Aerospace Science and Technology 75 (2018) 13–23

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

An approach and landing guidance design for reusable launch vehicle based on adaptive predictor–corrector technique

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ARTICLE INFO

Article history:
Received 20 September 2017
Received in revised form 7 November 2017
Accepted 27 December 2017
Available online 31 January 2018

Keywords:
Approach and landing
All-coefficient adaptive control theory
Predictor–corrector
Process constraints
Robustness

ABSTRACT

In this study, a novel predictor–corrector guidance law based on the all-coefficient adaptive control theory is proposed for the approach and landing phase of an unpowered reusable launch vehicle (RLV). The flight phase includes two portions: the initial gliding flight phase and the final exponential flare one. The equilibrium glide condition and an exponential function of altitude are used to parameterize the guidance commands of two portions and generate the guidance sequence. Based on the first order characteristic model which has the advantages of less characteristic parameters and easy analysis, the all-coefficient adaptive predictor–corrector guidance method is presented. The guidance law has the ability of generating new trajectories online according to the current states and the final conditions of the landing point. Then, the stability and finite-time convergence of the guidance law are analyzed. Considering the process constraints, the fusion guidance law is obtained. Finally, simulation results demonstrate the effectiveness and robustness of the proposed guidance law, with respect to the large initial states errors and parameter uncertainties. The simulations also show that the system under the proposed guidance law converges to a small neighborhood of zero after limited steps.

1. Introduction

The RLV is a highly integrated product of many aerospace technologies, and has the properties of reusability, reliability and strong maneuverability. Due to these properties, the launch preparation time of RLV and costs of the space transportation can be reduced enormously [1,2]. The descent flight of RLV commonly consists of three parts: initial reentry phase, terminal area energy management (TAEM) phase, and final approach & landing phase. In recent decades, there is an increasing demand for developing advanced guidance technologies to deal with poor vehicle performance, large initial condition errors and so on. At present, the guidance methods of reentry are generally divided into two kinds: the method of tracking nominal trajectory, and the predictor–corrector guidance method based on the landing point prediction [3,4].

Scholars have carried out a great deal of research on the reentry guidance of RLV, including the trajectory generation and guidance methods. For approach & landing phase, the trajectory generation technologies mainly include the off-line and on-line methods. With the on-line method, the trajectory can be obtained quickly and real-timely to meet the current flight condition [5]. According to the methods of generating trajectories, the guidance strategies for the approach and landing of RLV can be divided into the methods based on offline trajectory, and the adaptive guidance methods based on online trajectory. The former is simple for implementation, but is no longer suitable for large deviation [6]. The latter is capable of dealing with the large initial states errors, parameter disturbances and system failure, but has critical real-time requirement and large computational burden, which lead to the difficulty in engineering application [7,8]. As more and more advanced guidance and control methods are applied in the aerospace engineering, the guidance methods based on online trajectory have become a tendency [9–11]. Kluever presented an online trajectory design method for the approach & landing of RLV, and the whole trajectory was divided into several segments [12]. The trajectory from the current state to the desired landing point was obtained online, through iterating the flight path angle at the start of flare phase, and a backward trajectory propagation method. To enable autonomous operation of RLV, Barron Associates Inc. proposed the optimum-path-to-go trajectory-reshaping algorithm based on trajectory database generated in advance [13,14]. According to the current states of RLV, an optimal trajectory was selected online through the polynomial-based neural network. Hull et al. presented an online trajectory reconfiguration method under failure of effectors for the TAEM and approach & landing phases, in order

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https://doi.org/10.1016/j.ast.2017.12.037
1270-9638/

to maintain stability and tracking performance [15]. Considering the failure of rudder planes, Girerd et al. studied the methods of online trajectory planning for the TAEM and landing phases [16]. Harl proposed a guidance law for the approach & landing of RLV which allowed for trajectories to be generated online through the use of a closed-loop control law. Then a concept of Sliding Mode Terminal Guidance was utilized which took advantage of the finite-time reaching phase of the sliding mode technique [17]. Jiang et al. proposed the online trajectory generation and guidance method for the approach & landing phase, using motion primitives and neighboring optimal control, so as to improve the robustness [18]. In [19], an autonomous approach and landing guidance law was presented for landing a RLV using the multiple sliding surfaces guidance technique. The designed guidance law can generate new trajectories online without any specific requirement on offline analysis, so the designed guidance law is flexible and robust.

