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Robust Exponential H_∞ Fault Tolerant Control for Sampled-Data Control Systems With Actuator Failure: A Switched System Method

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ABSTRACT In this paper, the robust exponential H_∞ fault tolerant control problem is investigated, which is concerned with uncertainties, disturbances and actuator failures. Determined by whether the actuator fails or not, the continuous-time system is remodeled as a switched system. Then a sampled-data controller is designed. Through Lyapunov functional theory and the admissible edge-dependent average dwell time method, some sufficient conditions are derived to ensure that the closed-loop system is robustly exponentially stable with exponential H_∞ performance. The corresponding controller gains can also be obtained via linear matrix inequalities (LMIs). Finally, two examples are presented to verify the validity of the relevant results.

INDEX TERMS Actuator failures, admissible edge-dependent average dwell time, exponential H_∞ fault tolerant control, sampled-data control systems, switched systems.

I. INTRODUCTION

In practice, the computer acts as a digital controller to implement the control function of continuous-time systems. However, the enormous amount of data makes the continuous-time controller no longer applicable. Under this circumstance, the sampled-data control (SDC) comes into being. SDC is a kind of time-triggered control method, and only updates the control information at some specified time instants. Due to its superiority such as easy implementation, high robustness and lower requirements for network bandwidth, SDC has been widely used in many fields [1]–[3]. The system under SDC is viewed as a sampled-data control system (SDCS), which is a hybrid system simultaneously including continuous-time and discrete-time signals. Many methods are proposed to handle the modeling and stability analysis of this hybrid system, in which one of the most popular methods is the input delay approach, see [3]–[5] and the references therein. In [3], the sampled-data control system is transmitted to a time-varying delay system, and sampled-data stabilization of systems with polytopic type uncertainties and regional stabilization by sampled-data saturated state-feedback are presented, respectively. In [5], a memory sampled-data control scheme that involves a constant signal transmission delay is employed to tackle the stabilization problem for T-S fuzzy systems.

With the development of modern control technology, the control systems have shown some remarkable properties: great dimensions and complex structures. Once the system goes wrong, the system performance will be destroyed, even leading to huge economic losses. Therefore, to increase the system reliability, fault tolerant control (FTC) technology has been widely concerned in recent years [6]–[9]. Due to the aging of key components of the actuator and unknown changes in the external environment, actuator failure is unavoidable in many real systems. Therefore, how to design a suitable controller to tolerate the failure of certain control elements and maintain the system performance is a meaningful study. In [6], the actuator fault model is presented and H_∞ FTC scheme is investigated for networked control systems. In [7], some sufficient conditions are given to guarantee the asymptotic mean-square stability of the systems associated

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with the stochastic actuator failures. The robust reliable H_∞ controller is constructed for systems with nonlinear actuator fault in [8].

In the past few decades, switched systems have received widespread attention because they are successfully applied in many fields, such as network control systems [10], stirred tank reactors [11], power electronics [12], etc.. Those studies have shown that the design of switching signal is critical to stability analysis and control synthesis [13]–[23]. Up to date, many time-constraint switching signal design methods, such as average dwell time (ADT) method [17]–[20], mode-dependent average dwell time method [21]–[23], admissible edge-dependent average dwell time (AED-ADT) method [24]–[26] and so on, are all used to design the switching signal. Studies have shown that AED-ADT method is more practical and effective than MDADT switching and ADT switching, because it is related to the former mode and the latter one at the switching instant [24], [25].

Recently, the switched system method has been used to cope with FTC problem with actuator failures [27]–[31], which dominant idea is to treat the system as a switched system depending on the degree of actuators failure. In [27]–[29], the problem of FTC is investigated for many kinds of systems via the switched system method, where the switching signal is designed by using ADT method. It is worth pointed out that in the above references, the continuous-time controller is designed. Due to the high bandwidth requirements of continuous-time controllers, it is worthwhile to study the problem of sampled-data control with actuator failures for saving communication resource. Furthermore, the uncertainties and disturbances are inevitable during modeling, hence the robustness and H_∞ performance of the system also need to get some attention.

On the basis of the above analysis, this study presents the robust exponential H_∞ FTC problem for sampled-data control systems (SDCSs) with uncertainties, disturbances and actuator failures. Firstly, by whether the actuators fail or not, the system is modeled as a switched system. Then the design of the sampled-data controller is given, and the original system is transformed into a switched system with time-varying delay. The robust exponential stability with H_∞ performance of the SDCS is analyzed, and the corresponding controller gains is provided via solving some LMIs. Finally, two examples are presented to verify the validity of the relevant results.

II. PROBLEM FORMULATION

Consider a continuous-time linear system as follows

$$\dot{x}(t) = \bar{A}x(t) + \bar{B}_2u(t) + \bar{B}_1\omega(t), \tag{1a}$$
$$z(t) = \bar{C}x(t) + \bar{D}_2u(t) + \bar{D}_1\omega(t), \tag{1b}$$

where $x(t) \in \mathbb{R}^n$ is the state, $u(t) \in \mathbb{R}^p$ is the control input, $z(t) \in \mathbb{R}^q$ is the control output, $\omega(t) \in L_2[0,\infty)$ is the disturbance. Let $\bar{A} = A + \Delta A$, $\bar{B}_2 = B_2 + \Delta B_2$, $\bar{B}_1 = B_1 + \Delta B_1$, $\bar{C} = C + \Delta C$, $\bar{D}_2 = D_2 + \Delta D_2$, $\bar{D}_1 = D_1 + \Delta D_1$, where A, B_2, B_1, C, D_2 and D_1 are the constant matrices with appropriate dimensions. ΔA, ΔB_2, ΔB_1, ΔC, ΔD_1 and ΔD_2 are uncertainties satisfying

$$\begin{bmatrix} \Delta A & \Delta B_2 & \Delta B_1 \\ \Delta C & \Delta D_2 & \Delta D_1 \end{bmatrix} = \begin{bmatrix} M_1 \\ M_2 \end{bmatrix} F(t) \begin{bmatrix} N_1 & N_2 & N_3 \end{bmatrix} \tag{2}$$

with $F^T(t)F(t) \leq I$, in which M_1, M_2, N_1, N_2, N_3 are the constant matrices with appropriate dimensions.

If the actuator failures occur, the controller information cannot be transmitted normally, which will damage the system performance. Therefore, how to guarantee the performance of the control system in this situation becomes very significant. This paper designs a group of controllers based on whether the corresponding actuator fails or not. Once the actuator failure is detected, the corresponding controller is applied. Under this circumstance, the system is modeled as a switched system. Suppose that at any time instant t_k, at least one actuator is not out of work, and other actuators will be repaired when the failures are detected. Assuming the total number of actuators is m, there will be $2^m - 1$ modeling possibilities under the calculation method of the combination. System (1) with actuator failure can be modeled as

$$\dot{x}(t) = \bar{A}x(t) + \bar{B}_{2\sigma(t)}u(t) + \bar{B}_1\omega(t), \tag{3a}$$
$$z(t) = \bar{C}x(t) + \bar{D}_{2\sigma(t)}u(t) + \bar{D}_1\omega(t), \tag{3b}$$

where $\sigma(t)$ represents the switching signal and its value is taken from a set $\Lambda = \{1, 2, \ldots, 2^m - 1\}$. $\bar{B}_{2\sigma(t)} = B_{2\sigma(t)} + \Delta B_{2\sigma(t)}$, $\bar{D}_{2\sigma(t)} = D_{2\sigma(t)} + \Delta D_{2\sigma(t)}$, and if $\sigma(t) = j$, it indicates the j-th subsystem is activated and works. Corresponding to (2), the uncertainties ΔB_{2j} and ΔD_{2j} satisfy

$$\begin{bmatrix} \Delta B_{2j} \\ \Delta D_{2j} \end{bmatrix} = \begin{bmatrix} M_1 \\ M_2 \end{bmatrix} F(t)N_{2j}, \quad j \in \Lambda, \tag{4}$$

where N_{2j} are the constant matrices with appropriate dimensions.

Remark 1: Note that the matrices B_j and D_j are mode-dependent under the actuator failures. Correspondingly, the uncertainties ΔB_{2j} and ΔD_{2j} are also associated to the switching mode. Here, for simplicity, we only suppose the matrix N_j is related to the switching mode, and the matrices M_1 and M_2 are independent on the one.

