ARTICLE TEMPLATE

Integrated Fault Tolerant Control Approach for Linear Time Delay Systems Using Dynamic Event-Triggered Mechanism

M. S. Qian[a] and X. G. Yan[b]

[a]College of Electrical Engineering and Control Science, Nanjing Tech University, Nanjing 211816, China; [b]School of Engineering & Digital Arts, University of Kent, Canterbury, CT2 7NT, UK

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ABSTRACT
In this study, a novel integrated fault estimation (FE) and fault tolerant control (FTC) design approach is developed for a system with time-varying delays and additive fault based on a dynamic event-triggered communication mechanism. The traditional static event-triggered mechanism is modified by adding an internal dynamic variable to increase the inter-event interval and decrease the amount of data transmission. Then, a dynamical observer is designed to estimate both the system state and the unknown fault signal simultaneously. A fault estimation-based FTC approach is then given to remove the effects generated by unknown actuator faults, which guarantees that the faulty closed-loop systems are asymptotical stable with a disturbance attenuation level γ. By theory analysis, the zeno phenomenon is excluded in this study. Finally, a real aircraft engine example is provided to illustrate the feasibility of the proposed integrated FE and FTC method.

KEYWORDS
Fault tolerant control; fault estimation; event-triggered control; H-infinity control

1. Introduction

Feedback control systems for engineering applications including power systems, manufacturing systems, and chemical processes strongly depend on actuator, sensor and data acquisition/interface components to ensure proper interactions between the physical controlled systems and control devices. Faults in some components of these system may lead to a drastic reduction of system performance or loss of stability, which even cause the physical system damage. Therefore, there is a growing demand for reliability, safety and fault tolerance in control systems '(Boem, Ferrari, Parisini, & Polycarpou, 2013; Guan, Yang, & Jiang, 2019)'. It is necessary to design control systems which are capable of tolerating potential faults in order to improve the reliability and availability, while providing a desirable performance. These types of control systems are often known as fault tolerant control systems, which are able to accommodate component faults automatically. They are capable of maintaining the overall system stability and acceptable performance even in the presence of faults. In other words, a closed loop control system which could tolerate component malfunctions while maintaining desir-

CONTACT X. G. Yan. Email: x.yan@kent.ac.uk

able performance and system stability, is said to be a fault tolerant control system '(Du, Cocquempot, & Jiang, 2019; Shao, Yang, & Jiang, 2018)'. Moreover, actuator faults frequently occur in practical engineering due to saturation, bias, stuck or loss of effectiveness. Thus, fault diagnosis and FTC against actuator faults are of extensive application and practical significance.

Generally speaking, a fault tolerant control (FTC) system can be divided into two categories: passive and active. In the past few decades, much attention has been paid to these two types of different FTC methods. In '(Yang, Shi, Li,& Li, 2014)', an active FTC method is proposed for a class of T-S fuzzy systems based on the delta operator approach, which guarantees that the closed-loop fuzzy delta operator system is asymptotically stable. In '(Liu, Ho, & Shi, 2015)', an adaptive backstepping control-based FTC strategy is developed for a class of continuous-time Markovian jump systems with matched and mismatched external disturbances, and the stochastic stability of the faulty closed-loop system is guaranteed. In '(Chen, Shi, & Liu, 2019)', the fault estimation (FE) problem is investigated for a class of Markovian jump systems by using two types of adaptive observer methods, which avoids the sliding surface switching problem for jumping systems based on sliding mode observer approaches. In '(Yoo, 2016)', a distributed fault detection and accommodation scheme is proposed for a class of large-scale nonlinear systems with unknown interaction time delay fault to guarantee that the state tracking errors of each subsystem converge to a small neighborhood of the origin. In '(Zhang, Jiang, Shi, & Pan, 2019)', a novel distributed fault estimation approach is developed for the interconnected systems with external disturbances by using unknown input observer (UIO) technique, in which the external disturbance is completely decoupled to improve the fault estimation performance. In '(Li, & Yang, 2014; Yan, & Edwards, 2007, 2008; Yang, & Wang, 2015)', fault detection and isolation (FDI) strategies are proposed for a class of nonlinear control systems with uncertainties using a bank of FDI observers, where FTC is not considered. In the aforementioned work, various components of the controlled system including actuator, controller, filter and sensor are all linked directly.

With the rapid development of digital network technology, networked control systems (NCSs) have obtained considerable research interests and extensive applications due to the advantages of simple installation, low cost and flexibility '(Li,& Yang, 2015)'. It is very important to study the fault diagnosis and FTC approach for networked control systems. In '(Mao, Jiang, & Shi, 2010)', the nonlinear NCSs are transformed into two subsystems by decoupling the system faults. Then a FTC strategy is designed for the NCSs by using impulsive system technique. The authors in '(Qiu, Jiang, Wen, & Mao, 2015)' investigate the problem of fault estimation and accommodation for a class of networked control systems with nonuniform sampling time intervals. An observer-based reliable adaptive output tracking control scheme is designed in '(Sakthivel, Selvaraj, Lim, & Karimi, 2017)' for a class of networked control systems with external disturbance and actuator failure by utilizing the equivalent-input disturbance technique. The fault estimation problem is studied in '(Song, Hu, Chen, Ji, & Liu, 2016)' for NCSs in the simultaneous presence of packet dropouts and stochastic nonlinearity via recursive approach. The co-design of fault detection filter and controller is addressed for networked unmanned surface vehicles in '(Wang, & Han, 2016)'.

It should be noted that the system information in communication architecture of NCSs is exchanged and transmitted through a shared communication network, and the sampling/communication mechanism plays a critical role in the analysis and synthesis of networked systems '(Liu, & Yang, 2018)'. Generally, control/filtering tasks of NCSs are executed in a periodic way, which paves an effective way to analyze and design networked systems by applying the fruitful sample data system theory '(Su, Liu, Shi, & Song, 2018)'. Nevertheless, time-triggered mechanism increases the burden of communication network and the consumption of system energy because a large number of redundant data packets are transmitted over shared communication network '(Chen, Sun,& Karimi, 2019; Ryan, Heffernan, & Leen, 2006; Saha, Roy, & Ramesh, 2016)'. As an attractive alternative to time-driven scheme, the static event-triggered mechanism (ETM) has been developed recently and obtained persistent research attention due to its effective performance in reducing the amount of data transmission '(Liu, Su, Shi, Nguang, & Shen, 2019; Liu, Wang, He, & Zhou, 2017; Pan, & Yang, 2019; Wu, & Zhang, 2018)'. The authors in '(Liu, Su, Shi, Nguang, & Shen, 2019)' design a nonlinear fault detection filter for networked switched control systems with repeated scalar nonlinearities and stochastic disturbances based on an event-triggered scheme. A sliding mode controller is designed for uncertain systems with time-varying state delays and unmatched nonlinearities in '(Coutinho, Oliveira, V. S. Cunha, 2013)', which guarantees finite-time convergence of the tracking error to zero. In '(Cunha, Costa, Hsu,& Oliveira, 2015)' an output-feedback control algorithm is presented based on output-feedback sliding-mode control for systems subjected to actuator and internal dynamics failures. The authors in '(Liu, Wang, He, & Zhou, 2017)' design a novel filter for a class of stochastic nonlinear systems under sensor saturation case by using a recursive algorithm and the event-triggered measurement transmissions. In '(Wu, & Zhang, 2018)', a scheduling and FTC co-design approach is developed for a nonlinear networked control system with the Markovian delay and packet disordering by using the adaptive approximation technique. Nevertheless, to the best of authors' knowledge, the existing research results on event-triggered fault estimation and FTC are still quite limited in the literature, and the available results on event-triggered FTC mainly focus on passive FTC. It needs to be mentioned that passive FTC strategy has limited fault-tolerant capacities since reconfiguration of controller is not utilized.

The direct use of fault estimation (FE) without the need of fault detection procedure and controller switching mechanism provides the great convenience, which has a very broad application prospect in the design of FTC system. To the best of our knowledge, the results about the integrated FE/FTC design for the faulty time delay system are limited, which remains challenging and motivates us to do this study. Recently, Lan and Patton, et. al. propose an integrated FE/FTC strategy for a 3-DOF helicopter system in actuator fault case, such that the reliability and desirable control performance are achieved. Motivated by the result in '(Lan, Patton, & Zhu, 2017)' and the discussion above, the integrated FE/FTC approach for a class of linear time delay systems is investigated by employing dynamic event-triggered mechanism. The method proposed in this paper not only improves the reliability and security of the system with time-varying delays and additive actuator fault, but also need much less communication resources than traditional static event-triggered mechanisms. The main contributions of this paper are stated as follows:

(i) By modifying the static event-triggered mechanism, a dynamic event-triggered communication scheme is introduced in the framework of integrated FE and FTC to save the limited communication resources.

(ii) A fault/state estimation observer design method is proposed to estimate the state variable and unknown actuator fault simultaneously. Meanwhile, an observer-based fault tolerant controller is developed to offset the negative impact of actuator fault in the closed loop system, and achieve the target of integrated FE/FTC design.

(iii) The inter-event intervals of dynamic event generator are proved to have a positive lower bound, which guarantees the zeno phenomenon is excluded in the closed-loop system.

It should be noted that Zeno phenomenon exists in hybrid systems, which can be described informally as the system making an infinite number of jumps in a finite amount of time. It has been discussed in the existing work, see for example '(Abdelrahim, Postoyan, Daafouz, & Nesic, 2016)'.

The rest of this work is organized as follows. In Section 2, the framework of integrated FE and FTC is formulated for linear time delay systems under dynamic event-triggered communication case. In Section 3, the integrated design criteria of state/fault estimation observer, fault tolerant controller and dynamic ETM are given. Meanwhile, the existence of a positive lower bound on inter-event intervals ensures that zeno behavior is excluded. Section 4 demonstrates the simulation results and Section 5 concludes the paper.

2. Problem Formation

Consider the following continuous-time linear time delay system '(Ge, Frank & Lin, 1996; Wu, Weng, Tian, & Shi, 2008)'

$$\begin{cases} \dot{x}(t) = (A+\Delta A)x(t) + A_\tau x(t-\tau(t)) + B(u(t)+f(t)) + Dd(t) \\ y(t) = Cx(t) \\ x(t) = \phi(t),\ t \in [-\bar{\tau}, 0] \end{cases} \tag{1}$$

where $x(t) \in R^n$ is the state vector, $x(t-\tau(t)) \in R^n$ is the delayed state vector. $y(t) \in R^p$ is the measurable output, $u(t) \in R^m$ is the control input, $f(t) \in R^m$ denotes the time varying function produced by unknown additive actuator fault. $d(t) \in R^l$ denotes the unknown disturbance, which belongs to $L_2[0, +\infty)$. A, A_τ, B, C and D are known constant matrices with appropriate dimensions. $\Delta A = E\Delta HT$ is the considered parameter uncertainty where ΔH represents uncertainty satisfying $\Delta H^T \Delta H \le I$, E and T are two known matrices with appropriate dimensions. $\tau(t)$ is the known time-varying delay that satisfies $0 < \tau(t) \le \bar{\tau}$ and $\bar{\tau}$ is a known positive constant. $\phi(t)$ is the initial condition related to time delay, which is a continuous vector-valued function defined in $[-\bar{\tau}, 0]$.

