Non-fragile Reliable Passive Control for Switched Systems Using an Event-triggered Scheme

Xiaona Wang, Yongzhao Wang, Wenqiong Hou

Abstract—**This paper considers the non-fragile reliable passive for switched systems based on event-triggered scheme. In particular, exogenous disturbance and actuator failures are considered, and the control input is segmented by the proposed event-triggered transmission scheme. Then, a closed-loop state feedback switched systems is established. Based on average dwell time scheme, some stability criteria and satisfactory passive performance of the switched with actuator failures and exogenous disturbance are obtained by Lyapunov function technique. In addition, the reliable feedback controller can be designed through a special matrix transformation. Finally, the rationality of the method is given through a simulation example.**

Index Terms—**Reliable, Event-triggered, Switched systems, Exogenous disturbance.**

I. Introduction

SWITCHED systems can be used to efficiently simulate industrial practice systems due to the advantages of high exibility and maintenance. Over the last years, with the progress of technology and the development of economy, many engineering systems have been modeled using switched systems, and they have become very common in our life, such as networked systems [1], intelligent vehicle systems [2], chemical processing [3], power plant boiler-turbine system [4], neural network tracking control system [5] and the references cited therein. Recently, such system has gained extensive attention from researchers and many valuable results have been obtained. In [6], the piecewise Lyapunov functionals is considered, and the issue of exponential stability is investigated. The author considers the use of persistent dwell time control law, the problem of Takagi-Sugeno fuzzy switched systems is investigated in [7], and some stability criteria are proposed based on multiple L-K functional technique. Specifically, the time delay between the controller and the subsystem is considered in [8], and the proposed switched systems can consist of all unstable subsystems, then some sufficient condition are proposed to guarantee stability of switched systems under asynchronous switching by applying mode-dependent average dwell time law.

In actual engineering system, the actuators of the control system are suffered from failures by limited system properties and operating performance, and they can lead to performance degradation. In addition, the presence of external disturbances and small uncertainties in the actuators can lead to system unstable [9-11]. In fact, these phenomena are very common in industrial production, and researchers are making a lot of efforts to solve these problems. With the development of the research, many advanced and highlighted results related to the non-fragile and reliable control have been studied in recent years. For instance, the mixed actuator failures are often encountered in industrial production. The author considered this common situation in [12], and some stability criteria of discrete-time Markov jump system are obtained. In [13], the reliable control for uncertain continuous time systems is investigated by dissipative analysis. Meanwhile, by employing delay fractioning approach, H_∞, passivity, (Q, S, R) dissipative control problems can obtained respectively from the proposed conditions. Considering that distributed and discrete delays appear randomly in the network environment, [14] considers the stability problem of stochastic networks through L-K function technology, and some stability criteria and satisfactory passive performance are obtained under actuator failure. In particular, these questions are also the main concern for switched systems. However, it should be pointed out that when the system is subjected to a complex external environment, H_∞ control method is not competent for disturbance suppression function. In fact, the passivity has been introduced as a performance index to overcome this obstacle. For example, when considering switched systems with random items and uncertain items, [15] presents a method to deal with actuator faults, and some stability criteria and satisfactory passive performance of the switched with actuator failures and exogenous disturbance are proposed under state switching. By means of dissipative theory, [16] deals with a more complex system, that is, a switched system with nonlinear functions satisfying Lipschitz's condition, and the reliability and stability are studied in [16]. Based on the above analysis, we understand that there are few researches on the passivity of switched systems containing non-fragile items and actuator failures. This leads to our current research motivation.

On another research front, the sampled-data control systems are superior in flexibility, maintainability and simpler installation than traditional control systems. The periodical sampling mechanism (or time-triggered mechanism) is often investigated to obtain the instantaneous sampling information of physical plants states in earlier studies. In general, the communication bandwidth is limited in the network transmis-

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sion and the data sampling and transmission in a periodicity will result in a large amount of network data, which will cause data congestion and network delay in the network channel [17-22]. Hence, with the development of modern network communication technology and the improvement of data communication reliability requirements in work and life, the event-triggered mechanism is introduced to deal with or improve the problems arising from time-triggered scheme while retaining a satisfactory performance. Specially, with the popularity of the event-triggered control method, the research of adding this method to the switched system has also been extensively developed. In [23], a special nonlinear problem often encountered in industrial production, namely actuator saturation phenomenon, is considered. By introducing event-triggered method, the stability of switched system in the network environment is solved. [24] proposed the problem of asynchronous phenomenon, and dynamic input quantization and constrained switching are considered at the same time under the constructed event-triggered condition. In [25], the author analyzes the advantages and disadvantages of trigger conditions, and some stability criteria are obtained based on state switching law. In particular, from the perspective of practical applications, the event-triggered transmission scheme may be a better choice. Moreover, to our best knowledge, the passivity of switched systems containing non-fragile items and actuator failures has not been yet completely solved by event-triggered strategy and results are relatively infrequent.

In order to fill this gap, the purpose of this article is to address the non-fragile reliable passive event trigger control problem of the switched systems affected by exogenous disturbance and actuator failure. The main contributions of this article include three aspects:

• The influence of actuator failures and exogenous disturbance are taken into consideration simultaneously. Then, the non-fragile control input is segmented and a closed-loop state feedback switched systems is established under event-triggered transmission scheme.

• By using Lyapunov stability theory, some stability criteria and satisfactory passive performance of the switched with actuator failures and exogenous disturbance are obtained.

• The reliable feedback controller can be designed by using a proficient matrix decoupling method.

