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Terminal guidance strategy for a hybrid thrust-tether lunar landing scheme

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Abstract

A hybrid thrust-tether lunar landing scheme and its terminal guidance strategy are proposed in this paper, which has potential application in avoiding the dusts aroused by the plume of thrusters. The combined lander is made up of a descent stage and a rover, which are connected by a tethered device. An innovative combination of fuzzy and variable-structure controllers is introduced to guide the terminal landing, which is more robust than some classical guidance laws derived from the linearized dynamics. At the beginning of this phase, the combined lander carries out the targeting guidance law from the height of 250 m to the desired landing site. When the combined lander arrives at the height of about 20 m, the tethered device is triggered to release the rover which is controlled by the tensioning force provided by the motor and windlass. In releasing the rover, the descent stage is required to hover above the lunar surface at a certain height until the rover meets safe landing conditions. After the rover cuts off the tether, the descent stage will be driven by the deputy thrusters as far away from the rover as possible. A typical scenario is implemented numerically to demonstrate the stabilization of the horizontal initial velocity even in nonzero azimuth angle case. To investigate the robustness of the closed-loop guidance law, a Monte-Carlo simulation is performed to create all the scenarios parameterized by the errors in initial position and velocity which is the result of last powered descent phase.

Keywords: Hybrid thrust-tether landing scheme; Lunar soft landing; Guidance strategy; Fuzzy control; Variable-structure control

1. Introduction

Lunar soft landing is one of the most important steps to achieve lunar exploration and first implemented by Soviet Union's Luna 9 (Chenoweth, 1971; Azimov, 2013). Soft landing requires a vertical touchdown velocity to be zero relative to Moon or less than a certain value to ensure the safety of scientific instruments.

Soft landing is essentially classified as an optimal control problem minimizing the landing time or fuel consumption (Acikmese et al., 2013). Ramanan and Madan (2005) considered the landing problem parameterized by thrust direction angles and then solved it by Pontryagin maximum principle. Guo and Han (2009) designed an open-loop optimal descent guidance law and then implemented a sensitive analysis with respect to the initial landing conditions and control parameters. Liu et al. (2008) solved how to design an open-loop optimal trajectory by a control parameterization method as well as a time scaling transform. Teo et al. (1993) regarded the soft landing as an optimization with inequality constraints, and used the constraint transcription method to work out it.

Generally, an open-loop control law is derived from the nominal landing dynamics to create reference landing trajectory. However, a closed-loop guidance law is designed

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to weaken the unmodeled terms in landing dynamics, which is part of Guidance, Navigation and Control (abbr. GNC) system of a lander (Lee et al., 2010). Zhou et al. designed a closed-loop guidance law to yield a corresponding fuel-optimal descent trajectory using the method of control parameterization and time scaling transform (Zhou et al., 2010). According to their numerical results, they declared the proposed approach is "highly efficient" to solve this optimal control problem. Considering the disturbance from thrust errors, Zhang and Duan (2012) investigated a robust H_∞ feedback controller to track the nominal reference trajectory. For optimal descent tracking, Li et al. (2011) developed an adaptive backstepping controller to cope with the input saturation and failure, which enables the embedded autonomy of lander system, and weakens the unknown bounded terms. Izzo et al. (2011) presented a constant-optic-flow guidance scheme for automated landing systems based on a polynomial approximation of the horizontal spacecraft velocity and then proved it was a good approximation for the actual optimal constant-optic-flow descent, while only depending on two parameters: the descent duration and range. Zhang and Duan (2013) addressed an integrated translational and rotational descending strategy to meet the requirements of vertical attitude and low touchdown velocity. Lee (2011) studied the guidance algorithms for Altair landing mission and formulated fuel-optimal guidance law with a cost function that penalizes both the touchdown velocity and fuel cost of the descent engine. In this formulation, there is no requirement to achieve zero touchdown velocity. In comparing the computed optimal control results with the preflight landing trajectory design of the Apollo-11 mission, it was noted interesting similarities between their landing performances.

Different from the thruster used to decrease the lander's velocity in lunar soft landing, an airbag or parachute is suitable for Maritain soft landing because the appreciable atmosphere on Mars contributes to velocity decrease (Rea and Sostaric, 2005). In the past decades of years, all the successful lunar landers were disturbed by the dusts aroused by the plume of thrusters, such as Surveyor, Apollo, Luna (Huang and Wang, 2007). The dusts and plume may pollute the optical instruments of landers. In addition, the plume may cause small rocks splashing at a high velocity, which threatens both landers and astronauts (see Tables 1–3).

To avoid the disturbances aroused by the plume of thrusters, Régnier and Koeck (2005) proposed for ESA's ExoMars mission the concept of connected parachute and airbags by tether without any analysis on the guidance law. Xu and Zhu (2007) proposed a tethered strategy for lunar soft landing and employed a modified PID law to guide the terminal descent phase, but their laws tend to be more fuel consuming because the thruster lasts working to lift the descent stage. Moreover, they did not design a specific controller to minimize the horizontal deviations. During releasing the rover, the reduction in tether's length results in negative damping ratio, which proves the tether's law of Xu and Zhu failed in stabilizing the azimuth angle of tether (Xu and Zhu, 2007). Their design methodology is based on the linearized equation which has difficulty in stabilizing the unmodeled nonlinear terms in real dynamics (Zhou and Xu, 2006).

The Mars Science Laboratory (abbr. MSL) mission developed by NASA requires delivering highly capable and mobile rovers safely and gently in an upright orientation. The airbag landing system used to deliver early rovers is incapable of landing the MSL rover. Thus, the skycrane concept is proposed to employ several bridles connecting the rover and descent stage, and supply variable forces by eight thrusters equipped on the descent stage (Steltzner et al., 2014). It is more difficult to manufacture the variable thruster than constant one in aerospace industry (Baker et al., 2014). The MSL excludes the bridle's tensioning force law for tracking reference trajectory because of the constant bridle's length before touchdown, which does not allow to release and also shrink the tether (Singh et al., 2007). Moreover, the MSL controller is only working on the vertical axis without any consideration on the horizontal axis (Açıkmeşe et al., 2014).

To improve the work of Xu and Zhu (2007) and the MSL skycrane, a new hybrid thrust-tether lunar landing scheme is proposed to avoid the dusts aroused by the plume of thrusters. The whole lander is made up of a descent stage and a rover, which are connected by a tethered device. The combined lander carries out a fuzzy controller to target at the height from 250 m to the desired landing site, and then the tethered device is triggered to release the rover at the moment when the combined lander arrives at the height of about 20 m. With the help of a variable-structure guidance law, the descent stage hovers above the lunar surface at a certain height until the rover meets safe landing conditions, and then the rover cuts off the tether. Subsequently, the descent stage will fly as far away from the rover as possible. To evaluate the performance of the combined fuzzy and variable-structure guidance law, a Monte-Carlo simulation is performed numerically to create all the scenarios parameterized by the errors in initial position and velocity which is the result of last powered descent phase.

2. The dynamics of hybrid thrust-tether landing system

2.1. The structure of hybrid thrust-tether landing system

Different from the traditional thrust-only landing schemes, a new hybrid thrust-tether scheme is proposed in this paper. The whole combined lander is made up of a descent stage and a rover, which are connected by a tethered device. The tethered device consists of a motor, a windlass and tether, and the motor and windlass are installed on the descent stage as well as two ends of tether fastened on the rover and windlass. Thus, the deployment of the rover can be controlled by the length or tensioning force of the tether, with the help of main and deputy thrusters equipped on the descent stage. During the terminal landing phase, the descent stage is required to hover above