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# Intelligent landing strategy for the small bodies: from passive bounce to active trajectory control

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ABSTRACT

Landing exploration is an important way to improve the understanding of small bodies. Considering the weak gravity field as well as the strict attitude constraints which make bounce a common situation and a tough issue for safe landing on small bodies, a novel active trajectory control-based intelligent landing strategy is proposed to improve the safety and reliability of mission. The scenarios of intelligent landing strategy for both safe landing and hopping exploration are introduced in detail and a potential structure for autonomous navigation and control system is presented. Furthermore, a convex optimization-based control algorithm is developed, which is the key technology fulfilling the active trajectory control. Meanwhile a novel discretization method based on the fourth-order Runge-Kutta rule is proposed to improve the accuracy. A helpful adjustment process of time-to-landing is also introduced when the feasible trajectory does not exist. Comprehensive simulations about the proposed intelligent landing strategy are performed to demonstrate the improved safety and accuracy of both landing and hopping exploration on small bodies. Meanwhile, the performance and accuracy of the proposed convex optimization-based control algorithms is also compared and discussed thoroughly. Some useful conclusions for control system design are also obtained.

## 1. Introduction

Mars and small bodies such as asteroids and comets, which contain high scientific values, are the main targets in the Solar system for planetary exploration. With the development of aerospace technology, the way of planetary exploration has been shifted from flyby to planetary landing. In order to gather more scientific material, future planetary exploration missions may need the capability of precise landing at predefined location of great scientific interests. NASA has also emphasized the need for fundamental researches on safe and pinpoint landing of robotic and manned spacecraft on Mars and small bodies in the future [1].

The technologies of Mars landing have been developed since the Viking 1 and 2 missions [2]. Since then, seven NASA robotic systems have been landed successfully on the Mars surface [3]. Except for the ongoing Mars Science Laboratory mission, other landers or rovers were landed by the passive energy dissipation touchdown system such as airbag and legs [3]. The easy implementation and high reliability make the airbag and legs preferred choices for low weight mission. For one thing, the relatively high gravity acceleration guarantees that the lander may stop after several passive bouncing movements even though with the certain initial velocity. On the other hand, the size of Mars and the accuracy requirement of landing attitude make the landing accuracy of the airbag and legs acceptable for a safe touchdown. However, things are complete different for the landing on small bodies. On one hand, the size of asteroids varies greatly from 100 s meters to almost 1000 km [4], over 90% of which have a diameter of less than 1 km. They are much smaller than the Mars. On the other, the main difference between the small bodies and Mars is the weak gravity [5–7], which makes passive bounce a common situation and a tough issue for safe landing. Therefore, the commonly used touchdown systems on Mars are no longer suitable for small bodies. The touchdown system and corresponding landing strategy for small bodies have to be designed with much stricter requirements and constrains (e.g. landing velocity and attitude constrains).

The weak gravity field near a small body results in the fact that any perturbation or velocity deviation caused by navigation and control system errors may push the lander away from the surface. The

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touchdown systems for small body landers are designed to avoid potential bouncing at a low velocity. In the Hayabusa mission, a rover named “MINERVA (Micro/Nano Experimental Robot Vehicle for Asteroid)” was supposed to land on the surface of asteroid Itokawa. The rover had the shape of a hexadecagonal-pole, and was designed to land at a very low speed [8]. However, the rover MINERVA failed to touchdown because of an unpredictable increase of velocity [9]. Meanwhile, a target marker, which was a reflective bag filled with balls, was deployed onto Itokawa by the lander and was used for optical navigation during the final landing phase. The touchdown energy could be consumed through the impact of each ball and this made the target markers stay on the surface after impact [10]. For the final touchdown of Rosetta mission, the lander Philae was planned to perform a series of operations to avoid bouncing. First, legs could dissipate most part of the energy after collision. Then, a cold gas system could provide downward thrust and two anchor harpoons were designed to fire into the ground to fix the lander [11,12]. But because the cold gas system and the anchoring harpoons did not work, Philae bounced passively several times after landing attempt and lost control [13]. The touchdown dynamics of Philae is further researched regarding asymmetric load cases and contact dynamics on granular soil [14]. It is obvious that the lack of control during the landing phase is a major contributor to the failure of these touchdown systems. In order to improve the safety and accuracy, researches on trajectory control for pinpoint landing on the small bodies have been carried out [15–18]. However, these researches mainly focused on the touchdown without bouncing. If no subsequent trajectory control is employed after the unpredicted bounce, the safety and reliability of landing cannot be guaranteed. So an intelligent landing strategy should be considered for the unexpected bounce instead of just avoiding the bounce by structure design.