Design the sampled-data controller as

$$u(t) = K_{\sigma(t)}x(t_k), \quad t \in [t_k, t_{k+1}), \tag{5}$$

where t_k is the k-th sampling instant, $k = 0, 1, 2, \cdots$. Denoting $h_k = t_{k+1} - t_k$ and $\tau(t) = t - t_k$, system (3) is rewritten as

$$\dot{x}(t) = \bar{A}x(t) + \bar{B}_{2\sigma(t)}K_{\sigma(t)}x(t - \tau(t)) + \bar{B}_1\omega(t), \tag{6a}$$
$$z(t) = \bar{C}x(t) + \bar{D}_{2\sigma(t)}K_{\sigma(t)}x(t - \tau(t)) + \bar{D}_1\omega(t), \tag{6b}$$
$$x(t) = \phi(t), \quad t \in [-h, 0), \tag{6c}$$

where $\phi(t)$ implies a bounded continuous function, and $\tau(t)$ represents the sampling time-varying delay with

$$0 \leq \tau(t) \leq h_k \leq h, \quad h \triangleq \max\{h_k\}. \tag{7}$$

Let the switching instant as t_{p_q}, $q = 0, 1, 2, \cdots$, and $t_{p_0} = t_0$. In this paper, suppose the switch occurs at a certain sampling instant, that is, $t_{p_q} \in \{t_k, k = 0, 1, 2, \cdots\}$.

Remark 2: It is necessary to point out that the j-th closed-loop subsystem is stable under the controller (5), which is corresponding to the case that, at any time instant t_k, at least one actuator is not out of work.

When switched delay system (6) is robustly exponentially stable with H_∞ performance, then we can say system (1) can be robustly exponentially stabilized by the sampled-data controller (5) with the actuator failures. In this paper, the problem of robust exponential H_∞ FTC for system (1) is described as follows.

Robust exponential H_∞ FTC problem: For system (1), design a sampled-data controller (5) with switching signal $\sigma(t)$, which satisfies the following conditions:

1) for $\omega(t) \equiv 0$, the system equilibrium point of (6a) is robustly exponentially stable;

2) for all nonzero $\omega(t) \in L_2[0, \infty)$, the following inequality holds in zero initial condition

$$\beta \int_{t_0}^{\infty} e^{-\iota(s-t_0)} z^T(s)z(s)ds \le \gamma^2 \int_{t_0}^{\infty} \omega^T(s)\omega(s)ds, \quad (8)$$

where $\beta > 0$, $\gamma > 0$, and $\iota > 0$ are constant scalars.

In order to express formulation clearly, there are some definitions and lemmas for reviewing.

Definition 1 ([32]): For the scalars $a > 0$, $c > 0$, and any initial condition $\phi(t_0)$, if the state $x(t)$ satisfies $\|x(t)\| \le ce^{-a(t-t_0)}\|\phi(t_0)\|$, $\forall t > t_0$, then the robust exponential stability of switched delay system (6a) can be guaranteed under the designed switching law.

Definition 2 ([24]): For the switching signal $\sigma(t)$ and $\forall(i,j) \in \Lambda \times \Lambda, i \ne j$, let $N^\sigma_{i,j}(t_0, t)$ and $T_{i,j}(t_0, t)$ denote the total switching numbers from subsystem i to j and the running duration of subsystem j over the time interval $[t_0, t)$, respectively. $\sigma(t)$ is said to have an admissible edge-dependent average dwell time (AED-ADT) $\tau^a_{i,j}$ if the positive numbers $\tau^a_{i,j}$ and $N^0_{i,j}$ satisfy

$$N^\sigma_{i,j}(t_0, t) \le N^0_{i,j} + \frac{T_{i,j}(t_0, t)}{\tau^a_{i,j}}, \quad \forall t > t_0, \quad (9)$$

where $N^0_{i,j}$ are called as the admissible edge-dependent chatter bounds.

Lemma 1 ([33]): For the positive definite matrix $M > 0$, the following inequality holds

$$\begin{aligned}\int_{\iota_1}^{\iota_2} & \dot{x}^T(s)M\dot{x}(s)ds \\ &\ge \frac{3}{\iota_2 - \iota_1}\Omega^T M \Omega \\ &\quad + \frac{1}{\iota_2 - \iota_1}(x(\iota_2) - x(\iota_1))^T M (x(\iota_2) - x(\iota_1)), \end{aligned} \quad (10)$$

where $x(t)$ is a differentiable vector-valued function defined on $[\iota_1, \iota_2]$, $\Omega = x(\iota_2) + x(\iota_1) - \frac{2}{\iota_2-\iota_1}\int_{\iota_1}^{\iota_2} x(s)ds$.

III. MAIN RESULTS

A. ROBUST EXPONENTIAL STABILITY

Suppose $\sigma(t_{p_q}) = j$ when $t \in [t_{p_q}, t_{p_{q+1}})$, $q = 0, 1, 2, \cdots$. For j-th subsystem of system (6a) with $\omega(t) = 0$, construct the Lyapunov-Krosovskii functional as

$$V_j(t) = x^T(t)P_jx(t) + \int_{-h}^{0}\int_{t+\theta}^{t} \dot{x}^T(s)e^{\alpha_j(s-t)}Q_j\dot{x}(s)dsd\theta, \quad (11)$$

where scalars $h > 0$, $\alpha_j > 0$, matrices $P_j > 0$, $Q_j > 0$, $j \in \Lambda$. Then we can obtain the following proposition.

Proposition 1: For given scalars $\alpha_j > 0$, $h > 0$ and $\varepsilon > 0$, the inequality

$$V_j(t) \le e^{-\alpha_j(t-t_{p_q})}V_j(t_{p_q}) \quad (12)$$

holds if there exist matrices $P_j > 0$, $Q_j > 0$ and K_j such that the following inequality is true

$$\begin{bmatrix} \Phi_j & \varepsilon\mathcal{M}_j & \mathcal{N}_j \\ * & -\varepsilon I & 0 \\ * & * & -\varepsilon I \end{bmatrix} < 0, \quad (13)$$

where

$$\Phi_j = \begin{bmatrix} \Phi_j(1,1) & \Phi_j(1,2) & \Phi_j(1,3) & hA^TQ_j \\ * & \Phi_j(2,2) & \Phi_j(2,3) & h(B_jK_j)^TQ_j \\ * & * & \Phi_j(3,3) & 0 \\ * & * & * & -hQ_j \end{bmatrix},$$

$$\mathcal{M}_j = \begin{bmatrix} P_jM_1 \\ 0 \\ 0 \\ hQ_jM_1 \end{bmatrix}, \quad \mathcal{N}_j = \begin{bmatrix} N_1^T \\ K_j^TN_{2j}^T \\ 0 \\ 0 \end{bmatrix},$$

with

$$\begin{aligned} \Phi_j(1,1) &= A^TP_j + \alpha_jP_j + P_jA - \frac{4}{h}e^{-\alpha_jh}Q_j, \\ \Phi_j(1,2) &= P_jB_jK_j - \frac{2}{h}e^{-\alpha_jh}Q_j, \\ \Phi_j(1,3) &= \Phi_j(2,3) = \frac{6}{h}e^{-\alpha_jh}Q_j, \\ \Phi_j(2,2) &= -\frac{4}{h}e^{-\alpha_jh}Q_j, \\ \Phi_j(3,3) &= -\frac{12}{h}e^{-\alpha_jh}Q_j. \end{aligned}$$

Proof: By taking the derivative of (11) when $t \in [t_{p_q}, t_{p_{q+1}})$, $q = 0, 1, 2, \cdots$ with $\sigma(t_{p_q}) = j$, it yields

$$\begin{aligned} \dot{V}_j(t) &= 2x^T(t)P_j\dot{x}(t) + h\dot{x}^T(t)Q_j\dot{x}(t) \\ &\quad - \int_{t-h}^{t} \dot{x}^T(s)e^{\alpha_j(s-t)}Q_j\dot{x}(s)ds \\ &\quad - \alpha_j\int_{-h}^{0}\int_{t+\theta}^{t} \dot{x}^T(s)e^{\alpha_j(s-t)}Q_j\dot{x}(s)dsd\theta \\ &\le 2x^T(t)P_j\dot{x}(t) + h\dot{x}^T(t)Q_j\dot{x}(t) \\ &\quad - \int_{t-\tau(t)}^{t} \dot{x}^T(s)e^{-\alpha_jh}Q_j\dot{x}(s)ds \\ &\quad + \alpha_jx^T(t)P_jx(t) - \alpha_jV_j(t). \end{aligned} \quad (14)$$

In terms of Lemma 1, there yields

$$-\int_{t-\tau(t)}^{t} e^{-\alpha_j h}\dot{x}^T(s)Q_j\dot{x}(s)ds \leq \frac{e^{-\alpha_j h}}{h}\eta^T(t)\begin{bmatrix} -4Q_j & -2Q_j & 6Q_j \\ * & -4Q_j & 6Q_j \\ * & * & -12Q_j \end{bmatrix}\eta(t), \quad (15)$$

where

$$\eta(t) = \text{col}\Big\{x(t),\ x(t-\tau(t)),\ \frac{1}{\tau(t)}\int_{t-\tau(t)}^{t} x(s)ds\Big\}.$$