II. Problem formulation and preliminaries

The switched systems considered is as follows:

$$\begin{cases} \dot{x}(t) = A_{\sigma(t)}x(t) + B_{\sigma(t)}u^f(t) + C_{\sigma(t)}v(t) \\ z(t) = E_{\sigma(t)}x(t) + F_{\sigma(t)}v(t), \end{cases} \tag{1}$$

The state vector, the actuator fault and disturbance, respectively, are represented by $x(t) \in R^n$, $u^f(t) \in R^m, v(t)$. The measured output is represented by $z(t) \in R^n$. Specifically, The switching law function is represented by $\sigma(t)$, and it is assumed that there are s subsystems. t_k is recorded as the switching instant. For convenience of expression, we denote $\sigma(t) = i$.

It is worth mentioning that with the increasing complexity of industrial system models and the uncertainty of the working environment, the actuator failure usually occurs in the process of controlling the dynamic system, and it will work abnormally under certain actual conditions. Therefore, we design the reliability controller based on the practical application and the comprehensive control method of the model.

$$u^f(t) = M_i u(t), \forall t \in [t_0, \infty) \tag{2}$$

The model of actuator fault matrix $M_i, i \in N$ is given below:

$$M_i = diag\{m_{i1}, m_{i2}, \ldots, m_{il}\}, \tag{3}$$

where $0 \leq \underline{m}_{ik} \leq m_{ik} \leq \overline{m}_{ik} \leq 1, k = 1, 2, \ldots, l$. $\underline{m}_{ik}$ and $\overline{m}_{ik}$ are known constants. Given the following matrix relationship.

$$\begin{aligned} L_i &= diag\{l_{i1}, l_{i2}, \ldots, l_{il}\}, J_i = diag\{j_{i1}, j_{i2}, \ldots, j_{il}\} \\ M_{i0} &= diag\{\tilde{m}_{i1}, \tilde{m}_{i2}, \ldots, \tilde{m}_{il}\}, \end{aligned} \tag{4}$$

where $l_{ik} = \frac{m_{ik} - \tilde{m}_{ik}}{\tilde{m}_{ik}}, j_{ik} = \frac{\overline{m}_{ik} - \underline{m}_{ik}}{\overline{m}_{ik} + \underline{m}_{ik}}, \tilde{m}_{ik} = \frac{1}{2}(\underline{m}_{ik} + \overline{m}_{ik})$. According to (4), then

$$M_i = M_{i0}(I + L_i), \tag{5}$$

where $|L_i| = diag\{|l_{i1}|, |l_{i2}|, \ldots, |l_{i1}|\}, |L_i| \leq J_i \leq I$.

Remark 1. It is well known that actuators are suffers from failures by limited system properties and operating performance. In addition, when the system suffers from external interference, the existence of this factor will cause stability of system to be damaged and performance degradation. Taking into account the actual situation and the application in engineering practice, we have considered all the above situations. The model considered in this paper is more comprehensive and more practical.

Under the event trigger mechanism, we will show the entire process framework of the switched systems operation through Figure 1. In particular, an event detector is introduced in Figure 1. The significance of the event detector is to determine newly sampled information by using the event trigger condition, and then pass the data to the controller. If the trigger condition is satisfied, a new trigger instant will be generated; if not, the next trigger instant will be judged by the trigger condition. We consider the following mode-dependent event-triggered conditions:

$$\mathrm{tr}_{k+1} = \mathbf{inf}\{t > \mathrm{tr}_k | e^T(t)\Phi_i e(t) > \rho_i x^T(t)\Phi_i x(t)\} \tag{6}$$

The measurement error is represented by $e(t) = x(t) - x(\mathrm{tr}_k)$, and the event-triggered weighting matrix are represented by Φ_i. The event-triggered constant threshold is represented by ρ_i and $\rho_i \in [0, 1)$. m sampling data generated on the interval $[t_k, t_{k+1})$ in the following analysis, and the first sampling time in the above interval is represented by $x(\mathrm{tr}_{k+1})$, then the piecewise non-fragile control inputs $u(t)$ can be given by

$$u(t) = \begin{cases} (K_i + \Delta K_i)x(\mathrm{tr}_k) & t \in [t_k, \mathrm{tr}_{k+1}), \\ (K_i + \Delta K_i)x(\mathrm{tr}_{k+1}) & t \in [\mathrm{tr}_{k+1}, \mathrm{tr}_{k+2}), \\ \cdots, & \\ (K_i + \Delta K_i)x(\mathrm{tr}_{k+m}) & t \in [\mathrm{tr}_{k+m}, t_{k+1}). \end{cases} \tag{7}$$

where K_i is the controller gain and the perturbations satisfying $\Delta K_i = H_i F_i(t) O_i$, $F_i^T(t)F_i(t) \leq I$, where $F_i(t)$ are unknown matrix functions. O_i and H_i are given constant matrices. The state $x(\mathrm{tr}_k)$ is sampled and transmitted at event-triggered sampling instant tr_k.

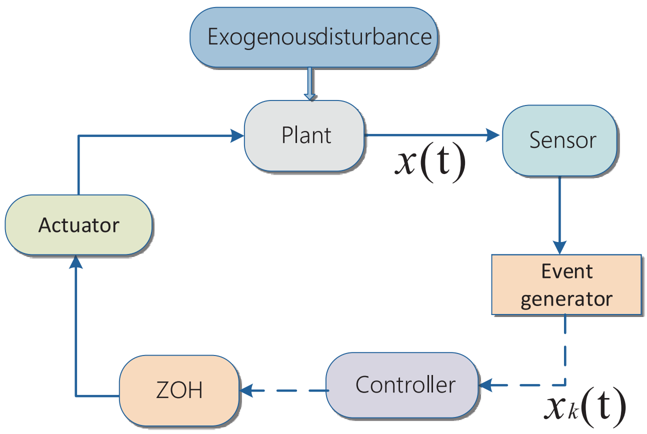

Fig. 1: Event-triggered control structure

Remark 2. Compared with the periodical sampling mechanism in [16] and [22], an event-triggered mechanism condition is introduced in (6) to reduce some unnecessary waste of communication transmissions from a resource utilisation point of view. Moreover, the piecewise non-fragile control input in the presence of the additive gain perturbations of the form ΔK_i is imposed in (7), and the closed-loop state feedback switched system can keep continuous via a zero-order holder (ZOH).

