# Fault Estimation and Fault-Tolerant Control for Networked Systems Based on an Adaptive Memory-Based Event-Triggered Mechanism

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***Abstract*—This paper mainly focuses on the problem of networked fault estimation (FE) and fault-tolerant control (FTC). A novel adaptive memory-based mechanism is proposed by introducing the latest piece of historical output information. The historical information at each instant is matched with a corresponding weight such that the closer information is, the more contribution to the releasing event. Many unexpected triggering events can be avoided under this communication protocol, especially for the scenarios of the system with jitter disturbance or random noise. Moreover, to make the instantaneous data releasing rate adapt to the requirement of the control system, a time-varying threshold of the event-triggered mechanism is designed. Therefore, the burden of network bandwidth can be greatly decreased. Based on this proposed communication protocol, a new fault and state estimation model is developed. The fault-tolerant controller uses the estimations to compensate for the influence induced by the network and the fault. Sufficient conditions are derived to co-design the parameters of FE, FTC, and adaptive memory-based event-triggered mechanism. Finally, the performance of the proposed communication mechanism, FE, and FTC is evaluated on an example of the F-404 engine system.**

***Index Terms*—Adaptive memory-based event-triggered mechanism, Fault estimation, Fault-tolerant control.**

## I. Introduction

HIGH safety and high reliability are the fundamental requirements of modern engineering systems. However, unexpected faults, such as actuator stuck and sensor saturation are common phenomenon in practical industry processes. The system's performance with a certain fault, especially with a severe fault, will be deteriorated, increasing potential safety problems. To maintain the control performance of the system in the presence of certain bounded faults, fault detection (FD), FE, and FTC are necessary to tackle these problems. Over the past decades, the problems of FD, FE, and FTC have attracted extensive attention, see for example, [1]–[6], and references therein.

The FD concerns with monitoring the control system, identifying when a fault has occurred. To obtain acceptable control performances of the system with faults, two design methods are usually adopted: passive FTC [7] and active FTC [8], [9]. The main purpose of passive FTC is to design a tolerant controller to make the system insensitive to unexpected faults, for example, in [7], a reliable controller was designed by assuming the actuator failure is governed by a series of random variables. The authors in [10] developed a robust adaptive FTC to achieve asymptotic tracking for a cascaded system subject to actuator failures. In [11], a passive FTC was investigated for T-S fuzzy-based nonlinear systems against bounded actuator faults. It is noticed that these passive FTC methods do not depend on fault information. In contrast with the passive FTC, the active FTC method needs to make full use of fault information to compensate for the influence of the fault in the control process. In [12], By using integral sliding-mode control technology, a finite-time FE-based FTC scheme was proposed to address the trajectory-tracking problem of surface vehicles. To realize the voltage compensation of dual three-phase permanent-magnet synchronous motor against multi-faults, the current-sensor fault was estimated to design a fault-tolerant controller in [13]. It can be manifested that the active FTC method is more effective and reliable on the condition that the fault information can be obtained or estimated. In the past decades, considerable efforts have been dedicated to the issue of active fault-tolerant control to deal with various fault problems [14]–[16].

It is known that signal transmission plays a vital role in the control loop. The signal transmission in the literature listed above is based on traditional point-to-point (P2P) communication. Under this transmission style, the control scale, flexibility, and reliability will be limited [17]–[19]. With the

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development of the technology of computation, network, and control theory, network communication of the control system has gradually been an alternative to the traditional P2P-based communication control system. However, some features of communication networks for networked control systems (NCSs), such as time delay, limited network bandwidth, etc. will deteriorate or destabilize the control performance. Therefore, over the past two decades, considerable attention has been received for improving the performance of NCSs [20]–[22], for example, in [20], the authors modeled the network-induced delay as an interval time-varying delay. The network-induced delay is assumed to be governed by some random distributions in [23], [24]. In traditional control design, digital signal transmission with a fixed period from one terminal to the others is usually adopted, and the fixed period is set small enough to ensure the control system with a satisfying performance in the worst situation [25]. Consequently, this time-triggered mechanism (TTM) with high-frequency sampling and broadcasting will inevitably aggravate the burden of a network, even leading to network congestion.

To effectively save network bandwidth when designing NCSs, numerous results regarding the event-triggered mechanism (ETM) have been proposed in recent years, such as [26]–[32]. Unlike TTM, signal transmission with ETM depends on a condition used to generate releasing event, rather than a periodic time sequence. The control strategy with these event-triggering conditions ensures the stability of the system. In [33], the data transmission was designed by utilizing a mechanism of time-driven sampling and event-driven releasing. The parameters of the controller and the ETM can be co-designed by using such an approach of model transferring. This method was successfully extended to the design of networked FTC, such as in [34], under this framework, the data releasing rate can be dramatically decreased, while the control performance can be maintained to an acceptable level. In [35], an annulus-based ETM was proposed to decrease the amount of data releasing for time-varying FD systems. To improve the adaptation of the event-triggering condition, adaptive/ dynamic ETMs were developed [36]–[39], for example, in [38], [39], the thresholds were designed to be a dynamic that changes with the current sampling information and the latest released information. Distributed adaptive ETM in [36], [40] was investigated for consensus of linear multi-agent systems (MASs) against multiplicative faults and disturbances, where the parameters of the triggering function depend on both the state and the running time to enhance the adaption to the condition. It is noticed that the ETMs in the literature as mentioned above only use the current information to decide the next releasing instant. Sometimes it may lead to an unnecessary releasing event. Fewer results are reported to use the ETM with historical information for the design of FTC. Theses research gaps are our primary motivation for the current study.