Define the output error of system (1) as follows

$$e_y(t) = y(t_k) - y(t) \tag{2}$$

Here $e_y(t)$ is introduced to trigger the output update inside of the event generator (see Figure 1). It is not the observation error. In order to save the communication and energy resources, an event generator is adopted in this study, see Figure 1, where ZOH denotes the zero order hold. When only the event-triggered condition is satisfied, the sampling measurement is transmitted through the shared communication network. Let t_k $(k \in N, t_0 = 0)$ be the triggering instants of event generator. Then, consider the dynamic ETM described by '(Girard, 2015)'

$$t_{k+1} = \inf\{t > t_k \mid \mu(t) + \alpha[\beta y^T(t)\Xi y(t) - e_y^T(t)\Xi e_y(t)] \le 0\} \tag{3}$$

where the constants $\alpha > 0$ and $0 < \beta < 1$ are the design parameters, $\Xi > 0$ is a symmetric positive definite matrix. $\mu(t) \in R$ is the internal dynamic variable with the following dynamics '(Girard, 2015)'

$$\dot{\mu}(t) = -\lambda\mu(t) + \beta y^T(t)\Xi y(t) - e_y^T(t)\Xi e_y(t) \tag{4}$$

where $\lambda > 0$ is a positive scalar and initial condition $\mu(0) = \mu_0 \geq 0$.

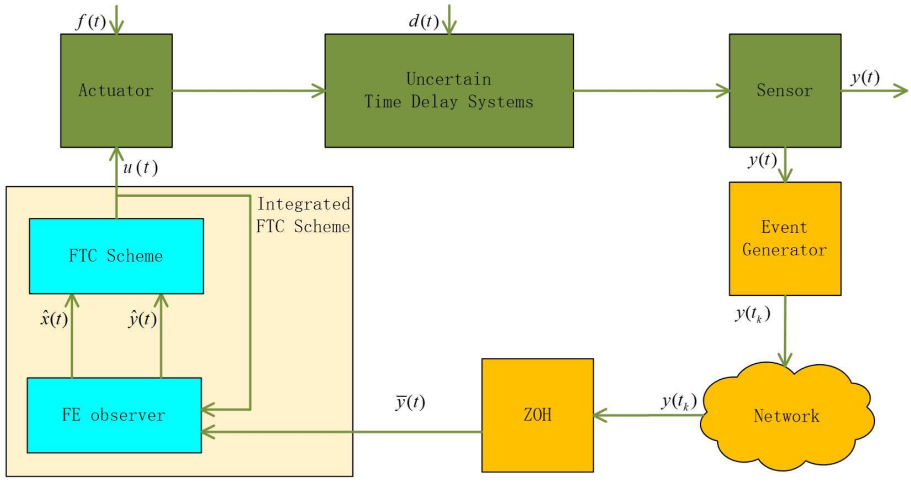

Figure 1. The diagram of event-triggered integrated FE and FTC strategy

The parameters α, β and λ of (3) and (4) are determined later. After the appropriate parameters are designed, the ideal event-triggered time intervals can be obtained.

According to the property of the zero order hold (ZOH), the input signal of FE observer is described by

$$\bar{y}(t) = y(t_k), \quad t \in [t_k,\ t_{k+1}) \tag{5}$$

Notice that $\bar{y}(t)$ is the latest sample value of $y(t)$ at time t_k. For the purpose of the integrated FE/FTC scheme design, a state/fault estimation observer designed using the event-triggered input for $t \in [t_k, t_{k+1})$ is described by '(Wang, Fei, Wang, & Liu, 2019)'

$$\dot{\hat{x}}(t) = A\hat{x}(t) + A_\tau\hat{x}(t-\tau(t)) + Bu(t) + L\hat{e}_y(t) + B\hat{f}(t) \tag{6}$$

$$\dot{\hat{f}}(t) = E_1\hat{e}_y(t) + E_2\dot{\hat{e}}_y(t) \tag{7}$$

$$\hat{y}(t) = C\hat{x}(t) \tag{8}$$

where $\hat{e}_y(t) = \bar{y}(t) - \hat{y}(t)$, $\hat{x}(t) \in R^n$ is the estimated state, $\hat{x}(t-\tau(t)) \in R^n$ represents the estimated delayed state, $\hat{f}(t) \in R^m$ is the estimated fault function, $\hat{y}(t) \in R^p$ denotes the observer output. L, E_1 and E_2 are unknown gain matrices to be designed later.

Based on (6)-(8), a fault compensation-based integrated fault tolerant controller is designed as '(Wang, Fei, Wang, & Liu, 2019)'

$$u(t) = K\hat{x}(t) - B^\dagger B\hat{f}(t) \tag{9}$$

where $K \in R^{m\times n}$ is the gain matrix to be designed later, and $B^\dagger \in R^{m\times n}$ is the pseudo inverse matrix of B.

Remark 1. It should be noted that the term $\dot{\hat{e}}_y(t)$ is used in equation (7), where $\hat{e}_y(t) = \bar{y}(t) - \hat{y}(t)$. It is clear to see from (5) that $\hat{e}_y(t)$ is usually not continuous at t_k which results in that $\dot{\hat{e}}_y(t)$ does not exist at t_k. Therefore, the right hand side of equation (7) is not continuous. In this case, the derivative of $\hat{e}_y(t)$ as well as the solution of the equation (7) are defined in Filippov sense '(Filippov, 1983)'. It should be emphasized that the equation (7) is only used for analysis. In practical implementation, only $\hat{f}(t)$ is required which, from (7), can be obtained by

$$\hat{f}(t) = E_1 \int_0^t \hat{e}_y(s)ds + E_2 \left(\hat{e}_y(t) - \hat{e}_y(0)\right)$$

so this does not pose a problem.

Define the following new error variables and the augmented variables

$$\begin{gathered}
\tilde{x}(t) = x(t) - \hat{x}(t), \quad \tilde{x}_\tau(t) = x(t-\tau(t)) - \hat{x}(t-\tau(t)) \\
\tilde{f}(t) = f(t) - \hat{f}(t), \quad \tilde{y}(t) = y(t) - \hat{y}(t), \quad G(t) = [\Delta Ax(t),\ 0,\ \Delta Ax(t)]^T \\
h(t) = [\tilde{x}^T(t),\ \tilde{f}^T(t),\ x^T(t)]^T, \quad \bar{d}(t) = [d^T(t),\ \dot{f}^T(t),\ \dot{e}_y^T(t),\ \dot{\tilde{y}}^T(t)]^T
\end{gathered}$$

Then, from (1)-(9), the following augmented system is obtained after some manipulations '(Dong, Wang, Ding, & Gao, 2015; Onyeka, Yan, Mao, Jiang & Zhang, 2019)'

$$\begin{cases} \dot{h}(t) = \bar{A}h(t) + \bar{A}_\tau h(t-\tau(t)) + G(t) + \bar{D}\bar{d}(t) + \bar{F}e_y(t) \\ z(t) = h(t) \end{cases} \tag{10}$$

where $z(t)$ is the output of augmented system,

$$\begin{gathered}
\bar{A} = \begin{bmatrix} A_1 & 0 \\ A_2 & A_3 \end{bmatrix},\ A_1 = \bar{A}_1 - \bar{L}\bar{C},\ \bar{A}_1 = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix}, A_2 = \begin{bmatrix} -BK & B \end{bmatrix} \\
A_3 = A + BK, \quad \bar{F} = \begin{bmatrix} -\bar{L} \\ 0 \end{bmatrix}, \quad \bar{D} = \begin{bmatrix} D_1 \\ D_2 \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix}, \quad \bar{L} = \begin{bmatrix} L \\ E_1 \end{bmatrix} \\
D_{11} = \begin{bmatrix} D & 0 \\ 0 & I \end{bmatrix}, \quad D_{12} = \begin{bmatrix} 0 & 0 \\ -E_2 & -E_2 \end{bmatrix}, \quad D_{21} = \begin{bmatrix} D & 0 \end{bmatrix}, \quad D_{22} = \begin{bmatrix} 0 & 0 \end{bmatrix} \\
\bar{C} = \begin{bmatrix} C & 0 \end{bmatrix}, \quad \bar{A}_\tau = \begin{bmatrix} \bar{A}_{\tau 1} & 0 \\ 0 & A_\tau \end{bmatrix}, \quad \bar{A}_{\tau 1} = \begin{bmatrix} A_\tau & 0 \\ 0 & 0 \end{bmatrix}
\end{gathered}$$

The main objective of this paper is to design an integrated FE/FTC strategy for the continuous-time linear time delay systems (1) using dynamic event-triggered communication mechanism, namely, to design fault estimation observer (6)-(8), fault-tolerant controller (9), and dynamic event-triggered mechanism (3) such that '(Gao, Jiang, Shi, Liu, & Xu, 2012)'

(i) the derived augmented systems (10) are asymptotical stable when $\bar{d}(t) = 0$;

(ii) under the zero initial state condition and for arbitrary non-zero $\bar{d}(t) \in L_2[0, +\infty)$, $z(t)$ satisfies the following $\mathcal{H}_\infty$ disturbance attenuation level γ

$$\int_0^\infty z^T(t)z(t)dt \leq \gamma^2 \int_0^\infty \bar{d}^T(t)\bar{d}(t)\mathrm{d}t \tag{11}$$

Some necessary Assumptions and Lemmas are given at first, which will be used to further analysis and design.

Assumption 1 '(Ma, Jin, & Gu, 2015; Wang, Fei, Wang, & Liu, 2019)' It is assumed that the fault function and its derivative are uniformly bounded, i.e., $\|f(t)\| \leq f_0$, $\|\dot{f}(t)\| \leq f_1$ for all $t \geq 0$, where f_0 and f_1 are two known positive constants.

Assumption 2 '(Yang, Huang, Jiang, & Polycarpou, 2019)' It is assumed that (A, B) is controllable.

It should be noted that in Assumption 1, it is required that the fault and its derivative are bounded, which is reasonable in reality. It should be emphasized that the bounds are not required to be known in this work. The Assumption 2 is essential for a control system.

