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ITERATIVE LEARNING OBSERVER-BASED FAULT TOLERANT CONTROL APPROACH FOR SATELLITE ATTITUDE SYSTEM WITH MIXED ACTUATOR FAULTS

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Abstract. *In this paper, an iterative learning observer-based fault tolerant attitude tracking control scheme is proposed to the satellite attitude system with mixed actuator faults. Firstly, the nonlinear satellite attitude control system model and the mixed actuator fault model are given. Next, an iterative learning observer is designed for the faulty satellite attitude system to obtain the estimated unknown torque input produced by the mixed actuator faults. On this basis, a fault tolerant attitude tracking controller is designed by using backstepping control technique to guarantee the stability of the satellite closed-loop attitude system. Finally, simulation results are given to illustrate the effectiveness of the proposed fault tolerant control approach.*
Keywords: Fault tolerant control, Iterative learning observer, Fault estimation, Actuator fault

1. **Introduction.** With the performance requirement increase of modern satellite, attitude control system becomes more and more complex. Attitude stabilization is a very critical technology for satellite during operation, many important results have been reported in the past decade for spacecraft maneuver stabilization, but most of the existing results deal only with uncertainty and external disturbance, it is assumed that there is no actuator/sensor fault occurring during the entire attitude maneuver. In reality, the on-orbit satellite often shows some unknown faults, and it may cause satellites to fail to work or even ultimately fail to the mission. Therefore, it is necessary to design a fault tolerant controller for the satellite attitude system to improve the reliability and security.

Recently, many researchers pay more attention to the research on fault diagnosis and fault tolerant control (FTC) for satellite, for example, a fault tolerant control strategy is presented in [1] for a faulty spacecraft based on variable structure control technique, which is implemented without explicit fault detection and isolation (FDI) processes. A fault tolerant attitude tracking control scheme with thruster redundancy is proposed in [2] for a flexible spacecraft, and it guarantees that all the signals of the attitude system are uniformly ultimately bounded. A robust actuator fault diagnosis scheme is developed in [3] for satellite attitude system subject to model uncertainty, space disturbance torque and gyro drift by using unknown input observer technique. An active fault tolerant attitude stabilization control approach is presented in [4] to a flexible spacecraft. This is accomplished by an observer-based fault detection and diagnosis (FDD) mechanism to

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reconstruct unknown fault. In [5], the fault tolerant tracking control problem is studied for a spacecraft with actuator faults by using on-line control allocation scheme, a time-varying dead-zone modification technique is employed in parameter adaptation. In [6], a finite time FTC scheme is developed for a rigid spacecraft using both fuzzy logic system and fast nonsingular terminal sliding mode control. A nonlinear fault estimation observer is designed in [7] for a satellite attitude system to obtain the estimation of unknown fault; on this basis, an active FTC approach is then presented utilizing backstepping control technique. In [8], a prescribed performance index is introduced to FTC design for a rigid spacecraft, such that the expected tracking error is guaranteed. In [9], the cooperative tracking problem is investigated for a group of nonlinear system, and the designed controller could tolerate the actuator faults and suppress the external disturbance. An adaptive robust FTC approach is proposed in [10] for a spacecraft attitude system using extended state observer technique, and it ensures that the closed-loop attitude system reaches the designed sliding mode surface in finite time. It is noted that the FTC schemes described above could only solve the fault accommodation problem in the case of single type fault, the FTC problem in mixed type fault case for satellite attitude system has not been fully investigated yet, and the corresponding results are very limited in the literature, which remains challenging and motivates us to do this study.

In this paper, an iterative learning observer (ILO)-based fault tolerant attitude controller is designed to the satellite attitude system with mixed actuator faults. A fault estimation observer design method is proposed for the satellite dynamic equation by using iterative learning algorithm to obtain the estimated unknown input produced by the occurring mixed fault. Then a fault tolerant attitude control scheme is presented by using backstepping control technique to guarantee the stability of the closed loop attitude system. Simulation results demonstrate the effectiveness and good tracking performance of the designed FTC scheme.

The remainder of the paper is organized as follows. The satellite attitude system with actuator fault is presented in Section 2. Iterative learning observer-based fault estimation scheme is given in Section 3. An integral sliding mode-based fault tolerant attitude controller is developed in Section 4. To verify the effectiveness of the proposed FTC, simulation studies are given in Section 5. Finally, the conclusion is given in Section 6.