Then, by combining (1) and (7), the following system is generated:

$$\begin{cases} \dot{x}(t) = (A_i + B_i M_i (K_i + \Delta K_i))x(t) + C_i v(t) \\ \qquad - B_i M_i (K_i + \Delta K_i) e(t), \\ z(t) = E_i x(t) + F_i v(t). \end{cases} \tag{8}$$

Before proving the theorem, we give some definitions and lemmas that have an effect on the calculation process.

Definition 1.([26]) *For $T > t \geq 0$, $N_\sigma(t,T)$ represents the number of switching an interval (t,T). If exist $N_0 \geq 1, \tau_\alpha \geq 0$, the following inequality*

$$N_\sigma(t,T) \leq N_0 + \frac{(T-t)}{\tau_\alpha} \tag{9}$$

holds, then, the constant τ_α is called the average dwell time.

Definition 2.([27]) *When $v(t) = 0$, the closed-loop (8) with is exponentially stable for any $\sigma(t)$, if the following inequality*

$$\|x(t)\|^2 \leq \eta e^{-\delta(t-t_0)} \|x(t_0)\|, \quad \forall t \geq t_0, \eta \geq 1, \delta > 0, \tag{10}$$

holds.

Definition 3.([15]) *Given $\gamma > 0$, the closed-loop (8) is said to be exponential stabilization and and satisfies passive performance, if (1) and (2) hold:*
(1) When $v(t) = 0$, the closed-loop (8) is exponentially stabilizable .
(2) There is

$$2\int_0^T z^T(t) v(t) dt \geq -\gamma \int_0^T v^T(t) v(t) dt, \quad \gamma > 0. \tag{11}$$

holds under any nonzero exogenous disturbance.

Lemma 1([27]) *Given matrix $\Lambda = \begin{pmatrix} \Lambda_{11} & \Lambda_{12} \\ * & \Lambda_{22} \end{pmatrix}$ with $\Lambda_{11} = \Lambda_{11}^T, \Lambda_{22} = \Lambda_{22}^T$, then the following conditions are equivalent:*

(1) $\Lambda < 0$,

(2) $\Lambda_{11} < 0, \Lambda_{22} - \Lambda_{12}^T \Lambda_{11}^{-1} \Lambda_{12} < 0$,

(3) $\Lambda_{22} < 0, \Lambda_{11} - \Lambda_{12} \Lambda_{22}^{-1} \Lambda_{12}^T < 0$.

Lemma 2([15]) *For matrices P, Q and S with appropriate dimensions with $S^T = S$. Then, for all $S^T S \leq I$, there exists $\theta > 0$, such that*

$$PSQ + Q^T S^T P^T \leq \theta P P^T + \theta^{-1} Q^T Q.$$

III. Main Results

In the following, the influence of actuator failures and exogenous disturbance are taken into consideration simultaneously under the proposed event-triggered mechanism. We consider the first case, that is, when $v(t) = 0$.

A. Stability analysis

Theorem 1. *Given positive scalar $\alpha, \varepsilon_{1i}, \varepsilon_{2i}, \varepsilon_{3i}$ and $\lambda \geq 1$, if exist positive definite matrices $X_i, \bar{\phi}_i$ and matrices Y_i, such that the following matrix inequalities hold for all $i, j \in N, i \neq j$,*

$$X_i \leq \mu X_j \quad i,j \in M, \tag{12}$$

$$\check{\Theta}_i = \begin{bmatrix} \check{\Theta}_{11}^i & \hat{\Theta}_{12}^i & \hat{\Theta}_{13}^i & \hat{\Theta}_{14}^i & \tilde{\Theta}_{15}^i & 0 & \hat{\Theta}_{17}^i \\ * & -\bar{\phi}_i & 0 & 0 & 0 & \tilde{\Theta}_{26}^i & \hat{\Theta}_{27}^i \\ * & * & -I & 0 & 0 & 0 & \hat{\Theta}_{37}^i \\ * & * & * & -I & 0 & 0 & \hat{\Theta}_{47}^i \\ * & * & * & * & -\varepsilon_{1i} I & 0 & 0 \\ * & * & * & * & * & -\varepsilon_{2i} & 0 \\ * & * & * & * & * & * & \hat{\Theta}_{77}^i \end{bmatrix} < 0 \tag{13}$$

where

$$\Sigma_{11}^i = A_i X_i + X_i A_i^T + B_i M_{i0} Y_i + Y_i^T M_{i0}^T B_i^T + \alpha X_i + \rho_i \bar{\Phi}_i + \varepsilon_{3i} B_i M_{i0} J_i M_{i0} B_i,$$

$$\hat{\Theta}_{27}^i = -Y_i^T J_i^{\frac{1}{2}}, \; \hat{\Theta}_{37}^i = \hat{\Theta}_{47}^i = H_i^T J_i^{\frac{1}{2}}, \; \hat{\Theta}_{12}^i = -B_i M_{i0} Y_i,$$

$$\hat{\Theta}_{13}^i = \hat{\Theta}_{14}^i = B_i M_{i0} H_i, \hat{\Theta}_{15}^i = \sqrt{\varepsilon_{1i}} X_i O_i^T,$$

$$\hat{\Theta}_{26}^i = \sqrt{\varepsilon_{2i}} X_i O_i^T, \; \hat{\Theta}_{17}^i = Y_i^T J_i^{\frac{1}{2}}, \; \hat{\Theta}_{77}^i = -\varepsilon_{3i} I,$$

then, the resulting closed-loop system (8) when $v(t) = 0$ is exponentially stabilizable for $\tau_a > \tau_a^* = \frac{\ln \lambda}{\alpha}$. Moreover, the controller gains are given by $K_i = Y_i X_i^{-1}$.