Lemma 1 '(Wang, & Yang, 2015)'. It is supposed that there exist two continuous functions $\nu_1(t)$ and $\nu_2(t)$, and function $g(t, \nu(t))$ is continuously differentiable for $t > 0$ and monotonous increasing for $\nu(t)$. If the following conditions are satisfied

$$\dot{\nu}_1 = g(t, \nu_1(t)),\ \nu_1(t_0) = \nu_{10},\ \dot{\nu}_2(t) \leq g(t, \nu_2(t)),\ \nu_2(t_0) \leq \nu_{10}$$

then $\nu_2(t) \leq \nu_1(t)$ for $t > 0$.

Lemma 2 '(Fei, Guan, & Gao, 2018)'. For a given full-column rank matrix $S \in R^{n\times m}$, there exist two orthogonal matrices $M \in R^{n\times n}$ and $N \in R^{m\times m}$ such that the following condition holds

$$MSN = \begin{bmatrix} M_1 \\ M_2 \end{bmatrix} SN = \begin{bmatrix} \Pi \\ 0 \end{bmatrix} \tag{12}$$

where $M_1 \in R^{m\times n}$, $M_2 \in R^{(n-m)\times n}$, $\Pi = \text{diag}\{\kappa_1, \cdots, \kappa_m\}$, κ_j $(j = 1, 2, \cdots, m)$ are the nonzero singular values of matrix S. If matrix $G \in R^{n\times n}$ has the following form

$$G = M^T \begin{bmatrix} G_1 & 0 \\ 0 & G_2 \end{bmatrix} M = M_1^T G_1 M_1 + M_2^T G_2 M_2 \tag{13}$$

where $G_1 > 0$ and $G_2 > 0$, there is a nonsingular matrix $H \in R^{m\times m}$ satisfying $GS = SH$.

Lemma 3. Consider $\mu(t)$ in (3) being a locally Lipschtiz continuous $\mathcal{K}_\infty$ function, $\beta \in (0, 1)$, $\alpha > 0$, $\Xi > 0$, let y, e_y, μ be given by (1)-(4). Then, for $t > 0$, $\mu(t) + \alpha[\beta y^T(t)\Xi y(t) - e_y^T(t)\Xi e_y(t)] \geq 0$ and $\mu(t) \geq 0$.

Proof: By construction, the ETM (3) ensures $\mu(t)+\alpha[\beta y^T(t)\Xi y(t)-e_y^T(t)\Xi e_y(t)] \geq 0$ for $t > 0$. If $\alpha = 0$, $\mu(t) \geq 0$ holds. Then, assume that $\alpha \neq 0$, the first inequality gives us $\beta y^T(t)\Xi y(t) - e_y^T(t)\Xi e_y(t) \geq -\frac{\mu(t)}{\alpha}$. From (4), one has that for $t > 0$

$$\dot{\mu}(t) \geq -(\lambda + \frac{1}{\alpha})\mu(t),\ \mu_0 \geq 0$$

Then by the solution of first-order linear differential equation and Lemma 1, it follows that $\mu(t) \geq \mu_0 e^{-(\lambda+\frac{1}{\alpha})t}$. Therefore $\mu(t) \geq 0$ holds for $t > 0$.

Remark 2. The internal dynamic variable $\mu(t)$ in (3) can be considered as a filtered value of $\beta y^T(t)\Xi y(t) - e_y^T(t)\Xi e_y(t)$. If the internal dynamic variable $\mu(t)$ is removed, the dynamic ETM in (3) will be transformed into the traditional static ETM as follows

'(Wang, Fei, Wang, & Liu, 2019)':

$$t_{k+1} = \inf\{t > t_k \mid \beta y^T(t)\Xi y(t) - e_y^T(t)\Xi e_y(t) \le 0\}$$

which means that the static event-triggered strategy is regarded as a special case of dynamic ETM (3) as $\alpha \to +\infty$. Compared with static event-triggered scheme, it is not needed for dynamic ETM that $\beta y^T(t)\Xi y(t) - e_y^T(t)\Xi e_y(t)$ remains nonnegative by means of internal dynamic variable $\mu(t)$. Therefore, the introduction of internal variable $\mu(t)$ will be helpful for enlarging the time intervals between two consecutive triggering events.

3. Main Results

3.1. Integrated FE/FTC scheme design

In this section, the first result of this study is given to ensure asymptotical stability with a prescribed $\mathcal{H}_\infty$ disturbance suppression level for the resulting augmented systems (10).

Theorem 1. For a given $\mathcal{H}_\infty$ disturbance attenuation level $\gamma > 0$, and the integrated FE and FTC in (6)-(9), if there exist three positive definite symmetric matrices P, Q and Ξ with a given scalar $0 < \beta < 1/2$ such that the following inequality holds

$$\bar{\Upsilon} = \begin{bmatrix} \bar{\Upsilon}_{11} & P\bar{A}_\tau & P\bar{D} & P\bar{F} & P\bar{E} \\ * & -Q & 0 & 0 & 0 \\ * & * & -\gamma^2 I & 0 & 0 \\ * & * & * & -\Xi & 0 \\ * & * & * & * & -I \end{bmatrix} < 0 \tag{14}$$

where $\bar{\Upsilon}_{11} = P\bar{A} + \bar{A}^T P + \bar{T}^T\bar{T} + I + Q + \beta\vec{C}^T\Xi\vec{C}$, $\vec{C} = [0\ 0\ C]$, I is a unit matrix with appropriate dimension. Then, the augmented systems (10) are asymptotically stable with a prescribed $\mathcal{H}_\infty$ disturbance attenuation level γ.

Proof. Firstly, let's analyze the dynamic characteristics of the internal dynamic variable $\mu(t)$ for $t > 0$. It is easy to know from (3)-(4) that

$$\dot{\mu}(t) + \lambda\mu(t) = \beta y^T(t)\Xi y(t) - e_y^T(t)\Xi e_y(t) \ge -\frac{\mu(t)}{\alpha}$$

with $\mu(0) = \mu_0 \ge 0$.

According to Lemma 3, the following inequalities hold

$$\mu(t) \ge \mu_0 e^{-(\lambda + \frac{1}{\alpha})t},\ \mu(t) \ge 0 \tag{15}$$

Construct the Lyapunov-Krasovskii functional as follows

$$V(t) = h^T(t)Ph(t) + \int_{t-\tau(t)}^{t} h^T(s)Qh(s)\mathrm{d}s + \mu(t) \tag{16}$$

where $P > 0$ and $Q > 0$ are two positive definite matrices, and $\mu(t) \ge 0$ is guaranteed by (15).

Consider systems (10). Taking the first derivative of $V(t)$ yields

$$\begin{aligned}\dot{V}(t) &= h^T(t)(P\bar{A}+\bar{A}^TP)h(t)+2h^T(t)P\bar{A}_\tau h(t-\tau(t)) \\ &\quad +2h^T(t)PG(t)+2h^T(t)P\bar{D}\bar{d}(t) \\ &\quad +2h^T(t)P\bar{F}e_y(t)+h^T(t)Qh(t)-h^T(t-\tau(t))Qh(t-\tau(t))+\dot{\mu}(t)\end{aligned}$$

According to $\Delta A = E\Delta HT$ and $\Delta H^T\Delta H \le I$, it is easily known that

$$\begin{aligned}2h^T(t)PG(t) &= 2h^T(t)P\begin{bmatrix}E\\0\\E\end{bmatrix}\Delta HTx(t) \\ &\le h^T(t)P\begin{bmatrix}E\\0\\E\end{bmatrix}\begin{bmatrix}E\\0\\E\end{bmatrix}^TPh(t)+x^T(t)T^T\Delta H^T\Delta HTx(t) \\ &\le h^T(t)P\begin{bmatrix}E\\0\\E\end{bmatrix}\begin{bmatrix}E\\0\\E\end{bmatrix}^TPh(t)+x^TT^TTx(t) \\ &\triangleq h^T(t)P\bar{E}\bar{E}^TPh(t)+h^T\bar{T}^T\bar{T}h(t)\end{aligned} \tag{17}$$

where $\bar{E}=[E^T,0,E^T]^T$ and $\bar{T}=[T,0,0]$.

Substituting (17) into $\dot{V}(t)$, the following inequality could be obtained that

$$\begin{aligned}\dot{V}(t) &\le h^T(t)(P\bar{A}+\bar{A}^TP+P\bar{E}\bar{E}^TP+\bar{T}^T\bar{T})h(t)+2h^T(t)P\bar{A}_\tau h(t-\tau(t)) \\ &\quad +2h^T(t)P\bar{D}\bar{d}(t)+2h^T(t)P\bar{F}e_y(t)+h^T(t)Qh(t) \\ &\quad -h^T(t-\tau(t))Qh(t-\tau(t))-\lambda\mu+\beta y^T(t)\Xi y(t)-e_y^T(t)\Xi e_y(t)\end{aligned} \tag{18}$$

where equation (4) is used to obtain the last expression above.

When $\bar{d}(t)=0$, it follows from (18) that

$$\dot{V}(t) \le \xi^T(t)\Upsilon\xi(t)$$

where $\xi(t)=[h^T(t),h^T(t-\tau(t)),e_y^T(t)]^T$ and

$$\Upsilon = \begin{bmatrix} P\bar{A}+\bar{A}^TP+P\bar{E}\bar{E}^TP+\bar{T}^T\bar{T}+Q+\beta\vec{C}^T\Xi\vec{C} & P\bar{A}_\tau & P\bar{F} \\ * & -Q & 0 \\ * & * & -\Xi\end{bmatrix}$$

It is easy to see that $\Upsilon<0$ if $\bar{\Upsilon}<0$ in (14). According to the Lyapunov stability analysis, from condition (14), the resulting augmented systems (10) are asymptotically stable.

In order to analyze the disturbance suppression performance, an $\mathcal{H}_\infty$ performance function $J(t)$ is defined as

$$J(t)=\int_0^\infty (z^T(t)z(t)-\gamma^2\bar{d}^T(t)\bar{d}(t))dt \tag{19}$$

where γ is a positive constant.