2. Problem Statement and Preliminaries.

In this section, the Euler moment equations are adopted to describe the attitude system of a rigid satellite. The kinematic equation of satellite is given by [3]

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \frac{1}{\cos\theta} \begin{bmatrix} \cos\theta & \sin\varphi\sin\theta & \cos\varphi\sin\theta \\ 0 & \cos\varphi\cos\theta & -\sin\varphi\cos\theta \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} + \frac{\omega_0}{\cos\theta} \begin{bmatrix} \sin\psi \\ \cos\theta\cos\psi \\ \sin\theta\sin\psi \end{bmatrix} \tag{1}$$

where φ, θ, ψ are roll angle, pitch angle and yaw angle, respectively. ω_1, ω_2 and ω_3 are the angular velocity of satellite in a body-fixed reference frame. ω_0 is the constant orbital rate.

It is assumed that the Euler angles vary in a small range, and then the kinematic equation (1) is simplified as the following form

$$\dot{\sigma} = \omega + F\sigma \tag{2}$$

where $\omega = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}$, $\sigma = \begin{bmatrix} \varphi \\ \theta \\ \psi \end{bmatrix}$ and $F = \begin{bmatrix} 0 & 0 & \omega_0 \\ 0 & 0 & 0 \\ -\omega_0 & 0 & 0 \end{bmatrix}$.

The dynamic equation of satellite with inertia uncertainty is given by [3]

$$J\dot{\omega} = -\omega^{\times} J\omega + u_a + T_d \tag{3}$$

where $J = J_0 + \Delta J$ is the inertia matrix, J_0 is the nominal part of inertia matrix, ΔJ is the uncertain part of inertia matrix, $u_a = [u_{a1}, u_{a2}, u_{a3}]^T$ is the control torques generated by three orthogonal reaction wheels, $T_d = [T_{d1}, T_{d2}, T_{d3}]^T$ represents the external disturbance torques, and $\omega^\times$ is a skew-symmetric matrix with the following form

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

After some manipulations, Equation (3) is transformed into the following form

$$\dot{\omega} = -J_0^{-1}\omega^\times J_0\omega + J_0^{-1}u_a + J_0^{-1}d \tag{4}$$

where $d = T_d - \omega^\times \triangle J\omega - \triangle J\dot{\omega}$, which is viewed as a generalized perturbation for satellite.

In this paper, the actuator faults under consideration could be expressed as [5]

$$u_a^F = \rho(t)u + f(t) = u + u_f \tag{5}$$

where $u = [u_1, u_2, u_3]^T$ denotes the output commands of attitude controller. $\rho(t) = \mathrm{diag}\{\rho_1, \rho_2, \rho_3\}$ denotes the loss of effectiveness (LOE) factor with $0 < \bar{\rho}_i < \rho_i(t) \leq 1$ $(i = 1, 2, 3)$, $\bar{\rho}_i$ is the small positive scalar. $f = [f_1, f_2, f_3]^T$ denotes the bias faults. $u_f = [u_{f1}, u_{f2}, u_{f3}]^T$ denotes the unexpected control input produced by the loss of effectiveness fault and/or bias fault.

Substracting (5) into (4), it can be seen that

$$\dot{\omega} = -J_0^{-1}\omega^\times J_0\omega + J_0^{-1}(u + u_f) + J_0^{-1}d \tag{6}$$

To achieve the objective of this study, the following assumptions are introduced, which will be used in the controller design and the closed-loop stability analysis.

Assumption 2.1. *The generalized perturbation $d(t)$ is norm bounded and it satisfies $\|d\| \leq \bar{d}$, where $\bar{d}$ is a positive constant.*

Assumption 2.2. *The nonlinear function $\omega^\times J\omega$ in the dynamics Equation (6) is locally Lipschitz bounded with respect to a Lipschitz constant α, namely,*

$$\|\hat{\omega}^\times J_0\hat{\omega} - \omega^\times J_0\omega\| \leq \alpha\|\hat{\omega} - \omega\| = \alpha\|\tilde{\omega}\|$$

3. **Iterative Learning Observer Design.** In this section, an iterative learning observer is designed in (7) and (8) for the satellite dynamic Equation (6), which could achieve the accurate estimation of the unexpected control input u_f.

