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Fault Tolerant Tracking Control Scheme for UAV Using Dynamic Surface Control Technique

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Abstract In this paper, a novel fault tolerant control (FTC) approach is proposed for a hypersonic unmanned aerial vehicle (UAV) attitude dynamical system with actuator loss-of-effectiveness (LOE) fault. Firstly, the nonlinear attitude dynamics of hypersonic UAV is given, which represents the dynamic characteristics of UAV in ascent/reentry phases. Then a fault detection scheme is presented by designing a nonlinear fault detection observer (FDO) for the faulty attitude dynamical system of UAV. Moreover, the fault tolerant control scheme is proposed on the basis of the dynamic surface control technique, which guarantees the asymptotic output tracking and ultimate uniform boundedness of the closed-loop dynamical systems of UAV in the actuator LOE faulty case. Finally, simulation results are given to illustrate the effectiveness of the developed FTC scheme.

Keywords Fault detection · Fault tolerant control · Dynamic surface control · Loss-of-effectiveness (LOE) fault

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1 Introduction

The hypersonic unmanned aerial vehicle (UAV) is a kind of new aerospace vehicle, which will play a very important role in future air space activity [15]. Different from the traditional aerospace vehicle, the flight control system of hypersonic UAV in ascent and descent modes involves attitude maneuvering through a wide range of flight conditions, wind disturbances, and plant uncertainties including aerodynamic surfaces and engine failures [3], meanwhile, the attitude dynamics of hypersonic UAV includes serious multivariate coupling and strong nonlinearity [6]. As a new aerospace vehicle, the hypersonic UAV attitude dynamics will inevitably be subjected to all kinds of system fault, which are caused by all kinds of actuators, sensors or other system components. To improve the reliability of hypersonic UAV, the fault tolerant control (FTC) technique must be considered when we design a flight control system of UAV [9, 18].

It is well known that the fault tolerant approach can be classified into two types: passive and active [16, 23]. In the case of passive FTC, a fixed controller is proposed to tolerate only a limited predetermined faults throughout the whole control process, the very limited fault tolerance capability is the major drawback of this approach [2, 13, 19, 20, 22]. In the case of active FTC, it relies on the fault diagnosis mechanism to detect, isolate and identify the faults in real time, and then a reconfiguration mechanism is synthesized to reconfigure the controllers according to the online fault diagnosis information [8, 12, 26]. Generally speaking, active FTC is less conservative than the passive one and has increasingly been the main methodology in the field of FTC design.

In [1], Benallegue et al. design a disturbance observer-based sliding mode control scheme for UAV, which can increase the robustness to the model uncertainties and external disturbances without using high control gains. In [4], Bollino et al. propose a robust guidance and control architecture for a flight control system that incorporates elements of recent advances in the areas of optimal trajectory generation and reconfigurable control. In [14], Natesan et al. present a trajectory tracking controller design approach for an UAV using the linear parameter varying (LPV) method. In [5], a gain scheduled-based attitude controller design approach is proposed for the aircraft. In [21], an aerodynamic surfaces control allocation scheme is presented for reusable launch vehicle (RLV). It is worth pointing out that the results developed in [1, 4, 5, 14, 21] only consider the controller design problem for aircrafts in actuator/sensor fault free case, those might not be suitable for aircraft attitude dynamics in actuator/sensor fault case. In [11], Komatsu et al. design a passive fault tolerant controller for aircraft attitude dynamics using a μ-synthesis approach. In [27], Zhu et al. present a direct fault tolerant controller method for the attitude control of aircraft using a singular perturbation approach. However, the FTC schemes developed in [11] and [27] do not depend on fault detection and control switching mechanism, which belong to passive FTC. In [7], Jiang et al. investigate the problem of actuator fault accommodation for a near space vehicle attitude dynamics via T-S fuzzy models, however, for the plant of consideration exists a model error, and the obtained result might not be used for the nonlinear aircraft attitude dynamics. To the best of our knowledge, the active FTC issue for aircraft attitude dynamics has not been fully investigated yet, which remains challenging and motivates us to do this study.

In [17], Wang et al. present an adaptive dynamic surface control for a class of linear multivariable systems. We refer to the design approach obtained in [17] and use it to design an active fault tolerant control scheme for a hypersonic UAV with actuator loss-of-effectiveness faults. A nonlinear fault detection observer is designed to detect the actuator fault occurring in the attitude systems of UAV, which determines the switching time from normal controller to the FTC one. When an actuator fault occurs, we design an dynamic surface control-based active FTC scheme which guarantees the attitude of the faulty UAV asymptotically tracking the desired command signal. Finally, simulation result shows that the proposed approach has good fault tolerant capability.

2 The Attitude Dynamics of UAV

The attitude dynamics for a hypersonic UAV with parameter uncertainty and external disturbance input is given by [15]

$$(J+\Delta J)\dot{\omega}=-\omega^{\times}(J+\Delta J)\omega+u+d, \tag{1}$$

where $J\in\mathbb{R}^{3\times 3}$ is the nominal inertia matrix, $\Delta J\in\mathbb{R}^{3\times 3}$ is an uncertain part of the inertia matrix, which is caused by fuel consumption and variations of particular payloads from a nominal one. $\omega=[p\ q\ r]^T$ is the angular rate vector, $u=[u_1\ u_2\ u_3]^T$ is the control torque vector, $d=[d_1\ d_2\ d_3]^T$ is the external disturbance vector. The operator $\omega^{\times}$ denotes a skew-symmetric matrix acting on the vector $\omega=[\omega_1\ \omega_2\ \omega_3]^T$ and has the following form:

$$\omega^{\times}=\begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}.$$

For the simplicity of this study, The hypersonic UAV attitude dynamics (1) is rewritten as

$$J\dot{\omega}=-\omega^{\times}J\omega+u+\eta(\omega,d), \tag{2}$$

where $\eta(\omega,d)=-\Delta J\dot{\omega}-\omega^{\times}\Delta J\omega+d$ represents the combination of parameter uncertainty and external disturbance. In the following, we introduce an assumption condition for $\eta(\omega,d)$.