Proof: For $[t_k, t_{k+1})$, we assume that the ith subsystem is activated. The following multiple L-K functional is considered:

$$V(t) = V_i(t) = x^T(t) P_i x(t) \tag{14}$$

Derivation of (14), we have

$$\begin{aligned} \dot{V}_i(t) = & x^T(t)[P_i(A_i + B_i M_i K_i) + (A_i + B_i M_i K_i)^T P_i \\ & + 2 P_i B_i M_i \Delta K_i] x(t) - e^T(t) K_i^T M_i^T B_i^T P_i x(t) \\ & - x^T(t) P_i B_i M_i K_i e(t) - 2x^T(t) P_i B_i M_i \Delta K_i e(t) \end{aligned} \tag{15}$$

Further, we have

$$\begin{aligned}2x^T(t)P_iB_iM_i\Delta K_ix(t) \le& x^T(t)(\varepsilon_{1i}^{-1}P_iB_iM_iH_iH_i^TM_i^TB_i^TP_i\\&+\varepsilon_{1i}O_i^TO_i)x(t)\\2x^T(t)P_iB_iM_i\Delta K_ie(t) \le& \varepsilon_{2i}^{-1}x^T(t)(P_iB_iM_iH_iH_i^TM_i^TB_i^TP_i)\\&x(t)+\varepsilon_{2i}e^T(t)O_i^TO_ie(t)\end{aligned} \tag{16}$$

Form (6), we have

$$\rho_ix^T(t)\Phi_ix(t)-e^T(t)\Phi_ie(t)\ge 0 \tag{17}$$

By (15)-(17), then

$$\begin{aligned}\dot V_i(t)+\alpha V_i(t)\le& x^T(t)[P_i(A_i+B_iM_iK_i)+\varepsilon_{1i}O_i^TO_i\\&+\varepsilon_{1i}^{-1}P_iB_iM_iH_iH_i^TM_i^TB_i^TP_i+(A_i\\&+B_iM_iK_i)^TP_i+\rho_i\Phi_i+\varepsilon_{2i}^{-1}P_iB_iM_iH_i\\&\times H_i^TM_i^TB_i^TP_i+\alpha P_i]x(t)-e^T(t)\Phi_ie(t)\\&-e^T(t)K_i^TM_i^TB_i^TP_ix(t)\\&-x^T(t)P_iB_iM_iK_ie(t)\\&+\varepsilon_{2i}e^T(t)O_i^TO_ie(t)\\=&\eta^T(t)\Theta_i\eta(t),\end{aligned} \tag{18}$$

where

$$\eta^T(t)=\begin{bmatrix}x^T(t) & e^T(t)\end{bmatrix},\Theta_i=\begin{bmatrix}\Theta_{11}^i & \Theta_{12}^i\\ * & \Theta_{22}^i\end{bmatrix},$$

$$\begin{aligned}\Theta_{11}^i=&P_i(A_i+B_iM_iK_i)+(A_i+B_iM_iK_i)^TP_i+\alpha P_i\\&+\varepsilon_{1i}^{-1}P_iB_iM_iH_iH_i^TM_i^TB_i^TP_i+\varepsilon_{1i}O_i^TO_i\\&+\rho_i\Phi_i+\varepsilon_{2i}^{-1}P_iB_iM_iH_iH_i^TM_i^TB_i^TP_i,\\\Theta_{12}^i=&-P_iB_iM_iK_i,\ \Theta_{22}^i=\varepsilon_{2i}O_i^TO_i-\Phi_i.\end{aligned}$$

Applying Lemma 1, we understand that $\Theta_i<0$ is equivalent to

$$\begin{bmatrix}\bar\Theta_{11}^i & \Theta_{12}^i & \Theta_{13}^i & \Theta_{14}^i & \Theta_{15}^i & 0\\ * & -\Phi_i & 0 & 0 & 0 & \Theta_{26}^i\\ * & * & -I & 0 & 0 & 0\\ * & * & * & -I & 0 & 0\\ * & * & * & * & -\varepsilon_{1i}I & 0\\ * & * & * & * & * & -\varepsilon_{2i}I\end{bmatrix}<0 \tag{19}$$

where

$$\begin{aligned}\bar\Theta_{11}^i=&P_i(A_i+B_iM_iK_i)+(A_i+B_iM_iK_i)^TP_i+\alpha P_i\\&+\rho_i\Phi_i,\\\Theta_{13}^i=&\Theta_{14}^i=P_iB_iM_iH_i,\Theta_{15}^i=\sqrt{\varepsilon_{1i}}O_i^T,\Theta_{26}^i=\sqrt{\varepsilon_{2i}}O_i^T.\end{aligned}$$

Multiply both sides of (19) by Υ_i. Denote $\Upsilon_i=diag\{P_i^{-1},P_i^{-1},I,I,I,\ I\}$. $P_i^{-1}=X_i,Y_i=K_iX_i,\bar\Phi_i=X_i\Phi_iX_i$, we have

$$\begin{bmatrix}\tilde\Theta_{11}^i & \tilde\Theta_{12}^i & \tilde\Theta_{13}^i & \tilde\Theta_{14}^i & \tilde\Theta_{15}^i & 0\\ * & -\bar\Phi_i & 0 & 0 & 0 & \tilde\Theta_{26}^i\\ * & * & -I & 0 & 0 & 0\\ * & * & * & -I & 0 & 0\\ * & * & * & * & -\varepsilon_{1i}I & 0\\ * & * & * & * & * & -\varepsilon_{2i}I\end{bmatrix}<0 \tag{20}$$

where

$$\begin{aligned}&\tilde\Theta_{11}^i=A_iX_i+X_iA_i^T+B_iM_iY_i+\alpha X_i+Y_i^TM_i^TB_i^T+\rho_i\bar\Phi_i,\\&\tilde\Theta_{12}^i=-B_iM_iY_i,\tilde\Theta_{13}^i=\tilde\Theta_{14}^i=B_iM_iH_i,\tilde\Theta_{15}^i=\sqrt{\varepsilon_{1i}}X_iO_i^T,\\&\tilde\Theta_{26}^i=\sqrt{\varepsilon_{2i}}X_iO_i^T.\end{aligned}$$