$$\dot{\hat{\omega}} = -J_0^{-1}\hat{\omega}^\times J_0\hat{\omega} + J_0^{-1}(u + \hat{u}_f) + J_0^{-1}\Gamma\tilde{\omega} + J_0^{-1}\bar{d}\,\mathrm{sgn}(\tilde{\omega}) \tag{7}$$

$$\hat{u}_f = l_1\hat{u}_f(t - T) + l_2\tilde{\omega} \tag{8}$$

where $\tilde{\omega} = \omega - \hat{\omega}$, T is the updating interval, which is taken as the sampling time interval in this paper, Γ is a positive definite matrix, and l_1 and l_2 are two positive scalars.

Subtracting (6) from (7), one has

$$\dot{\tilde{\omega}} = -J_0^{-1}\Gamma\tilde{\omega} + J_0^{-1}\hat{\omega}^\times J_0\hat{\omega} - J_0^{-1}\omega^\times J_0\omega + J_0^{-1}\tilde{u}_f + J_0^{-1}d - J_0^{-1}\bar{d}\,\mathrm{sgn}(\tilde{\omega}) \tag{9}$$

where $\tilde{u}_f = u_f - \hat{u}_f$.

Define the performance index

$$I_p = \lim_{t\to\infty}\frac{1}{t}\int_0^t \left(\|\tilde{\omega}\|^2 + \|\tilde{u}_f\|^2\right) \mathrm{d}t$$

The preceding analysis leads to the following theorem, which is useful in the FTC design.

Theorem 3.1. *For the faulty satellite attitude systems (1) and (6), an iterative learning observer is designed as (7) and (8), if the following inequalities are satisfied*

$$\tau_1 = \lambda_{\min}(\Gamma) - \alpha - \frac{1}{2} - \eta_2 \geq 0 \tag{10}$$

$$\tau_2 = 1 - \eta_1 > 0 \tag{11}$$

$$\tau_3 = \eta_3 \|\Delta_1\|^2 \geq 0 \tag{12}$$

where $\eta_1 = l_1^2(1+\varepsilon_1+\varepsilon_2)$, $\eta_2 = l_2^2\left(1+\varepsilon_3+\frac{1}{\varepsilon_1}\right)$ *for some positive constants* ε_i $(i=1,2,3)$. *Then the observer error system (9) is ultimately uniformly bounded, and the designed iterative learning observer (7) and (8) could achieve the satisfactory fault estimation.*

Proof: Consider a candidate Lyapunov function of the form

$$V_1(t) = \frac{1}{2}\tilde{\omega}^T J_0 \tilde{\omega} + \int_{t-T}^{t} \tilde{u}_f^T(t)\tilde{u}_f(t)\mathrm{d}t \tag{13}$$

Derivation along the Lyapunov function gives

$$\begin{aligned}\dot{V}_1(t) &= \frac{1}{2}\tilde{\omega}^T J_0 \dot{\tilde{\omega}} + \frac{1}{2}\dot{\tilde{\omega}}^T J_0 \tilde{\omega} + \tilde{u}_f^T\tilde{u}_f - \tilde{u}_f^T(t-T)\tilde{u}_f(t-T) \\ &= \tilde{\omega}^T\left[-\Gamma\tilde{\omega} + \hat{\omega}^\times J_0\hat{\omega} - \omega^\times J_0\omega + \tilde{u}_f + d - \bar{d}\mathrm{sgn}(\tilde{\omega})\right] \\ &\quad + \tilde{u}_f^T\tilde{u}_f - \tilde{u}_f^T(t-T)\tilde{u}_f(t-T)\end{aligned} \tag{14}$$

It is noted that

$$\tilde{u}_f = \hat{u}_f - u_f = l_1\tilde{u}_f(t-T) + l_2\tilde{\omega} + l_2u_f(t-T) - u_f = l_1\tilde{u}_f(t-T) + l_2\tilde{\omega} + \Delta_1 \tag{15}$$

where $\Delta_1 = l_1u_f(t-T) - u_f$, and then it follows that

$$\begin{aligned}\tilde{u}_f^T\tilde{u}_f &= l_1^2\tilde{u}_f^T(t-T)\tilde{u}_f(t-T) + l_2^2\tilde{\omega}^T\tilde{\omega} + \Delta_1^T\Delta_1 + 2l_1l_2\tilde{u}_f^T(t-T)\tilde{\omega} \\ &\quad + 2l_1\tilde{u}_f^T(t-T)\Delta_1 + 2l_2\tilde{\omega}^T\Delta_1\end{aligned} \tag{16}$$