Assumption 1 The combination of parameter uncertainty and external disturbance represented by $\eta(\omega,d)$ in (2) is the unknown nonlinear function of ω and d, but bounded by the known constant $\overline{\eta}$. Specifically, it is assumed that $\forall\omega\in\mathbb{R}^3,\ d\in\mathbb{R}^3$, $|\eta_i(\omega,d)|<\overline{\eta}_i$ $(i=1,2,3)$, $\overline{\eta}_i$ is the known constant.

The attitude kinematics of a hypersonic UAV is described by

$$\dot{\gamma}=\mathcal{R}(\gamma)\omega. \tag{3}$$

The rotational matrix $\mathcal{R}(\gamma)\in\{\mathcal{R}_1(\gamma),\mathcal{R}_2(\gamma)\}$ is given by

$$\mathcal{R}_1(\gamma)=\begin{bmatrix}1 & \tan\theta\sin\varphi_b & \tan\theta\cos\varphi_b\\ 0 & \cos\varphi_b & -\sin\varphi_b\\ 0 & \sin\varphi_b/\cos\theta & \cos\varphi_b/\cos\theta\end{bmatrix},\quad \gamma=\begin{bmatrix}\varphi_b\\ \theta\\ \psi\end{bmatrix};$$

$$\mathcal{R}_2(\gamma)=\begin{bmatrix}\cos\alpha & 0 & \sin\alpha\\ 0 & 1 & 0\\ \sin\alpha & 0 & -\cos\alpha\end{bmatrix},\quad \gamma=\begin{bmatrix}\varphi\\ \alpha\\ \beta\end{bmatrix},$$

where $\mathcal{R}_1(\gamma)$ is used in the ascent phase and $\mathcal{R}_2(\gamma)$ is used in the reentry phase. γ represents the attitude angle of UAV. φ_b, θ, ψ are roll angle, pitch angle and yaw angle, respectively; φ, α and β are bank angle, angle of attack and sideslip angle, respectively.

It is well known that the command torque u is related to the deflection command vector δ, namely,

$$u=B\delta,$$

where $B\in\mathbb{R}^{3\times m}$, m is the number of the control-surface deflection variables. In this paper, we choose the X-33 hypersonic unmanned aerial vehicle as the studied plant. Figure 1 shows the configuration of the X-33 hypersonic unmanned aerial vehicle. It has four sets of control surfaces: rudders, body flaps, inboard and outboard elevons, with left and right side for each set. Each of the control surfaces can independently be actuated with one actuator for each surface. The control-surface deflection variables, collectively known as the effector vector, are given by

$$\delta=[\delta_{\mathrm{rei}},\delta_{\mathrm{lei}},\delta_{\mathrm{rft}},\delta_{\mathrm{lft}},\delta_{\mathrm{rvr}},\delta_{\mathrm{lvr}},\delta_{\mathrm{reo}},\delta_{\mathrm{leo}}]^T,$$

where δ_{rei} and δ_{lei} are the right and left inboard elevons, δ_{rft} and δ_{lft} are the right and left body flaps, δ_{rvr} and δ_{lvr} are the right and left rudders, δ_{reo} and δ_{leo} are the right and left outboard elevons. All of the control-surface deflections are in degrees. The sign convention is positive body flap deflection is down, positive elevon deflection is down, and positive rudder deflection is left looking forward.

3 Main Results

3.1 Fault Detection Scheme

It is noted that the hypersonic UAV attitude dynamics described by (2) is in actuator fault free case. To formulate the fault tolerant control problem, the faulty attitude dynamics of hypersonic UAV must be established, the type of actuator fault considered in this study is the loss of control effectiveness. A hypersonic UAV attitude dynamics under actuator fault case is given by

$$J\dot{\omega}=-\omega^{\times}J\omega+B(I-F)\delta+\eta(\omega,d),\tag{4}$$

where $F=\mathrm{diag}\{f_i\}$ $(i=1,2,\dots,8)$ and $f_i\in[0,\varepsilon_i]$, f_i is an unknown constant, ε_i represents the maximum percentage of the admissible loss of control effectiveness satisfying $0\le\varepsilon_i<1$.

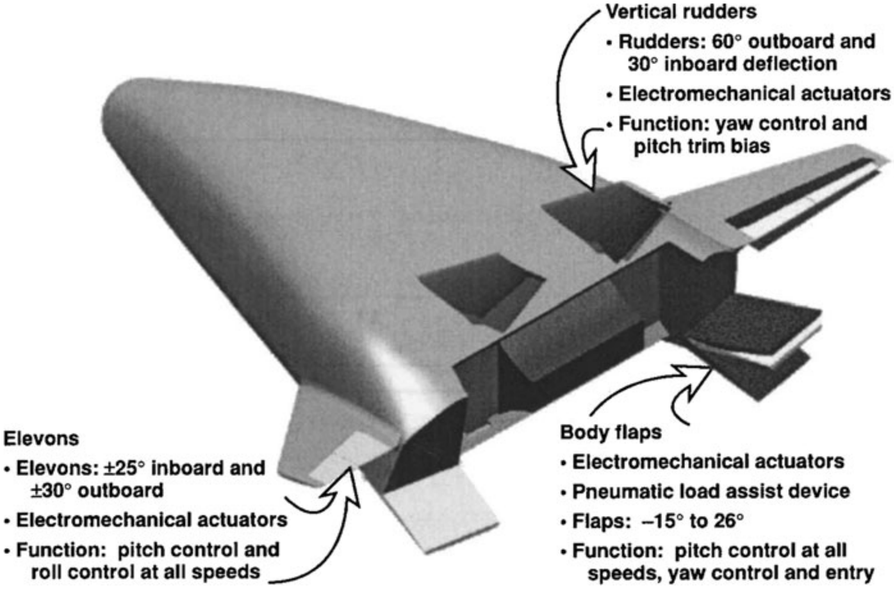


Fig. 1 The configuration of the X-33 hypersonic unmanned aerial vehicle

For the simplicity of this study, the faulty attitude dynamics of UAV (4) is rewritten as

$$\dot{\omega} = -J^{-1}\omega^{\times}J\omega + J^{-1}B\delta + J^{-1}\eta(\omega, d) - J^{-1}BF\delta. \tag{5}$$