On the other hand, the weak gravity makes the bounce on surface an efficient manner to move around on a small body. Actually, several hopping devices have been designed for the small body explorations. The hopper PROP-F for Phobos 2 mission was equipped with a spring mechanism for hopping [19], but the hopping action was possible only with the right attitude on the surface. The mobile system of MINERVA for Hayabusa mission was an internal torque which was designed to generate a reaction force against the surface of the asteroid [9]. Hayabusa-2 contains a MASCOT hopper, whose momentum pulse is generated by a lever arm [20]. Meanwhile, Ulamec et al. proposed a hopping device which contains whiskers used for both hopping and self-orientating on its edge [21]. Mega presented a hopper platform for highland terrain based on simple mechanical concepts [22]. By turning a robot by using its internal torque, Kubota et al. proposed a new type of hopping mechanism [23]. A prototype rover was also developed to show the effectiveness by micro gravity experiments. However, the direction and attitude during the hopping movement of these hoppers are only decided by the initial velocity pulse, and no control process is implemented, which limits the safety and accuracy of surface exploration.

Consequently, adopting an active trajectory control is important and essential to improve the safety and stability of both landing and exploration on small body. This paper proposes the concept of intelligent landing strategy with the capability of active trajectory control for small body explorations for the first time. Meanwhile a convex optimization-based control algorithm is innovatively introduced to achieve the active trajectory control. Furthermore, in order to improve the computation accuracy, a fourth-order Runge-Kutta rule based discretization method is also proposed instead of the traditional method based on the state transition matrix. For the cases when feasible trajectory does not exist, a possible solution is also proposed. The paper is organized as follows. In Section II, the concept of active trajectory control-based intelligent landing strategy is introduced, and the implementations for both safe landing and hopping exploration on a small body are presented. Meanwhile, the structure and functions of required navigation and control system are also discussed. Next, the novel trajectory control algorithm, discretization method, and the adjustment process of time-to-landing, which are the key technologies fulfilling the active trajectory control, are proposed in Section III. Then, in Section IV, comprehensive simulations about the intelligent landing strategy are performed, and the improved performance is also discussed. Finally, section V gives the conclusions of the paper.

## 2. The concept of intelligent landing strategy

As discussed previously, the implementation of active trajectory control is important to improve the safety and stability of small body exploration missions. The proposed active trajectory control-based intelligent landing strategy can be used for both safe touchdown and hopping exploration on the small body.

### 2.1. Intelligent landing strategy for safe touchdown

A safe touchdown is the precondition for a successful small body landing mission. However, rebounding is a common situation in the weak gravity environment. This will be dangerous if no subsequent trajectory control is employed. The failure of lander Philae is also caused by the unpredictable bouncing at the landing attempt. Therefore, the active trajectory control after the detection of bounce is essential to release the burden for the control system and to improve the safety of small body landing.

The purpose of intelligent landing strategy for safe landing is to control the lander in real-time to reach the previous or a new landing site and perform the touchdown again. This function is truly meaningful in the situation when high relative velocity may make the lander escape away from small body. If a bounce is detected after the touchdown attempt, it is required to plan a new path to guide the lander reaching the original landing site. If the previous landing site is not suitable for relanding, a new landing site can be selected onboard due to the slow motion of the lander under the weak gravity field. In this case, a velocity pulse (see $\Delta \boldsymbol{v}_0$ in Fig. 1) is exerted to push the lander above the surface again and make the lander move towards the new target site through hopping. This velocity pulse gives the control system enough time to rearrange the touchdown. The amplitude of velocity pulse can be computed simply by projectile motion based on an onboard-stored gravity field model. Certainly, the amplitude of this velocity pulse must be bounded so that the lander should not escape immediately.

Several factors need to be considered when selecting the new landing site. Besides common considerations for planetary landing

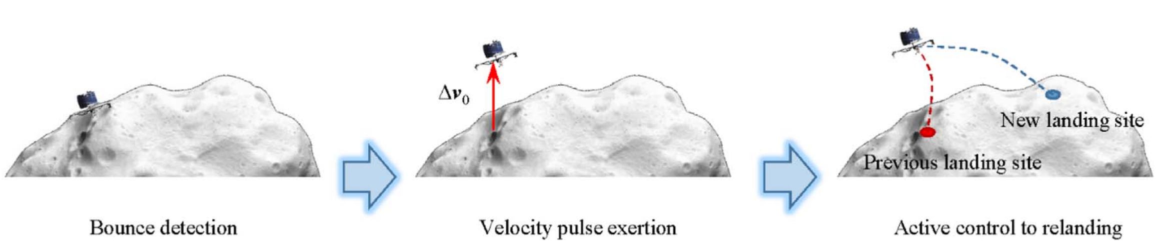


**Fig. 1.** The scenario of intelligent landing strategy for safe landing.

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