From the above proof, we know that systems (10) are asymptotically stable if Υ are negative-definite. So we can conclude that $\bar{d}(t) \in L_2[0, +\infty)$, and for any nonzero $\bar{d}(t)$ the following equation can be obtained under zero initial condition

$$\begin{aligned} J(t) &= \int_0^{\infty} (\dot{V}(t) + z^T(t)z(t) - \gamma^2 \bar{d}^T(t)\bar{d}(t))\mathrm{d}t - V(\infty) \\ &\leq \int_0^{\infty} (\dot{V}(t) + z^T(t)z(t) - \gamma^2 \bar{d}^T(t)\bar{d}(t))\mathrm{d}t \end{aligned} \tag{20}$$

Substituting (18) into (20), the following inequality is derived

$$\begin{aligned} J(t) \leq\ & 2h^T(t)P\dot{h}(t) + h^T(t)Qh(t) - h^T(t-\tau(t))Qh(t-\tau(t)) - \lambda\mu + \beta y^T(t)\Xi y(t) \\ & - e_y^T(t)\Xi e_y(t) + h^T(t)h(t) - \gamma^2 \bar{d}^T(t)\bar{d}(t) \leq \bar{\xi}^T(t)\vec{\Upsilon}\bar{\xi}(t) \end{aligned} \tag{21}$$

where $\bar{\xi}(t) = [h^T(t),\ h^T(t-\tau(t)),\ \bar{d}^T(t),\ e_y^T(t)]^T$ and

$$\vec{\Upsilon} = \begin{bmatrix} \bar{\Upsilon}_{11} + P\bar{E}\bar{E}^T P & P\bar{A}_\tau & P\bar{D} & P\bar{F} \\ * & -Q & 0 & 0 \\ * & * & -\gamma^2 I & 0 \\ * & * & * & -\Xi \end{bmatrix}$$

with $\bar{\Upsilon}_{11}$ is defined in (14).

By applying the Schur complement into the inequality $\bar{\Upsilon} < 0$ in (14), it could be seen that $J(t) \leq \bar{\xi}^T(t)\vec{\Upsilon}\bar{\xi}(t) < 0$. It is known from (21) that the $\mathcal{H}_\infty$ disturbance suppression performance (11) is satisfied. The proof of Theorem 1 is completed.

Note that, Theorem 1 only analyzes the stability of the augmented systems (10), but the unknown gain parameters of the integrated FE and FTC scheme (6)-(9) can not be solved from (14) directly. In the following, the feasible design procedures are given by Theorem 2 and Theorem 3.

Theorem 2. For a given $\mathcal{H}_\infty$ disturbance attenuation level $\gamma > 0$, and the integrated FE and FTC scheme designed as (6)-(9), if there exist positive definite matrices P_1, P_2, Q_1, Q_2 and Ξ, real matrices $\tilde{L}$, $\bar{K}$, $\bar{E}_2$ and a nonsingular matrix H such that the following conditions are satisfied

$$W = \begin{bmatrix} W_{11} & W_{12} & P_1\bar{A}_\tau & 0 & W_{15} & W_{16} & P_1\bar{E}_1 & 0 \\ * & W_{22} & 0 & P_2 A_\tau & W_{25} & 0 & 0 & P_2 E \\ * & * & -Q_1 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & -Q_2 & 0 & 0 & 0 & 0 \\ * & * & * & * & -\gamma^2 I & 0 & 0 & 0 \\ * & * & * & * & * & -\Xi & 0 & 0 \\ * & * & * & * & * & * & -I & 0 \\ * & * & * & * & * & * & * & -I \end{bmatrix} < 0 \tag{22}$$

$$P_2 B = BH \tag{23}$$

where $W_{11} = (P_1\bar{A}_1 - \tilde{L}\bar{C}) + (P_1\bar{A}_1 - \tilde{L}\bar{C})^T + I_{n+r} + Q_1 + diag\{T^T T, 0\}$, $W_{12} = [-B\bar{K}\ \ P_2 E_1]^T$, $W_{15} = [P_1 D_{11}\ \ \bar{D}_{12}]$, $W_{16} = -\tilde{L}$, $W_{22} = (P_2 A + B\bar{K})^T + (P_2 A + B\bar{K}) + \beta C^T \Xi C + I_n + Q_2$, $W_{25} = [P_2 D_{21}\ 0]$, $\bar{D}_{12} = \begin{bmatrix} 0 & 0 \\ \bar{E}_2 & \bar{E}_2 \end{bmatrix}$, $\bar{E}_1 = \begin{bmatrix} E \\ 0 \end{bmatrix}$. Then, the augmented systems (10) are asymptotically stable with a given $\mathcal{H}_\infty$ disturbance attenuation level γ. Meanwhile, the gain matrices of the designed FE/FTC scheme (6)-(9) can be obtained by $\bar{L} = P_1^{-1}\tilde{L}$, $K = H^{-1}\bar{K}$, $D_{12} = P_1^{-1}\bar{D}_{21}$.

Proof. In (16), it is assumed that P and Q have the following forms respectively

$$\begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix}, \quad \begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix}$$

where $P_1 \in R^{(n+m)\times(n+m)}$, $P_2 \in R^{n\times n}$, $Q_1 \in R^{(n+m)\times(n+r)}$, $Q_2 \in R^{n\times n}$. Let $\tilde{L} = P_1\bar{L}$, $\bar{K} = HK$. Meanwhile, it is assumed that there exists a matrix H with appropriate dimensions satisfying $P_2B = BH$. After some calculations, it is not difficult to find that the inequality (14) described in Theorem 1 is equivalent to the conditions (22) and (23). Then Theorem 2 holds by applying the similar proof process used in Theorem 1.

Although Theorem 2 gives the design procedures about the unknown gain matrices of the integrated FE and FTC (6)-(9), the equality constraint condition (23) is required in Theorem 2, which makes (22) not to be a LMI and thus can not be solved directly by LMI toolbox. For this problem, the equality constrain (23) should be converted into a standard LMI by using Lemma 2.

Consider the fact that $\mathrm{rank}(B) = m$. From Lemma 2, there exist two orthogonal matrices $M \in R^{n\times n}$, $N \in R^{m\times m}$ such that

$$MBN = \begin{bmatrix} M_1 \\ M_2 \end{bmatrix} BN = \begin{bmatrix} \Gamma \\ 0 \end{bmatrix} \tag{24}$$

where $M_1 \in R^{m\times n}$, $M_2 \in R^{(n-m)\times n}$, $\Gamma = \mathrm{diag}\{\rho_1, \cdots, \rho_m\}$ with $\rho_j (j = 1, 2, \cdots, m)$ the nonzero singular value of B. Then, according to Lemma 2, if the matrix P_2 can be represented by

$$P_2 = M^T \begin{bmatrix} V_1 & 0 \\ 0 & V_2 \end{bmatrix} M = M_1^T V_1 M_1 + M_2^T V_2 M_2 \tag{25}$$

where $V_1 > 0$, $V_2 > 0$. There is a nonsingular matrix $H \in R^{m\times m}$ satisfying $P_2B = BH$.

Based on the description above, the integrated design procedures of fault estimation observer, fault tolerant controller and dynamic ETM are to be developed by the following theorem.

Theorem 3. For a given $\mathcal{H}_\infty$ disturbance attenuation level $\gamma > 0$, and the integrated FE and FTC scheme designed as (6)-(9), if there exist positive definite matrices P_1, Ξ, V_1 and V_2, real matrices $\tilde{L}$, $\bar{K}$, $\bar{E}_2$ such that the following inequality holds

$$\bar{W} = \begin{bmatrix} \bar{W}_{11} & \bar{\Psi}_{12} & P_1\bar{A}_\tau & 0 & \bar{W}_{15} & \bar{W}_{16} & P_1\bar{E}_1 & 0 \\ * & \bar{W}_{22} & 0 & \bar{W}_{24} & \bar{W}_{25} & 0 & 0 & \bar{W}_{28}E \\ * & * & -Q_1 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & -Q_2 & 0 & 0 & 0 & 0 \\ * & * & * & * & -\gamma^2 I & 0 & 0 & 0 \\ * & * & * & * & * & -\Xi & 0 & 0 \\ * & * & * & * & * & * & -I & 0 \\ * & * & * & * & * & * & * & -I \end{bmatrix} < 0 \tag{26}$$

where $\bar{W}_{24} = M_1^T V_1 M_1 A_\tau + M_2^T V_2 M_2 A_\tau$, $\bar{W}_{28} = M_1^T V_1 M_1 + M_2^T V_2 M_2$ and $\bar{W}_{ij}$ is derived from the corresponding W_{ij} in (22) by replacing P_2 with $M_1^T V_1 M_1 + M_2^T V_2 M_2$,

$\bar{E}_1 = \begin{bmatrix} E \\ 0 \end{bmatrix}$. Then, the augmented systems (10) are asymptotically stable with a prescribed $\mathcal{H}_\infty$ disturbance attenuation level γ. In addition, the gain parameters of the designed FE and FTC scheme (6)-(9) can be obtained by $\bar{L} = P_1^{-1}\tilde{L}$, $K = N\Gamma^{-1}V_1^{-1}\Gamma N^T\bar{K}$, $D_{12} = P_1^{-1}\bar{D}_{21}$.

Proof. Similar to the proof in Theorems 1-2, Theorem 3 can be obtained directly.

Remark 3. Compared with the fault estimation observer design approaches developed in '(Chen, Shi, & Liu, 2019; Du, Cocquempot, & Jiang, 2019; Qiu, Jiang, Wen, & Mao, 2015)', the input signal $\bar{y}(t)$ of fault estimation observer (7) is generated by the event generator and ZOH. It increases the design difficulty of fault estimation observer, and this will be a focus of this study. In addition, the developed results could effectively alleviate network transmission and online computing pressure compared with the designed observer in '(Chen, Shi, & Liu, 2019; Du, Cocquempot, & Jiang, 2019; Qiu, Jiang, Wen, & Mao, 2015)'.

Remark 4. In '(Wang, Fei, Wang, & Liu, 2019)', the authors propose a fault estimation and fault-tolerant control approach for linear networked control systems, the fault estimation algorithm is designed as $\dot{\hat{f}} = E_1\hat{e}_y(t)$, which has poor fault estimation accuracy and usually generates relatively large estimation error. Compared with the fault estimation result obtained in '(Wang, Fei, Wang, & Liu, 2019)', the fault estimation algorithm (7) in this paper has been modified by introducing the differential term $\dot{\hat{e}}_y(t)$, which enhances the fault estimation accuracy. In turn, the closed-loop fault tolerant control performance has also been improved. It should be noted that the static event-triggered mechanism is used to the data transmission in '(Wang, Fei, Wang, & Liu, 2019)', while the dynamic event-triggered mechanism is used to the data transmission in this study.

The following procedure is used to implement the control scheme given by (1).

Step 1: Verify the full-column rank matrix B by using the criterion rank$(B) = m$ and find the pseudo inverse matrix B^+.

Step 2: Verify the controllability of B by using the criterion rank$(B, AB, \ldots, A^{n-1} B) = n$, which guarantees that Assumption 2 holds.

Step 3: Apply Lemma 2 to remove the equality constraint (23) and then the matrix P_2 can be deduced as shown in (25).

Step 4: Select an appropriate γ such that (26) is resolvable and $\bar{L}$, $\bar{K}$ are obtained. One should start with a large value of γ and then decrease this value incrementally. Note that γ represents disturbance attenuation level of system and the choice of γ is not unique.