In any position, a fault detection scheme is presented based on an intuitive algorithm. For the faulty system (5), a nonlinear fault detection observer is designed as

$$\dot{\hat{\omega}} = -\lambda(\hat{\omega} - \omega) - J^{-1}\omega^{\times}J\omega + J^{-1}B\delta, \tag{6}$$

where $\hat{\omega}$ is the estimated angular rate, and $\lambda = \mathrm{diag}\{\lambda_1, \lambda_2, \lambda_3\}$, $-\lambda_i < 0$ $(i = 1, 2, 3)$ are the poles of fault detection observer (6), which are determined in advance.

Note that $J^{-1}\eta = [(J^{-1}\eta)_1,\ (J^{-1}\eta)_2,\ (J^{-1}\eta)_3]^T$. Let $\tilde{\omega} \triangleq \omega - \hat{\omega}$ be the observer error vector, the adaptive thresholds $\overline{\epsilon}$ for fault detection can be chosen as

$$\overline{\epsilon}_i \triangleq e^{-\lambda_i t}\tilde{\omega}_i(0) + \int_0^t e^{-\lambda_i(t-\tau)}\left(J^{-1}\overline{\eta}\right)_i \mathrm{d}\tau \quad (i = 1, 2, 3). \tag{7}$$

The second term of $\overline{\epsilon}_i$ in (7) can be implemented as the output of a linear filter (with transfer function $\frac{1}{s+\lambda_i}$ and zero initial conditions) with input given by $(J^{-1}\overline{\eta})_i$. The decision for the occurrence of a fault (detection) is made when the modulus of at least one of the observer error components $|\tilde{\omega}_i|$ exceeds its corresponding adaptive threshold. More precisely, the fault detection time T_d is defined as the first instant of time such that $|\tilde{\omega}_i| > \overline{\epsilon}_i$ $(i = 1$, or $i = 2$, or $i = 3)$ for $t > T_0$; that is,

$$T_d \triangleq \mathbf{inf} \bigcup_{i=1}^{3} \left\{t > T_0 : |\tilde{\omega}_i| > \overline{\epsilon}_i\right\}. \tag{8}$$

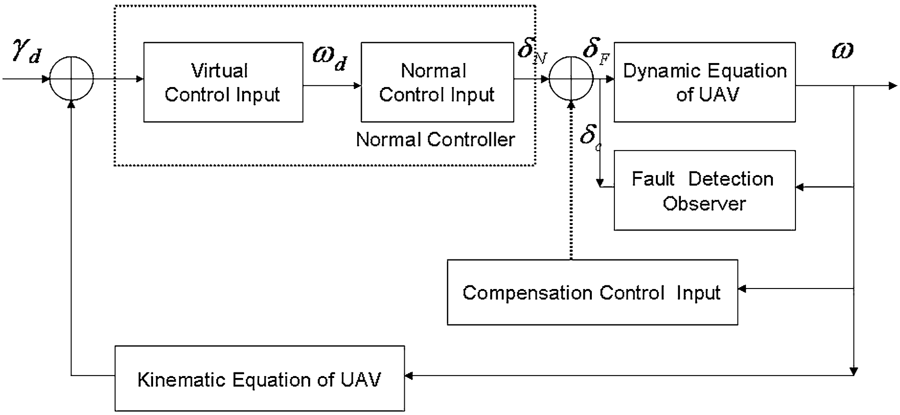


Fig. 2 Block diagram of UAV using dynamic surface control

Remark 1 For an active FTC system, fault detection is necessary to determine the time that the system faults occurred. Therefore, it is a prerequisite for fault identification and fault tolerant control design. Compared with the constant detection threshold provided in [7], it can be seen that the fault detection threshold $\bar{\epsilon}$ described by (7) is the adaptive one, and thus can reduce the missing alarm and false alarm rates of actuator fault detection, which is less conservative than that presented in [7].

3.2 Fault Tolerant Tracking Scheme

The main objective of this study is to design a fault tolerant controller for the faulty system (5), to ensure that the closed-loop signals are bounded and the attitude of UAV γ asymptotically tracks a reference command γ_d.

In this section, *a normal control input* δ_N is first designed for the attitude dynamics of hypersonic UAV in actuator fault free case using both adaptive and dynamic surface control techniques. when an actuator fault occurs, a compensation control input δ_C is designed and added to the normal control input δ_N for reducing the effects of actuator fault. Figure 2 shows the configuration of the fault tolerant control scheme for UAV using the dynamic surface control scheme.

In order to design a normal control input δ_N, we define the following new variables:

$$x_1 = \gamma \in \mathbb{R}^3, \qquad x_2 = \omega \in \mathbb{R}^3. \tag{9}$$

Then the attitude dynamics of UAV (1) and (3) are transformed into the following form:

$$\dot{x}_1 = \mathcal{R}(x_1)x_2, \tag{10}$$

$$\dot{x}_2 = -J^{-1}x_2^{\times}Jx_2 + J^{-1}B\delta + J^{-1}\eta(x_2, d). \tag{11}$$

It can be easily seen that (10)–(11) is a general nonlinear system, which will be used for the attitude tracking control design. From (10)–(11), it can be seen that the attitude control systems of UAV (1) and (3) have been transformed into a class of triangular nonlinear form. Then the standard dynamic surface control approach with adaptive technique is applied to the design of normal control input δ_N.