By virtue of the ability of reshaping the trajectory in real time, the predictor–corrector guidance method has been widely applied in the initial reentry phase when the situations of large initial dispersions or failure vehicle performance happen [20–24]. But it hasn't been used in the approach & landing phase. What's more, the application of conventional predictor–corrector guidance method based on iteration is subject to the processing speed of computer, and the convergence of algorithm couldn't be guaranteed. The adaptive predictor–corrector guidance method proposed by Jun Hu as the designer of the guidance, navigation, and control system of spaceship, could achieve high guidance accuracy and autonomous capability [25,26]. More importantly, the method has less computational burden, and has been tested in the Chinese actual lunar return mission [27].

As one of the major achievements in this paper, a novel predictor–corrector guidance method based on all-coefficient adaptive control theory is presented for the phase which is from the latter portion of TAEM to the final landing point. It is the first time that the adaptive predictor–corrector guidance method is used in this phase, which has the advantages of high accuracy, and being independent of the pre-determined reference trajectories. What's more, the iteration process isn't needed, which relieves the calculation burden of computer and makes the method more practical and applicable than the conventional predictor–corrector guidance method based on iteration. In the adaptive predictor–corrector guidance method, the first-order characteristic model is presented. Compared with the traditional second-order characteristic model, the first-order characteristic model has the advantages of less characteristic parameters and easy analysis. The algorithm convergence of predictor–corrector guidance method is always concerned by scholars, and it is important for the actual engineering application, but it has not been proven strictly. In this paper, the stability analysis of adaptive predictor–corrector guidance method is discussed. Due to the small calculation burden, simple form and stability-guaranteed, the proposed guidance law is suitable for engineering application. In addition, the constraints of flight process should be considered in the engineering problem, and then the fusion guidance algorithm is obtained.

The rest of this paper is organized as follows. Section 2 details the RLV model and gives the problem formulation. The all-coefficient adaptive predictor–corrector guidance method is proposed in section 3, which concludes the stability analysis, the process constraints control and the whole guidance scheme. Numerical simulations on a RLV are presented to demonstrate the application of the derived algorithm in section 4. Finally, some conclusions are drawn in section 5.

2. Problem formulation

2.1. Dynamic motion model and terminal landing conditions

In this paper, the flight phase starts from the latter portion of TAEM phase when the RLV is aligned with the landing runway, so the lateral motion dynamics is ignored. The RLV is considered as a point mass and its motion equations in the vertical plane are described by [28]:

$$\frac{dh}{dt} = v\sin\gamma \tag{1}$$

$$\frac{dv}{dt} = -D - g\sin\gamma \tag{2}$$

$$\frac{d\gamma}{dt} = \frac{1}{v}(L - g\cos\gamma) \tag{3}$$

$$\frac{ds}{dt} = v\cos\gamma \tag{4}$$

where h is the altitude, v represents the velocity, γ is the flight path angle, s represents the downtrack position along the runway centerline. The aerodynamic drag and lift accelerations are defined by

$$D = \frac{0.5\rho v^2}{B}, \qquad L = \frac{C_L}{C_D}D \tag{5}$$

where C_D and C_L are drag and lift coefficients respectively, ρ is atmospheric density calculated by an exponential model $\rho = \rho_0 e^{-\beta h}$, where ρ_0 represents the atmospheric density at sea level and β is the atmospheric density scale. B is the ballistic coefficient calculated as $B = \frac{m}{C_D S}$, where m is the mass of RLV, and S represents the aerodynamic reference area. C_D can be computed by the standard drag polar equation $C_D = C_{D_0} + KC_L^2$, where C_{D_0} represents the drag coefficient at zero-lift, K is the coefficient relative to induced drag, and they are both the functions of Mach number.

In the above equations of motion, the time is selected as the independent variable. For the approach and landing of RLV, however, the altitude is preferred against time as independent variable since the time of whole flight phase is not a key variable in comparison to the altitude changing. The altitude is a monotonically decreasing variable and the final objective is to land at the predetermined height. What's more, it has been pointed out in [29] that the robustness of algorithm is stronger, if the monotonic variable which is related to flight states is chosen as the independent variable. The equations of motion can be rewritten as the following form which is used to develop guidance law

$$\frac{dv}{dh} = -\frac{D}{v\sin\gamma} - \frac{g}{v} \tag{6}$$

$$\frac{d\gamma}{dh} = \frac{L - g\cos\gamma}{v^2\sin\gamma} \tag{7}$$

$$\frac{ds}{dh} = \frac{1}{\tan\gamma} \tag{8}$$

In practice, the RLV should be softly land at the predetermined runway and the flight path angle must be pulled up to near-zero at landing point, in order to achieve a minimal vertical velocity and guarantee the safety of undercarriage. Consequently, the following final constraints at touchdown must be involved in the guidance law design

$$v_f \le v_{f\,\max} \tag{9}$$

$$\left|h'_f\right| \le h'_{f\,\max} \tag{10}$$