Substituting (5) into (20), the following formula can be obtained:

$$\begin{aligned}&\hat\Theta_i+\begin{bmatrix}B_iM_{i0}\\0\\0\\0\\0\\0\end{bmatrix}L_i\begin{bmatrix}Y_i & -Y_i & H_i & H_i & 0 & 0\end{bmatrix}\\&+\begin{bmatrix}Y_i^T\\-Y_i^T\\H_i^T\\H_i^T\\0\\0\end{bmatrix}L_i^T\begin{bmatrix}M_{i0}^TB_i^T & 0 & 0 & 0 & 0 & 0\end{bmatrix}\end{aligned} \tag{21}$$

where

$$\hat\Theta_i=\begin{bmatrix}\hat\Theta_{11}^i & \hat\Theta_{12}^i & \hat\Theta_{13}^i & \hat\Theta_{14}^i & \tilde\Theta_{15}^i & 0\\ * & -\bar\phi_i & 0 & 0 & 0 & \tilde\Theta_{26}^i\\ * & * & -I & 0 & 0 & 0\\ * & * & * & -I & 0 & 0\\ * & * & * & * & -\varepsilon_{1i}I & 0\\ * & * & * & * & * & -\varepsilon_{2i}I\end{bmatrix} \tag{22}$$

where

$$\begin{aligned}\hat\Theta_{11}^i=&A_iX_i+X_iA_i^T+B_iM_{i0}Y_i+Y_i^TM_{i0}^TB_i^T+\alpha X_i\\&+\rho_i\bar\Phi_i,\\\hat\Theta_{12}^i=&-B_iM_{i0}Y_i,\hat\Theta_{13}^i=\hat\Theta_{14}^i=B_iM_{i0}H_i.\end{aligned}$$

From (5) and Lemma 2, we have Θ_i is equivalent to (13) to

$$\begin{aligned}&\hat\Theta_i+\begin{bmatrix}B_iM_{i0}\\0\\0\\0\\0\\0\end{bmatrix}L_i\begin{bmatrix}Y_i & -Y_i & H_i & H_i & 0 & 0\end{bmatrix}\\&+\begin{bmatrix}Y_i^T\\-Y_i^T\\H_i^T\\H_i^T\\0\\0\end{bmatrix}L_i^T\begin{bmatrix}M_{i0}^TB_i^T & 0 & 0 & 0 & 0 & 0\end{bmatrix}\\&\le\hat\Theta_i+\begin{bmatrix}B_iM_{i0}\\0\\0\\0\\0\\0\end{bmatrix}J_i\begin{bmatrix}Y_i & -Y_i & H_i & H_i & 0 & 0\end{bmatrix}\\&+\begin{bmatrix}Y_i^T\\-Y_i^T\\H_i^T\\H_i^T\\0\\0\end{bmatrix}J_i^T\begin{bmatrix}M_{i0}^TB_i^T & 0 & 0 & 0 & 0 & 0\end{bmatrix}\end{aligned} \tag{23}$$

$$\hat{\Theta}_i + \varepsilon_{3i} \begin{bmatrix} B_i M_{i0} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} J_i \begin{bmatrix} B_i M_{i0} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}^T + \varepsilon_{3i}^{-1} \begin{bmatrix} Y_i^T \\ -Y_i^T \\ H_i^T \\ H_i^T \\ 0 \\ 0 \end{bmatrix} J_i^T \begin{bmatrix} Y_i & -Y_i & H_i & H_i & 0 & 0 \end{bmatrix} < 0 \tag{24}$$

Then,

$$\dot{V}_i(t) + \alpha V_i(t) < 0. \tag{25}$$

So

$$(e^{\alpha t} V_i(t))' = \alpha e^{\alpha t} V_i(t) + e^{\alpha t} \dot{V}_i(t) \le 0. \tag{26}$$

The integral of (26) is obtained

$$V_{\sigma(t)}(t) \le V_{\sigma(t_k)}(t_k) e^{-\alpha(t-t_k)}, \quad t_k \le t < t_{k+1}. \tag{27}$$

From (12), we can get

$$V_{\sigma(t_k)}(t_k) \le \lambda V_{\sigma(t_k^-)}(t_k^-). \tag{28}$$

From (27) and (28) the relation $N_\sigma(t_0, t) \le \frac{t-t_0}{\tau_a}$, we have

$$\begin{aligned} V_{\sigma(t)}(t) &\le \lambda V_{\sigma(t_k^-)}(t_k{}^-) e^{-\alpha(t-t_k)} \\ &\le \cdots \\ &\le \lambda^{N_\sigma(t_0,t)} V_{\sigma(t_0)}(t_0) e^{-\alpha(t-t_0)}, \\ &\le e^{-(t-t_0)(\alpha - \ln\lambda/\tau_a)} V_{\sigma(t_0)}(t_0). \end{aligned} \tag{29}$$

From (14), then

$$V_{\sigma(t)}(t) \ge a\|x(t)\|^2, \quad V_{\sigma(t_0)}(t_0) \quad \le b\|x(t_0)\|^2, \tag{30}$$

where

$$a = \min_{i \in \bar{N}} \lambda_{\min}(P_i), \quad b = \max_{i \in \bar{N}} \lambda_{\max}(P_i).$$

So

$$\|x(t)\| \le \sqrt{\frac{b}{a}} \, \|x(t_0)\| \, e^{-\frac{1}{2}\left(\alpha - \frac{ln\lambda}{\tau_a}\right)(t-t_0)}. \tag{31}$$

Therefore, through the above proof process, we can draw the conclusion of the Theorem 1 from Definition 2.

