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Desensitized optimal trajectory for landing on small bodies with reduced landing error

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ABSTRACT

This paper aims at desensitizing the optimal trajectory for landing on the small bodies with reduced landing error in the presence of initial state error, parameters uncertainties of the target body (the gravity and the body's rotation rate) and thrust error (the error in thrust magnitude and direction). The motion of the lander is expressed in the body-fixed coordinate frame, and the thruster is considered to be variable. Instead of directly optimizing the landing trajectory, this paper propagates the linear covariance of the stochastic landing dynamics equations, and minimizes the fuel consumption as well as the covariance. Firstly, the stochastic state equations including the effects of these uncertainties are constructed. The rotation rate is augmented as the new state of the state equations, and the uncertainties in gravity and thruster are modeled as the stochastic process noise acting on the lander. Then, the closed-loop linear covariance is derived and optimized with the fuel consumption performance index as a penalty factor. Finally, several sets of simulations are performed in the scenarios of Eros 433 and Vesta. The open-loop trajectory is firstly performed in the scenario of Eros 433 and the result shows that these uncertainties contribute greatly to the trajectory dispersions. The 3σ trajectory dispersions for tracking the optimal and desensitized optimal trajectory show that the desensitized approach reduces the landing error effectively. And the statistic landing velocities show that the desensitized approach meets the requirement of soft and stable landing on small bodies. To especially discuss the fuel consumption of optimal and desensitized optimal trajectory, the simulation in the scenario of Vesta is performed. The results show that the desensitized optimal approach takes only about 1.01 kg more fuel for the lander of 800 kg size. And the landing error of desensitized trajectory is reduced significantly compared to that of the optimal trajectory. The total simulations in the scenario of Eros 433 and Vesta indicate that the desensitized approach is fuel-saving, and can reduce the landing error effectively for landing on small bodies.

0. Introduction

Solar system's small bodies (e.g., asteroids and comets) have received increased attention in recent years, and three spacecrafts have landed on the small bodies up to date. NASA's Near Earth Asteroid Rendezvous (NEAR) mission landed spacecraft on Eros 433 in 2001 [4]; Hayabusa by Japan Aerospace Exploration Agency (JAXA) landed on the asteroid Itokawa in 2005, and has safely returned to Earth with rock sample [19]. Rosetta has already landed on comet 67P/Churyumov–Gerasimenko in November 2014 [25]. The Philae lander of the Rosetta mission lands at the comet with about 1 m/s. However, the landing velocity of 1 m/s results in bouncy landing, and the process is illustrated in Fig. 1. The Philae lander finally stops in the shadow region of the cliffs. For lack of enough solar power, the Philae lander is still in the sleep mode. To avoid the bouncy landing on small bodies, it's expected to reduce the landing error, especially the velocity error.

The gravity of majority asteroids is very weak, so the existing initial state error, parameters uncertainties of the target body (the gravity and the body's rotation rate) and thrust error (the error in thrust magnitude and direction) significantly influence the spacecraft dynamics. Moreover, the small bodies are abnormal in size, shape and so on, leading to very complex dynamics in the vicinity of small bodies. All these challenges make it difficult to achieve precision and soft landing on small bodies [16]. Although the open-loop control strategy is easy to be implemented in the prac-

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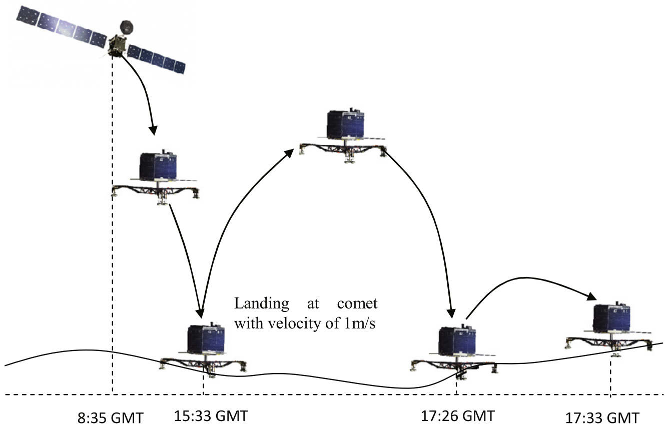

Fig. 1. Illustration of the landing process of Philae lander.

tical landing mission, the landing accuracy can't be guaranteed. A freely descent landing strategy is proposed and the landing error is analyzed [2]. The results show that significant sources of uncertainties contribute to the trajectory dispersions. And all the uncertainties finally result in a 6-dimensional landing error. To reduce the effects of the uncertainties, much work has focused on the design of feedback controller [3,7,20,24]. And the research shows that the feedback controller improves the landing accuracy effectively in general cases. However, the ability of the feedback controller for reducing the landing error may be weakened in the case of tracking the optimal trajectory. The solution of optimal trajectory relies on the dynamics model of the small bodies, and thus the complex dynamics has significant effect. Data driven/model free solutions for control/optimization issues are studied in [21–23], and show extremely strength for the difficulty in obtaining the physical models for complicated processes. However, the incompleteness of mission data stops its current application in space exploration mission. Previous research shows that the thrust profile of optimal landing trajectory is of maximum–minimum–maximum structure [10,18]. And the saturation phenomenon easily occurs for tracking this kind of thrust structure in the presence of these uncertainties. And the thrust saturation will finally result in large landing error in the practical landing mission [17].