Substituting (6a) ($\omega(t)=0$) and (15) into (14) leads to

$$\begin{aligned}\dot{V}_j(t) &\leq 2x^T(t)P_j\Big(\bar{A}x(t)+\bar{B}_{2j}K_jx(t-\tau(t))\Big) \\ &\quad + h\Big(\bar{A}x(t)+\bar{B}_{2j}K_jx(t-\tau(t))\Big)^T Q_j \\ &\quad \times \Big(\bar{A}x(t)+\bar{B}_{2j}K_jx(t-\tau(t))\Big) \\ &\quad + \frac{e^{-\alpha_j h}}{h}\eta^T(t)\begin{bmatrix} -4Q_j & -2Q_j & 6Q_j \\ * & -4Q_j & 6Q_j \\ * & * & -12Q_j \end{bmatrix}\eta(t) \\ &\quad + \alpha_j x^T(t)P_jx(t) - \alpha_j V_j(t) \\ &= \eta^T(t)\begin{bmatrix} \Phi_j(1,1) & \Phi_j(1,2) & \Phi_j(1,3) \\ * & \Phi_j(2,2) & \Phi_j(2,3) \\ * & * & \Phi_j(3,3) \end{bmatrix}\eta(t) \\ &\quad + \eta^T(t)\begin{bmatrix} \Delta\mathcal{A} & P_j\Delta B_{2j}K_j & 0 \\ * & 0 & 0 \\ * & * & 0 \end{bmatrix}\eta(t) \\ &\quad + h\eta^T(t)\begin{bmatrix} \bar{A}^T \\ (\bar{B}_{2j}K_j)^T \\ 0 \end{bmatrix} Q_j \begin{bmatrix} \bar{A} & \bar{B}_{2j}K_j & 0 \end{bmatrix}\eta(t) \\ &\quad -\alpha_j V_j(t), \end{aligned} \quad (16)$$

where $\Delta\mathcal{A} = P_j\Delta A + \Delta A^T P_j$. On the basis of (13) and Schur complete lemma, we have

$$\Phi_j + \varepsilon\mathcal{M}_j\mathcal{M}_j^T + \varepsilon^{-1}\mathcal{N}_j\mathcal{N}_j^T < 0, \quad (17)$$

which combining with Lemma 4 in [34] implies that

$$\Phi_j + \Delta\Phi_j < 0, \quad (18)$$

where

$$\Delta\Phi_j = \begin{bmatrix} \Delta\mathcal{A} & P_j\Delta B_{2j}K_j & 0 & h\Delta A^T Q_j \\ * & 0 & 0 & h(\Delta B_{2j}K_j)^T Q_j \\ * & * & 0 & 0 \\ * & * & * & 0 \end{bmatrix}.$$

From Schur complete lemma, one gets

$$\begin{bmatrix} \Phi_j(1,1) & \Phi_j(1,2) & \Phi_j(1,3) \\ * & \Phi_j(2,2) & \Phi_j(2,3) \\ * & * & \Phi_j(3,3) \end{bmatrix} + h\begin{bmatrix} \bar{A}^T \\ (\bar{B}_{2j}K_j)^T \\ 0 \end{bmatrix} Q_j \begin{bmatrix} \bar{A} & \bar{B}_{2j}K_j & 0 \end{bmatrix} + \begin{bmatrix} \Delta\mathcal{A} & P_j\Delta B_{2j}K_j & 0 \\ * & 0 & 0 \\ * & * & 0 \end{bmatrix} < 0. \quad (19)$$

Hence we obtain

$$\dot{V}_j(t) \leq -\alpha_j V_j(t). \quad (20)$$

Integrating (20) from t_{p_q} to t leads to (12). The proof is completed.

From Proposition 1, the robust exponential stability is presented for system (6a) with $\omega(t)=0$.

Theorem 1: For given scalars $\alpha_i > 0$, $\mu_{ij} > 1$, $h > 0$, $\varepsilon > 0$, switched system (6a) with $\omega(t)=0$ is robustly exponentially stable under the designed switching signal satifying

$$\tau_{ij}^a \geq \tau_{ij}^* = \frac{\ln \mu_{ij}}{\alpha_j}, \quad (21)$$

if the existence of the matrices $P_j > 0$, $Q_j > 0$ and K_j, which makes (13) and the following inequalities hold

$$P_j \leq \mu_{ij}P_i, \quad Q_j \leq \mu_{ij}Q_i, \quad (22)$$

where $i, j \in \Lambda$ and $i \neq j$.

Proof: Suppose that $t \in [t_{p_q}, t_{p_{q+1}})$, $\forall (i,j) \in \Lambda \times \Lambda$, and $\sigma(t_{p_q}) = j$, $\sigma(t_{p_{q-1}}) = i$,

$$V_{\sigma(t)}(t) \leq e^{-\alpha_{\sigma(t)}(t-t_{p_q})}V_{\sigma(t_{p_q})}(t_{p_q}). \quad (23)$$

By iterating (23) from t_0 to t, for any time interval $t \in [t_{p_q}, t_{p_{q+1}})$, then the above inequality leads to

$$\begin{aligned} V_{\sigma(t)}(t) &\leq e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}V_{\sigma(t_{p_q})}(t_{p_q}) \\ &\leq \mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}V_{\sigma(t_{p_{q-1}})}(t_{p_q}) \\ &\leq \mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})} \\ &\quad \times e^{-\alpha_{\sigma(t_{p_{q-1}})}(t_{p_q}-t_{p_{q-1}})}V_{\sigma(t_{p_{q-1}})}(t_{p_{q-1}}) \\ &\leq \vdots \\ &\leq e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}e^{-\alpha_{\sigma(t_0)}(t_1-t_0)}\mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})} \\ &\quad \times \prod_{l=0}^{l=q-2} e^{-\alpha_{\sigma(t_{l+1})}(t_{l+2}-t_{l+1})}\mu_{\sigma(t_{p_l}),\sigma(t_{p_{l+1}})} \\ &\quad \times V_{\sigma(t_{p_0})}(t_{p_0}). \end{aligned} \quad (24)$$

By Definition 2, we have

$$\begin{aligned} V_{\sigma(t)}(t) &\leq e^{\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}N_{i,j}^{\sigma}(t_{p_0},t)\ln\mu_{i,j}-\alpha_j T_{i,j}(t_{p_0},t)} \\ &\quad \times V_{\sigma(t_{p_0})}(t_{p_0}) \\ &\leq e^{\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}(N_{i,j}^0+\frac{T_{i,j}(t_{p_0},t)}{\tau_{i,j}^a})\ln\mu_{i,j}} \\ &\quad \times e^{\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}-\alpha_j T_{i,j}(t_{p_0},t)} \\ &\quad \times V_{\sigma(t_{p_0})}(t_{p_0}) \\ &\leq e^{\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}(\frac{\ln\mu_{i,j}}{\tau_{i,j}^a}-\alpha_j)T_{i,j}(t_{p_0},t)} \\ &\quad \times e^{\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}N_{i,j}^0\ln\mu_{i,j}}V_{\sigma(t_{p_0})}(t_{p_0}). \end{aligned} \quad (25)$$

From (11), we have

$$\beta_1\|x(t)\|^2 \leq V_{\sigma(t)}(t) \leq \beta_2\|\phi(t)\|^2, \tag{26}$$

where $\beta_1 = \min_{j\in\Lambda}\{\lambda_{\min}(P_j)\}$, $\beta_2 = \max_{j\in\Lambda}\{\lambda_{\max}(P_j) + \frac{h}{\alpha_j}\lambda_{\max}(Q_j)\}$.

Consequently, from (25) and (26), one has

$$\|x(t)\|^2 \leq \frac{\beta_2}{\beta_1}e^{\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}(\frac{\ln\mu_{i,j}}{\tau^a_{i,j}}-\alpha_j)T_{i,j}(t_0,t)} \times e^{\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}N^0_{i,j}\ln\mu_{i,j}}\|\phi(t_0)\|^2. \tag{27}$$

Set $c = \max_{i,j\in\Lambda,i\neq j}\sqrt{\frac{\beta_2}{\beta_1}e^{\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}N^0_{i,j}\ln\mu_{i,j}}}$, $a = \max_{i,j\in\Lambda,i\neq j}\frac{1}{2}\left\{\alpha_j - \frac{\ln\mu_{i,j}}{\tau^a_{i,j}}\right\}$, then (27) implies

$$\|x(t)\| \leq ce^{-a(t-t_0)}\|x(t_0)\|. \tag{28}$$

From Definition 1, we have system (6a) with $\omega(t) = 0$ is robustly exponentially stable. The proof is completed.

Remark 3: In this paper, the slow switching signal is applied based on the AED-ADT approach, because we suppose that all of the closed-loop subsystems are stable on the basis of at least one actuator does not fail. Once the failures of all the actuators are considered, then the unstable subsystems will occur. In this case, a switching law with both fast and slow switching will be adopted, which is our future study.