Step 5: Compute the observer gain matrix L using the equation $\bar{L} = P_1^{-1}\tilde{L}$ and $\bar{L} = [L; E1]$ in (10).

Step 6: Compute the control gain matrix K using the equation $K = N\Gamma^{-1}V_1^{-1}\Gamma N^T\bar{K}$.

Step 7: Construct the fault tolerant controller $u(t) = K\hat{x}(t) - B^+B\hat{f}(t)$ in (9) with parameters K obtained in step 6 and B^+ in step 1.

3.2. Exclusion on Zeno behavior

Note that an infinite times triggered phenomenon within a finite time is the Zeno phenomenon '(Abdelrahim, Postoyan, Daafouz, & Nesic, 2016)'. Thus the minimum inter-event intervals of the considered event-triggered dynamical systems should be positive in order to prevent the Zeno phenomenon. The sections above have analyzed the stability of the controlled augmented system (10), and sets of sufficient conditions have been provided to guarantee that the controlled system (10) is asymptotically stable. In this subsection, under the assumption that the system (10) is asymptotically stable which implies that all the states of system (10) are bounded, the existence of a positive lower bound on inter-event intervals of the considered dynamic event generator will be investigated.

The following result is now ready to be presented.

Theorem 4. Consider the event-triggered linear time delay systems (1) with the integrated FE and FTC scheme (6)-(9). Then, the inter-event intervals of dynamic event-triggered mechanism (3) are bounded by a positive constant δ, which has the following form

$$\delta = \begin{cases} (1/a)\ln\left((a/\bar{b})\varepsilon + 1\right), & a \neq 0 \\ (1/\bar{b})\varepsilon, & a = 0 \end{cases} \tag{27}$$

where $\bar{b}$ is a positive constant,

$$\varepsilon = \sqrt{\frac{2\beta\frac{\lambda_{max}(\Xi)}{\lambda_{min}(\Xi)}}{\left(1 - 2\beta\frac{\lambda_{max}(\Xi)}{\lambda_{min}(\Xi)}\right)}}\|y(t_k)\|, \quad a = |\lambda_{max}(A_3)| \tag{28}$$

The matrix A_3 is defined in (10) and Ξ satisfies (26).

Proof. Note that $e_y(t) = y(t_k) - y(t),\ t \in [t_k, t_{k+1})$, it can be seen that

$$\dot{e}_y(t) = -\dot{y}(t) = -C[Ax(t) + A_\tau x(t-\tau(t)) + \Delta Ax(t) + B(u(t) + f(t)) + Dd(t)]$$

Substituting FTC scheme $u(t) = K\hat{x}(t) - B^\dagger B\hat{f}(t)$ into the above equality yields

$$\dot{e}_y(t) = -C[A_3x(t) + A_2q(t) + A_\tau x(t-\tau(t)) + \Delta Ax(t) + Dd(t)]$$

where $q(t) = [\tilde{x}^T(t), \tilde{f}^T(t)]^T$.

From Assumption 1, it follows that

$$\begin{aligned} \|\dot{e}_y(t)\| &= \|CA_3x(t) + CA_2q(t) + CA_\tau x(t-\tau(t)) + \Delta Ax(t) + CDd(t)\| \\ &\leq \|A_3\|\|y(t_k) - e_y(t)\| + \|CA_2\|\|q(t)\| + \|E\|\|T\|\|x(t))\| \\ &\quad + \|CD\|d_0 + \|CA_\tau\|\|x(t-\tau(t))\| \\ &\leq \|A_3\|\|y(t_k)\| + \|A_3\|\|e_y(t)\| + \|CA_2\|\|q(t)\| + \|E\|\|T\|\|x(t))\| \\ &\quad + \|CA_\tau\|\|x(t-\tau(t))\| + \|CD\|d_0 \\ &\leq a\|e_y(t)\| + \bar{b} \end{aligned} \tag{29}$$

where a is given in (28), $b = |\lambda_{max}(A_3)|\|y(t_k)\| + \|CA_2\|\|q(t)\| + \|CA_\tau\|\|x(t-\tau(t))\| + \|E\|\|T\|\|x(t))\| + \|CD\|d_0$ and $\bar{b}$ is the upper bound of b.

Remark 5. Noting that the augmented systems (10) are proved to be asymptotically stable with a prescribed $\mathcal{H}_\infty$ disturbance attenuation level γ in Theorem 3, namely, the original system (1), its error system and fault estimated error system are all asymptotically stable with the $\mathcal{H}_\infty$ performance. Therefore, $y(t_k)$, $\tilde{x}(t)$, $\tilde{f}(t)$, $x(t-\tau(t))$ and $e_y(t)$ are bounded, that is, there exist a positive constant $\bar{b}$ and a

nonnegative function $\omega(t)$ such that $b \leq \bar{b}$ and $\|e_y(t)\| \leq \omega(t)$.
Construct a dynamical system

$$\dot{\omega}(t) = a\omega(t) + \bar{b}, \quad t \in [t_k,\ t_{k+1}) \tag{30}$$

where $\omega(t_k) = 0$, a and b are given in (28) and (29), respectively.
Then it is clear to see that

$$\|e_y(t)\| \leq \omega(t) \tag{31}$$

where $\omega(t)$ is the solution to (30).
The solution of (30) is deduced as

$$\omega(t) = \begin{cases} \frac{\bar{b}}{a}(e^{a(t-t_k)} - 1), & a \neq 0 \\ \bar{b}(t - t_k), & a = 0 \end{cases} \tag{32}$$

Considering the dynamic ETM (3), for $t \in [t_k, t_{k+1})$, we have

$$\mu(t) + \alpha(\beta y^T(t)\Xi y(t) - e_y^T(t)\Xi e_y(t)) > 0 \tag{33}$$

From (33), it can be readily known that

$$\|e_y(t)\| < \frac{1}{\sqrt{\lambda_{min}(\Xi)}}\sqrt{\beta y^T(t)\Xi y(t) + \frac{\|\mu(t)\|}{\alpha}}$$

$$\leq \frac{1}{\sqrt{\lambda_{min}(\Xi)}}\sqrt{\beta\lambda_{max}(\Xi)\|y(t)\|^2 + \frac{\|\mu(t)\|}{\alpha}}$$

$$= \sqrt{\beta\frac{\lambda_{max}(\Xi)}{\lambda_{min}(\Xi)}\|y(t_k) - e_y(t)\|^2 + \frac{\|\mu(t)\|}{\lambda_{min}(\Xi)\alpha}} \tag{34}$$

From (34), the following inequality holds,

$$\|e_y(t)\|^2 < \beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}(\|y(t_k) - e_y(t)\|)^2 + \frac{\|\mu(t)\|}{\lambda_{min}(\Xi)\alpha}$$

$$= \beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}(\|y(t_k)\|^2 + \|e_y(t)\|^2 - 2y(t_k)e_y(t)) + \frac{\|\mu(t)\|}{\lambda_{min}(\Xi)\alpha}$$

$$\leq 2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\|y(t_k)\|^2 + 2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\|e_y(t)\|^2 + \frac{\|\mu(t)\|}{\lambda_{min}(\Xi)\alpha} \tag{35}$$

which leads to

$$\left(1-2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\right)\|e_y(t)\|^2 \leq 2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\|y(t_k)\|^2 + \frac{\|\mu(t)\|}{\lambda_{min}(\Xi)\alpha} \tag{36}$$

or

$$\|e_y(t)\| \leq \sqrt{\frac{2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\|y(t_k)\|^2 + \frac{\|\mu(t)\|}{\lambda_{min}(\Xi)\alpha}}{\left(1-2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\right)}} \tag{37}$$

If $a \neq 0$, it follows from (32) and (37) that

$$t - t_k \geq \frac{1}{a}\ln\left(\frac{a}{\bar{\bar{b}}}\sqrt{\frac{2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\|y(t_k)\|^2 + \frac{\|\mu(t)\|}{\lambda_{min}(\Xi)\alpha}}{\left(1-2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\right)}} + 1\right)$$

$$> \frac{1}{a}\ln\left(\frac{a}{\bar{\bar{b}}}\sqrt{\frac{2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\|y(t_k)\|^2}{\left(1-2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\right)}} + 1\right) = \frac{1}{a}\ln\left(\frac{a}{\bar{\bar{b}}}\sqrt{\frac{2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}}{\left(1-2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\right)}}\|y(t_k)\| + 1\right) \triangleq \delta \tag{38}$$

If $a = 0$, it follows that

$$t - t_k \geq \frac{1}{\bar{\bar{b}}}\sqrt{\frac{2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\|y(t_k)\|^2 + \frac{\|\mu(t)\|}{\lambda_{min}(\Xi)\alpha}}{\left(1-2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\right)}}$$

$$> \frac{1}{\bar{\bar{b}}}\sqrt{\frac{2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\|y(t_k)\|^2}{\left(1-2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\right)}} = \frac{1}{\bar{\bar{b}}}\sqrt{\frac{2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}}{\left(1-2\beta\frac{\lambda_{max(\Xi)}}{\lambda_{min}(\Xi)}\right)}}\|y(t_k)\| \triangleq \delta \tag{39}$$

Consider $0 < \beta < \frac{1}{2}\frac{\lambda_{min(\Xi)}}{\lambda_{max}(\Xi)} < 1/2$. It is easy to see that $\delta > 0$, which means the Zeno phenomenon is excluded.

Remark 6. The integrated FE and FTC problem for a linear 3-DOF helicopter flight control system has been studied in '(Lan, Patton, & Zhu, 2017)'. However, the delayed state variable and dynamic event-triggered mechanism are not considered in '(Lan, Patton, & Zhu, 2017)'. Inspired by the work in '(Lan, Patton, & Zhu, 2017)', the integrated design approach of state/fault estimation observer, fault tolerant controller and dynamic ETM have been developed for linear time delay systems with actuator faults in this study, which can be considered as an expansion of the results obtained in '(Lan, Patton, & Zhu, 2017)'.

Remark 7. Compared with active FTC '(Qian, Jiang, & Liu, 2016; Qian, Zheng, & Cheng, 2019; Wang, & Han, 2016; Yang, Lin, Chen, & Wang, 2019)', the integrated FE and FTC scheme developed in this paper does not need fault detection and isolation module. It will not lead to the time delay problem of fault accommodation, and the impact of unknown fault could be eliminated as soon as possible. Compared with passive FTC '(Gao, Jiang, Shi, Liu, & Xu, 2012)', which has the limited fault acceptability only for the small amplitude fault, the integrated FE and FTC scheme developed in this paper provides more accurate fault estimation and the fault compensation-based fault tolerant control algorithm for the considered plant, such that the closed loop control performance is guaranteed even in the presence of large amplitude faults.