Theorem 1 *Consider the healthy UAV attitude dynamics* (1) *and* (3) *under Assumption* 1, *and the following normal control input and adaptive update law*:

$$\delta_N = B^T\big(B\cdot B^T\big)^{-1}\big[-k_2z_2 + x_2^\times Jx_2 - \operatorname{sign}(z_2)\hat{\eta} + J\dot{\alpha}_2\big], \tag{12}$$

$$\dot{\hat{\eta}} = c_1z_2 \tag{13}$$

can guarantee the asymptotic output tracking of UAV attitude control system in actuator fault free case.

Proof *Step 1.* In (10), we assume that x_2 is a virtual control input, and we let

$$z_1 = x_1 - \gamma_d \tag{14}$$

which is called the first error surface, $\gamma_d \in \mathbb{R}^3$ is the desired attitude angle of UAV.

Taking the time derivative of z_1, one has

$$\dot{z}_1 = \dot{x}_1 - \dot{\gamma}_d = \mathcal{R}(x_1)x_2 - \dot{\gamma}_d = \mathcal{R}(x_1)\big[x_2 - \mathcal{R}^{-1}(x_1)\dot{\gamma}_d\big]. \tag{15}$$

Selecting an appropriate virtual control x_{2d} as

$$x_{2d} = -k_1z_1 + \mathcal{R}^{-1}(x_1)\dot{\gamma}_d. \tag{16}$$

Introduce a new state variable α_2 and let x_{2d} pass through a first-order filter with time constant ε_2 to obtain α_2:

$$\varepsilon_2\dot{\alpha}_2 + \alpha_2 = x_{2d}, \qquad \alpha_2(0) = x_2(0). \tag{17}$$

Step 2. Consider system (11), and let

$$z_2 = x_2 - \alpha_2 \tag{18}$$

which is called the second error surface. Taking the time derivative of z_2, we have

$$\dot{z}_2 = -J^{-1}x_2^\times Jx_2 + J^{-1}B\delta + J^{-1}\eta(x_2, d) - \dot{\alpha}_2. \tag{19}$$

From (19), the normal control input and the parameter updating law are designed as

$$\delta_N = B^T\big(B\cdot B^T\big)^{-1}\big[-k_2z_2 + x_2^\times Jx_2 - \operatorname{sign}(z_2)\hat{\eta} + J\dot{\alpha}_2\big], \tag{20}$$

$$\dot{\hat{\eta}} = c_1z_2. \tag{21}$$

The adaptive dynamic surface control technique has been developed in [17] for a class of linear multivariable control systems. In this paper, this method is modified and applied to the design of the UAV attitude control system; the stability analysis of the closed-loop control system is given in the following.

Firstly, we define the filter error as $\phi = \alpha_2 - x_{2d}$. After some manipulations, we have

$$\dot{\phi} = \dot{\alpha}_2 - \dot{\bar{x}}_2 = -\frac{\phi}{\varepsilon_2} + k_1\dot{z}_1 - \dot{\mathcal{R}}^{-1}(x_1)\dot{\gamma}_d - \mathcal{R}^{-1}(x_1)\ddot{\gamma}_d. \tag{22}$$

Considering a Lyapunov function candidate as follows:

$$V = V_1 + V_2 \triangleq \frac{1}{2}\big(z_1^2 + \phi^2\big) + \frac{1}{2}\left(z_2^2 + \frac{1}{c_1}\tilde{\eta}^2\right), \tag{23}$$

where $V_1 = \frac{1}{2}(z_1^2 + \phi^2)$, $V_2 = \frac{1}{2}(z_2^2 + \frac{1}{c_1}\tilde{\eta}^2)$ with $\tilde{\eta} = \bar{\eta} - \hat{\eta}$.

Firstly, one takes the time derivative of V_1, and one can obtain

$$\dot{V}_1 = z_1^T \dot{z}_1 + \phi^T \dot{\phi}$$
$$= z_1^T \mathcal{R}(x_1)\big[x_2 - \mathcal{R}^{-1}(x_1)\dot{\gamma}_d\big] + \phi^T \left[-\frac{\phi}{\varepsilon_2} + k_1 \dot{z}_1 - \dot{\mathcal{R}}^{-1}(x_1)\dot{\gamma}_d - \mathcal{R}^{-1}(x_1)\ddot{\gamma}_d\right]. \tag{24}$$

Meanwhile, subtracting (15) from (24), one has

$$\begin{aligned}\dot{V}_1 &\le -k_1 \mathcal{R}(x_1)\|z_1\|^2 + z_1^T \mathcal{R}(x_1)(x_2 - x_{2d}) + \phi^T \\ &\quad \times \left[-\frac{\phi}{\varepsilon_2} + k_1 \dot{z}_1 - \dot{\mathcal{R}}^{-1}(x_1)\dot{\gamma}_d - \mathcal{R}^{-1}(x_1)\ddot{\gamma}_d\right] \\ &\le -k_1 \big\|\mathcal{R}(x_1)\big\| \|z_1\|^2 - \frac{1}{\varepsilon_2}\|\phi\|^2 + \kappa,\end{aligned} \tag{25}$$

where $\kappa = z_1^T \mathcal{R}(x_1)(x_2 - x_{2d}) + k_1 \phi^T \dot{z}_1 + \phi^T \dot{\mathcal{R}}^{-1}(x_1)\dot{\gamma}_d + \phi^T \mathcal{R}^{-1}(x_1)\ddot{\gamma}_d$.