B. ROBUST EXPONENTIAL H_∞ PERFORMANCE

This subsection studies the robust exponential H_∞ performance for system (6).

Theorem 2: Given scalars $\alpha_j > 0$, $\mu_{ij} > 1$, $h > 0$, $\gamma > 0$, $\varepsilon > 0$, system (6) is robustly exponentially stable with H_∞ performance γ under the designed switching signal satisfying (21), if there exist matrices $P_j > 0$, $Q_j > 0$ and K_j such that (22) and

$$\begin{bmatrix} \Xi_{11} & \Xi_{12} \\ * & \Xi_{22} \end{bmatrix} < 0 \tag{29}$$

hold, where

$$\Xi_{12} = \begin{bmatrix} \Phi_j(1,1) & \Phi_j(1,2) & \Phi_j(1,3) & P_jB_1 \\ * & \Phi_j(2,2) & \Phi_j(2,3) & 0 \\ * & * & \Phi_j(3,3) & 0 \\ * & * & * & -\gamma^2 I \end{bmatrix},$$

$$\Xi_{11} = \begin{bmatrix} hA^TQ_j & C^T & \varepsilon P_jM_1 & N_1^T \\ h(B_{2j}K_j)^TQ_j & K_j^TD_{2j}^T & 0 & K_j^TN_{2j}^T \\ 0 & 0 & 0 & 0 \\ 0 & D_1^T & 0 & N_3^T \end{bmatrix},$$

$$\Xi_{22} = \begin{bmatrix} -hQ_j & 0 & \varepsilon hQ_jM_1 & 0 \\ * & -I & \varepsilon M_2 & 0 \\ * & * & -\varepsilon I & 0 \\ * & * & * & -\varepsilon I \end{bmatrix}.$$

Proof: From Theorem 1, we can see system (6a) is robustly exponentially stable when $\omega(t) = 0$. In the sequel, the exponential H_∞ performance is analyzed.

When $\omega(t) \neq 0$, taking the derivative of (11) along the trajectory of system (6a), it yields

$$\begin{aligned}
&\dot{V}_j(t) - \gamma^2\omega^T(t)\omega(t) + z^T(t)z(t) \\
&\leq 2x^T(t)P_j\Big(\bar{A}x(t) + \bar{B}_{2j}K_jx(t-\tau(t))) + \bar{B}_1\omega(t)\Big) \\
&\quad +h\Big(\bar{A}x(t) + \bar{B}_{2j}K_jx(t-\tau(t)) + \bar{B}_1\omega(t)\Big)^TQ_j \\
&\quad \times\Big(\bar{A}x(t) + \bar{B}_{2j}K_jx(t-\tau(t)) + \bar{B}_1\omega(t)\Big) \\
&\quad +\frac{e^{-\alpha_jh}}{h}\eta^T(t)\begin{bmatrix} -4Q_j & -2Q_j & 6Q_j \\ * & -4Q_j & 6Q_j \\ * & * & -12Q_j \end{bmatrix}\eta(t) \\
&\quad +\Big(\bar{C}x(t) + \bar{D}_{2j}K_jx(t-\tau(t)) + \bar{D}_1\omega(t)\Big)^T \\
&\quad \times\Big(\bar{C}x(t) + \bar{D}_{2j}K_jx(t-\tau(t)) + \bar{D}_1\omega(t)\Big) \\
&= \xi^T(t)\begin{bmatrix} \Phi_j(1,1) & \Phi_j(1,2) & \Phi_j(1,3) & P_jB_1 \\ * & \Phi_j(2,2) & \Phi_j(2,3) & 0 \\ * & * & \Phi_j(3,3) & 0 \\ * & * & * & -\gamma^2 I \end{bmatrix}\xi(t) \\
&\quad +\xi^T(t)\begin{bmatrix} \Delta\mathcal{A} & P_j\Delta B_{2j}K_j & 0 & P_j\Delta B_1 \\ * & 0 & 0 & 0 \\ * & * & 0 & 0 \\ * & * & * & 0 \end{bmatrix}\xi(t) \\
&\quad +h\xi^T(t)\begin{bmatrix} \bar{A}^T \\ (\bar{B}_{2j}K_j)^T \\ 0 \\ \bar{B}_1^T \end{bmatrix}Q_j\begin{bmatrix} \bar{A}^T \\ (\bar{B}_{2j}K_j)^T \\ 0 \\ \bar{B}_1^T \end{bmatrix}^T\xi(t) \\
&\quad +\Big(\bar{C}x(t) + \bar{D}_{2j}K_jx(t-\tau(t)) + \bar{D}_1\omega(t)\Big)^T \\
&\quad \times\Big(\bar{C}x(t) + \bar{D}_{2j}K_jx(t-\tau(t)) + \bar{D}_1\omega(t)\Big) \\
&\quad +\alpha_jx^T(t)P_jx(t) - \alpha_jV_j(t) - \gamma^2\omega^T(t)\omega(t),
\end{aligned} \tag{30}$$

where $\xi(t) = \mathrm{col}\{\eta(t),\ \omega(t)\}$. From the proof of Proposition 1, (29) and Schur complete lemma, one obtains

$$\dot{V}_j(t) \leq -\alpha_jV_j(t) + \gamma^2\omega^T(t)\omega(t) - z^T(t)z(t). \tag{31}$$

Then for any $t \in [t_{p_q},\ t_{p_{q+1}})$, integrating (31), it holds

$$V_{\sigma(t)}(t) \leq e^{-\alpha_{\sigma(t_{pq})}(t-t_{pq})}V_{\sigma(t_{pq})}(t_{pq}) + \int_{t_{pq}}^{t} e^{-\alpha_{\sigma(t_{pq})}(t-s)}\Gamma(s)ds, \tag{32}$$

where $\Gamma(t) = -z^T(t)z(t) + \gamma^2\omega^T(t)\omega(t)$. (22) and (32) imply that

$$\begin{aligned}
V_{\sigma(t)}(t) &\leq e^{-\alpha_{\sigma(t_{pq})}(t-t_{pq})}V_{\sigma(t_{pq})}(t_{pq}) \\
&\quad + \int_{t_{pq}}^{t} e^{-\alpha_{\sigma(t_{pq})}(t-s)}\Gamma(s)ds \\
&\leq \mu_{\sigma(t_{p_{q-1}}),\sigma(t_{pq})}e^{-\alpha_{\sigma(t_{pq})}(t-t_{pq})}V_{\sigma(t_{p_{q-1}})}(t_{pq}) \\
&\quad + \int_{t_{pq}}^{t} e^{-\alpha_{\sigma(t_{pq})}(t-s)}\Gamma(s)ds \\
&\leq \mu_{\sigma(t_{p_{q-1}}),\sigma(t_{pq})}e^{-\alpha_{\sigma(t_{pq})}(t-t_{pq})}
\end{aligned}$$