Remark 8. In '(Chen, Sun,& Karimi, 2019)', an adaptive event-triggered mechanism (AETM) is investigated for discrete time-varying systems by using finite-time generalized dissipative filter. To reduce the communication network resources, two adaptive event-triggered mechanisms are taken into consideration in sensor-to-observer and observer-to-controller channels in '(Chen, Karimi,& Sun, 2019)'. The thresholds of both AETMs are adjusted according to the estimation error rather than some fixed ones and an observer-based time-varying control are obtained, which ensure the time-varying error system to be finite time stable. In '(Kommuri, Defoort, Karimi, & Veluvolu, 2016)', a robust observer-based sensor fault-tolerant control is designed for PMSM in electric vehicles but the event-triggered mechanism is not considered. While a dynamic event-triggered mechanism similar to AETM is proposed in this study, which further considers the time-varying delays and actuator faults. Thus our control scheme is an expansion and improvement of the existing work in '(Chen, Karimi,& Sun, 2019; Chen, Sun,& Karimi, 2019; Kommuri, Defoort, Karimi, & Veluvolu, 2016)'.

Remark 9. Based on the work in '(Girard, 2015)', a strategy for the choice of parameters in (3) and (4) can be given as follows. Firstly, it should be noted that the parameter λ in (4) affects the minimum inter-execution time of the dynamic ETM (3). Assume that ς is an upper bound of the spectral radius $\rho(A + BK)$. To exclude Zeno behavior and guarantee a larger minimum inter-execution time, it needs $\lambda = (1-\beta)\kappa \leq 2\varsigma$ where $0 < \kappa \leq 2\rho(A + BK) \leq 2\varsigma, 0 < \beta < 1$. Then the value of β determines the degradation of the decay rate of the Lyapunov function $\dot{V}_1(t) = h(t)^T h(t)$ with respect to the "ideal" closed-loop system. Noting that the "ideal" closed-loop system is the system (10) with $V_1(0) = J(0)$ and $J(t)$ is the quadratic integral performance index as shown in (19), we can tune the decay rate of the Lyapunov function by choosing $\mu(0) = 0$ and $\beta = 1 - \lambda/\kappa$. Finally, the parameter α directly affects the degradation of the performance index (19). Simultaneously, the best lower bound on the minimum inter-execution time is obtained for $\alpha \in [0, 1/(2\varsigma - \lambda)]$. In order to minimize the degradation of the performance index, α should be chosen as large as possible. Thus, it is reasonable to choose $\alpha = 1/(2\varsigma - \lambda)$.

4. Simulation

In this section, an F-404 aircraft engine system, in '(Chen, Huang, & Fu, 2016)' is employed to demonstrate the advantages of the designed integrated FE and FTC scheme based on dynamic event-triggered communication mechanism. The matrix parameters of the considered linear time delay system are given by

$$A = \begin{bmatrix} -1.46 & 0 & 2.428 \\ 0.164 & -0.4 & -0.3788 \\ 0.3107 & 0 & -2.231 \end{bmatrix}, \ A_\tau = \begin{bmatrix} 0.21 & -0.1 & 0 \\ 0.11 & -0.35 & 0 \\ -0.2 & 0.1 & 0.76 \end{bmatrix}, \ D = \begin{bmatrix} 0.5 \\ 1.5 \\ 1 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.11 & 0 \\ 0.14 & -0.4 \\ 0.1 & 0 \end{bmatrix}, \ C = \begin{bmatrix} -0.1 & 0 & 1 \\ 0.15 & -2 & -0.1 \\ 0.1 & 0.2 & 0.1 \end{bmatrix}$$

$$E = \begin{bmatrix} 0.1 & 0 & 0.15 \\ 0.15 & 0.1 & 0.2 \\ 0.2 & 0.1 & 0.1 \end{bmatrix}, \ T = \begin{bmatrix} 0.1 & 0 & 0.1 \\ 0 & 0.1 & 0 \\ 0.1 & 0 & 0.1 \end{bmatrix}, \ \Delta H = \sin(t) \quad (40)$$

In the F-404 aircraft engine system, $x_1(t)$ and $x_2(t)$ represent the horizontal position of the aircraft, $x_3(t)$ is the altitude of the aircraft, $u_1(t)$ and $u_2(t)$ are the opening angles of engine throttle. In simulation, it is assumed that an abrupt actuator fault occurred in the second channel at the 10th second, namely,

$$f_1(t) = 0, \quad f_2(t) = \begin{cases} 0, & 0 \le t < 10 \\ 0.3\sin(0.4(t-10)), & \text{otherwise} \end{cases}$$

The state time delay $\bar{\tau}$ considered in this study is assumed to be $0.1s$, and the initial values of the observer and system are selected as $\hat{x}(0) = [0, \ 0, \ 0]^T$, $\hat{f}_1(0) = \hat{f}_2(0) = 0$, respectively. $\phi(t) = \cos(t)[0.2, \ -0.2, \ 0.1]^T$ for $t \in [-0.1, 0]$, $d(t) = 0.2e^{-0.2t}\sin(0.2t)$. The upper and lower bounds of control input are set as 8 and -5, respectively.

According to the above design procedure, we can implement the controller and estimator design and simulation. First, it is clear that $f_1(t)$ and $f_2(t)$ are norm bounded. Meanwhile $||\dot{f}_1(t)|| = 0, ||\dot{f}_2(t)|| \le 0.12$, namely both the synthetic effects of time-varying fault and its derivative are norm bounded for the real system (40), which satisfy the Assumption 1. The given system is controllable as $\text{rank}(B, AB, A^2B) = 3$, which implies that Assumption 2 holds. All the assumption conditions of Theorem 1-3 are satisfied so the control scheme can be carried out.

It is clear that B is the full column rank since $\text{rank}(B) = 2$ and one yields the pseudo inverse matrix of B

$$B^+ = \begin{bmatrix} 5 & 0 & 5 \\ 1.75 & -2.5 & 1.75 \end{bmatrix}$$

The following matrices can be calculated according to Lemma 2.

$$M_1 = \begin{bmatrix} -0.0953 & -0.9917 & -0.0867 \\ 0.7338 & -0.1288 & 0.6671 \end{bmatrix}, \ M_2 = \begin{bmatrix} -0.6727 & 0 & 0.7399 \end{bmatrix}$$

$$\Gamma = \begin{bmatrix} 0.4270 & 0 \\ 0 & 0.1393 \end{bmatrix}, \ N = \begin{bmatrix} -0.3700 & 0.9290 \\ 0.9290 & 0.3700 \end{bmatrix}$$

The dynamic event-triggered mechanism parameters are chosen as $\beta = 0.25$, $\alpha = 0.02$, $\lambda = 10$, $\mu(0) = 0$. By selecting $\mathcal{H}_\infty$ disturbance attenuation level $\gamma = 1.3$, the unknown gain matrices of the integrated FE and FTC scheme can be solved using Matlab tool box. Then the gain matrix K of the controller and the gain matrix L of the estimator can be obtained as follows.

$$K = \begin{bmatrix} -76.0556 & 6.3110 & -84.5783 \\ -27.3250 & 72.4479 & -30.5436 \end{bmatrix}, L = \begin{bmatrix} 1.8447 & -0.1459 & 0.8225 \\ -0.0850 & -4.9284 & 0.4556 \\ 0.7750 & -0.3503 & 0.3745 \end{bmatrix}$$

For the considered linear time delay systems (1) under the designed integrated FE and FTC strategy (6)-(9), simulation results are obtained using Matlab. To be more comprehensive, the disturbance effects should be discussed under different settings. In connection with this, let $d(t)$ be $0.05e^{-0.2t}\sin(0.2t)$, $0.2e^{-0.2t}\sin(0.2t)$ and $0.5e^{-0.2t}\sin(0.2t)$, respectively. Thus the state estimated error curves are depicted with three different disturbance conditions in Figure 2. The simulation shows that the estimation error increases with the increase of the magnitude of $d(t)$, which shows that the influence of disturbance on the system enhances with the increase of $d(t)$. Moreover, it is also proved that our robust control method is only effective for bounded disturbances. If the bound of disturbance exceeds the prescribed upper bound, the control performance may not be guaranteed. Notice that the follow-up simulation results are obtained based on the $d(t) = 0.2e^{-0.2t}\sin(0.2t)$. The system state trajectories and their estimated values are displayed in Figure 3, and the control input curves are shown in Figure 4. It is clear to see that the closed loop time delay system under the integrated FE and FTC approach proposed in this paper is almost not affected by the considered actuator fault signal $f_2(t)$. Meanwhile, the actual actuator fault signal $f_2(t)$ and its estimation $\hat{f}_2(t)$ are depicted in Figure 5, which indicates that the proposed fault estimation algorithm (7) achieves a good fault estimation performance. Figure 6 shows the dynamics of $\mu(t)$ and release instants intervals of event generator with dynamic ETM (3). In order to illustrate the superiority of the proposed integrated FE and FTC strategy, some simulation comparisons are discussed as follows. In '(Wang, Fei, Wang, & Liu, 2019)', a static ETM-based FE and FTC scheme is developed for a linearized networked control system, it is used to stabilize the considered linear time delay systems (1) in actuator faulty case. The corresponding simulation results are displayed in Figures 7-9. Figure 7 exhibits the system state estimation error curves, Figure 8 displays the system state trajectories and their estimated values curves, and Figure 9 shows the control input curves. It is easily seen from Figures 7-9 that the faulty closed loop time delay system has poor control performance. Figure 10 shows the fault estimation curve, which has obviously fault estimation error. Figure 11 is the release instants and release intervals of event generator with static ETM. To demonstrate the superiority of our control scheme, the integral of squared state estimated errors and control inputs has been listed in Table 1 compared with the scheme in '(Wang, Fei, Wang, & Liu, 2019)', where $e_i = x_i - \hat{x}_i$ (i=1,2,3). The difference between the two schemes lies in the event-triggered mechanism and fault estimator. It is clear that the integral of squared state estimated errors and control inputs is smaller using DETM, which shows our control scheme has better control performance.