Motivated by the above literature, the memory-based event-triggered mechanism was proposed to design the FE and the FTC for networked control systems. The main contribution of this paper is threefold as follows.

1) A new memory-based event-triggered mechanism was developed. The weighted historical information is introduced

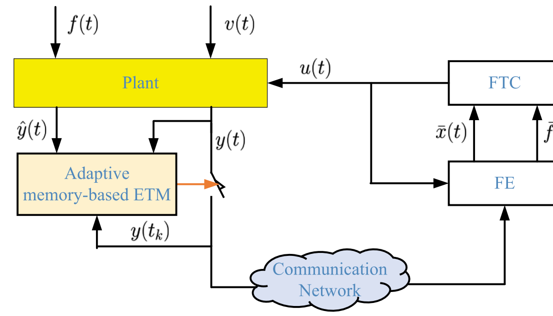


Fig. 1. The framework of the adaptive event-triggered FE-based FTC.

in the triggering function, by which the unexpected releasing event under the traditional ETM can be avoided due to the instantaneous random jitter (RJ);

2) A new fault estimation model is constructed to match the memory-based ETM, under which the estimation accuracy of the observer can be guaranteed.

3) The FE and FTC can be co-calculated conveniently based on the conditions that guarantee the stabilization of the augmented system by converting a nonlinear matrix inequality into an optimization problem.

The rest of this study is organized as follows. Section II presents the framework of networked FE and FE-based FTC. Section III gives the coordinated design method of the FE and the FTC. Finally, a semi-physical simulation platform for an aircraft engine system (AES) is presented to show the effectiveness and advantages of the proposed approach in Section IV. Conclusion V summarizes this study.

Notation: In this paper, $\partial[M, N]$ represents $N^T MN$. $\mathbf{col}\{\cdot\}$ stands for a column vector. $\mathbf{He}\{\mathbf{M}\} = M + M^T$.

## II. Problem Formulation

As shown in Fig. 1, the framework of networked FE and the corresponding FTC is depicted. To relieve the burden of network bandwidth, the adaptive memory-based ETM is introduced.

### A. Plant Model

Consider the following linear time-invariant system with fault and external disturbance:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + \Gamma f(t) + Dv(t) \\ y(t) = Cx(t) \\ z(t) = Fx(t), \end{cases} \tag{1}$$

where $x(t) \in \mathbb{R}^n$, $y(t) \in \mathbb{R}^{n_y}$, $u(t) \in \mathbb{R}^m$, $z(t) \in \mathbb{R}^{n_z}$, $f(t) \in \mathbb{R}^{n_f}$, and $v(t) \in \mathbb{R}^{n_v}$ denote the system state, measured output, control input, system output, system fault and external disturbance, respectively. $A, B, C, D, F$ and $\Gamma$, are known matrix with appropriate dimensions. In this study, the pairs $(A, C)$ and $(A, B)$ are assumed to be observable and controllable, $v(t)$ and $\dot{f}(t)$ belong to $l_2[0, \infty)$.

From Fig. 1, one can see that the input of the adaptive memory-based ETM includes not only the current output information $y(t)$ but also $\hat{y}(t)$ with historical information.To facilitate the description of $\hat{y}(t)$, we first define

$$\xi(s) = \mathbf{col}\{g(s), g_1(s), \ldots, g_{p-1}(s)\}, \tag{2}$$

$$\mathscr{G}(s) = \xi(s) \otimes I_n, \tag{3}$$

where $g(s)$ is a function that satisfies $\int_{t-w}^{t} g(s)ds = 1$, $w$ is a given constant that represents the length of historical information to be used as the input to fault/state estimation observer. For $\mathscr{G}(s)$, we assume it has the following property:

$$\frac{\mathscr{G}(s)}{ds} = \mathcal{G}\,\mathscr{G}(s), \tag{4}$$

where $\mathcal{G}_{pn\times pn}$ is a given constant matrix.

Next, we define

$$\tilde{y}(t) = \alpha_1\hat{y}(t) + \alpha_2 y(t), \tag{5}$$

where $\hat{y}(t) = \int_{t-w}^{t} g(s-t)y(s)ds$ and $\sum_{i=1}^{2}\alpha_i = 1, \alpha_i > 0$.

*Remark 1:* It is noticed that $\hat{y}(t)$ in (5) is average historical information. Meanwhile, $g(s)$ can be regarded as a weight of $y(s)$ at instant $s$. If one chooses $g(s)$ as a monotone increasing function for $s \in [-w\ 0]$ in (5), it means that the closer the time is to current instant $t$, the bigger the weight is.

