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Nussbaum-based fuzzy adaptive nonlinear fault-tolerant control for hypersonic vehicles with diverse actuator faults

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ABSTRACT

Stability is a challenging problem for control system of the hypersonic vehicle when partial loss of effectiveness fault and stuck fault happen on elevators and engine. In this paper, a fuzzy adaptive nonlinear fault-tolerant control (FTC) method based on Nussbaum gain technique is proposed for hypersonic vehicles with diverse faults. The cases that one of elevators is lock-in-place and another elevator or the engine is partial loss of effectiveness are addressed. The longitudinal model is transformed into the strict feedback formation. The baseline controllers for altitude and velocity commands tracking are designed using dynamic surface control (DSC) and dynamic inversion. The partial loss of effectiveness faults of elevators and engine are combined in the control gain functions, and Nussbaum approach is introduced to avoid singularity of controllers. The unknown nonlinear functions involving the stuck fault and original uncertain nonlinear items are approximated by fuzzy logic systems. The norm estimation technique is utilized to reduce the number of fuzzy adaptive parameters. This greatly alleviates the calculation burden. It is guaranteed that all signals of the closed-loop FTC system are semi-global uniformly ultimately bounded. Finally, the numerical simulations involving diverse faults demonstrate the effectiveness of the proposed FTC approach.

1. Introduction

As the promising vehicles for cost-efficient access to space and global reach, hypersonic vehicles offer broad application prospects in both military and civilian. The design of control system for the vehicle is a challenging task due to its strong nonlinear, coupling, and multivariable characteristics and various uncertainties. During the past few decades, there has been a great deal of research on the control strategy of the hypersonic vehicle. Many control methods have been attempted, such as robust control [1], adaptive control approach [2], backstepping technique [3], sliding mode control (SMC) [4], predictive control [5] and intelligent control [6]. However, hypersonic flight of the vehicle in near space is characterized by strongly variable flight conditions and complex environment, and thereby the actuator and sensor faults may happen. Since the occurring time and the size of the faults are generally unknown, the existence of faults will cause deterioration of system performance and lead to instability of the control system even produce catastrophic accidents. Although failure problems can be solved using hardware redundancy, high overall cost will be unavoidable. Therefore, the novel and effective fault-tolerant control (FTC) algorithm became particularly important for hypersonic vehicles.

Normally, FTC means that the closed-loop system has the ability to keep stable and satisfy desired performance as much as possible when faults happen [7]. In recent years, FTC has received more and more attention, and many effective FTC approaches have been proposed for faulty system [8–15]. Generally, FTC is classified into two types: passive fault-tolerant control (PFTC) [16] and active fault-tolerant control (AFTC) [17]. In PFTC, the controller is designed for presumed faults and used throughout the faulty or normal case. In the past few decades, several approaches have been developed, e.g. LMI-based approach [18], pole assignment technique [19], etc. It is easy to design the PFTC controller for known faults since the online faults information is not essential. However, PFTC controller is generally more conservative, and control performance might be worse. Moreover, it has a limited fault tolerant capability for unknown system faults. In AFTC, controller can compensate the system faults by synthesizing a new control strategy or reconfiguring the controller online in terms of the real-time fault information. Commonly, the unknown fault is identified online by fault detection and diagnosis (FDD) mechanism [20] or adaptive approach [21]. Compared with PFTC, AFTC is more flexible and less conservative.

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Recently, the FTC has been widely attempted for faulty hypersonic vehicles. In [13] and [22], the fault diagnosis mechanism is discussed for the T–S model of the hypersonic vehicle with actuator faults, and the FTC controller is reconstructed based on the estimated fault information obtained by sliding mode observers. Jiang et al. [23] design an adaptive neural network observer to estimate the faults, and a reconfigurable command-filter backstepping controller is designed to accommodate control effector damage. Qian et al. [24] develop a novel dynamic surface control (DSC) technique-based FTC approach, and design a nonlinear fault detection observer to detect loss of actuator effectiveness faults.

In FDD, however, it is difficult to choose the reasonable threshold to judge faults. Once the threshold is not proper, wrong operation of the actuators might happen, and the stability of the system will become bad.

Generally, the faults are unknown, and there exist uncertain system parameters and unknown external disturbances in the dynamics of hypersonic vehicles. Hence, adaptive technique is more effective than FDD for FTC controller design. For the attitude dynamics of the hypersonic vehicle with actuator faults, an adaptive fault-tolerant compensation controller is designed based on the online estimation of actuator faults, where an adaptive term is added to the normal control law to compensate the actuator-fault [25]. In [26], an adaptive FTC algorithm is developed for the longitudinal model of the hypersonic vehicle with partial loss of actuator effectiveness and input saturation, in which two adaptive laws are designed to estimate the upper bound of the minimum value of the actuator efficiency factor and external disturbances. Zhao et al. [27] use an adaptive algorithm to estimate actuator faults and disturbances, and design a dynamic sliding mode FTC controller for attitude system. In [28], for the longitudinal dynamics of the hypersonic vehicle with parameter uncertainties and actuator fault, parameter adaptive laws are designed to estimate both the unknown flight dynamic parameters and the actuator fault. For attitude tracking of spacecraft, Cai el al. [29] propose the indirect adaptive FTC scheme, where uncertainties, disturbances and actuator failures are treated as a lumped uncertainty, and estimated via adaptive strategy online.

