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Research article

Adaptive-gain fast super-twisting sliding mode fault tolerant control for a reusable launch vehicle in reentry phase

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ABSTRACT

In this paper, a novel adaptive-gain fast super-twisting (AGFST) sliding mode attitude control synthesis is carried out for a reusable launch vehicle subject to actuator faults and unknown disturbances. According to the fast nonsingular terminal sliding mode surface (FNTSMS) and adaptive-gain fast super-twisting algorithm, an adaptive fault tolerant control law for the attitude stabilization is derived to protect against the actuator faults and unknown uncertainties. Firstly, a second-order nonlinear control-oriented model for the RLV is established by feedback linearization method. And on the basis a fast nonsingular terminal sliding mode (FNTSM) manifold is designed, which provides fast finite-time global convergence and avoids singularity problem as well as chattering phenomenon. Based on the merits of the standard super-twisting (ST) algorithm and fast reaching law with adaption, a novel adaptive-gain fast super-twisting (AGFST) algorithm is proposed for the finite-time fault tolerant attitude control problem of the RLV without any knowledge of the bounds of uncertainties and actuator faults. The important feature of the AGFST algorithm includes non-overestimating the values of the control gains and faster convergence speed than the standard ST algorithm. A formal proof of the finite-time stability of the closed-loop system is derived using the Lyapunov function technique. An estimation of the convergence time and accurate expression of convergence region are also provided. Finally, simulations are presented to illustrate the effectiveness and superiority of the proposed control scheme.

1. Introduction

Reusable Launch Vehicles (RLVs) have gradually developed to be used repeatedly to access the space allowing for reducing the flight operation costs [1]. A multitude of favorable research has been investigated at NASA's Marshall Space Flight Center to improve safety, reliability and affordability for RLV [2,3]. Whereas the philosophy sounds interesting and attracting, a major challenge posed from outer space into earth's atmosphere is that of atmospheric reentry. During the reentry phase a plenty of stringent constraints and unknown uncertainties come into action [4]. Considering these inevitable issues, the control system requires to have capabilities of optimality, robustness and reconfiguration.

The main goal of the reentry attitude controller is ensuring that the attitude angle tracks the guidance commands accurately in spite of the uncertainties and unknown external disturbances. Additionally, the safety of the RLV has been and will continue to be an important issue in the reentry phase [5]. Generally speaking, fault tolerant control has been a hot research area in the security control of the aircraft. The main design schemes for fault tolerant control are classified as either passive or active [6]. Passive schemes operate independently of any fault information and basically exploit the robustness of the underlying controller. Such schemes are usually less complex, but in order to cope with ‘worst case’ fault effects, are conservative. Active fault tolerant controllers react to the occurrence of faults, typically using information from a fault detection and isolation scheme, and invoke some form of reconfiguration. This represents a more flexible but complex architecture. Subsequent methods have tended to focus on online adaption or online controller synthesis [6]. Unsurprisingly, many robust control paradigms have been used as the basis for fault tolerant controllers. These include gain scheduling [7], adaptive control [8], H_∞ [9], model-following [10], pseudo-inverse methods [11,12], nonlinear dynamic inversion (NDI) [13,14], multiple model approaches [15] and model prediction control (MPC) [16,17].

It is noted that these existing robust fault tolerant control methods can only provide asymptotical stability rather than finite-time convergence. It is widely known that besides faster convergence rate, sliding mode control (SMC) as a representative technology of the field of finite-time convergence theory, usually performs higher accuracies, better disturbance

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rejection features and strong fault tolerance The possibilities of exploiting the inherent robustness properties of sliding mode for fault tolerance have previously been explored for aerospace applications and some works in [18–24] have argued that SMC has the potential to become an alternative to reconfigurable control. To develop these outstanding characteristics of SMC such as faster convergence, robustness to unknown uncertainties and strong capability of resistance to nonlinear fault tolerant systems, some efforts, such as terminal SM control (TSMC) method [25,26], nonsingular TSMC (NTSMC) approach [27], fast TSMC (FTSMC) technique [28] and nonsingular FTSMC (NFTSMC) law [29]. Additionally, another research issue not to be tackled in current SMC algorithms is the undesirable ‘chattering’ phenomenon due to the discontinuous control action. The most traditional way for reducing chattering is to replace the discontinuous control function by “saturation” or “sigmoid ones” [29]. Although this approach yields continuous control and chattering elimination, it constrains the system's trajectories not to the sliding mode (SM) surface but to its vicinity losing the robustness to the uncertainties. Recently, a new approach called higher order SMC (HOSMC) has been proposed to attenuate the chattering effect [30–33]. Using the HOSM control method allows driving to zero the sliding variable and its consecutive derivatives in the presence of the unknown disturbances/uncertainties and thereby, can improve on the accuracy of the sliding variable stabilization [34]. Several favorable attempts to apply this technique to hypersonic vehicle flight control [35,36] have been undertaken. However, one of the disadvantage of imposing an r-th order SMC on the vehicle is the necessity of having $s, \dot{s}, \ddot{s}, \ldots, s^{(r-1)}$ (where s is the sliding variable) available. Second order sliding mode control (SOSMC), as one special case of HOSMC, does not require the derivative information.