*Remark 2:* As mentioned in Remark 1, $\hat{y}(t)$ is average historical information owning to the sliding window with a fixed window width $w$. Such a widow slides with time $t$. If $w \to 0$, it tends to be a memoryless ETM, while $w$ is chosen too big, more useful information may be missed. Therefore, a reasonable $w$ is the result of multiple trials.

*Remark 3:* From (5), one knows that the historical information and the current information are matched with respective weights. The bigger $\alpha_1$ is, the more historical information in the ETM and FE is. Especially, if one sets $\alpha_1 = 0$, the transmission signal turns to be a traditional one.

## B. Memory-Based ETM

To alleviate the burden of the communication network, an adaptive memory-based ETM is introduced (see Fig. 1).

We define

$$\varphi(\varpi(t,t_k), y(t)) = \varpi^T(t)\Omega\varpi(t,t_k) - \delta(t)y^T(t)\Omega y(t), \tag{6}$$

where $\varpi(t,t_k) = \tilde{y}(t) - y(t_k)$ and $t_k$ is the $k$-th triggering instant. $y(t_k)$ is the system output that is successfully transmitted over the communication network at instant $t_k$. $\delta(t)$ is a scalar function designed by

$$\delta(t) = \bar{\delta} - 2(\bar{\delta} - \underline{\delta})/\pi \arctan\left(\frac{\varrho\ \varpi^T(t)\Omega\varpi(t,t_k)}{y^T(t)\Omega y(t)}\right) \tag{7}$$

for $t \in [t_k, t_{k+1})$, where $0 < \underline{\delta} < \bar{\delta} \le 1$ and $\varrho > 0$.

Then, the next triggering instant can be expressed by

$$t_{k+1} = \inf\ \{t | t > t_k, \varphi(\varpi(t,t_k), y(t)) > 0\} \tag{8}$$

*Remark 4:* It is noticed that instantaneous RJ may arouse unexpected triggering events when using the traditional ETM. Such the event is called the bad event in the following. The historical information with a sliding window $w$ being introduced to generate the absolute error of the ETM in (8) can avoid the occurrence of bad events, which will be demonstrated in Section IV.

*Remark 5:* From (7), one knows that the threshold is variable and has the following properties and advantages: (1) $\underline{\delta} \le \delta(t) \le \bar{\delta}$; and (2) the threshold decreases with the relative error $\frac{\varrho\ \varpi^T(t)\Omega\varpi(t,t_k)}{y^T(t)\Omega y(t)}$, which means the bigger $\tilde{y}(t)$ deviates $y(t_k)$, the smaller $\delta(t)$ is, leading to much more releasing events. Accordingly, the control performance can be ensured.

## C. The Framework of FE and FTC

For the sake of compensating for the influence of faults and solve the asynchronization problem induced by the network, a fault estimation observer is considered, which is constructed as follows:

$$\begin{cases} \dot{\bar{x}}(t) = A\bar{x}(t) + Bu(t) + \Gamma\bar{f}(t) + L(y(t_k) - \bar{y}(t)) \\ \dot{\bar{f}}(t) = E(y(t_k) - \bar{y}(t)) \\ \bar{y}(t) = \alpha_1 C\int_{t-w}^{t} g(s-t)\bar{x}(s)ds + \alpha_2 C\bar{x}(t), \end{cases} \tag{9}$$

where $\bar{x}(t) \in \mathbb{R}^n$, $\bar{y}(t) \in \mathbb{R}^{n_y}$ and $\bar{f}(t) \in \mathbb{R}^{n_f}$ denote the observer state, output and the estimated fault signal, respectively. $L$ and $E$ are parameters to be designed.

Based on the above fault observer, we now consider the following FTC strategy

$$u(t) = -B^{\dagger}\Gamma\bar{f}(t) + K\bar{x}(t), \tag{10}$$

where $K$ is the observer-based fault-tolerant controller gain to be designed, and $B^{\dagger}$ is the matrix that satisfies $(I - BB^{\dagger})\Gamma = 0$.

Defining $e_x(t) = x(t) - \bar{x}(t)$ and $e_f(t) = f(t) - \bar{f}(t)$, and recalling the definition of $\varpi(t,t_k)$ yields that

$$\begin{cases} \dot{e}_x(t) = (A - \alpha_2 LC)e_x(t) + \Gamma e_f(t) + L\varpi(t,t_k) \\ \qquad\qquad - \alpha_1 LC\mathbb{H}_0\displaystyle\int_{t-w}^{t}\mathscr{G}(s-t)e_x(s)ds \\ \dot{e}_f(t) = -\alpha_1 EC\mathbb{H}_0\displaystyle\int_{t-w}^{t}\mathscr{G}(s-t)e_x(s)ds \\ \qquad\qquad - \alpha_2 ECe_x(t) + E\varpi(t,t_k) + \dot{f}(t). \end{cases} \tag{11}$$