Similar to the derivative of V_1, one can obtain the following:

$$\begin{aligned}\dot{V}_2 &= z_2^T \dot{z}_2 + \tilde{\eta}^T \dot{\tilde{\eta}} \\ &= z_2^T \big[-J^{-1} x_2^{\times} J x_2 + J^{-1} B\delta + J^{-1}\eta(x_2, d) - \dot{\alpha}_2\big] + \tilde{\eta}^T \dot{\tilde{\eta}}.\end{aligned} \tag{26}$$

Subtracting (20) into (26), which can be transformed into the following form:

$$\dot{V}_2 \le -k_2\|z_2\|^2 + \frac{1}{c_1}\tilde{\eta}^T (c_1 z_2 - \dot{\hat{\eta}}) = -k_2\|z_2\|^2. \tag{27}$$

From (24) and (27), it can be easily found that

$$\dot{V} = \dot{V}_1 + \dot{V}_2 \le -k_1 \big\|\mathcal{R}(x_1)\big\| \|z_1\|^2 - \frac{1}{\varepsilon_2}\|\phi\|^2 - k_2\|z_2\|^2 + \kappa. \tag{28}$$

Selecting an appropriate $\varepsilon_2 > 0$, such that $\dot{V} < 0$, then the Lyapunov stability theory guarantees the global uniform boundedness of z_1 and z_2. It follows that $z_1 \to 0$ as $t \to \infty$. Since $z_1 = x_1 - \gamma_d$, x_1 is also bounded and $\lim_{t\to 0} x_1 = \gamma_d$. Therefore, the asymptotic output tracking of the UAV attitude control system can be guaranteed by Theorem 1. □

From the above analysis, the proposed normal controller (12) and adaptive update law (13) can achieve the asymptotical tracking of the closed-loop attitude control system of UAV in actuator fault free case. In the following, we extend the above result to deal with the fault tolerant control problem of UAV attitude control system, a compensation control input δ_C will be developed on the basis of the nominal controller δ_N to compensate for the effects of actuator fault. Thus, the fault tolerant control input δ_F of the faulty attitude control system (5) consists of two parts, that is,

$$\delta_F = \delta_N + \delta_C. \tag{29}$$

For the fault tolerant controller design, the same procedure of the first design step is as the design of the nominal control input δ_N. Here, the detailed description to step 2 is developed. In terms of (5) and (19), we can obtain

$$\begin{aligned}\dot{z}_2 &= -J^{-1}x_2^{\times}Jx_2 + J^{-1}B(I-F)\delta + J^{-1}\eta(x_2,d) - \dot{\alpha}_2\\ &= -J^{-1}x_2^{\times}Jx_2 + J^{-1}B(\delta_N+\delta_C) - J^{-1}BF(\delta_N+\delta_C) + J^{-1}\eta(x_2,d) - \dot{\alpha}_2\\ &= -J^{-1}x_2^{\times}Jx_2 + J^{-1}B\delta_N - J^{-1}BF\delta_N + J^{-1}B(I-F)\delta_C + J^{-1}\eta(x_2,d) - \dot{\alpha}_2\\ &= -J^{-1}x_2^{\times}Jx_2 + J^{-1}B\delta_N - J^{-1}BF\delta_N + J^{-1}B\varsigma\delta_C + J^{-1}\eta(x_2,d) - \dot{\alpha}_2,\end{aligned}\tag{30}$$

where $\varsigma = I_3 - F$. It can be easily known that $\|\varsigma\| < 1$.

Now a compensation control input δ_C is designed as

$$\delta_C = -\operatorname{sign}(z_2)B^T\left(B\cdot B^T\right)^{-1}\left[\|B\delta_N\| + \frac{\lambda\|B\delta_N\|}{\bar{\varsigma}}\right],\tag{31}$$

where $\bar{\varsigma} = 1 - \max\{f_i\}(i=1,2,3)$, $\lambda > 0$ is a positive constant.

From (29)–(31), the time derivative of V_2 is given by

$$\begin{aligned}\dot{V}_2 &= z_2^T\dot{z}_2 + \tilde{\eta}^T\dot{\tilde{\eta}}\\ &= z_2^T\left[-J^{-1}x_2^{\times}Jx_2 + J^{-1}B\delta_N - J^{-1}BF\delta_N + J^{-1}B\varsigma\delta_C + J^{-1}\eta(x_2,d) - \dot{\alpha}_2\right]\\ &\quad + \tilde{\eta}^T\dot{\tilde{\eta}}\\ &\le -k_2\|z_2\|^2 + z_2^T\left[J^{-1}B\varsigma\delta_C - J^{-1}BF\delta_N\right]\\ &\le -k_2\|z_2\|^2 + z_2^T\left[J^{-1}B\varsigma\delta_C - J^{-1}BF\delta_N\right]\\ &\le -k_2\|z_2\|^2 - z_2^TJ^{-1}BF\delta_N - \left\|z_2^T\right\|J^{-1}\varsigma\left[\|B\delta_N\| + \frac{\lambda\|B\delta_N\|}{\bar{\varsigma}}\right]\\ &\le -k_2\|z_2\|^2 - z_2^TJ^{-1}BF\delta_N - \left\|z_2^T\right\|J^{-1}(I-F)\|B\delta_N\| - \lambda\left\|z_2^T\right\|J^{-1}\|B\delta_N\|\\ &\le -k_2\|z_2\|^2 - \left\|z_2^T\right\|J^{-1}\|B\delta_N\| - \lambda\left\|z_2^T\right\|J^{-1}\|B\delta_N\|\\ &\le -k_2\|z_2\|^2 - (1+\lambda)\left\|z_2^T\right\|\|J^{-1}\|\|B\delta_N\|\\ &\le -k_2\|z_2\|^2.\end{aligned}\tag{32}$$

Note that the inequality $0 < \bar{\varsigma} < \|\varsigma\|_{\min} \le 1$ is used in the operation of (32). From (32) and the similar stability analysis in Theorem 1, the following result can be obtained.