Table 1. The integral of squared state estimated errors and control inputs with two different schemes

Triggered Type	e_1	e_2	e_3	u_1	u_2
DETM	0.2167	0.3412	0.5565	861.663	810.8917
SETM	0.3344	0.4645	0.6883	972.9942	895.6125

By simulation comparisons, it can be seen that the static ETM-based FE and FTC approach proposed in '(Wang, Fei, Wang, & Liu, 2019)' does not completely offset the

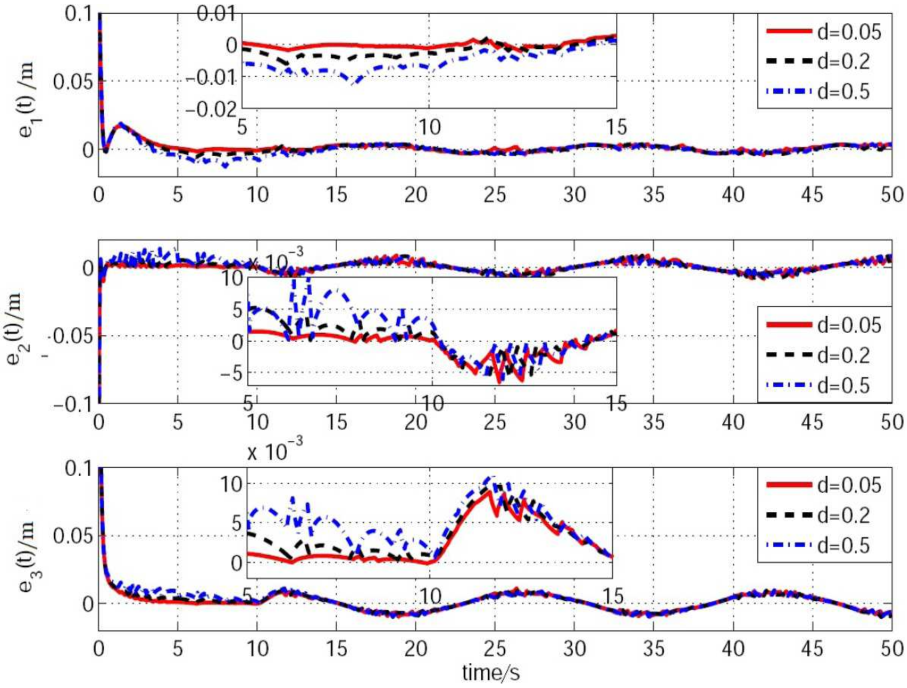

Figure 2. The time responses of the state estimated error using our FE/FTC scheme

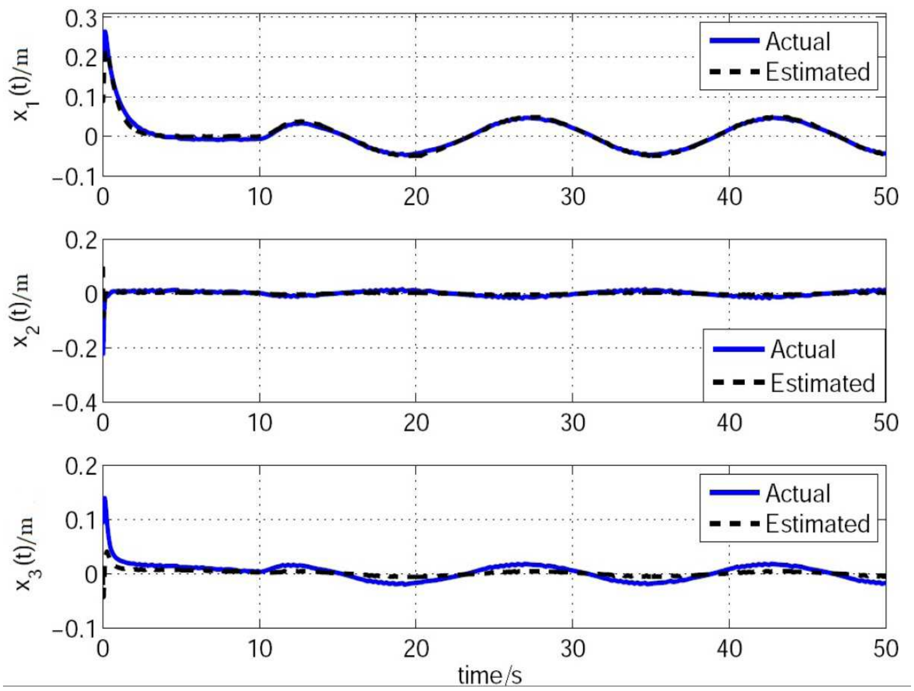

Figure 3. The time responses of the state and its estimation using our FE/FTC scheme

effects of actuator failure described above. The main reason is that the designed fault estimation algorithm in '(Wang, Fei, Wang, & Liu, 2019)' only uses the proportional control algorithm, namely, $\dot{\hat{f}} = E_1\hat{e}_y(t)$, which may lead to a larger error between the estimated fault and the actual fault, and further negative influence on the control performance of the whole closed-loop systems. In this study, a modified fault estimation algorithm is developed by adding one differential term in controller, namely, $\dot{\hat{f}} = E_1\hat{e}_y(t) + E_2\dot{\hat{e}}_y(t)$, such that the fault estimation performance is obviously improved. On this basis, the closed-loop control performance is also greatly improved. It can be concluded that the proposed FE and FTC strategy based on dynamic event-triggered mechanism has provided better performance of fault estimation and accommodation.

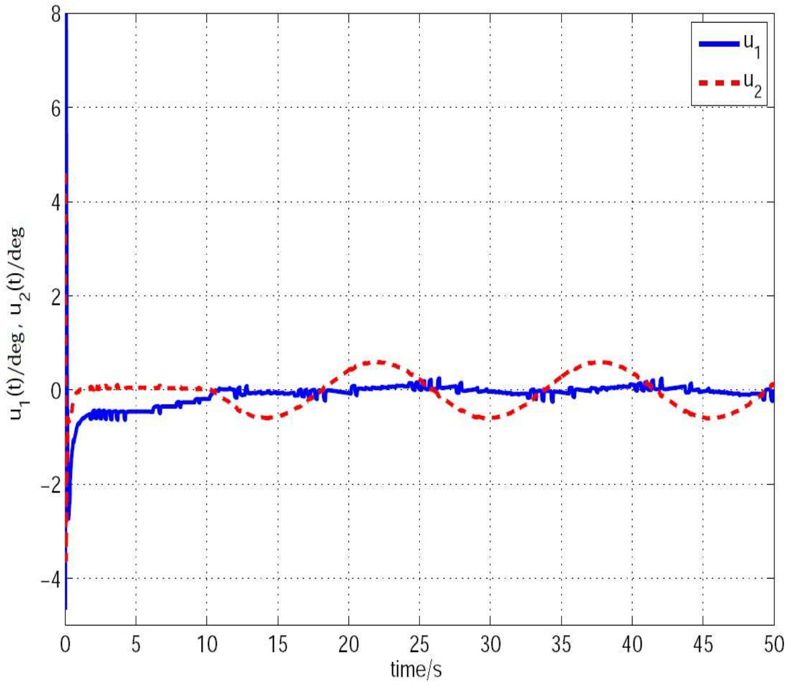

Figure 4. The time responses of the control input signals using our FE/FTC scheme

5. Conclusion

In this study, an integrated FE and FTC strategy is developed for a class of linear time delay systems with actuator faults using dynamic event- triggered mechanism. The dynamic event-triggered mechanism is a modification of the one in '(Wang, Fei, Wang, & Liu, 2019)' by adding an internal dynamic variable, such that the inter-event intervals increase while the number of transmission decreases. The integrated design of FE and FTC approach is then given by linear matrix inequality technique and the asymptotical stability of the whole closed loop systems is analyzed by the Lyapunov approach. It has also shown that the zeno behavior is excluded by analyzing the bound of inter-event intervals. Finally, an aircraft engine system simulation is given to show the better control performance of the proposed approach by simulation comparison. In addition, it is a challenge issue to consider sensor fault or obtain a delay-related

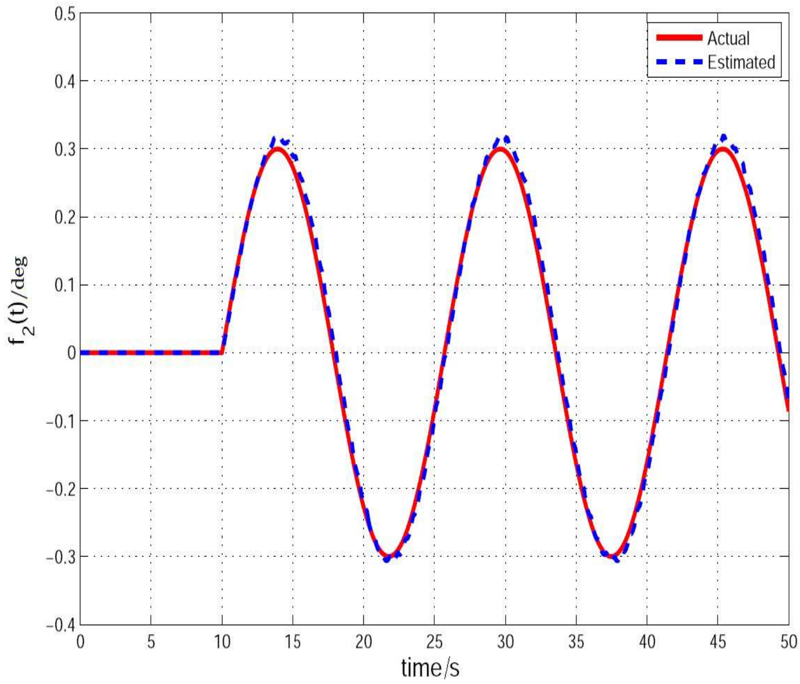

Figure 5. The time responses of the actual fault and its estimation using our FE/FTC scheme

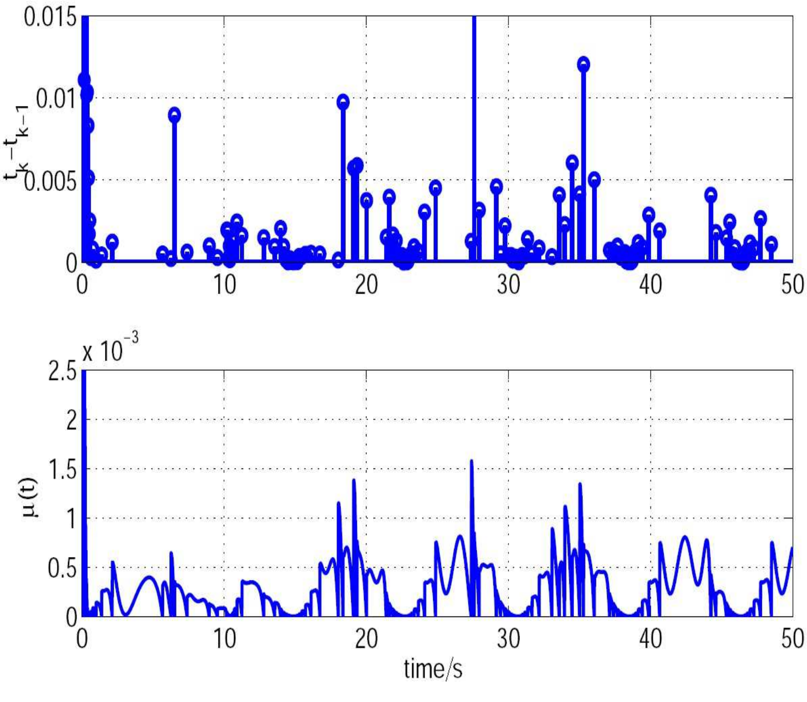

Figure 6. Triggering instants and intervals of event generator using our FE/FTC scheme