By define $\psi(t) = [e_x^T(t), e_f^T(t), x^T(t)]^T$ and $\nu(t) = [v^T(t), \dot{f}^T(t)]^T$, we can obtain the following augmented system:

$$\begin{aligned} \dot{\psi}(t) = \mathcal{A}\psi(t) - \alpha_1\mathcal{J}C\mathbb{H}_0\int_{t-w}^{t}\mathscr{G}(s-t)e_x(s)ds \\ + \mathcal{J}\varpi(t,t_k) + \mathcal{D}\nu(t) \end{aligned} \tag{12}$$

where $\mathcal{A} = \mathcal{A}_0 + \mathcal{A}_1$, $\mathbb{H}_0 = [I_n, \underbrace{0_n \cdots, 0_n}_{p-1}]$, and

$$\mathcal{A}_0 = \left[\begin{array}{cc|c} A & \Gamma & 0 \\ 0 & 0 & 0 \\ \hline 0 & \Gamma & A \end{array}\right], \mathcal{D} = \left[\begin{array}{cc} D & 0 \\ 0 & I \\ \hline D & 0 \end{array}\right],$$

$$\mathcal{A}_1 = \left[\begin{array}{c|c} [-\alpha_2 \mathfrak{L} C \quad 0_{(n+n_f)\times n_f}] & 0_{(n+n_f)\times n} \\ \hline [-BK \quad 0_{n\times n_f}] & BK \end{array}\right],$$

$$\mathcal{J} = \begin{bmatrix} \mathfrak{L} \\ 0 \end{bmatrix}, \mathfrak{L} = \begin{bmatrix} L \\ E \end{bmatrix}.$$

The main purpose of this study is to design a networked fault-tolerant control strategy such that the system with the memory-based ETM in (8) has an $H_\infty$ performance $\gamma$, i.e.,

1) The system (12) with $\nu(t) = 0$ is asymptotically stable;

2) The system (12) for $\nu(t) \neq 0$ satisfies $\int_{t_0}^{\infty} z^T(t) z(t) dt \leq \gamma^2 \int_{t_0}^{\infty} \nu^T(t) \nu(t) dt$ under zero initial condition.

The following lemma that plays an essential role in deriving the main results will be introduced first before proceeding further.

*Lemma 1:* For a vector function $\psi : \mathcal{E} \to \mathbb{R}^{n_\psi}$ with $n_\psi = 2n + n_f$ and a symmetric positive definite matrix $Q \in R^{n\times n}$, the following integral inequality holds:

$$\int_{\mathcal{E}} \eth[Q, \psi(s)] ds \geq \eth\left[\mathcal{M} \otimes Q, \int_{\mathcal{E}} \mathscr{G}(s) \psi(s) ds\right] \quad (13)$$

where $\mathcal{M} = [\int_{\mathcal{E}} \xi(s) \xi^T(s) ds]^{-1}$, $\xi(s)$ and $\mathscr{G}(s)$ are defined in (2) and (3), respectively.

## III. Networked FE and FTC Design

In this section, we first analyze the stability and $H_\infty$ performance of the system (12) in Theorem 1 and then develop the approach of the networked FE and FTC with the novel communication protocol presented in (8) in Theorem 2.

For the purpose of simplifying the prescription, we give the following notations:

$$\begin{aligned}
\mathbb{I}_1 &= \begin{bmatrix} I_{n_\psi} & 0_{n_\psi \times pn} & 0_{n_\psi} & 0_{n_\psi \times n_y} & 0_{n_\psi \times n_v} & 0_{n_\psi} \end{bmatrix}, \\
\mathbb{I}_2 &= \begin{bmatrix} 0_{pn \times n_\psi} & I_{pn} & 0_{pn \times n_\psi} & 0_{pn \times n_y} & 0_{pn \times n_v} & 0_{pn \times n_\psi} \end{bmatrix}, \\
\mathbb{I}_3 &= \begin{bmatrix} 0_{n_\psi} & 0_{n_\psi \times pn} & I_{n_\psi} & 0_{n_\psi \times n_y} & 0_{n_\psi \times n_v} & 0_{n_\psi} \end{bmatrix}, \\
\mathbb{I}_4 &= \begin{bmatrix} 0_{n_y \times n_\psi} & 0_{n_y \times pn} & 0_{n_y \times n_\psi} & I_{n_y} & 0_{n_y \times n_v} & 0_{n_y \times n_\psi} \end{bmatrix}, \\
\mathbb{I}_5 &= \begin{bmatrix} I_{n_v \times n_\psi} & 0_{n_v \times pn} & 0_{n_v \times n_\psi} & 0_{n_v \times n_y} & I_{n_v} & 0_{n_v \times n_\psi} \end{bmatrix}
\end{aligned}$$

with $n_\psi = 2n + n_f, n_\nu = n_v + n_f, n_\eta = (p+2)n + n_f$.