According to the Young's inequality, it is not difficult to find that

$$2l_1l_2\tilde{u}_f^T(t-T)\tilde{\omega} \leq \varepsilon_1 l_1^2\tilde{u}_f^T(t-T)\tilde{u}_f(t-T) + \frac{l_2^2}{\varepsilon_1}\tilde{\omega}^T\tilde{\omega} \tag{17}$$

$$2l_1\tilde{u}_f^T(t-T)\Delta_1 \leq \varepsilon_2 l_1^2\tilde{u}_f^T(t-T)\tilde{u}_f(t-T) + \frac{1}{\varepsilon_2}\Delta_1^T\Delta_1 \tag{18}$$

$$2l_2\tilde{\omega}^T\Delta_1 \leq \varepsilon_3 l_2^2\tilde{\omega}^T\tilde{\omega} + \frac{1}{\varepsilon_3}\Delta_1^T\Delta_1 \tag{19}$$

where ε_1 and ε_2 are two positive constant scalars.

Substituting inequalities (17)-(19) into (16) gives

$$\begin{aligned}\tilde{u}_f^T\tilde{u}_f &\leq l_1^2(1+\varepsilon_1+\varepsilon_2)\tilde{u}_f^T(t-T)\tilde{u}_f(t-T) + l_2^2\left(1+\frac{1}{\varepsilon_1}\right)\tilde{\omega}^T\tilde{\omega} + \left(1+\frac{1}{\varepsilon_2}\right)\Delta_1^T\Delta_1 \\ &= \eta_1\tilde{u}_f^T(t-T)\tilde{u}_f(t-T) + \eta_2\tilde{\omega}^T\tilde{\omega} + \eta_3\Delta_1^T\Delta_1\end{aligned} \tag{20}$$

where $\eta_1 = l_1^2(1+\varepsilon_1+\varepsilon_2)$, $\eta_2 = l_2^2\left(1+\varepsilon_3+\frac{1}{\varepsilon_1}\right)$ and $\eta_3 = 1+\frac{1}{\varepsilon_2}+\frac{1}{\varepsilon_3}$.

From (14) and (20), it can be seen that

$$\begin{aligned}\dot{V}_1 &\leq \left(\alpha - \lambda_{\min}(\Gamma) + \frac{1}{2} + \eta_2\right)\|\tilde{\omega}\|^2 + (\eta_1 - 1)\tilde{u}_f^T(t-T)\tilde{u}_f(t-T) + \eta_3\Delta_1^T\Delta_1 \\ &= -\left(\lambda_{\min}(\Gamma) - \alpha - \frac{1}{2} - \eta_2\right)\|\tilde{\omega}\|^2 - (1-\eta_1)\|\tilde{u}_f(t-T)\|^2 + \eta_3\|\Delta_1\|^2 \\ &= -\tau_1\|\tilde{\omega}\|^2 - \tau_2\|\tilde{u}_f\|^2 + \tau_3\end{aligned} \tag{21}$$

In terms of the inequalities (10)-(12) and the Babalat lemma, it is easily known that the observer error system (9) is ultimately uniformly bounded. By selecting the appropriate Γ, the satisfactory fault estimation $\hat{u}_f$ could be obtained online. Thus, the proof is completed.

4. **Fault Tolerant Controller Design.** In this section, a fault tolerant controller is designed by using both the classical backstepping control scheme and integral sliding mode technique. Firstly, two new error variables are defined as follows,

$$z_1 = \sigma - \sigma_d, \qquad z_2 = \omega - \omega_d \tag{22}$$

where σ_d is the desired attitude angle command, and ω_d is the desired angular velocity command.

The first integral sliding mode surface is defined for the attitude angle loop

$$s_1 = z_1 + a_1 \int_0^t z_1 dt \tag{23}$$

where a_1 is a positive scalar.