$$
\begin{aligned}
&\times\Big(e^{-\alpha_{\sigma(t_{p_{q-1}})}(t_{p_q}-t_{p_{q-1}})}V_{\sigma(t_{p_{q-1}})}(t_{p_{q-1}})\\
&+\int_{t_{p_{q-1}}}^{t_{p_q}} e^{-\alpha_{\sigma(t_{p_{q-1}})}(t-s)}\Gamma(s)ds\Big)\\
&+\int_{t_{p_q}}^{t} e^{-\alpha_{\sigma(t_{p_q})}(t-s)}\Gamma(s)ds\\
=\ &\mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}\\
&\times e^{-\alpha_{\sigma(t_{p_{q-1}})}(t_{p_q}-t_{p_{q-1}})}V_{\sigma(t_{p_{q-1}})}(t_{p_{q-1}})\\
&+\mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}\\
&\times\int_{t_{p_{q-1}}}^{t_{p_q}} e^{-\alpha_{\sigma(t_{p_{q-1}})}(t-s)}\Gamma(s)ds\\
&+\int_{t_{p_q}}^{t} e^{-\alpha_{\sigma(t_{p_q})}(t-s)}\Gamma(s)ds\\
\le\ &\mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}\\
&\times e^{-\alpha_{\sigma(t_{p_{q-1}})}(t_{p_q}-t_{p_{q-1}})}\mu_{\sigma(t_{p_{q-2}}),\sigma(t_{p_{q-1}})}\\
&\times V_{\sigma(t_{p_{q-2}})}(t_{p_{q-1}})+\mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}\\
&\times\int_{t_{p_{q-1}}}^{t_{p_q}} e^{-\alpha_{\sigma(t_{p_{q-1}})}(t-s)}\Gamma(s)ds\\
&+\int_{t_{p_q}}^{t} e^{-\alpha_{\sigma(t_{p_q})}(t-s)}\Gamma(s)ds\\
\le\ &\cdots\\
\le\ &e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}e^{-\alpha_{\sigma(t_{p_{q-1}})}(t_{p_q}-t_{p_{q-1}})}\cdots\\
&\times e^{-\alpha_{\sigma(t_0)}(t_{p_1}-t_0)}\mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}\\
&\times\mu_{\sigma(t_{p_{q-2}}),\sigma(t_{p_{q-1}})}\cdots\mu_{\sigma(t_0),\sigma(t_{p_1})}V_{\sigma(t_0)}(t_0)\\
&+e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}e^{-\alpha_{\sigma(t_{p_{q-1}})}(t_{p_q}-t_{p_{q-1}})}\cdots\\
&\times e^{-\alpha_{\sigma(t_{p_1})}(t_2-t_{p_1})}\mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}\\
&\times\mu_{\sigma(t_{p_{q-2}}),\sigma(t_{p_{q-1}})}\cdots\mu_{\sigma(t_0),\sigma(t_{p_1})}\\
&\quad\times\int_{t_0}^{t_{p_1}} e^{-\alpha_{\sigma(t_0)}(t_{p_1}-s)}\Gamma(s)ds\\
&+e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}e^{-\alpha_{\sigma(t_{p_{q-1}})}(t_{p_q}-t_{p_{q-1}})}\cdots\\
&\times e^{-\alpha_{\sigma(t_2)}(t_3-t_2)}\mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}\\
&\times\mu_{\sigma(t_{p_{q-2}}),\sigma(t_{p_{q-1}})}\cdots\mu_{\sigma(t_{p_1}),\sigma(t_2)}\\
&\times\int_{t_{p_1}}^{t_2} e^{-\alpha_{\sigma(t_{p_1})}(t_2-s)}\Gamma(s)ds\\
&+\cdots\\
&+e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}e^{-\alpha_{\sigma(t_{p_{q-1}})}(t_{p_q}-t_{p_{q-1}})}\\
&\times\mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}\mu_{\sigma(t_{p_{q-2}}),\sigma(t_{p_{q-1}})}\\
&\times\int_{t_{p_{q-2}}}^{t_{p_{q-1}}} e^{-\alpha_{\sigma(t_{p_{q-2}})}(t_{p_{q-1}}-s)}\Gamma(s)ds\\
&+e^{-\alpha_{\sigma(t_{p_q})}(t-t_{p_q})}\mu_{\sigma(t_{p_{q-1}}),\sigma(t_{p_q})}\\
&\times\int_{t_{p_{q-1}}}^{t_{p_q}} e^{-\alpha_{\sigma(t_{p_{q-1}})}(t_{p_q}-s)}\Gamma(s)ds\\
&+\int_{t_{p_q}}^{t} e^{-\alpha_{\sigma(t_{p_q})}(t-s)}\Gamma(s)ds\\
\le\ &\exp\Big(\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}N_{i,j}^{0}\ln\mu_{i,j}\Big)\\
&\times\exp\Big(\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}(\frac{\ln\mu_{i,j}}{\tau_{i,j}^{a}}-\alpha_j)T_{i,j}(t_0,t)\Big)\\
&\times V_{\sigma(t_0)}(t_0)+\int_{t_0}^{t}\exp\Big(\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}(-\alpha_j\\
&\times T_{i,j}(s,t)+N_{i,j}^{\sigma}(s,t)\ln\mu_{i,j})\Big)\Gamma(s)ds, \qquad (33)
\end{aligned}
$$

where $t_{p_0}=t_0$. Hence we have

$$
\begin{aligned}
&\int_{t_0}^{t}\exp\Big(\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}(-\alpha_jT_{i,j}(s,t)+N_{i,j}^{\sigma}(s,t)\\
&\quad\times\ln\mu_{i,j})\Big)z^T(s)z(s)ds\\
&\quad\le\gamma^2\int_{t_0}^{t}\exp\Big(\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}(-\alpha_jT_{i,j}(s,t)\\
&\quad+N_{i,j}^{\sigma}(s,t)\ln\mu_{i,j})\Big)\omega^T(s)\omega(s)ds. \qquad (34)
\end{aligned}
$$

Multiplying both sides of (34) by

$$
\exp\Big(\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}(-N_{i,j}^{\sigma}(t_0,t)\ln\mu_{i,j})\Big)
$$

leads to

$$
\begin{aligned}
&\int_{t_0}^{t}\exp\Big(\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}(-\alpha_jT_{i,j}(s,t)-N_{i,j}^{\sigma}(t_0,s)\\
&\quad\times\ln\mu_{i,j})\Big)z^T(s)z(s)ds\\
&\le\gamma^2\int_{t_0}^{t}\exp\Big(\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}(-\alpha_jT_{i,j}(s,t)-N_{i,j}^{\sigma}(t_0,s)\\
&\quad\times\ln\mu_{i,j})\Big)\omega^T(s)\omega(s)ds, \qquad (35)
\end{aligned}
$$

which combining the truth $N_{i,j}(t_0,s)\ln\mu_{i,j}\le N_{i,j}^{0}\ln\mu_{i,j}+\alpha_jT_{i,j}(t_0,s)$ further implies

$$
\int_{t_0}^{t}\kappa e^{-\underline{\alpha}(t-t_0)}z^T(s)z(s)ds\le\gamma^2\int_{t_0}^{t}e^{-\overline{\alpha}(t-s)}\omega^T(s)\omega(s)ds, \qquad (36)
$$

where $\kappa=\exp\Big(\sum_{j\in\Lambda}\sum_{i\in\Lambda,i\neq j}-N_{i,j}^{0}\ln\mu_{i,j}\Big)$, $-\underline{\alpha}=\min_{j\in\Lambda}\{-\alpha_j\}$, and $-\overline{\alpha}=\max_{j\in\Lambda}\{-\alpha_j\}$.

Note that

$$
\begin{aligned}
&\int_{t_0}^{\infty}\int_{t_0}^{t}\kappa e^{-\underline{\alpha}(t-t_0)}z^T(s)z(s)dsdt\\
&\quad=\int_{t_0}^{\infty}\int_{s}^{\infty}\kappa e^{-\underline{\alpha}(t-t_0)}z^T(s)z(s)dtds\\
&\quad=\frac{\kappa}{\underline{\alpha}}\int_{t_0}^{\infty}e^{-\underline{\alpha}(s-t_0)}z^T(s)z(s)ds, \qquad (37)
\end{aligned}
$$

$$\begin{aligned}&\int_{t_0}^{\infty}\int_{t_0}^{t} e^{-\overline{\alpha}(t-s)}\omega^T(s)\omega(s)dsdt\\&=\int_{t_0}^{\infty}\int_{s}^{\infty} e^{-\overline{\alpha}(t-s)}\omega^T(s)\omega(s)dtds\\&=\frac{1}{\overline{\alpha}}\int_{t_0}^{\infty}\omega^T(s)\omega(s)ds.\end{aligned}\tag{38}$$

From (36) to (38), we can obtain (8) is satisfied with $\beta=\frac{\kappa\overline{\alpha}}{\underline{\alpha}}$. The proof is completed.

Remark 4: When $\omega(t)\neq 0$, the relationship among $V_{\sigma(t)}(t)$, $V_{\sigma(t_{pq})}(t_{pq})$ and $\Gamma(t)=-z^T(t)z(t)+\gamma^2\omega^T(t)\omega(t)$ is given in (32). To obtain H_∞ performance, the iterative procedure is shown in (33), which is more complex under AED-ADT switching method. By scaling down the inequalities (36)-(38), (8) is obtained, which means H_∞ performance is guaranteed.

C. ROBUST EXPONENTIAL H_∞ FTC CONTROL

The existences of $P_jB_jK_j$ and $h(B_{2j}K_j)^TQ_j$ make (29) a nonlinear matrix inequality, which cannot be solved directly. The following theorem is presented to obtain the controller gains K_j.