*Theorem 1:* For given scalars $\bar{\delta}, w, \gamma, \beta, \alpha_i$ $(i = 1, 2)$ and matrices $K$, $L$ and $E$, the system (9) can asymptotically estimate the fault and the state of the plant with an $H_\infty$ performance level $\gamma$ under the adaptive memory-based ETM in (8), if there exist symmetric matrices $P = \begin{bmatrix} P_1 & P_2 \\ P_2^T & P_3 \end{bmatrix}$, $Q > 0, R > 0$, and matrices $U_1, U_2$ with appropriate dimensions, such that the following inequalities hold:

$$\Phi = \begin{bmatrix} P_1 & P_2 \\ P_2^T & P_3 + \mathcal{M} \otimes Q \end{bmatrix} > 0, \quad (14)$$

$$\begin{bmatrix} \Theta + \Theta_1 & * \\ F\mathbb{H}_2 \mathbb{I}_1 & -I \end{bmatrix} < 0, \quad (15)$$

where

$$\begin{aligned}
\Theta &= \mathbf{He}\{\mathbb{H}_3^T P \mathcal{T}_1\} + \mathbb{I}_1^T \mathbb{H}_1^T Q \mathbb{H}_1 \mathbb{I}_1 \\
&\quad - \mathbb{I}_3^T Q \mathbb{I}_3 + w \mathbb{I}_1^T \mathbb{H}_1^T R \mathbb{H}_1 \mathbb{I}_1 + \mathbb{I}_2^T \mathcal{T}_2 - \mathbb{I}_4^T \Omega \mathbb{I}_4 \\
&\quad + \bar{\delta}(C\mathbb{H}_2 \mathbb{I}_1)^T \Omega C \mathbb{H}_2 \mathbb{I}_1 - \gamma^2 \mathbb{I}_5^T \mathbb{I}_5, \\
\Theta_1 &= \mathbf{He}\{\mathcal{T}_3^T \mathcal{S}\}, \\
\mathcal{T}_3 &= [\beta \mathcal{U} \quad 0 \quad 0 \quad 0 \quad 0 \quad \mathcal{U}], \ \mathcal{U} = \mathrm{diag}\{U_1, U_2\}, \\
\mathcal{S} &= \begin{bmatrix} \mathcal{A} & -\alpha_1 \mathcal{J} C \mathbb{H}_0 & 0_{n_\psi \times n} & \mathcal{J} & \mathcal{D} & -I_{n_\psi} \end{bmatrix}, \\
\mathcal{T}_1 &= [\mathcal{T}_{11} \quad \mathcal{T}_{12}], \\
\mathcal{T}_{11} &= \begin{bmatrix} 0_{n_\psi} & 0_{n_\psi \times pn} & 0_{n_\psi} \\ \mathscr{G}(0)\mathbb{H}_1 & -\mathcal{G} & -\mathscr{G}(-w)\mathbb{H}_1 \end{bmatrix}, \\
\mathcal{T}_{12} &= \begin{bmatrix} 0_{n_\psi \times n_y} & 0_{n_\psi \times n_\nu} & -I_{n_\psi} \\ 0_{pn \times n_y} & 0_{pn \times n_\nu} & 0_{pn \times n_\psi} \end{bmatrix}, \\
\mathcal{T}_2 &= [0 \quad -\mathcal{M} \otimes R \quad 0 \quad 0 \quad 0 \quad 0], \\
\mathbb{H}_1 &= [I_n, \ 0_{n \times n_f}, \ 0_n], \ \mathbb{H}_2 = [0_n, \ 0_{n \times n_f}, \ I_n], \\
\mathbb{H}_3 &= \left[I_{n_\eta}, 0_{n_\eta \times n_\psi}, 0_{n_\eta \times n}, 0_{n_\eta \times n_\nu}, 0_{n_\eta \times n_\psi}\right].
\end{aligned}$$

*Proof:* For the convenience of expression, we first define

$$\begin{aligned}
\eta(t) &= \begin{bmatrix} \psi(t) \\ \int_{t-w}^{t} \mathscr{G}(s-t) e_x(s) ds \end{bmatrix}, \\
\phi(t) &= \mathbf{col}\{\eta(t), \ e_x(t-w), \ \varpi(t, t_k), \ \nu(t), \ \dot{\psi}(t)\}.
\end{aligned}$$

From Lemma 1, one knows that

$$\begin{aligned}
&\eth[P, \eta(t)] + \int_{t-w}^{t} \eth[Q, e_x(s)] ds \\
&\quad \geq \eth[P, \eta(t)] + \eth\left[\mathcal{M} \otimes Q, \int_{t-w}^{t} \mathscr{G}(s) e_x(s) ds\right] \\
&\quad = \eth[\Phi, \eta(t)]. \qquad (16)
\end{aligned}$$

Due to $\Phi > 0, R > 0$, we can construct the following Lyapunov-Krasovskii function.

$$\begin{aligned}
V(t) &= \eth[P, \eta(t)] + \int_{t-w}^{t} \eth[Q, e_x(s)] ds \\
&\quad + \int_{t-w}^{t} (s - t + w) \eth[R, e_x(s)] ds \qquad (17)
\end{aligned}$$

Take the derivative of $V(t)$ along the system (12), and it has

$$\begin{aligned}\dot{V}(t) &= 2\eta^T(t)P\dot{\eta}(t) + \eth[\mathbb{H}_1^T Q\mathbb{H}_1, \psi(t)] \\ &\quad - \eth[Q, e_x(t-w)] + w\,\eth[\mathbb{H}_1^T R\mathbb{H}_1, \psi(t)] \\ &\quad - \int_{t-w}^{t} \eth[R, e_x(s)]ds.\end{aligned}$$