At present, the super-twisting (ST) control algorithm is one of the most powerful SOSMC algorithms that can handle a relative degree equal to one. Generally, it generates the continuous control function that steers the sliding variable and its derivative to zero in finite time in the presence of the smooth uncertainties with bounded gradient, when this boundary is known. Since ST algorithm includes a discontinuous control function under the integral, chattering is not eliminated but attenuated. Moreover, ST algorithm can obtain superior rapidity and stability to HOSM controller and prevent from acquiring the high-order derivative [37]. However, Successful implementation of ST sliding mode controller for the fault tolerant control problem of the RLV requires the knowledge of the boundaries of the total fault and disturbance information [38,39]. In many practical cases, this boundary cannot be easily estimated. In order to maintain the robustness of the closed-loop system, the overestimating of the boundaries yields to larger control gains and leads to a higher chattering amplitude. Hence, a comprehensive study of the ST control algorithm with adaptation has been undertaken. The adaptive-gain fast ST (AGFST) control law, which handles the perturbed system with the additive uncertainty/disturbance of certain class with the unknown boundary, was proposed in [40]. More recently, two approaches to adapt the gain have been developed for the ST algorithm. The first attack is to reconstruct the uncertainty/disturbance and to adapt the gain according to its estimated value, as discussed in [41]. Although this method can track the required values of gains very accurately, it requires the knowledge of the bound of the derivative of the uncertainty. The second approach to adapt the controller gain is to detect the sliding mode: increasing the gain until the sliding surface is reached and decreasing the gain when the sliding mode has been established [42,43].

The motivation of the research is to develop a robust fast terminal sliding mode control (RFTSMC) method with AGFST algorithm for the fault tolerant control problem of the RLV. Compared with existing control methods, the main contributions of this paper are summarized as follows: i) the presented RFTSMC based on AGFST algorithm resolves the main obstacles for application of SMC, that is, chattering and high activity of control action. Furthermore, the adaptation with respect to the control gains overcomes the overestimating drawback and resolves robust gains being determined difficultly. ii) The proposed AGFST algorithm contains the merits of standard ST algorithm, constant and plus power rate reaching laws and adaption. It does not require any prior knowledge of model uncertainties, external disturbances and actuator faults; and provides strong robustness against the uncertainty/disturbance growing in time or together with the RLV tracking error. Additionally, it has faster convergence rate than standard ST algorithm. iii) The presented RFTSMC based on AGFST algorithm is non-singularity and improves the convergence rate when the tracking error is far away from the origin. It will yield to be applied in practical systems. iv) The finite-time rigorous convergence is demonstrated, and the estimation of the convergence time and accurate expression of convergence region are also put forward.

The paper is organized as follows. In Section 2, the vehicle model with fault tolerant problem is formulated. The second-order nonlinear control-oriented model is established by feedback linearization in Section 3. In Section 4, the RFTSMC system is developed based on AGFST control algorithm, and the finite time stability of the closed-loop system with the proposed control law is analyzed. Illustrative simulations of the proposed control approach for the RLV and concluding remarks are given in Section 5 and Section 6, respectively.

2. Model description

The equations for six-degree-of-freedom rigid reentry flight vehicle are described in [35]. The motion of this vehicle can be divided into translational motion and rotational motion.

The dynamic equations of rotational motion of a reentry vehicle are given by [35,36]

$$\begin{bmatrix}\dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix} = -\bar{\boldsymbol{I}}^{-1}\left\{\begin{bmatrix}p\\ q\\ r\end{bmatrix}\times\left(\bar{\boldsymbol{I}}\begin{bmatrix}p\\ q\\ r\end{bmatrix}\right)+\boldsymbol{M}_c+\Delta\boldsymbol{M}\right\} \tag{1}$$

where p, q and r represent the roll, pitch and yaw angular rates, respectively. $\boldsymbol{M}_c=[M_l,M_m,M_n]^{\mathrm{T}}$ is the control torque vector, in which M_l, M_m and M_n are the roll, pitch and yaw control torques defined in the body frame, respectively. $\Delta\boldsymbol{M}$ denotes the unknown bounded external disturbance moment. $\bar{\boldsymbol{I}}=\boldsymbol{I}+\Delta\boldsymbol{I}$ stands the inertial tensor in the body frame with $\Delta\boldsymbol{I}\in\Re^{3\times3}$ as the uncertain part of the inertia matrix. The nominal inertial tensor $\boldsymbol{I}$ is defined as

$$\boldsymbol{I}=\begin{bmatrix}I_x & 0 & -I_{zx}\\ 0 & I_y & 0\\ -I_{zx} & 0 & I_z\end{bmatrix}$$

due to mass symmetry about the x-axis in the body frame.

The kinematic equations of reentry vehicle are defined as [35,36]:

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