B. Passivity control

In the following subsection, we considered the issue of non-fragile reliable event-triggered passive control for the resulting system (8) with respect to the exogenous disturbance input $\omega(t) \neq 0$.

Theorem 2. *Given positive scalar $\alpha, \varepsilon_{1i}, \varepsilon_{2i}, \varepsilon_{3i}$ and $\lambda \ge 1$, if exist positive definite matrices $X_i, \bar{\phi}_i$ and Y_i, such that the following matrix inequalities hold,*

$$X_i \le \mu X_j \quad i, j \in N, \tag{32}$$

$$\begin{bmatrix} \bar{\Lambda}_{11}^i & \bar{\Lambda}_{12}^i & \bar{\Lambda}_{13}^i & \Lambda_{14}^i & \Lambda_{15}^i & \Lambda_{16}^i & 0 & \Lambda_{18}^i \\ * & -\bar{\phi}_i & 0 & 0 & 0 & 0 & \Lambda_{27}^i & \Lambda_{28}^i \\ * & * & \Lambda_{33}^i & 0 & 0 & 0 & 0 & \Lambda_{38}^i \\ * & * & * & -I & 0 & 0 & 0 & \Lambda_{48}^i \\ * & * & * & * & -I & 0 & 0 & 0 \\ * & * & * & * & * & -\varepsilon_{1i} I & 0 & 0 \\ * & * & * & * & * & * & -\varepsilon_{2i} I & 0 \\ * & * & * & * & * & * & * & \Lambda_{88}^i \end{bmatrix} < 0 \tag{33}$$

where

$$\begin{aligned} &\Lambda_{11}^i = A_i X_i + X_i A_i^T + B_i M_{i0} Y_i + Y_i^T M_{i0}^T B_i^T + \alpha X_i \\ &\qquad + \rho_i \bar{\Phi}_i + \varepsilon_{3i} B_i M_{i0} J_i M_{i0} B_i, \\ &\Lambda_{28}^i = -Y_i^T J_i^{\frac{1}{2}}, \Lambda_{38}^i = \Lambda_{48}^i = H_i^T J_i^{\frac{1}{2}}, \bar{\Lambda}_{13}^i = C_i - X_i E_i^T, \\ &\Lambda_{33}^i = -2F_i^T - \gamma^2 I, \Lambda_{14}^i = \Lambda_{15}^i = B_i M_{i0} H_i, \\ &\Lambda_{16}^i = \sqrt{\varepsilon_{1i}} X_i O_i^T, \Lambda_{27}^i = \sqrt{\varepsilon_{2i}} X_i O_i^T, \\ &\Lambda_{18}^i = Y_i^T J_i^{\frac{1}{2}}, \Lambda_{88}^i = -\varepsilon_{3i} I. \end{aligned}$$

Then, the resulting system (8) is passive and exponentially stabilizable with attenuation performance γ for $\tau_a > \tau_a^* = \frac{\ln\lambda}{\alpha}$. Moreover, the controller gains are given by $K_i = Y_i X_i^{-1}$.

Proof: For $v(t) \neq 0$, we choose L-K functional (14) of Theorem 1, thus

$$\begin{aligned} &\dot{V}_i(t) + \alpha V_i(t) - 2z^T(t)v(t) - \gamma^2 v^T(t)v(t) \\ &\le x^T(t)[P_i(A_i + B_i M_i K_i) + \varepsilon_{1i} O_i^T O_i + \rho_i \Phi_i \\ &\quad + \varepsilon_{1i}^{-1} P_i B_i M_i H_i H_i^T M_i^T B_i^T P_i + (A_i + B_i M_i K_i)^T \\ &\quad \times P_i + \alpha P_i + \varepsilon_{2i}^{-1} P_i B_i M_i H_i H_i^T M_i^T B_i^T P_i] x(t) \\ &\quad - x^T(t) E_i^T v(t) - v^T(t) E_i x(t) - \gamma^2 v^T(t) v(t) \\ &\quad - 2v^T(t) F_i^T v(t) - e^T(t) \phi_i e(t) + v^T(t) C_i P_i x(t) \\ &\quad - x^T(t) P_i B_i M_i K_i e(t) - e^T(t) K_i^T M_i^T B_i^T P_i x(t) \\ &\quad + x^T(t) P_i C_i \omega(t) + \varepsilon_{2i} e^T(t) O_i^T O_i e(t) \\ &= \zeta^T(t) \Lambda_i \zeta(t) \end{aligned} \tag{34}$$

where

$$\begin{aligned} &\Lambda_i = \begin{bmatrix} \Lambda_{11}^i & \Lambda_{12}^i & \Lambda_{13}^i \\ * & \Lambda_{22}^i & 0 \\ * & * & \Lambda_{33}^i \end{bmatrix}, \\ &\zeta^T(t) = \begin{bmatrix} \eta^T(t) & v^T(t) \end{bmatrix}, \\ &\Lambda_{11}^i = P_i(A_i + B_i M_i K_i) + (A_i + B_i M_i K_i)^T P_i + \rho_i \Phi_i \\ &\qquad + \varepsilon_{1i}^{-1} P_i B_i M_i H_i H_i^T M_i^T B_i^T P_i + \alpha P_i + \varepsilon_{1i} O_i^T O_i \\ &\qquad + \varepsilon_{2i}^{-1} P_i B_i M_i H_i H_i^T M_i^T B_i^T P_i, \\ &\Lambda_{22}^i = \varepsilon_{2i} O_i^T O_i - \Phi_i, \quad \Lambda_{13}^i = P_i C_i - E_i^T, \\ &\Lambda_{12}^i = -P_i B_i M_i K_i, \quad \Lambda_{33}^i = -2F_i^T - \gamma^2 I \end{aligned}$$

So,

$$\dot{V}(t) + \alpha V(t) - 2z^T(t)v(t) - \gamma^2 v^T(t)v(t) \le 0. \tag{35}$$

Integrating from t_k to t on both sides of (35), then

$$V(t) \le e^{-\alpha(t-t_k)} V(t_k) - \int_{t_k}^{t} e^{-\alpha(t-s)} \psi(s) ds. \tag{36}$$

where $\psi(t) = -2z^T(t)v(t) - \gamma^2 v^T(t)v(t)$.