Taking the derivation of (23) with respect to time yields

$$\dot{s}_1 = \dot{z}_1 + a_1 z_1 = \omega + F\sigma - \dot{\sigma}_d + a_1 z_1 = z_2 + \omega_d + F\sigma - \dot{\sigma}_d + a_1 z_1 \tag{24}$$

In this study, the exponentral reaching law is chosen as,

$$\dot{s}_1 = -k_1 s_1 - \mu_1 \text{sign}(s_1) \tag{25}$$

where $k_1 > 0$ and $\mu_1 > 0$ are two positive real scalars.

From (24) and (25), the following virtual control law ω_d is formulated as

$$\omega_d = -F\sigma + \dot{\sigma}_d - a_1 z_1 - k_1 s_1 - \mu_1 \text{sign}(s_1) \tag{26}$$

The second integral sliding mode surface is defined for the angular velocity loop

$$s_2 = z_2 + a_2 \int_0^t z_2 dt \tag{27}$$

where $z_2 = \omega - \omega_d$ is the tracking error, and $a_2 > 0$ is a free parameter chosen by the designer.

Taking the derivation of (27) with respect to time yields

$$\dot{s}_2 = \dot{z}_2 + a_2 z_2 = \dot{\omega} - \dot{\omega}_d + a_2 z_2 = -J_0^{-1}\omega^{\times} J_0 \omega + J_0^{-1}(u + u_f) + J_0^{-1} d - \dot{\omega}_d + a_2 z_2 \tag{28}$$

The exponential reaching law is selected for the above sliding surface.

$$\dot{s}_2 = -k_2 s_2 - \mu_2 \,\text{sign}(s_2) \tag{29}$$

where $k_2 > 0$ and $\mu_2 > 0$ are two positive real scalars.

Based on the above descriptions, the second result of this study is given in Theorem 4.1.

Theorem 4.1. *For the faulty satellite attitude systems (1) and (6), a fault tolerant control scheme is designed in (30) by using the estimated* $\hat{u}_f$

$$u = J_0 \left(J_0^{-1}\omega^{\times} J_0 \omega - J_0^{-1}\hat{u}_f - J_0^{-1} \frac{s_2 \bar{d}^2}{\|s_2\|\bar{d} + \xi e^{-\beta t}} - a_2 z_2 + \dot{\omega}_d - k_2 s_2 - \mu_2 \,\text{sign}(s_2) \right) \tag{30}$$

where ξ is a sufficiently small positive scalar and β is positive scalar. It guarantees that the faulty closed loop attitude systems (1) and (6) are ultimately uniformly bounded.

Proof: Consider the candidate Lyapunov function V_2 as follows

$$V_2 = \frac{1}{2} s_1^T s_1 + \frac{1}{2} s_2^T s_2 \tag{31}$$

With the aid of (24) and (28), the derivative of $\dot{V}_2$ can be derived as

$$\begin{aligned}\dot{V}_2 &= s_1^T\dot{s}_1 + s_2^T\dot{s}_2 \\ &= -k_1s_1^Ts_1 - k_2s_2^Ts_2 - \mu_1\|s_1\| - \mu_2\|s_2\| + s_1^Tz_2 \\ &\quad + s_2^T\left\{\tilde{u}_f + d - \frac{s_2\chi_a^2}{\|s_2\|\chi_a + \xi e^{-\beta t}}\right\}\end{aligned} \tag{32}$$

It is noted that

$$s_2^T\left\{d - \frac{s_2\chi_a^2}{\|s_2\|\chi_a + \xi e^{-\beta t}}\right\} \le \|s_2\|\|d\| - \frac{\|s_2\|^2\bar{d}^2}{\|s_2\|\bar{d} + \xi e^{-\beta t}} \le \xi e^{-\beta t} \tag{33}$$

Meanwhile, the following inequality can be obtained using the Young's inequality

$$s_1^Tz_2 \le \frac{1}{2}s_1^Ts_1 + \frac{1}{2}z_2^Tz_2 \le \frac{1}{2}s_1^Ts_1 + \frac{1}{2}s_2^Ts_2 \tag{34}$$

$$s_2^T\tilde{u}_f \le \frac{1}{2}s_2^Ts_2 + \frac{1}{2}\tilde{u}_f^T\tilde{u}_f \tag{35}$$