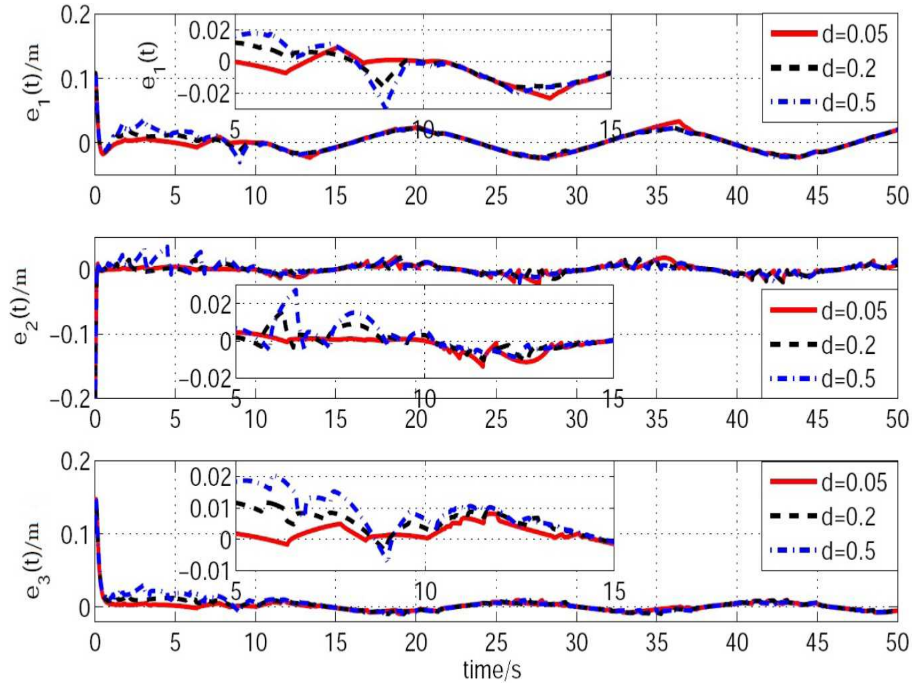

Figure 7. The time responses of the state estimated error using FE/FTC scheme in '(Wang, Fei, Wang, & Liu, 2019)'

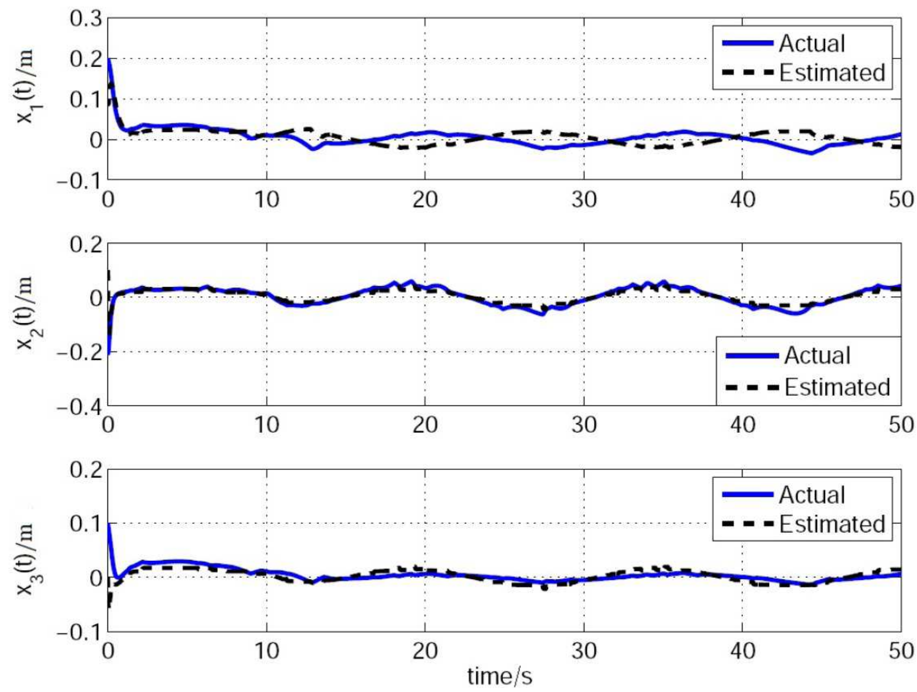

Figure 8. The time responses of the state and its estimation using FE/FTC scheme in '(Wang, Fei, Wang, & Liu, 2019)'

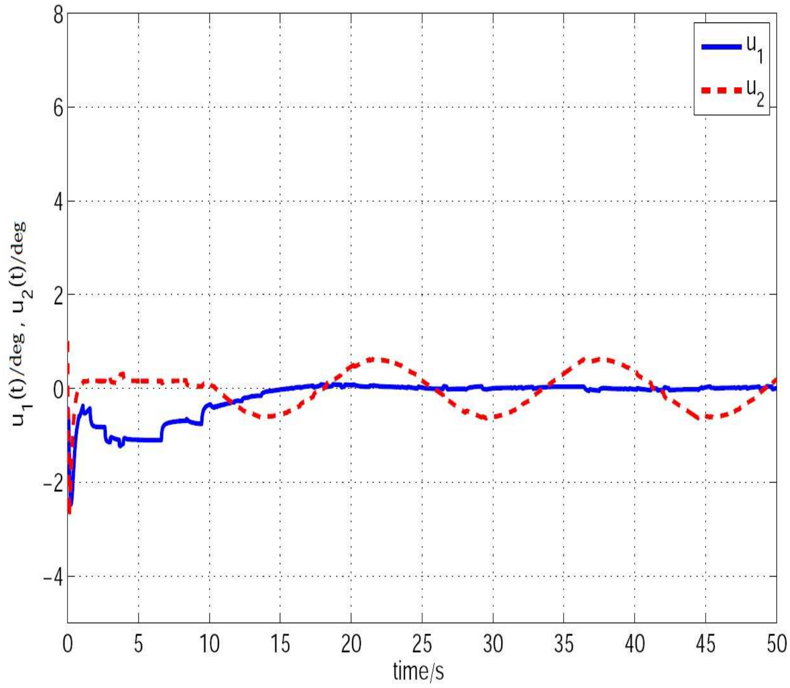

Figure 9. The time responses of the control input signals using FE/FTC scheme in '(Wang, Fei, Wang, & Liu, 2019)'

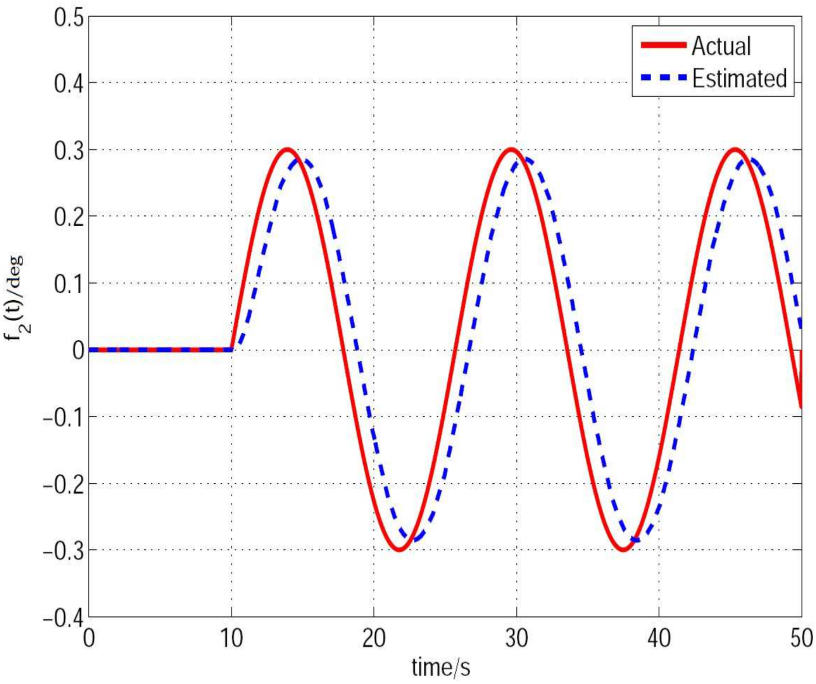

Figure 10. The time responses of the actual fault and its estimation using FE/FTC scheme in '(Wang, Fei, Wang, & Liu, 2019)'

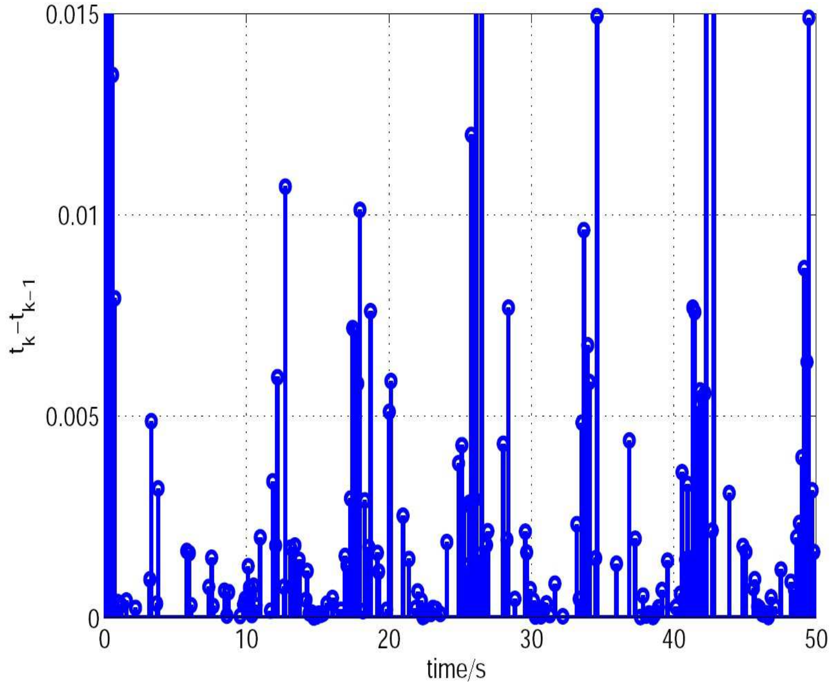

Figure 11. Triggering instants and intervals of event generator using FE/FTC scheme in '(Wang, Fei, Wang, & Liu, 2019)'

stability analysis result, and this problem will be one of our main works in the future.

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