Theorem 3: Given scalars $\alpha_j>0$, $\mu_{ij}>1$, $h>0$, $\gamma>0$, $\varepsilon>0$, the robust exponential H_∞ FTC control problem of system (1) is solved if there exist matrices $X_j>0$, $Y_j>0$, $\overline{K}_j$ such that the following inequalities hold

$$\begin{bmatrix}\Upsilon_{11} & \Upsilon_{12}\\ * & \Upsilon_{22}\end{bmatrix}<0,\tag{39}$$

$$\begin{bmatrix}-\mu_{ij}X_i & X_i\\ * & -X_j\end{bmatrix}<0,\tag{40}$$

$$\begin{bmatrix}-\mu_{ij}Y_i & Y_i\\ * & -Y_j\end{bmatrix}<0,\tag{41}$$

where

$$\Upsilon_{11}=\begin{bmatrix}\overline{\Psi}_j(1,1) & \Psi_j(1,2) & \Psi_j(1,3) & B_1\\ * & \Psi_j(2,2) & \Psi_j(2,3) & 0\\ * & * & \Psi_j(3,3) & 0\\ * & * & * & -\gamma^2 I\end{bmatrix},$$

$$\Upsilon_{12}=\begin{bmatrix}hX_jA^T & X_jC^T & \varepsilon M_1 & X_jN_1^T\\ h\overline{K}_j^TB_{2j}^T & \overline{K}_j^TD_{2j}^T & 0 & \overline{K}_j^TN_{2j}^T\\ 0 & 0 & 0 & 0\\ 0 & D_1^T & 0 & N_3^T\end{bmatrix},$$

$$\Upsilon_{22}=\begin{bmatrix}-hY_j & 0 & \varepsilon hM_1 & 0\\ * & -I & \varepsilon M_2 & 0\\ * & * & -\varepsilon I & 0\\ * & * & * & -\varepsilon I\end{bmatrix},$$

$$\overline{\Psi}_j(1,1)=X_jA^T+\alpha_jX_j+AX_j+\frac{4}{h}e^{-\alpha_jh}Y_j-\frac{8}{h}e^{-\alpha_jh}X_j,$$

$$\Psi_j(1,2)=B_{2j}\overline{K}_j-\frac{2}{h}e^{-\alpha_jh}X_j,$$

$$\Psi_j(1,3)=\frac{6}{h}e^{-\alpha_jh}X_j,\quad \Phi_j(2,3)=\frac{6}{h}e^{-\alpha_jh}Y_j,$$

$$\Psi_j(2,2)=-\frac{4}{h}e^{-\alpha_jh}Y_j,\quad \Psi_j(3,3)=-\frac{12}{h}e^{-\alpha_jh}Y_j.$$

Moreover, the controller gains are $K_j=\overline{K}_jY_j^{-1}$.

Proof: Let $X_j=P_j^{-1}$, $Y_j=Q_j^{-1}$ and $\overline{K}_j=K_jY_j$. Multiplying diag$\{X_j,Y_j,Y_j,I,Y_j,I,I,I\}$ on the left and right sides of the inequality (29) gives rise to

$$\begin{bmatrix}\Delta_{11} & \Upsilon_{12}\\ * & \Upsilon_{22}\end{bmatrix}<0,\tag{42}$$

where

$$\Delta_{11}=\begin{bmatrix}\Psi_j(1,1) & \Psi_j(1,2) & \Psi_j(1,3) & B_1\\ * & \Psi_j(2,2) & \Psi_j(2,3) & 0\\ * & * & \Psi_j(3,3) & 0\\ * & * & * & -\gamma^2 I\end{bmatrix},$$

and $\Psi_j(1,1)=X_jA^T+\alpha_jX_j+AX_j-\frac{4}{h}e^{-\alpha_jh}X_jQ_jX_j$. By Lemma 3 in [34], we have

$$-X_jQ_jX_j\le Y_j-2X_j.\tag{43}$$

(42) and (43) lead to (39). (40) and (41) are consistent with the following inequalities based on the Schur complement lemma,

$$-\mu_{i,j}X_i+X_iX_j^{-1}X_i\le 0,\tag{44}$$

$$-\mu_{i,j}Y_i+Y_iY_j^{-1}Y_i\le 0.\tag{45}$$

For (44), by pre-multiplying and post-multiplying X_i^{-1}, it yields $-\mu_{i,j}P_i+P_j\le 0$. Following the similar process, the inequality $-\mu_{i,j}Q_i+Q_j\le 0$ can be obtained by pre-multiplying and post-multiplying Y_i^{-1} on inequality (45). The proof is completed.

Remark 5: Notice that the parameter γ presents the disturbance rejection capacity. The smaller γ implies the better disturbance rejection performance is achieved. However, the upper bound of the sampling period is not too much, because the large sampling period will make the sampling information inaccurate. The relationship between these two parameter will be presented in the simulation.

IV. NUMERICAL EXAMPLES

In this section, two examples are presented to verify the effectiveness of the main results proposed in this paper.

Example 1: Consider system (1) with parameters as

$$A=\begin{bmatrix}0.2 & 0.1\\ 0.1 & -0.1\end{bmatrix},\quad B_2=\begin{bmatrix}0.3 & 0.2\\ 0.1 & 0.1\end{bmatrix},$$

$$B_1=\begin{bmatrix}-0.2 & 0.3\\ 0.2 & 0.1\end{bmatrix},\quad C=\begin{bmatrix}0.1 & 0.3\\ 0.1 & 0.1\end{bmatrix},$$

$$D_2=\begin{bmatrix}0.1 & 0.1\\ 0.1 & -0.2\end{bmatrix},\quad D_1=\begin{bmatrix}0.2 & -0.3\\ 0.1 & 0.1\end{bmatrix},$$

$$M_1=M_2=\begin{bmatrix}0.1 & 0.3\\ 0.1 & 0.1\end{bmatrix},\quad N_1=\begin{bmatrix}0.4 & 0.3\\ 0.1 & 0.1\end{bmatrix},$$

$$N_2=\begin{bmatrix}0.1 & -0.1\\ 0.1 & 0.1\end{bmatrix},\quad N_3=\begin{bmatrix}0.1 & 0.2\\ 0.1 & 0.15\end{bmatrix}.$$

Note that $m = 2$. Depending on whether the actuator fails or not, switched system model (6) contains three $(2^m - 1)$ subsystems, where

$$B_{21} = \begin{bmatrix} 0 & 0.2 \\ 0 & 0.1 \end{bmatrix}, \quad B_{22} = \begin{bmatrix} 0.3 & 0 \\ 0.1 & 0 \end{bmatrix},$$
$$D_{21} = \begin{bmatrix} 0 & 0.1 \\ 0 & -0.2 \end{bmatrix}, \quad D_{22} = \begin{bmatrix} 0.1 & 0 \\ 0.1 & 0 \end{bmatrix},$$
$$N_{21} = \begin{bmatrix} 0 & -0.1 \\ 0 & 0.1 \end{bmatrix}, \quad N_{22} = \begin{bmatrix} 0.1 & 0 \\ 0.1 & 0 \end{bmatrix},$$
$$B_{23} = B_2, \quad D_{23} = D_2, \quad N_{23} = N_2.$$

Let $h = 0.1$, $\varepsilon = 0.1$, $\gamma = 0.5$, and

$$\alpha_1 = 1.2, \quad \alpha_2 = 0.7, \quad \alpha_3 = 1.5, \quad \mu_{12} = 1.2, \quad \mu_{13} = 2, \quad \mu_{21} = 1.5, \quad \mu_{23} = 2.5, \quad \mu_{31} = 1.8, \quad \mu_{32} = 2.2. \tag{46}$$

From Theorem 3, we can obtain the bounds of the AED-ADTs are $\tau_{12}^* = 0.2605$, $\tau_{13}^* = 0.4621$, $\tau_{21}^* = 0.3379$, $\tau_{23}^* = 0.6109$, $\tau_{31}^* = 0.4898$, $\tau_{32}^* = 0.9902$, and the controller gains are

$$K_1 = \begin{bmatrix} 0 & 0 \\ -3.1138 & -3.0733 \end{bmatrix},$$
$$K_2 = \begin{bmatrix} -6.5421 & -4.5029 \\ 0 & 0 \end{bmatrix},$$
$$K_3 = \begin{bmatrix} -5.4412 & -2.2299 \\ -3.2499 & -1.5212 \end{bmatrix}.$$

The parameters α_j and μ_{ij}, $i, j \in \Lambda$ are set in (46). The relationship between parameters h and γ is demonstrated in Table 1 when $\varepsilon = 2$, from which we can see that the larger h can obtain the smaller γ.

TABLE 1. The relations between the value of h and γ_{min} when $\varepsilon = 2$.

h	0.1	0.2	0.3	0.4	0.5
$\gamma_{\min}$	1.24	0.88	50.72	0.63	0.58

Furthermore, the values of parameters γ and ε are also interactional, which relationship is listed in Table 2. As shown in Table 2, it can be found that the larger γ leads to the smaller ε.

TABLE 2. The relations between the value of γ and ε_{min} when $h = 0.1$.