Then, we have

$$\begin{aligned}V(t) &\leq e^{-\alpha(t-t_k)}V(t_k) - \int_{t_k}^{t} e^{-\alpha(t-s)}\psi(s)ds \\ &\leq \lambda^k V(t_0)e^{-\alpha t} - \mu^k \int_0^{t_1} e^{-\alpha(t-s)}\psi(s)ds \\ &\quad - \lambda^{k-1}\int_{t_1}^{t_2} e^{-\alpha(t-s)}\psi(s)ds \\ &\quad - \cdots - \lambda^{k-1}\int_{t_k}^{t} e^{-\alpha(t-s)}\psi(s)ds \\ &\leq e^{-\alpha t + N_\sigma(0,t)\ln\lambda}V(0) - \int_0^t e^{-\alpha t + N_\sigma(s,t)\ln\lambda}\psi(s)ds.\end{aligned} \tag{37}$$

So,

$$0 \leq -\int_0^t e^{-\alpha(t-s)+N_\sigma(s,t)\ln\lambda}\psi(s)ds. \tag{38}$$

Form $\tau_a > \tau_a^* = \frac{\ln\lambda}{\alpha}$, we have $N_\sigma(s,t) \leq \frac{t-s}{\tau_a} \leq \frac{(t-s)\alpha}{\ln\lambda}$. Then, we can get

$$-\int_0^t \psi(s)ds \geq 0. \tag{39}$$

Therefore,

$$2\int_0^t z^T(s)\omega(s)ds \geq -\gamma\int_0^t \omega^T(s)\omega(s)ds.$$

Therefore, through the above proof process, we can draw the conclusion of the Theorem 2 from Definition 2.

Remark 3. The Lyapunov function candidate (14) is mode dependent, which is essential to obtain less conservative result. Moreover, the event-triggered mechanism condition (6) is related to subsystem information, which is more practical than [28] and [29] in engineering application. Specifically, the L-K functional technique is used as an important method to deal with the switching signal sequence and event-triggered transmission sequence in this paper.

Remark 4. In actual engineering system, the designed controllers may be very sensitive when there are small uncertainties in controllers, that is to say, the system is fragile, and may be unstable or performance degradation. Therefore, when we deal with complex situations, considering the actual application performance level of the system, we need to consider non-fragility and reliability of controller.

Remark 5. It should be mentioned that there is still room to reduce the conservatism if free-weighting matrices technique can be employed to estimate the useful terms. In event-triggered control, due to the interaction between switching interval and the event-triggered interval, there may be a mismatch between the subsystems and their corresponding controllers, that is to say, there may be asynchrony between them. It is worth noting that if the two intervals are handled properly, the asynchronous phenomenon will not appear. This paper considers the synchronization of the subsystem and the controller.

Remark 6. It is clear that (32) and (33) are mutually dependent. The matrix X_i is obtain by solving linear matrix inequalities (32) and (33). Therefore, the following algorithm is given to solve the controller gain K_i.

Step 1: Choose some values for scalars α and λ.

Step 2: Define the variable X_i.

Step 3: Solving (32) and (33) through constant adjustment of the parameters.

Step 4: The controller gains are given by $K_i = Y_i X_i^{-1}$. Finally, the reliability controller can be designed by the above steps.

IV. Numerical examples

Based on the proof and analysis of the theorem, in order to obtain effective results, we will give an example.

Example 1. Consider the switched systems model where it is composed of two subsystems:

Mode 1:

$$A_1 = \begin{bmatrix} -1.5 & -1 \\ 0 & -1.1 \end{bmatrix},\ B_1 = \begin{bmatrix} 0.2 & 0 \\ -0.1 & 0.2 \end{bmatrix},$$
$$C_1 = \begin{bmatrix} 0.1 & 0 \\ 0 & -2 \end{bmatrix}, E_1 = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.2 \end{bmatrix},$$
$$F_1 = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix}, H_1 = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.2 \end{bmatrix},$$
$$O_1 = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.2 \end{bmatrix},$$

Mode 2:

$$A_2 = \begin{bmatrix} -1.2 & 0 \\ -1 & -0.6 \end{bmatrix},\ B_2 = \begin{bmatrix} 0.1 & -0.1 \\ 0 & 0.2 \end{bmatrix},$$
$$C_2 = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.2 \end{bmatrix}, E_2 = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.2 \end{bmatrix},$$
$$F_2 = \begin{bmatrix} 0.2 & 0 \\ 0 & -0.25 \end{bmatrix}, H_2 = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.2 \end{bmatrix},$$
$$O_2 = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.2 \end{bmatrix},$$

The actuator failures matrices are as follows:

$$0.2 \leq \mathrm{m}_{11} \leq 0.6, \quad 0.1 \leq \mathrm{m}_{12} \leq 0.9,$$
$$0.2 \leq \mathrm{m}_{21} \leq 0.8, \quad 0.1 \leq \mathrm{m}_{22} \leq 0.7.$$

According to (6) ,we can get

$$M_{10} = \begin{bmatrix} 0.6 & 0 \\ 0 & 0.3 \end{bmatrix}, J_1 = \begin{bmatrix} 0.5 & 0 \\ 0 & 0.5 \end{bmatrix},$$
$$M_{20} = \begin{bmatrix} 0.3 & 0 \\ 0 & 0.6 \end{bmatrix}, J_2 = \begin{bmatrix} 0.55 & 0 \\ 0 & 0.45 \end{bmatrix},$$

Let $\alpha = 0.7, \mu = 1.05, \gamma = 0.8, \varepsilon_{1i} = 1.1, \varepsilon_{2i} = 1.2, \varepsilon_{3i} = 1.4(i = 1,2), \rho_1 = 0.1, \rho_2 = 0.2,\ v(t) = \frac{2}{e^{5t}}$. By $\tau_a > \tau_a^* = \frac{\ln\lambda}{\alpha}$, we can get $\tau_a > 0.0697$.

