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Approach and landing guidance design for reusable launch vehicle using multiple sliding surfaces technique

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Abstract An autonomous approach and landing (A&L) guidance law is presented in this paper for landing an unpowered reusable launch vehicle (RLV) at the designated runway touchdown. Considering the full nonlinear point-mass dynamics, a guidance scheme is developed in three-dimensional space. In order to guarantee a successful A&L movement, the multiple sliding surfaces guidance (MSSG) technique is applied to derive the closed-loop guidance law, which stems from higher order sliding mode control theory and has advantage in the finite time reaching property. The global stability of the proposed guidance approach is proved by the Lyapunov-based method. The designed guidance law can generate new trajectories on-line without any specific requirement on off-line analysis except for the information on the boundary conditions of the A&L phase and instantaneous states of the RLV. Therefore, the designed guidance law is flexible enough to target different touchdown points on the runway and is capable of dealing with large initial condition errors resulted from the previous flight phase. Finally, simulation results show the effectiveness of the proposed guidance law in different scenarios.

1. Introduction

In recent decades, there is an increasing demand for the improvement of the reliability, safety and low-cost of the reusable launch vehicle (RLV) during the reentry process. The approach and landing (A&L) phase, as the terminal phase of the reentry flight, is responsible for directing the RLV from the terminal area energy management (TAEM) phase to runway touchdown.[1] In the reentry phase, the extreme working

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conditions constantly experienced, such as the poor vehicle performance, aerosurface failures and aerodynamic perturbation, so that it is indispensable for the RLV to evaluate the current performance onboard as well as re-target an alternative landing site if necessary.[2] As a consequence, the significant deviation from the desired trajectory commonly encountered at the approach and landing interface (ALI), under the circumstance of which the RLV can no longer follow a predesigned trajectory to perform a successful landing movement. Therefore, it is of necessary importance to develop advanced guidance technologies to generate feasible trajectories onboard without relying on the predesigned reference trajectories.[3]

Since the A&L phase plays a crucial role in the safety of the vehicle, many focuses have been put on the A&L guidance problem. A trajectory-planning based A&L guidance strategy was proposed,[1] where the whole trajectory was divided into several segments defined by a small set of geometric parameters. Through combining an iterative approach and a backward trajectory propagation scheme, a feasible reference trajectory that brought the RLV from its current state to a desired landing condition was obtained and both open-loop and closed-loop analysis were provided. This method was able to re-compute new reference A&L profiles even in the presence of severe wind, aerodynamic uncertainties as well as trajectory dispersions. Moreover, this approach was further extended to deal with a RLV with limited normal acceleration capabilities.[4] The design goal was achieved by minimizing the maximal load factor during the A&L phase. To ensure a better landing movement, a Mnmdani fuzzy PD controller was developed for the A&L phase.[5] The reliability and robustness of the controller was verified via Monte Carlo simulations considering various kinds of disturbances. The fault tolerant capability of an aircraft was further enhanced by the controllers proposed.[6,7] An Optimum-Path-To-Go (OPTG) algorithm, characterized by on-line trajectory reshaping and re-targeting capabilities with a huge number of off-line trajectories generated in advance was presented to deal with the A&L guidance problem.[8–10] Under given current states and certain vehicle parameters, the on-line trajectory command generation was thus available. Moreover, the OPTG was employed to cope with the control surface errors between the entry phase and the TAEM phase.[11] Besides, the capability to re-target at more suitable alternative landing sites was studied.[12]

Sliding mode control (SMC) has been widely used in the guidance law design due to its strong robustness in nature. A novel concept of the sliding mode terminal guidance (SMTG) was proposed to solve the A&L guidance problem, in which the finite-time-reaching phase of the sliding mode control was utilized and the desired terminal conditions could be achieved at the final instant.[13] Since the associated guidance command relied only on the initial and final conditions of the A&L phase, this strategy prevented itself from off-line requirements and was able to generate new trajectories online. A novel finite horizon suboptimal controller based on state dependent Riccati equation (SDRE) was discussed.[14] To solve the differential Riccati equation without backward integration, an approximate method was developed. The proposed controller was then employed to solve the on-line path-planning problem for the A&L phase, which presented robust under different initial conditions with small computational burdens.

It should be noted that the desired objective of the A&L phase is to softly land the RLV at the predetermined runway, and the final flight path angle should reach near-zero at touchdown in order to achieve a minimal vertical velocity. In addition, the visual reference should be preserved with respect to the center line of the runway before the RLV approaches the runway surface to guarantee a successful touchdown movement. Targeted at all these requirements, a nonlinear closed-form three-dimensional (3D) landing guidance law is developed in this paper. Based on the multiple sliding surface technique (MSST), the designed guidance law is adopted to address the problem of successfully landing an RLV even in the presence of large initial condition errors. The guidance logic is developed independently in different channels, i.e., the lateral channel and longitudinal channel. In each channel, the first sliding mode surface is specially designed according to the terminal constraints. Both the sliding mode function and its derivative to zero at the final instant are simultaneously achieved. By introducing a second sliding mode function, a backstepping approach is utilized to meet such requirements. Thus, the second sliding mode surface is concatenated to the first sliding mode surface: as long as the second sliding mode surface is established at a finite time, which is generally smaller than the total flight time, the first sliding mode will reach and then stay on its desired trajectory with the desired terminal system states. The finite time establishment of the second sliding mode is guaranteed by the Lyapunov stability theory. Due to its simple form and less information demand, the proposed guidance law is specifically suitable for the onboard implementation. Besides, the closed-loop dynamics are capable of counteracting the external disturbances by virtue of the strong robustness of SMC.

The rest of the paper is organized as follows. In Section 2, the A&L guidance problem of the RLV is formulated and the associated equations of motion are described. In Section 3, the MSST based guidance logics is analyzed in detail in the lateral channel and longitudinal channel, respectively. Section 4 performs the simulations to validate the effectiveness of the proposed guidance scheme under various conditions. Finally, Section 5 concludes this paper with the discussion on future work.

2. Motion and problem formulation

This section gives the dynamic model for the RLV during the A&L phase. For the sake of clarity, a diagram of the A&L

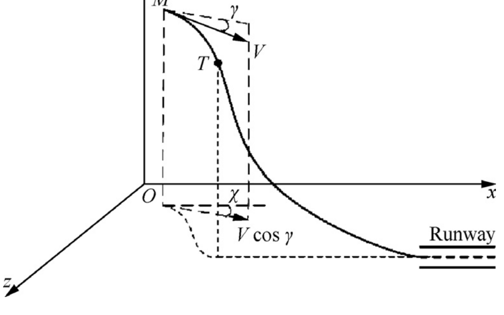

Fig. 1 Diagram of the A&L phase.

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