γ	1.5	1.6	1.7	1.8	1.9	2
$\varepsilon_{\min}$	0.54	0.44	0.38	0.33	0.29	0.26

Choose the switching sequence as $1 \rightarrow 3 \rightarrow 2 \rightarrow 1 \rightarrow 3 \rightarrow \cdots$, and the initial state is defined as $[-0.1, 0.2]^T$. The corresponding dwell-time is chosen as $\tau_{1,3} = 0.5$, $\tau_{3,2} = 1$, $\tau_{2,1} = 0.4$. Figure 1 presents the trajectory of state $x(t)$ converges to zero, which shows the effectiveness of the designed controller and switching signal. The trajectory of the corresponding control input $u(t)$ is demonstrated in Figure 2. Furthermore, choose the disturbance as

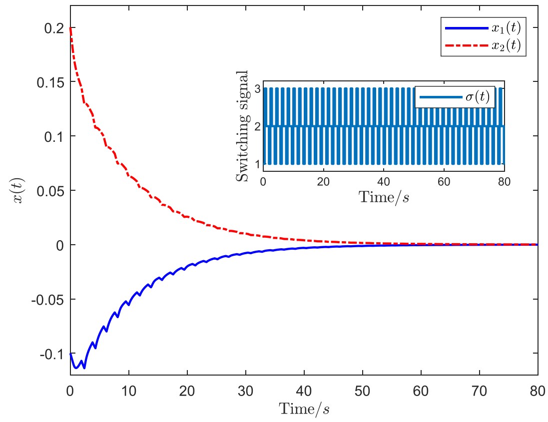

FIGURE 1. The state $x(t)$.

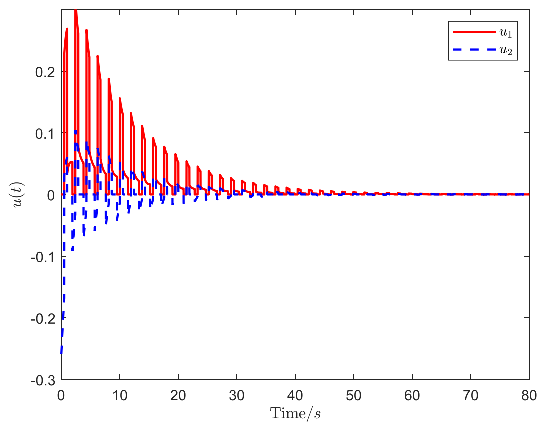

FIGURE 2. The control input $u(t)$.

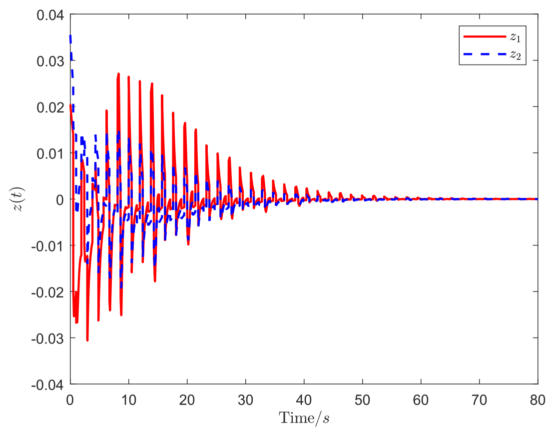

FIGURE 3. The control output $z(t)$.

$\omega(t) = [0.1 \exp(-0.2t) \;\; 0.1 \exp(-0.2t)]^T$. Then under the zero initial condition, the trajectory of the output $z(t)$ is depicted in Figure 3, from which we can see that the designed controller can suppress the disturbance well.

Example 2: Consider the model of rocket fairing structural-acoustics with disturbances borrowed the parameters from [35] as

$$A=\begin{bmatrix}0 & 1 & 0.0802 & 1.0415\\ -0.1980 & -1.15 & -0.0318 & 0.3\\ -3.0500 & 1.1880 & -1.4650 & 0.9\\ 0 & 0.0805 & 1 & 0\end{bmatrix},$$

$$B_2=\begin{bmatrix}1 & 1.55 & 0.75\\ 0.975 & 0.8 & 0.85\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix},\quad B_1=\begin{bmatrix}-2.35 & -0.175\\ -0.9875 & 0.6\\ 0 & 0\\ 0 & 0\end{bmatrix},$$

and the corresponding parameters including uncertainties and the output are as

$$C=\begin{bmatrix}1\\0\\0\\0\end{bmatrix}^T,\quad D_2=\begin{bmatrix}0.1\\0.1\\0.1\end{bmatrix}^T,\ D_1=\begin{bmatrix}0.1\\0.1\end{bmatrix}^T,$$

$$M_1=N_1=\begin{bmatrix}0.1 & 0.1 & 0.1 & 0.1\\ 0.1 & 0.1 & 0.1 & 0.1\\ 0.1 & 0.1 & 0.1 & 0.1\\ 0.1 & 0.1 & 0.1 & 0.1\end{bmatrix},\quad M_2=\begin{bmatrix}0.1\\0.1\\0.1\\0.1\end{bmatrix}^T,$$

$$N_2=\begin{bmatrix}0.1 & 0.1 & 0.1\\ 0.1 & 0.1 & 0.1\\ 0.1 & 0.1 & 0.1\\ 0.1 & 0.1 & 0.1\end{bmatrix},\quad N_3=\begin{bmatrix}0.1 & 0.1\\ 0.1 & 0.1\\ 0.1 & 0.1\\ 0.1 & 0.1\end{bmatrix}.$$

Note that $m=3$. Depending on whether the actuator fails or not, switched system model (6) contains seven (2^m-1) subsystems, where

$$B_{21}=\begin{bmatrix}0 & 1.55 & 0.75\\ 0 & 0.8 & 0.85\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix},\quad B_{22}=\begin{bmatrix}1 & 0 & 0.75\\ 0.975 & 0 & 0.85\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix},$$

$$B_{23}=\begin{bmatrix}1 & 1.55 & 0\\ 0.975 & 0.8 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix},\quad B_{24}=\begin{bmatrix}0 & 0 & 0.75\\ 0 & 0 & 0.85\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix},$$

$$B_{25}=\begin{bmatrix}0 & 1.55 & 0\\ 0 & 0.8 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix},\quad B_{26}=\begin{bmatrix}1 & 0 & 0\\ 0.975 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix},$$

$$D_{21}=\begin{bmatrix}0\\0.1\\0.1\end{bmatrix}^T,\quad D_{22}=\begin{bmatrix}0.1\\0\\0.1\end{bmatrix}^T,$$

$$D_{23}=\begin{bmatrix}0.1\\0.1\\0\end{bmatrix}^T,\quad D_{24}=\begin{bmatrix}0\\0\\0.1\end{bmatrix}^T,$$

$$D_{25}=\begin{bmatrix}0\\0.1\\0\end{bmatrix}^T,\quad D_{26}=\begin{bmatrix}0.1\\0\\0\end{bmatrix}^T,$$

$$N_{21}=\begin{bmatrix}0 & 0.1 & 0.1\\ 0 & 0.1 & 0.1\\ 0 & 0.1 & 0.1\\ 0 & 0.1 & 0.1\end{bmatrix},\quad N_{22}=\begin{bmatrix}0.1 & 0 & 0.1\\ 0.1 & 0 & 0.1\\ 0.1 & 0 & 0.1\\ 0.1 & 0 & 0.1\end{bmatrix},$$

$$N_{23}=\begin{bmatrix}0.1 & 0.1 & 0\\ 0.1 & 0.1 & 0\\ 0.1 & 0.1 & 0\\ 0.1 & 0.1 & 0\end{bmatrix},\quad N_{24}=\begin{bmatrix}0 & 0 & 0.1\\ 0 & 0 & 0.1\\ 0 & 0 & 0.1\\ 0 & 0 & 0.1\end{bmatrix},$$

$$N_{25}=\begin{bmatrix}0 & 0.1 & 0\\ 0 & 0.1 & 0\\ 0 & 0.1 & 0\\ 0 & 0.1 & 0\end{bmatrix},\quad N_{26}=\begin{bmatrix}0.1 & 0 & 0\\ 0.1 & 0 & 0\\ 0.1 & 0 & 0\\ 0.1 & 0 & 0\end{bmatrix},$$

$$B_{27}=B_2,\quad D_{27}=D_2,\quad N_{27}=N_2.$$

Let $h=0.1$, $\varepsilon=2$, $\gamma=0.8$, and these are values

$$\begin{aligned}&\alpha_1=1.2,\ \alpha_2=0.7,\ \alpha_3=1.5,\ \alpha_4=2.2,\ \alpha_5=0.9,\\ &\alpha_6=1.4,\ \alpha_7=1.8,\ \mu_{21}=1.3,\ \mu_{31}=1.2,\ \mu_{41}=2.2,\\ &\mu_{51}=1.5,\ \mu_{61}=1.2,\ \mu_{71}=1.8,\ \mu_{12}=2.2,\ \mu_{32}=2.5,\\ &\mu_{42}=1.8,\ \mu_{52}=2.6,\ \mu_{62}=1.2,\ \mu_{72}=1.5,\ \mu_{13}=1.3,\\ &\mu_{23}=1.6,\ \mu_{43}=1.2,\ \mu_{53}=1.2,\ \mu_{63}=1.2,\ \mu_{73}=1.2,\\ &\mu_{14}=1.5,\ \mu_{24}=1.8,\ \mu_{34}=2.2,\ \mu_{54}=3.2,\ \mu_{64}=2.5,\\ &\mu_{74}=3.2,\ \mu_{15}=1.5,\ \mu_{25}=2.1,\ \mu_{35}=2.0,\ \mu_{45}=1.8,\\ &\mu_{65}=1.2,\ \mu_{75}=2.0,\ \mu_{16}=1.4,\ \mu_{26}=1.6,\ \mu_{36}=1.7,\\ &\mu_{46}=1.8,\ \mu_{56}=2.0,\ \mu_{76}=1.2,\ \mu_{17}=2.1,\ \mu_{27}=2.3,\\ &\mu_{37}=1.8,\ \mu_{47}=2.5,\ \mu_{57}=3.2,\ \mu_{67}=2.8.\end{aligned}$$