Theorem 2 *Consider the faulty UAV attitude control system* (3) *and* (5); *the fault tolerant control input δ_F described in* (29) *can guarantee the asymptotic output tracking of UAV attitude control system.*

Proof This can easily be obtained from the above analysis and the proof is thus omitted here. □

Remark 2 The control input (5) is discontinuous due to the use of sign function sign(·), which may lead to the chattering effect. It is well known that a chattering effect often excites the unmodeled high frequency dynamic or even makes system unstable. In order to overcome this shortcoming, the varying boundary layers is employed to substitute for function sign(·), and then the normal control input δ_N can be modified as

$$\delta_N = B^T\left(B\cdot B^T\right)^{-1}\left[-k_2 z_2 + x_2^{\times} J x_2 - \frac{z_2}{\|z_2\| + \rho_1}\hat{\eta} + J\dot{\alpha}_2\right], \quad \dot{\hat{\eta}} = c_1 z_2 \tag{33}$$

the compensated control input δ_C can be modified as

$$\delta_C = -B^T\left(B\cdot B^T\right)^{-1}\frac{z_2}{\|z_2\| + \rho_2}\left[\|B\delta_N\| + \frac{\lambda\|B\delta_N\|}{\bar{\varsigma}}\right], \tag{34}$$

where $\rho_1 > 0$ and $\rho_2 > 0$ are two positive constant scalars.

Remark 3 In [10], Jiang et al. designed a nonlinear fault tolerant controller for flexible spacecraft with unknown bounded disturbances and actuator failures using both adaptive and backstepping control techniques. It is well known that dynamics surface is an improved backstepping control method, the primary advantage of dynamic surface control is that it can avoid the problem of "explosion of terms" inherent in the backstepping design procedure, by introducing a first-order low pass filter of the synthetic input at each step of the traditional backstepping approach. In this study, we modify the fault tolerant control method developed in [10] and design a fault tolerant tracking control scheme for UAV attitude dynamical systems utilizing dynamic surface control technique, which can eliminate the phenomenon of explosion of complexity.

Remark 4 In this study, a simply FTC approach is proposed for the attitude control systems of hypersonic UAV, which does not rely on the fault estimation information, so it only deals with the limited actuator fault. In [25], a decentralized fault diagnosis approach of complex processes is proposed based on multiblock kernel partial least squares technique. In [24], a novel fault detection scheme is given using the improved kernel principal component analysis and the improved kernel independent component analysis approach. In our future work, we will improve the fault tolerant control design so as to increase the fault tolerant capability by referring to the fault diagnosis approach proposed in [25] and [24].

4 Simulation Results

This section describes the numerical evaluation of the designed FTC scheme for the attitude control system of X-33 hypersonic UAV in reentry phase. The moment of inertia tensor is given by [15]

$$J_0 = \begin{pmatrix} 554486 & 0 & -23002 \\ 0 & 1136949 & 0 \\ -23002 & 0 & 1376852 \end{pmatrix}.$$

In Matlab simulation, it is assumed that the UAV flight altitude $H = 40$ km and $V = 2500$ m/s, and UAV attitude tracking commands γ_c (bank angle, angle of attack and sideslip angle) are 2 deg, 4 deg and 0 deg, respectively. We select the parameter uncertainty and external disturbance input $\eta(\omega, d) = 10^3 \sin\omega + 10^3 \sin t$ and upper bound $\bar{\eta} = 2\times 10^3$.

