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Attitude controller design for reusable launch vehicles during reentry phase via compound adaptive fuzzy H-infinity control

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ABSTRACT

In this paper, the attitude control problem of reusable launch vehicles (RLVs) during reentry phase is investigated by using compound adaptive fuzzy H-infinity control (CAFHC) strategy in the presence of parameter uncertainties and external disturbances. Firstly, the control-oriented attitude model is established by a model transformation based on the six-degree-of-freedom (6-DoF) dynamic model of the RLV. Secondly, a novel attitude control scheme is developed and the control strategy consists of two parts to achieve a stable and accurate attitude tracking during reentry flight process. An attitude tracking controller is designed utilizing adaptive fuzzy H-infinity control approach combined with an identification model to improve the attitude tracking performance in the interior of fuzzy approximation region of attitude angle. Next, an attitude stabilization controller based on boundary adaptive technique is employed to assure the robustness of the closed-loop system in the exterior of fuzzy approximation region of attitude angle. Furthermore, the stability of the closed-loop system is guaranteed within the framework of Lyapunov theory and the attitude tracking error converges to a small neighborhood around origin. Finally, the simulation results are presented to demonstrate that the effectiveness of the proposed control scheme for reentry RLV, and its tracking performance performs better than the other control method.

1. Introduction

With the aim to develop a more cost-effective and reliable approach to the space, reusable launch vehicles (RLVs) have attracted intensive research interest in the field of aerospace engineering [1][2][3]. Mainly due to the unique advantages in reusability, flexibility as well as low operational cost, RLVs have a good prospect in aerospace activities and broad applications in civilian and military fields [4]. Whereas the philosophy sounds interesting and attracting, a major challenging problem posed in flight missions is that of atmospheric reentry. During the reentry phase, the altitude and velocity of the vehicle vary rapidly and drastically as a RLV goes through a wide range of flight envelope. At the same time, RLVs are subject to the poor flight conditions, severe parameter uncertainties and unknown external disturbances [5][6][7]. Thus, the reentry attitude control of RLVs is still a challenging problem [8], and it is critical for the RLV to track the expected commands rapidly and accurately.

In the recent past, a variety of control approaches have been proposed for designing the flight controllers of the vehicle. In the early studies, the flight control problem was investigated based on a linearized model of aerocrafts [9][10], whereas it is unsuitable for highly nonlinear and multivariable model of the RLV. Then, gain scheduling (GS) [11][12][13] as a popular control approach was applied for flight control system design. Although gain scheduling control method is verified to be effective to solve some control issues for reentry vehicles, the system robustness and global stability cannot be guaranteed especially under the circumstance of abrupt change of the control parameters. In the work of [14], model predictive control (MPC) method was combined with feedback linearization to develop a controller for reentry vehicle. After that, the trajectory linearization control (TLC) [15][16][17] scheme was developed to improve the nonlinear performance of GS in flight control system for aircrafts. But the robust performance of this approach is finite as the tracking dynamics are linearized by the trajectory linearization controller. Analogously, dynamic inversion (DI) technique [18][19][20] was proposed to cope with the flight control problem of a reusable launch vehicle. However, the drawback of this strategy is poor in robustness for parameter uncertainties and modeling errors if improperly designed. Further,

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Lam and Krishnamurthy et al. have investigated an adaptive controller using the state dependent Riccati equation (SDRE) approach [21] to a twin-rotor aircraft, but it is difficult for SDRE to deal with the control system with a high order. In [22][23], backstepping methodology was implemented to design the flight control system of the vehicle. Nevertheless, it is worth noting that the external disturbance was not taken into consideration in [22]–[23].

For the purpose of designing an attitude controller with a good robust performance, Shtessel et al. [24][25] have explored the application of sliding mode control (SMC) scheme to attitude control system of RLVs. SMC technique is well known as a robust method to design control law for uncertain system. However, the boundary values of model uncertainties and external disturbances ought to be known a prior and it is hard to satisfy this requirement in practical experiment. In [26][27], robust control approach was used to tackle the flight control issue in the presence of hard constrains, model uncertainties and external disturbances for RLVs. Similarly, Jee and Yalagach et al. have addressed H-infinity control strategy [28] to design flight control system under the highly uncertainties and changing dynamics of aerodynamic coefficients for the RLV during reentry process. However, robust control scheme cannot achieve a good tracking performance easily since the robust controller is designed in the worst case of the control system. And then, adaptive control [29][30] technique was employed to combine with robust control method in order to compensate for its shortcomings and improve the system tracking performance. Recently, fuzzy logic system (FLS) [31][32][33][34] was applied to design the attitude controller of reentry vehicle for its good approximation to model uncertainties and unmodeled dynamics. This control approach is an efficient way to cope with the model uncertainties and external disturbances even if the boundaries of uncertainties and disturbances are unknown. Moreover, FLS are always combined with other control strategies, such as adaptive control [35], robust control [36], fault-tolerant control [37] and so on, with the goal to improve the tracking control performance of the flight control system and achieve a good robustness simultaneously. Besides, adaptive fuzzy control method is often combined with robust or H-infinity control method in many applications [38][39][40].