Substituting inequalities (33)-(35) into (32) gives

$$\dot{V}_2 = -\left(k_1 - \frac{1}{2}\right)s_1^Ts_1 - \left(k_2 - \frac{1}{2}\right)s_2^Ts_2 - \mu_1\|s_1\| - \mu_2\|s_2\| + \frac{1}{2}\tilde{u}_f^T\tilde{u}_f + \xi e^{-\beta t} \tag{36}$$

By selecting the appropriate k_1 and k_2, such that the following inequalities hold

$$\dot{V}_2 \le -\left(k_1 - \frac{1}{2}\right)s_1^Ts_1 - \left(k_2 - \frac{1}{2}\right)s_2^Ts_2 + \frac{1}{2}\|\tilde{u}_f\|^2 + \xi \le -\tau_1V_2 + \bar{\xi} \tag{37}$$

where $\tau_1 = \min\{2k_1 - 1, 2k_2 - 1\}$, and $\xi > 0$. Considering $\tilde{u}_f$ is the estimation error of the unexpected input torque, it should be a small positive scalar, and $\bar{\xi}$ is also a small positive scalar. From (37), it is seen that the attitude angles and angular velocities are ultimately uniformed bounded.

5. **Simulation Results.** In this section, numerical simulation is carried out to verify the effectiveness of the proposed control technique. The nominal inertial matrix J_0 of rigid satellite is given by

$$J_0 = \begin{bmatrix} 326 & 8.9 & 12.3 \\ 8.9 & 340 & 13.5 \\ 12.3 & 13.5 & 372 \end{bmatrix} \text{kg}\cdot\text{m}^2$$

The uncertain part of inertial matrix $\Delta J = \pm 0.15J_0$. The external perturbation T_d acting on the system is considered to be time varying, which incorporates all kinds of disturbances such as gravitational perturbations, and atmospheric drag,

$$T_d = 10^{-3}\begin{bmatrix} 3\sin(\pi t) + \cos(3\pi t) \\ 2\sin(3\pi t) + \cos(\pi t) \\ 3\cos(\pi t) + 2\sin(3\pi t) \end{bmatrix} + \begin{bmatrix} 0.001 \\ 0.001 \\ 0.001 \end{bmatrix} \text{N}\cdot\text{m}$$

The initial values of attitude angles are chosen as $\varphi(0) = 0.3$ deg, $\theta(0) = 0.2$ deg, $\psi(0) = -0.3$ deg, and the initial values of angular velocities are chosen as $\omega_1(0) = 0.2$ rad/s, $\omega_2(0) = 0$ rad/s, $\omega_3(0) = 0$ rad/s. The desired attitude angle command $\sigma_d = [\varphi_d, \theta_d, \psi_d]^T$ is given by $\varphi_d = 1$ deg, $\theta_d = 2$ deg, $\psi_d = 0$ deg. In the simulation, it is assumed that the first reaction flywheel shows a bias fault in the 30th second, the second reaction flywheel loses 20% control effectiveness in the 30th second, namely, $f_3(t) = 6\sin(t)$ and $\rho_2 = 0.8$ ($t > 30$ s). The gain parameters of iterative learning observer (7) and (8) are chosen as $\Gamma = \text{diag}\{5, 5, 5\}$, $l_1 = 1.2$, $l_2 = 1.3$. The gain parameters of the FTC controller (30) are selected as follows: $\varepsilon_1 = 0.5$, $\varepsilon_2 = 0.5$, $a_1 = 0.5$, $a_2 = 0.5$, $k_1 = 0.8$, $k_2 = 0.9$, $\mu_1 = 0.5$, $\mu_2 = 0.5$, $\beta = 0.8$, $\xi = 0.2$.

To show the effectiveness of the proposed FTC scheme for satellite attitude system with actuator faults, the necessary simulation comparison results are given in this position. When the above described unknown actuator fault occurs, the estimated unknown control input torque could be obtained by the updated algorithm (8), which is depicted in Figure 1, and the observer performance index is as shown in Figure 2. Figure 3 shows the attitude angle curves and the angular velocity curves using fault tolerant tracking control scheme developed in this study, and it is not difficult to find that the designed FTC approach could guarantee that the faulty closed loop attitude system has the satisfactory fault tolerant capability by using active adjustment scheme. Figure 4 shows the attitude angle curves and the angular velocity curves using fault tolerant tracking control scheme developed in [6], and it can be seen that the FTC scheme designed in [6] could