Based on above analysis, it's expected to optimize the landing trajectory considering the uncertainties. The nonlinear propagation of spacecraft trajectory uncertainties has been investigated in previous work [1,13]. These proposed methods are very helpful for characterizing the uncertainty propagation. However, they are not appropriate to be directly used in the optimization process due to the computational complexity. A desensitized optimal control (DOC) strategy is presented in [14] and [17]. The DOC strategy is to minimize the fuel consumption and reduce the sensitivity to state uncertainties at the same time. Then, the obtained trajectory is expected to be insensitive to the state perturbations. The validity is verified by the example of powered descent landing on Mars. Even if the DOC strategy improves the robustness of the powered descent trajectory, there are also some limitations. On one hand, the sensitivity only represents the degree of future state change with respect to the perturbations in the initial state. This indicates that the DOC strategy by sensitivity method has ignored the uncertainty models of the initial state. And the initial uncertainties in position and velocity are generally not on the same order for the landing mission. Thus, the sensitivity can't reflect the statistical knowledge of the landing trajectory completely. On the other hand, the modeling error including the parameters uncertainties and thrust error can't be directly formulated in the sensitivity matrix. For the mission of landing on small bodies, the up-mentioned two aspects have significant effect and prevent its direct application to desensitize the optimal trajectory for landing on small bodies. The linear covariance technique has been widely used for describing the trajectory dispersions for its convenience and relative high accuracy [6]. This paper intends to solve the problem by propagating the linear covariance, and minimizing the fuel consumption as well as the covariance. To take the parameters uncertainties and the thrust error into consideration, the stochastic state equations are first constructed. The rotation rate is firstly augmented as the new state of the state equations. Although all the uncertainties can be augmented as the new states of the state equations, this may cause unnecessary dimension increase of the linear covariance. The linear covariance is calculated by integration and called thousands of times in the optimization process, and thus, the dimension of the covariance needs to be minimized. Considering this, the effect of the uncertainties in gravity and thruster are modeled as the stochastic process noise acting on the lander. Then, the linear covariance of the constructed stochastic state equations can be propagated to express the trajectory dispersions in the presence of these existing uncertainties. Finally, the performance index including the linear covariance and fuel consumption can be derived. To minimize the performance, the obtained optimal trajectory is expected to be fuel-saving and desensitized to the uncertainties as well.

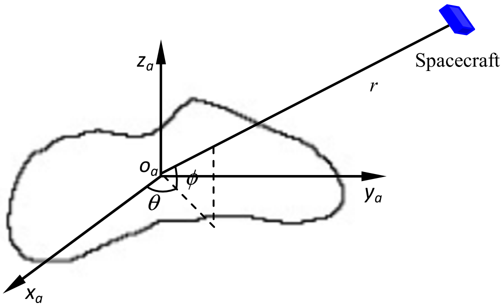

Fig. 2. Sketch map of the body-fixed coordinate frame.

This paper is organized as follows. In section 1, the landing dynamics equations and the gravity field model for landing on small bodies are described. And the optimal landing problem is also stated. In section 2, the trajectory optimization problem with reduced linear covariance is derived. The stochastic state equations including the effects of these uncertainties are constructed in subsection 2.1. And the closed-loop linear covariance equation is formulated, and the performance index including the fuel consumption and covariance are derived. The simulation results and the conclusions are respectively presented in sections 3 and 4.

1. Landing dynamics and optimal trajectory

In order to describe the motion of the lander, the body-fixed coordinate frame (Σ^a) is first defined. The origin of Σ^a is fixed with the mass center of the target body, the z_a-axis coincides with the body's maximum inertia axis, and the x_a-axis and the y_a-axis coincides with the minimum and intermediate inertia axis respectively, which are illustrated in Fig. 2. Assuming that the small body has uniform density and rotates uniformly about the principal axis corresponding to z_a-axis [11]. Assuming that only one thruster with variable thrust is considered, and the thrust passes through the center of the mass. Then, the dynamics for landing on small bodies described in Σ^a is as follows: