under influence of uncertainties. Stochastic optimal control methods solve the optimization problem with probabilistic uncertainties to design robust trajectories. Some of the methods can be categorized as robust control with hard constraints against boundary stochastic disturbance while the others can be labeled as chance-constrained control under unbounded uncertainties. Since robust control with hard constraints cannot be imposed on

unbounded distributions such as Gaussian distributions which most of the space mission designs consider, the chance-constrained method is more suitable for astrodynamics applications [5, 6]. Hence, our algorithm is developed based on the chance-constrained method.

Our algorithm is tested in the scenario which is similar to the one for Hayabusa2 [7]. In this scenario, the spacecraft initiates the RDV approach around 2,500 km from the target asteroid Ryugu and reaches the arrival point which is located 20 km from the asteroid. First, the reference trajectory and reference control inputs are computed by the convex optimization techniques in order to generate the trajectory quickly from the highly constrained optimization problem. Then, the reference trajectory and inputs are perturbed by several uncertainties, and the robust control inputs against these uncertainties are computed using the chance-constrained optimization method. Mote Carlo simulations are performed to demonstrate the robustness of our trajectory optimization algorithm against the uncertainties.

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