Fig. 3 The attitude tracking responses with δ_N in actuator fault free case

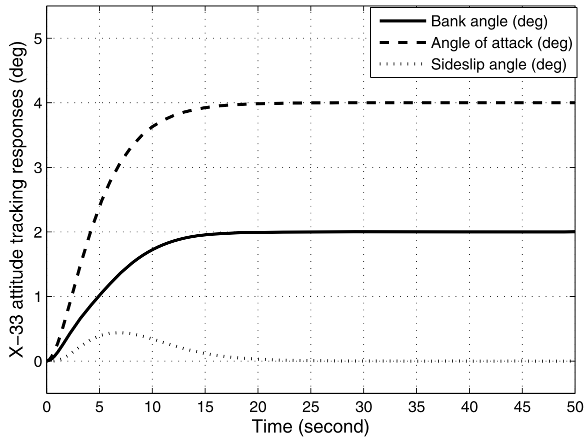


Fig. 4 The virtual control input x_{2d} in actuator fault free case

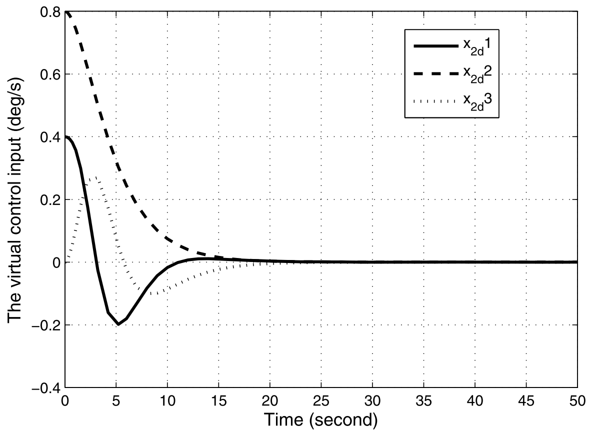


Fig. 5 The normal control torques u in actuator fault free case

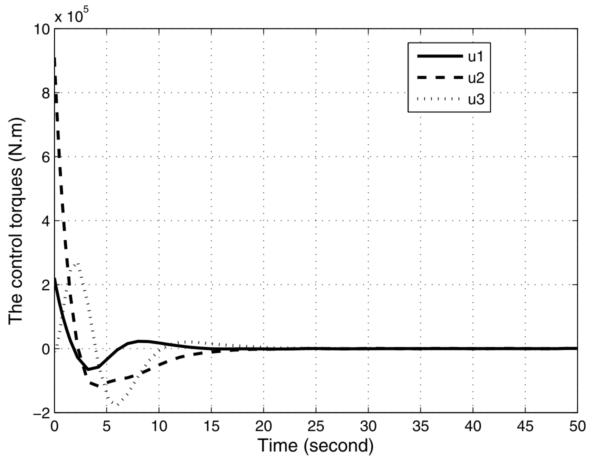


Fig. 6 The attitude tracking responses with δ_N in actuator fault case

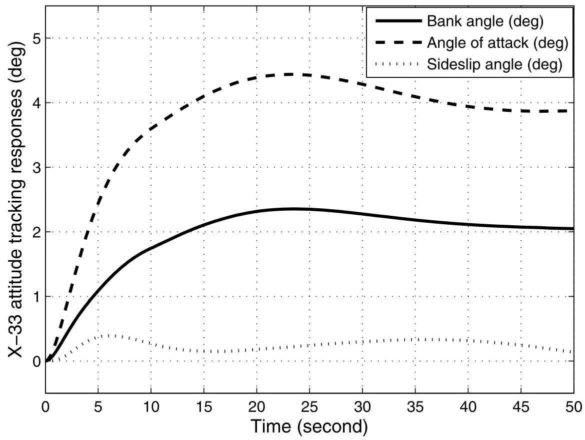


Fig. 7 The virtual control input x_{2d} in actuator fault case

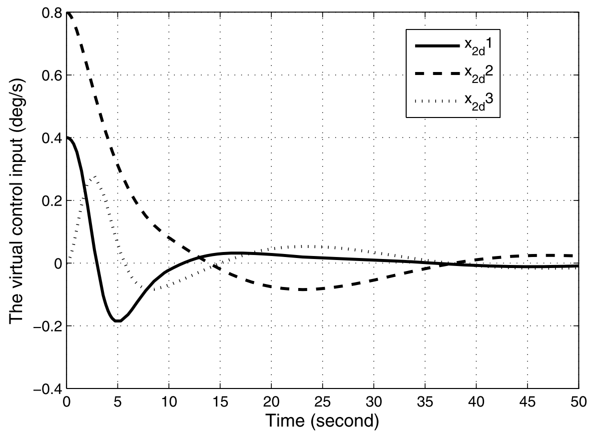
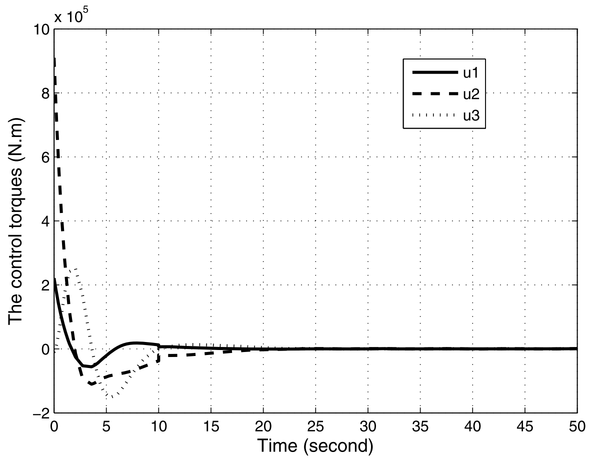


Fig. 8 The normal control torques u in actuator fault case



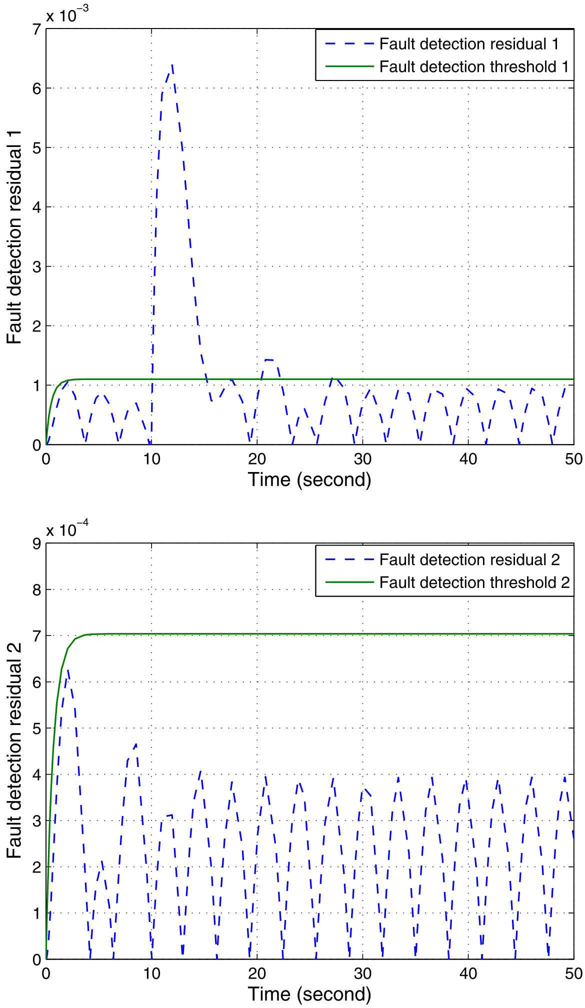


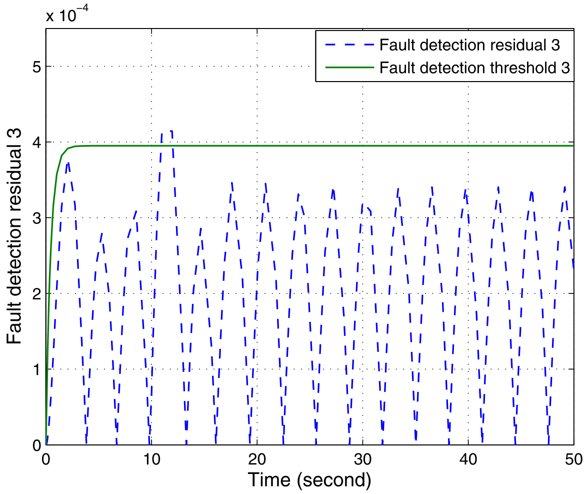
Fig. 9 Fault detection residuals with fault parameter $F = \mathrm{diag}\{0, 0, 0.5, 0, 0, 0, 0, 0\}$