It is noted that

$$\begin{aligned}\frac{d}{dt}\int_{t-w}^{t} \mathscr{G}(s-t)e_x(s)ds &= \mathscr{G}(0)\mathbb{H}_1\psi(t) - \mathscr{G}(-w)\mathbb{H}_1\psi(t-w) \\ &\quad - \mathcal{G}\int_{t-w}^{t} \mathscr{G}(s-t)e_x(s)ds. \qquad (18)\end{aligned}$$

Utilizing Lemma 1 once more yields that

$$\begin{aligned}\dot{V}(t) &\le 2\eta^T(t)P\mathcal{T}_1\phi(t) + \eth[\mathbb{H}_1^T Q\mathbb{H}_1, \psi(t)] \\ &\quad - \eth[Q, e_x(t-w)] + w\,\eth[\mathbb{H}_1^T R\mathbb{H}_1, \psi(t)] \\ &\quad + \eth[\mathbb{I}_2^T\mathcal{T}_2, \phi(t)]. \qquad (19)\end{aligned}$$

From (12), one knows that

$$2\mathcal{T}_3^T\mathcal{S}\phi(t) = 0. \qquad (20)$$

Recalling the event-triggering condition in (8) and combing (19)-(20), we have

$$\begin{aligned}\dot{V}(t) &+ z^T(t)z(t) - \gamma^2\nu^T(t)\nu(t) \\ &\le 2\eta^T(t)P\mathcal{T}_1\phi(t) + \eth[\mathbb{H}_1^T Q\mathbb{H}_1, \psi(t)] \\ &\quad - \eth[Q, e_x(t-w)] + w\,\eth[\mathbb{H}_1^T R\mathbb{H}_1, \psi(t)] \\ &\quad + \eth[\mathbb{I}_2^T\mathcal{T}_2, \phi(t)] - \eth[\mathbb{I}_4^T\mathbf{\Omega}\mathbb{I}_4, \phi(t)] \\ &\quad + \eth[\bar{\delta}(C\mathbb{H}_2\mathbb{I}_1)^T\mathbf{\Omega}(C\mathbb{H}_2\mathbb{I}_1), \phi(t)] \\ &\quad + \eth[(\mathcal{T}_3^T\mathcal{S} + \mathcal{S}^T\mathcal{T}_3), \phi(t)] \\ &\quad + \eth[(F\mathbb{H}_2\mathbb{I}_1)^T(F\mathbb{H}_2\mathbb{I}_1), \phi(t)] - \eth[\gamma^2\mathbb{I}_5^T\mathbb{I}_5, \phi(t)]. \qquad (21)\end{aligned}$$

Using Schur complement lemma to (15) follows that

$$\dot{V}(t) + z^T(t)z(t) - \gamma^2\nu^T(t)\nu(t) < 0. \qquad (22)$$

Then, one can easily obtain $\dot{V}(t) < 0$ with $\nu(t) = 0$ and $\int_{t_0}^{\infty} z^T(t)z(t)dt \le \gamma^2\int_{t_0}^{\infty}\nu^T(t)\nu(t)dt$ for $\nu \neq 0$. Thus, we complete the proof. ■

Next, we will develop the design method of FE and FTC for networked systems with the proposed adaptive memory-based ETM in terms of Theorem 1.

*Theorem 2:* For given scalars $\bar{\delta}, w, \gamma, \beta, \alpha_i$ $(i = 1, 2)$, the system (9) can asymptotically estimate the fault and the state of the plant with an $H_\infty$ performance level $\gamma$ under the adaptive memory-based ETM in (8), if there exist symmetric matrices $P = \begin{bmatrix} P_1 & P_2 \\ P_2^T & P_3 \end{bmatrix}$, $Q > 0, R > 0$, and matrices $U_1, U_2, \mathcal{N}_1, W, Y$ with appropriate dimensions such that the following inequalities hold:

$$\Phi = \begin{bmatrix} P_1 & P_2 \\ P_2^T & P_3 + \mathcal{M}\otimes Q \end{bmatrix} > 0, \qquad (23)$$

$$\begin{bmatrix} \Theta + \bar{\Theta}_1 & * \\ F\mathbb{H}_2\mathbb{I}_1 & -I \end{bmatrix} < 0, \qquad (24)$$

$$U_2B = BW, \qquad (25)$$

where

$$\begin{aligned}\bar{\Theta}_1 &= \mathbf{He}\{\bar{\mathcal{T}}_3^T\bar{\mathcal{S}}\}, \\ \bar{\mathcal{T}}_3 &= \begin{bmatrix} \beta I_{n_\psi} & 0 & 0 & 0 & 0 & I_{n_\psi} \end{bmatrix}, \\ \bar{\mathcal{S}} &= \begin{bmatrix} \bar{\mathcal{A}} & -\alpha_1\bar{\mathcal{J}}C\mathbb{H}_0 & 0_{n_\psi\times n} & \bar{\mathcal{J}} & \mathcal{U}\mathcal{D} & -\mathcal{U} \end{bmatrix}, \\ \bar{\mathcal{A}}_1 &= \left[\begin{array}{cc|c} [-\alpha_2\mathcal{N}_1C & 0_{(n+n_f)\times n_f}] & 0_{(n+n_f)\times n} \\ \hline [-BY & 0_{n\times n_f}] & BY \end{array}\right], \\ \bar{\mathcal{A}} &= \mathcal{U}\mathcal{A}_0 + \bar{\mathcal{A}}_1,\ \bar{\mathcal{J}} = \begin{bmatrix} \mathcal{N}_1 \\ \hline 0 \end{bmatrix}.\end{aligned}$$