From Theorem 3, the bounds of the AED-ADTs are as

$$\begin{aligned}&\tau^*_{21}=0.2186,\ \tau^*_{31}=0.1519,\ \tau^*_{41}=0.6570,\ \tau^*_{51}=0.3379,\\ &\tau^*_{61}=0.1519,\ \tau^*_{71}=0.4898,\ \tau^*_{12}=1.1264,\ \tau^*_{32}=1.3090,\\ &\tau^*_{42}=0.8397,\ \tau^*_{52}=1.3650,\ \tau^*_{62}=0.2605,\ \tau^*_{72}=0.5792,\\ &\tau^*_{13}=0.1749,\ \tau^*_{23}=0.3133,\ \tau^*_{43}=0.1215,\ \tau^*_{53}=0.1215,\\ &\tau^*_{63}=0.1215,\ \tau^*_{73}=0.1215,\ \tau^*_{14}=0.1843,\ \tau^*_{24}=0.2672,\\ &\tau^*_{34}=0.3584,\ \tau^*_{54}=0.5287,\ \tau^*_{64}=0.4165,\ \tau^*_{74}=0.5287,\\ &\tau^*_{15}=0.4505,\ \tau^*_{25}=0.8244,\ \tau^*_{35}=0.7702,\ \tau^*_{45}=0.6531,\\ &\tau^*_{65}=0.2026,\ \tau^*_{75}=0.7702,\ \tau^*_{16}=0.2403,\ \tau^*_{26}=0.3357,\\ &\tau^*_{36}=0.3790,\ \tau^*_{46}=0.4198,\ \tau^*_{56}=0.4951,\ \tau^*_{76}=0.1302,\\ &\tau^*_{17}=0.4122,\ \tau^*_{27}=0.4627,\ \tau^*_{37}=0.3265,\ \tau^*_{47}=0.5091,\\ &\tau^*_{57}=0.6462,\ \tau^*_{67}=0.5720,\end{aligned}$$

and the controller gains are

$$K_1=\begin{bmatrix}0 & 0 & 0 & 0\\ -3.4825 & 1.3523 & 0.1492 & -0.0879\\ 3.3217 & -2.6470 & -0.2950 & -0.1005\end{bmatrix},$$

$$K_2=\begin{bmatrix}-10.7412 & -1.1504 & 0.9035 & 0.0384\\ 0 & 0 & 0 & 0\\ 10.9651 & 0.3423 & -1.1382 & -0.2534\end{bmatrix},$$

$$K_3=\begin{bmatrix}3.8165 & -4.1435 & -0.2723 & -0.0544\\ -4.2765 & 2.8677 & 0.1716 & -0.1159\\ 0 & 0 & 0 & 0\end{bmatrix},$$

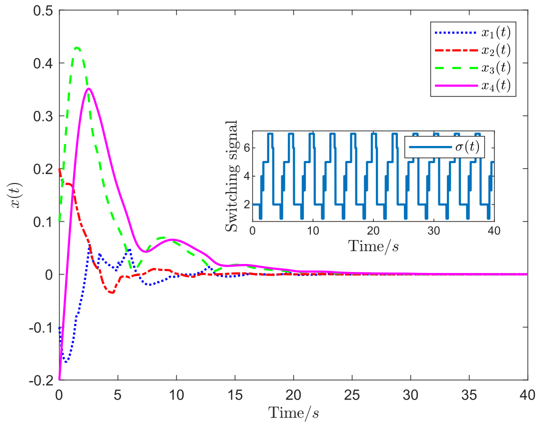

FIGURE 4. The state $x(t)$.

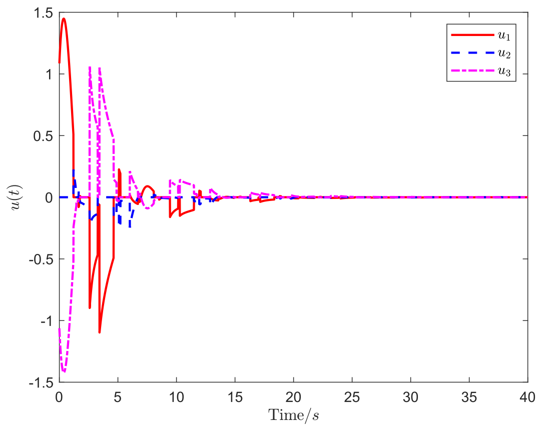

FIGURE 5. The control input $u(t)$.

$$K_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -0.8086 & -0.5301 & -0.0621 & -0.2435 \end{bmatrix},$$

$$K_5 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -0.6334 & -0.1717 & -0.0355 & -0.1701 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$K_6 = \begin{bmatrix} -0.4827 & -0.1365 & -0.0352 & -0.2061 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$K_7 = \begin{bmatrix} 2.0092 & -1.8095 & 2.3386 & 1.2040 \\ -1.8314 & 0.8916 & -0.4541 & -0.4334 \\ -0.4861 & 0.5920 & -2.2332 & -1.0993 \end{bmatrix}.$$

Choose the switching sequence as $2 \to 1 \to 4 \to 3 \to 5 \to 7 \to 6 \to 2 \to \cdots$, and the initial state as $[-0.1 \;\; 0.2 \;\; 0.1 \;\; -0.2]^T$. Let $\tau_{2,1} = 0.25$, $\tau_{1,4} = 0.2$, $\tau_{4,3} = 0.13$, $\tau_{3,5} = 0.8$, $\tau_{5,7} = 0.7$, $\tau_{7,6} = 0.15$, $\tau_{6,2} = 1.2$. Figure 4 presents the trajectory of state $x(t)$ converges to zero, which shows the designed controller and switching signal are effective. The trajectory of the corresponding control input $u(t)$ is demonstrated in Figure 5. Furthermore, choose the disturbance as $\omega(t) = [0.1\exp(-0.2t) \;\; 0.1\exp(-0.2t)]^T$. Then under the zero initial condition, the trajectory of the output $z(t)$ is depicted in Figure 6, from which we can see that the designed controller can suppress the disturbance well.

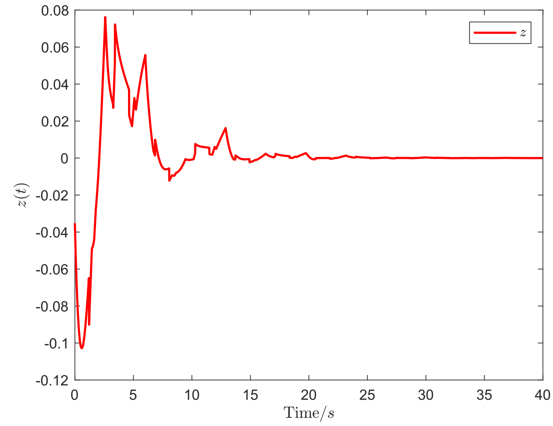

FIGURE 6. The control output $z(t)$.

V. CONCLUSION

In this paper, the robust exponential H_∞ fault tolerant control problem has been studied for the systems with uncertainties, disturbances and actuator failures. The considered system has been modeled as a switched system based on whether the actuator fails or not. The sampled-data controller has been designed, and the original system has been transformed to a switched system with time-varying delay. The AED-ADT method has been applied to design the switching signal to guarantee the robust exponential stability with H_∞ performance, and the corresponding controller gains have also been obtained. Finally, two examples have been presented to verify the effectiveness of the relevant results.

Based on this article, some relevant problems can be considered in the future as follows. 1). Design the controller by combination of time-triggered and event-triggered scheme to save the network resources by moving unneeded computation and transmission. 2). Design the switching signal by the combination of slow AED-ADT switching and fast AED-ADT switching method under the case that of all the actuators fail. 3). Construct a more complicated Lyapunov-Krosovskii functional related to time-varying delay $\tau(t)$ to reduce the conservation of the results, and so on.

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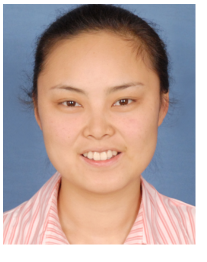

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