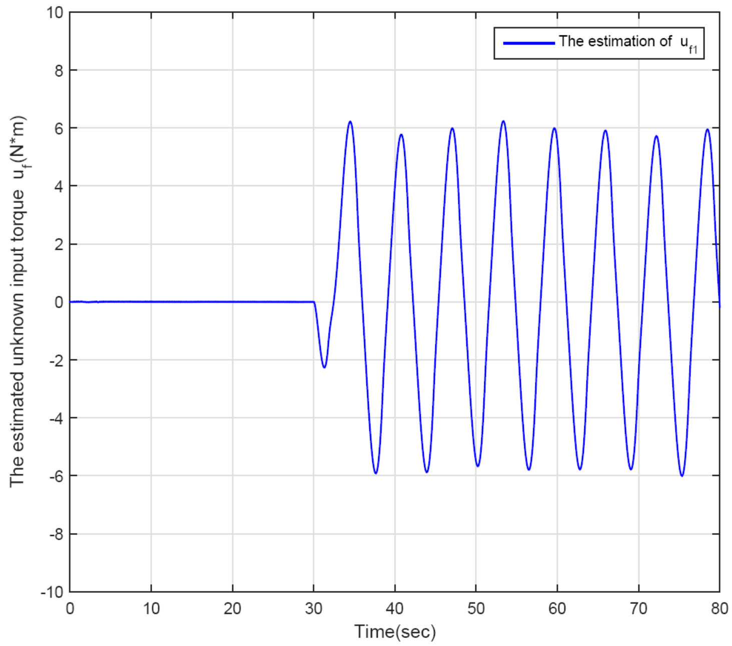

FIGURE 1. The estimated unknown input torque $\hat{u}_f$ using ILO

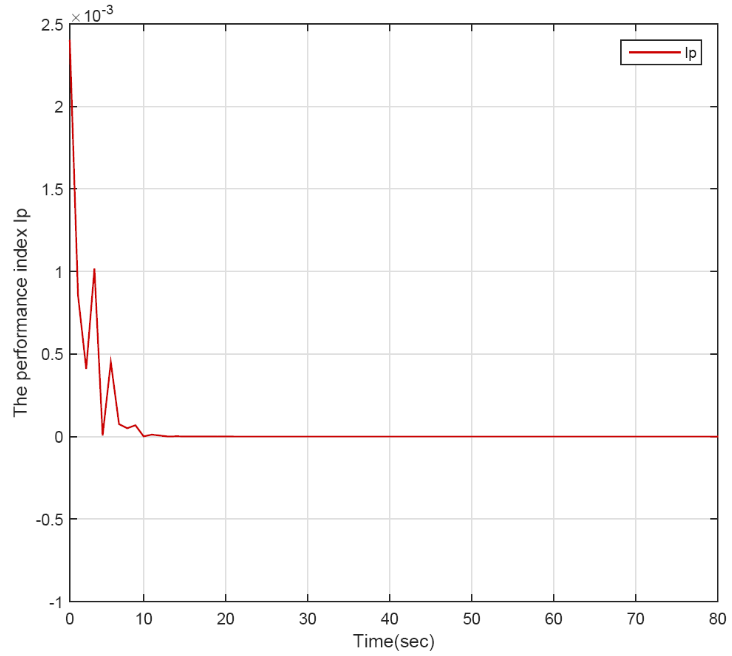

FIGURE 2. The performance index $I_p(t)$

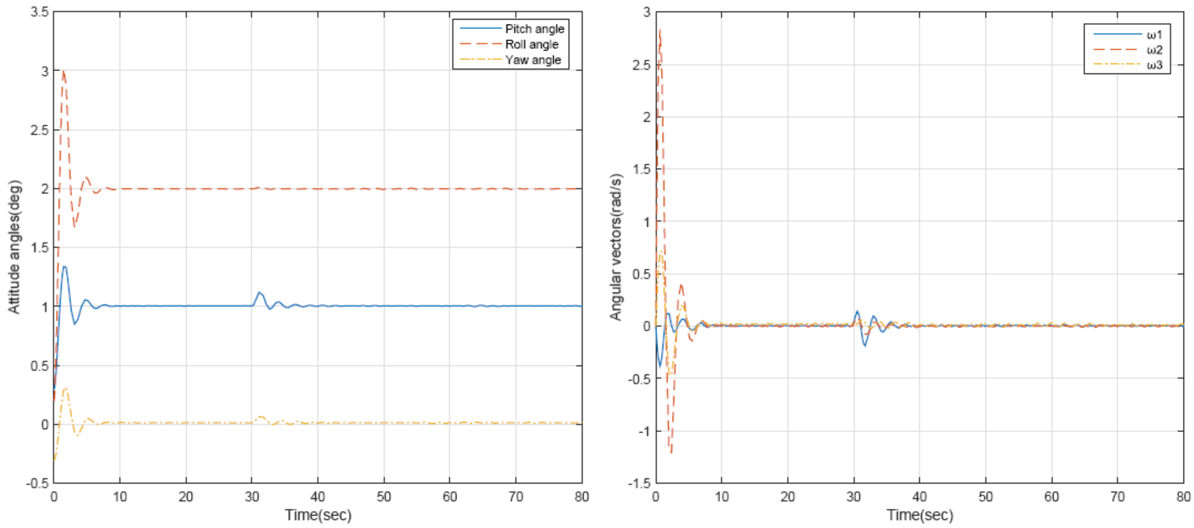

FIGURE 3. The attitude angle and angular velocity using FTC scheme developed in this study

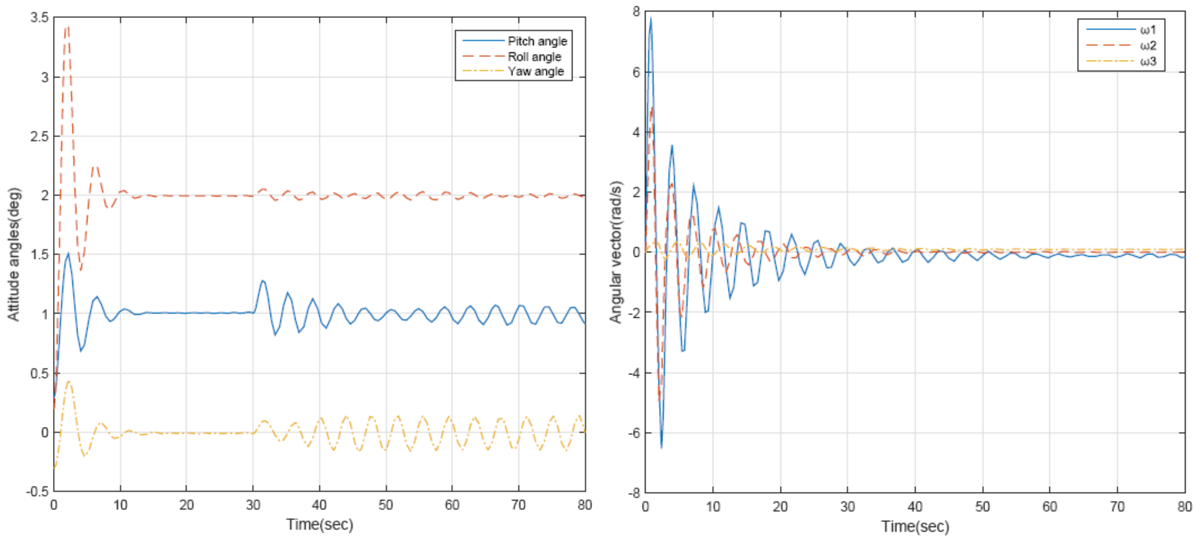

FIGURE 4. The attitude angle and angular velocity using FTC scheme developed in [6]

not fully compensate for the effects of unknown actuator fault to the closed loop attitude system. Summarizing the two simulated cases, it is noted that the proposed FTC scheme has better control performance and also has greater fault tolerance capability than the FTC scheme developed in [6].

6. **Conclusion.** In this paper, a fault tolerant tracking control strategy is proposed for a satellite attitude system with mixed actuator fault. By designing an iterative learning observer, a novel fault estimation algorithm is derived for the faulty attitude system in this study. On this basis, a backstepping-based FTC scheme is developed to guarantee the uniform ultimate boundedness of the closed loop attitude system in actuator faulty case. Finally, the effectiveness of the proposed approach is demonstrated in a satellite attitude system subject to the mixed actuator faults. In the future, the active FTC problem in mixed actuator case for satellite attitude system may be one of the issues that we need to address.

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