By solving (34) and (35), we have

$$X_1 = \begin{bmatrix} 0.5901 & -0.2513 \\ -0.2513 & 0.4494 \end{bmatrix},$$
$$X_2 = \begin{bmatrix} 0.5891 & 0.2508 \\ 0.2508 & 0.4470 \end{bmatrix},$$
$$Y_1 = \begin{bmatrix} -0.0222 & 0.0510 \\ 0.0808 & -0.0518 \end{bmatrix},$$
$$Y_2 = \begin{bmatrix} 0.0275 & 0.0381 \\ 0.1368 & 0.1257 \end{bmatrix}$$

Then, the controller gains are

$$K_1 = \begin{bmatrix} -0.0259 & 0.0285 \\ -0.0607 & -0.0436 \end{bmatrix},$$
$$K_2 = \begin{bmatrix} -0.0257 & -0.0239 \\ 0.0491 & 0.0219 \end{bmatrix}.$$

The system switched signal $\sigma(t)$ and the state trajectories during time interval $[0, 10]$ are given in Fig. 2 and Fig. 3, respectively. Fig.4 represents the event triggering instants. In the figure, 1 is used to indicate that new transmission

TABLE I: The event triggering times under different ρ_i

ρ_i	0	0.2	0.3	0.4	0.5	0.6	0.7	0.9
n	100	32	30	29	28	25	22	18

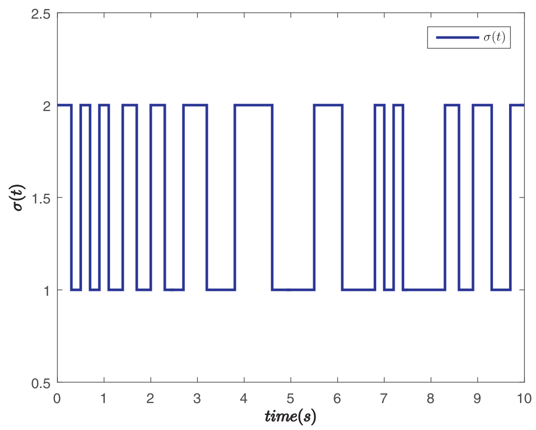

Fig. 2: The switching law.

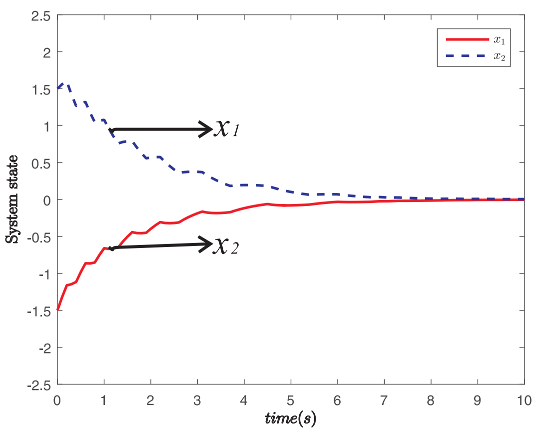

Fig. 3: State response.

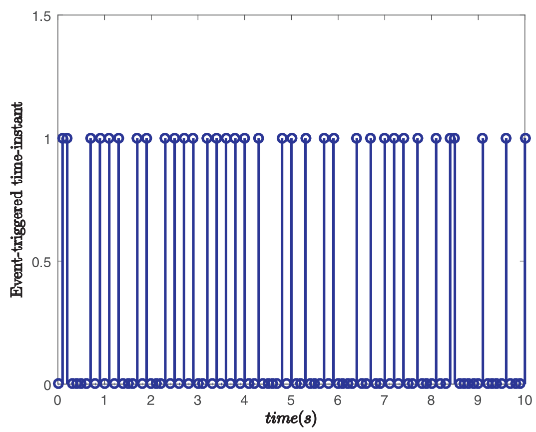

Fig. 4: Event-triggered time-instant.

data is generated at the current moment, and 0 is not violated. Moreover, only a few instants in Figure 4 violate the event trigger condition, that is, only 35 out of 100 samples violated the event-triggered mechanism condition (6). Obviously, from the analysis of the data results, the trigger condition we considered has a good effect in avoiding network congestion due to the reduction of data transmission. Then, the effectiveness of the method is verified.

In (6), an event-triggered mechanism with different triggering thresholds ρ_i is proposed. we understand that the thresholds of the event-triggered ρ_i has a great influence on the number of sampled data transmissions, namely, the frequency of event triggering is related to the thresholds scalar ρ_i. The smaller ρ_i is selected, the more frequently the sampling data is transmitted. Conversely, the larger ρ_i is the selected, the less frequently the sampling data is transmitted. From TABLE I, we can obviously see that the relationship between the selection of threshold scalar ρ_i and sampling data transmission.

V. Conclusions

The non-fragile reliable passive control for switched systems subject to exogenous disturbance and actuator failures has been investigated by using event-triggered method. A segmented non-fragile control input is presented for the considered switched systems with the effect of event-triggered control, then a closed-loop state feedback switched system model is established. Based on the multiple Lyapunov function technique, some stability criteria and satisfactory passive performance of the switched with actuator failures and exogenous disturbance are obtained. In addition, the reliable feedback controller can be designed through a special matrix transformation. Next, we will consider a common problem in engineering practice, that is, there is a large amount of delays in the network, where the introduction of an event-triggered strategy will cause asynchrony problems, and expand theoretical results to other fields[30-32].

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