To verify the superior performance of the FTC approach proposed in this study, it is assumed that the right body flap loses 50 % control effectiveness at 10 second in the simulation, namely,

$$F = \begin{cases} \mathrm{diag}\{0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0\} & t < 10\ \mathrm{s}, \\ \mathrm{diag}\{0,\ 0,\ 0.5,\ 0,\ 0,\ 0,\ 0,\ 0\} & t \geq 10\ \mathrm{s}. \end{cases}$$

To design the fault tolerant control input δ_F, we select the learning parameter $c_1 = 1.2$, and the positive constant scalars $\rho_1 = 2.5$ and $\rho_2 = 2.5$. The Matlab simulation results of UAV attitude tracking responses and fault detection curves are shown in Figs. 3–12. When all actuators are in healthy case, the simulation result about UAV attitude tracking response is depicted in Fig. 3 by using the normal control δ_N. The virtual control input x_{2d} and the final control torque u are shown in Fig. 4 and Fig. 5, respectively. When the actuator fault described above occurs, the X-33 attitude

Fig. 9 (*Continued*)



tracking responses and the control input responses using normal control input δ_N are depicted in Figs. 6, 7, 8. It can be seen that the designed normal control input δ_N could not guarantee the asymptotical output tracking of UAV attitude control system. By utilizing the designed fault detection observer, it could easily be found that an actuator fault occurs; the corresponding fault detection residual curves are depicted in Fig. 9, where it can be seen that the fault detection residual 1 is more than its corresponding adaptive detection threshold, and then produces a fault alarm. By means of the designed fault tolerant control input δ_N, it can be seen from Figs. 10, 11, 12 that the UAV attitude tracking responses and the control input responses have a satisfactory performance in spite of the actuator fault, which demonstrate the effectiveness of the developed FTC scheme.

5 Conclusions

This study presents a fault tolerant control approach for a class of unmanned aerial vehicle attitude dynamical systems with actuator loss-of-effectiveness fault. For the faulty UAV attitude control system, a fault detection scheme is proposed using the nonlinear fault detection observer technique. By utilizing the dynamic surface control technique, a fault tolerant control strategy is developed for the faulty UAV attitude control systems. On the basis of Lyapunov theory, the stability of the closed-loop control system is proved. Finally, the simulation results are given to show the effectiveness of the proposed FTC scheme.

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Fig. 10 The attitude tracking responses with δ_F in actuator fault case

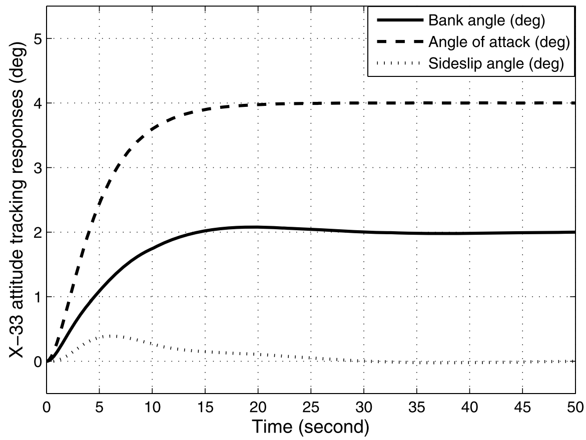


Fig. 11 The virtual control input x_{2d} in actuator fault case

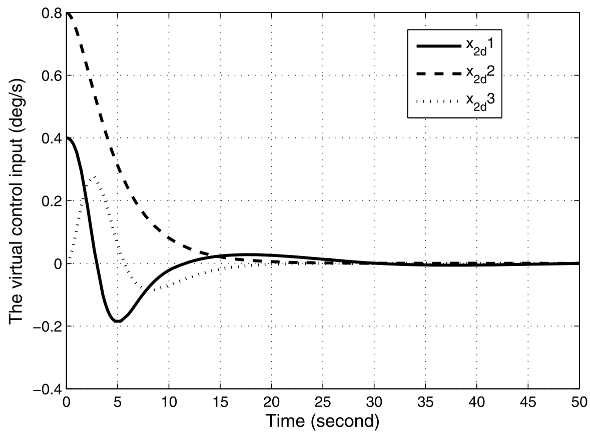
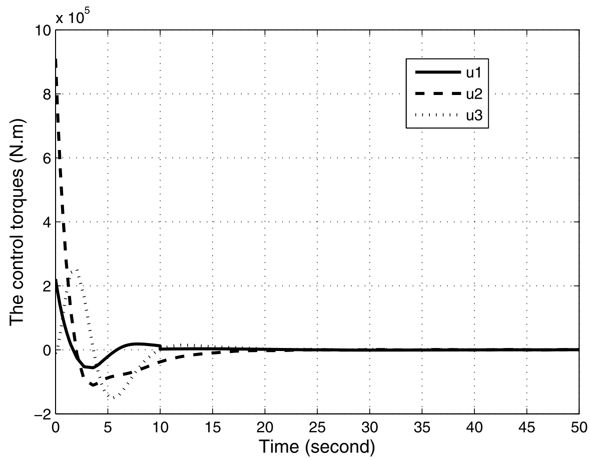


Fig. 12 The fault tolerant control torque u in actuator fault case



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