In this research, we will further focus on the attitude controller design problem of RLVs during its reentry phase where parameter uncertainties and external disturbances are considered, and propose a compound adaptive fuzzy H-infinity control (CAFHC) strategy. Wherein, the fuzzy logic system is introduced to approximate the uncertainty term, and the H-infinity controller is adopted to compensate for fuzzy modeling errors and the external disturbances. However, the introduction of H-infinity control term would degrade the approximation capability of FLS, which would further weaken the tracking performance of reentry RLV. In order to avoid the problem of "approximation capability weakening", a novel control scheme is developed and this control strategy mainly consists of two parts. An attitude tracking controller is designed utilizing adaptive fuzzy H-infinity control approach combined with an identification model to improve the attitude tracking performance, while an attitude stabilization controller based on boundary adaptive technique is employed to assure the system robustness and the boundedness of approximation error. Moreover, the stability analysis is carried out to demonstrate that the proposed strategy can guarantee the semi-global stability of the closed-loop system. Finally, the simulation results of 6-DoF dynamic mode for the RLV are presented to illustrate the effectiveness of the proposed control strategy.

The rest of this paper is organized as follows. The 6-DoF dynamic model and the control-oriented attitude model of reentry RLV are stated in Section 2. Next the attitude controller design strategy via CAFHC approach is developed, followed by the stability analysis of the closed-loop control system in Section 3. After that the numerical simulations applying the proposed control scheme are conducted, and the simulation results and discussions are presented in Section 4. Finally, the conclusion of the paper is drawn in Section 5.

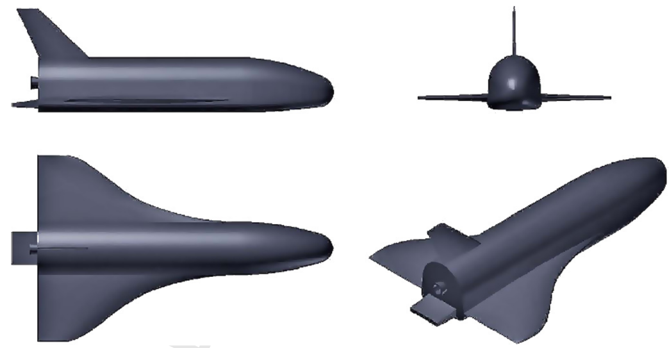

Fig. 1. The complete application model of RLV.

2. Problem formulation

In this section, the 6-DoF dynamic model of the RLV within its reentry phase is described, and the control-oriented attitude model is derived by a model transformation to design the attitude controller.

2.1. 6-DoF dynamic model of RLV

For the sake of simplicity, it is reasonable to assume that the impact of Earth's rotation on the flight control system is not taken into consideration in this work [5], and RLV is regarded as an unpowered rigid body flight vehicle during its reentry phase. The complete application model of RLV is given as depicted in Fig. 1. Generally, the 6-DoF dynamic model of RLV can be separated into the 3-DoF translational kinematic equations, and the 3-DoF rotational kinematic equations, which can be derived based on Ref. [41][42][43].

The 3-DoF translational kinematic equations are stated by six first-order equations as follows:

$$\begin{aligned}
\dot{x} &= V \cdot \cos\gamma \cdot \cos\chi \\
\dot{y} &= V \cdot \cos\gamma \cdot \sin\chi \\
\dot{z} &= V \cdot \sin\gamma
\end{aligned} \tag{1}$$

$$\begin{aligned}
\dot{V} &= \frac{1}{m}(-D - mg\sin\gamma) \\
\dot{\alpha} &= q - \tan\beta(p\cos\alpha + r\sin\alpha) \\
&\quad + \frac{1}{mV\cos\beta}[-L + mg\cos\gamma\cos\mu] \\
\dot{\beta} &= p\sin\alpha - r\cos\alpha + \frac{1}{mV}[Y + mg\cos\gamma\sin\mu]
\end{aligned} \tag{2}$$

where x, y and z denote the location of RLV referenced to the flight-path coordinate frame. V represents the flight velocity, and γ, χ and μ are the flight path angle, heading angle and bank angle, respectively. α, β are the angles of attack (AOA) and sideslip angle respectively. p, q and r are the roll, pitch and yaw rates, respectively. L, D and Y are aerodynamic lift, drag and side forces as described in (6).

The 3-DoF rotational kinematic equations are described by six first-order equations as follows:

$$\dot{p} = (c_1 r + c_2 p)q + c_3\bar{L} + c_4 N$$

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