and the other symbols are defined in Theorem 1. Furthermore, the parameters of FE and FTC are:

$$K = W^{-1}Y, \begin{bmatrix} L \\ \hline E \end{bmatrix} = U_1^{-1}\mathcal{N}_1.$$

*Proof:* Define $\mathcal{N}_1 = U_1\mathfrak{L}$, $U_2B = BW$, and $Y = WK$, then one can know that (24) is equivalent to (15). The proof is completed. ■

It is noticed that it is hard to find a feasible solution from Theorem 2 due to the equality constraint in (25). The following approximate algorithm is considered to get the parameters of ETM in (8), FE in (9), and controller gain in (10) by using LMI control toolbox.

It is known that (25) is equivalent to

$$\mathrm{trace}(U_2B - BW)^T(U_2B - BW) = 0 \qquad (26)$$

Due to the property in (26), the parameters to be resolved in Theorem 2 can be approximatively obtained by the following Theorem.

*Theorem 3:* For given positive scalars $\bar{\delta}, w, \gamma, \beta, \alpha_i$ $(i = 1, 2)$ and a small enough constant $\sigma > 0$, the system (9) can asymptotically estimate the fault and the state of the plant with an $H_\infty$ performance level $\gamma$ under the adaptive memory-based ETM in (8), if there exist symmetric matrices $P = \begin{bmatrix} P_1 & P_2 \\ P_2^T & P_3 \end{bmatrix}$, $Q > 0, R > 0$, and matrices $U_1, U_2, \mathcal{N}_1, W, Y$ with appropriate dimensions, such that the following inequalities hold:

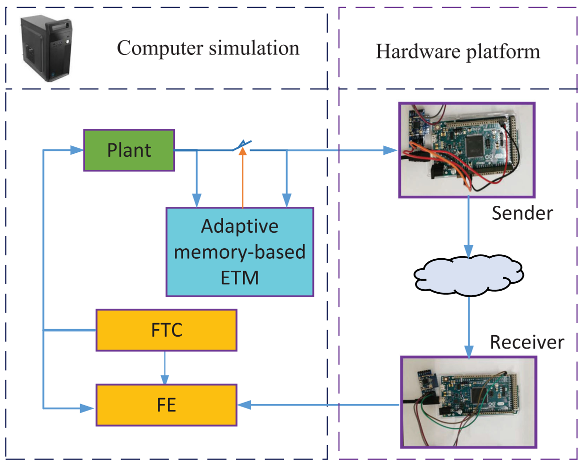


Fig. 2. Simulation platform.

$$\Phi = \begin{bmatrix} P_1 & P_2 \\ P_2^T & P_3 + \mathcal{M} \otimes Q \end{bmatrix} > 0, \quad (27)$$

$$\begin{bmatrix} \Theta + \bar{\Theta}_1 & * \\ F\mathbb{H}_2\mathbb{I}_1 & -I \end{bmatrix} < 0, \quad (28)$$

$$\begin{bmatrix} -\sigma I & * \\ U_2 B - BW & -I \end{bmatrix} < 0, \quad (29)$$

where the symbols are defined in Theorem 2. Furthermore, the parameters of FE and FTC are:

$$K = W^{-1}Y, \ \begin{bmatrix} L \\ E \end{bmatrix} = U_1^{-1}\mathcal{N}_1.$$

## IV. Case Study

In what follows, a practical example, the test run of an F-404 AES [41], is provided to show the effectiveness of the FE and FTC design method for networked systems with the proposed adaptive memory-based ETM. The platform of the system is presented in Fig. 2, from which one can see that the communication network is implemented by a pair of Zigbee modules, the other modules including plant, adaptive memory-based ETM, FE, and FTC are simulated by Simulation/Matlab in PC. The system matrices are given as:

$$A = \begin{bmatrix} -1.46 & 0 & 2.428 \\ 0.1643 & -0.4 & -0.3788 \\ 0.3107 & 0 & -2.231 \end{bmatrix}, \ B = \begin{bmatrix} 0.11 & 0 \\ 0.14 & -0.4 \\ 0.10 & 0 \end{bmatrix},$$

$$\Gamma = \begin{bmatrix} 0 \\ -0.4 \\ 0 \end{bmatrix}, D = \begin{bmatrix} 0.5 \\ 1.5 \\ 1 \end{bmatrix}, C = \begin{bmatrix} -0.1 & 0 & 1 \\ 0.15 & 2 & -0.1 \\ 0.1 & 0.2 & 0.1 \end{bmatrix},$$

and $F = I_3$.