It is known that fuzzy logic system has the ability of universal approximation [30]. Therefore, this technique is usually used to approximate unknown nonlinearities and uncertainties [31]. For example, for a class of uncertain nonlinear systems with actuator faults, Hao et al. [32] utilize fuzzy logic systems to approximate the unknown nonlinear functions and develop an adaptive FTC controller. In [33], an adaptive fuzzy backstepping FTC controller is designed for a class of uncertain nonlinear systems with the non-lower-triangular structure. Although many efforts have been made for loss of actuator effectiveness, there are few results to handle diverse faults simultaneously [34,35].

In this paper, an adaptive fuzzy nonlinear FTC design scheme based on Nussbaum technique is proposed for the hypersonic vehicle model in presence of diverse faults. We consider that one of elevators is lock-in-place (stuck fault), and another elevator and engine are normal or partial loss of effectiveness. The whole system is divided into two parts, i.e. altitude subsystem and velocity subsystem. The altitude subsystem is transformed into strict-feedback formation, and the velocity subsystem is simplified. The partial loss of actuator effectiveness and stuck faults are added to formulate the faulty models. The stuck fault and unknown nonlinear items involving uncertain parameters are lumped into different unknown nonlinear functions, approximated online by fuzzy logic systems. The computation burden of multiple adaptive parameter estimation is decreased greatly via norm estimation strategy. In addition, the Nussbaum gain method is introduced to solve the problem of completely unknown control gain direction caused by uncertain parameters and unknown loss of actuator effectiveness faults. Since DSC technique can eliminate the “explosion of complexity” of the conventional backstepping design perfectly, DSC and dynamic inversion are used to design two fuzzy adaptive FTC controllers for altitude and velocity subsystems respectively. The stability of the overall closed-loop control system is proved, and all signals are semi-global uniformly ultimately bounded.

The remainder of this paper is organized as follows. In Section 2, the longitudinal nonlinear model of the hypersonic vehicle is presented and the model is transformed into strict-feedback formation. In addition, diverse actuator faults are added to formulate the faulty models. The fuzzy adaptive FTC controller based on Nussbaum is designed in Section 3. In Section 4, simulation results are given to demonstrate the effectiveness of the proposed FTC strategy. Finally, the conclusion is made in Section 5.

2. Hypersonic vehicle models

2.1. Longitudinal dynamics of hypersonic vehicle

Consider the following longitudinal dynamics of the hypersonic vehicle model developed by USA Langley Research Center [36]:

$$\dot{V} = \frac{T\cos\alpha - D}{m} - \frac{\mu \sin\gamma}{r^2} \tag{1}$$

$$\dot{h} = V\sin\gamma \tag{2}$$

$$\dot{\gamma} = \frac{L + T\sin\alpha}{mV} - \frac{(\mu - V^2 r)\cos\gamma}{Vr^2} \tag{3}$$

$$\dot{\alpha} = q - \dot{\gamma} \tag{4}$$

$$\dot{q} = \frac{M_{yy}}{I_{yy}} \tag{5}$$

where V and h denote the flight velocity and altitude, and γ, α and q are flight-path angle, attack angle and pitch rate respectively. L, D, T and M_{yy} represent lift force, drag force, thrust force and pitch moment. m, μ, I_{yy} and r are the mass of flight, the earth gravity constant, the moment of inertia about pitch axis, and the radial distance from center of the earth.

The engine dynamics can be modeled as:

$$\ddot{\beta} = -2\xi\omega_n\dot{\beta} - \omega_n^2\beta + \omega_n^2\beta_c \tag{6}$$

where ξ and ω_n represent the engine damping ratio and the natural frequency. β denotes the actual throttle setting and β_c is desirable throttle setting.

The expressions of L, D, T and M_{yy} are written as:

$$L = \frac{1}{2}\rho V^2 S C_L$$

$$D = \frac{1}{2}\rho V^2 S C_D$$

$$T = \frac{1}{2}\rho V^2 S C_T$$

$$M_{yy} = \frac{1}{2}\rho V^2 S\bar{c}\big(C_M(\alpha) + C_M(\delta_e) + C_M(q)\big)$$

where

$$C_L = 0.6203\alpha$$

$$C_D = 0.645\alpha^2 + 0.0043378\alpha + 0.003772$$

$$C_T = \begin{cases} 0.02576\beta, & \beta < 1 \\ 0.0224 + 0.00336\beta, & \beta > 1 \end{cases}$$

$$C_M(\alpha) = -0.035\alpha^2 + 0.036617\alpha + 5.3261 \times 10^{-6}$$

$$C_M(q) = (\bar{c}/2V)q\big(-6.79\alpha^2 + 0.3015\alpha - 0.2289\big)$$

$$C_M(\delta_e) = c_e(\delta_e - \alpha)$$

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