By using Theorem 3 with $\underline{\delta} = 0.05, \bar{\delta} = 0.18, w = 0.06, \gamma = \sqrt{10}, \beta = 200, \alpha_1 = 0.7, \alpha_2 = 0.3$ and $\sigma = 0.001$, one can obtain the controller gain in (10) is

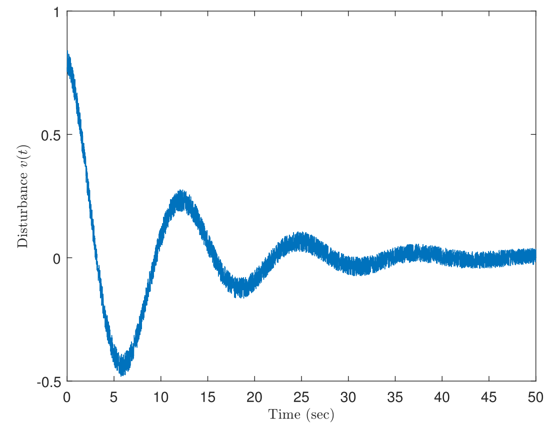


Fig. 3. The disturbance with random jitter.

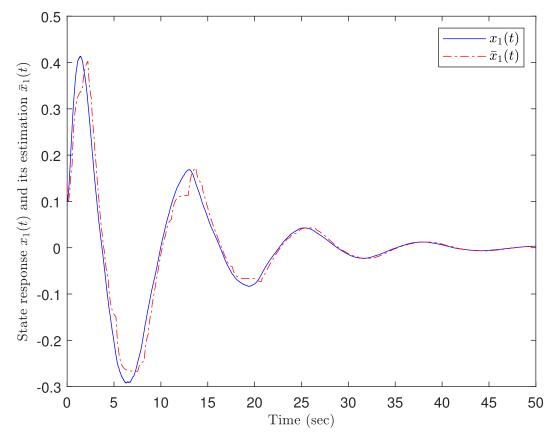


Fig. 4. State response $x_1(t)$ and its estimation $\bar{x}_1(t)$.

$$K = \begin{bmatrix} -7.8060 & 0.7715 & -5.1863 \\ -12.5312 & 13.5394 & -12.3676 \end{bmatrix},$$

and the parameters of FE in (9) are

$$L = \begin{bmatrix} 1.9513 & 1.0960 & 11.0304 \\ 4.8132 & -2.6073 & -11.9353 \\ 2.6512 & 0.2150 & 2.2646 \end{bmatrix},$$
$$E = [\,-1.5994 \quad 5.0764 \quad 35.4080\,],$$

and the weight matrix of the ETM in (8) is

$$\Omega = \begin{bmatrix} 3685.4720 & -902.1206 & -8747.6339 \\ -902.1206 & 674.3940 & 5743.5295 \\ -8747.6339 & 5743.5295 & 50547.2189 \end{bmatrix}.$$

Assume the initial state of the plant and the fault estimation observer are $x(0) = \bar{x}(0) = [0.10.2 - 0.1]^T$. Different types of fault (solid blue line in Fig. 7) that injects into the system is considered to show the effectiveness and the advantages of the designed FTC strategy, which is expressed by

$$f(t) = \begin{cases} 0.3e^{-0.2(t-10)^2} - 0.2e^{-0.1(t-25)^2} & t \le 40 \\ 0.3 & t > 40 \end{cases}$$

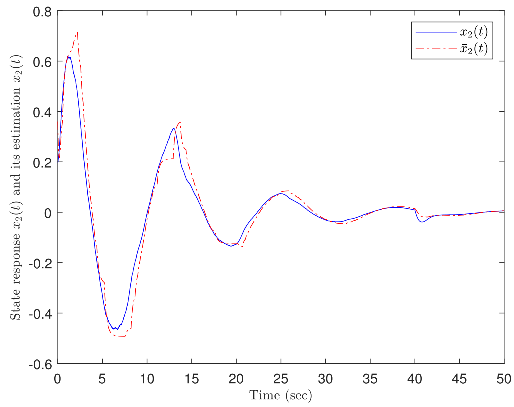


Fig. 5. State response $x_2(t)$ and its estimation $\bar{x}_2(t)$.

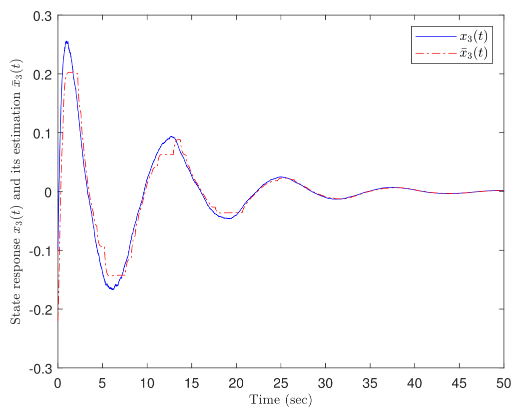


Fig. 6. State response $x_3(t)$ and its estimation $\bar{x}_3(t)$.

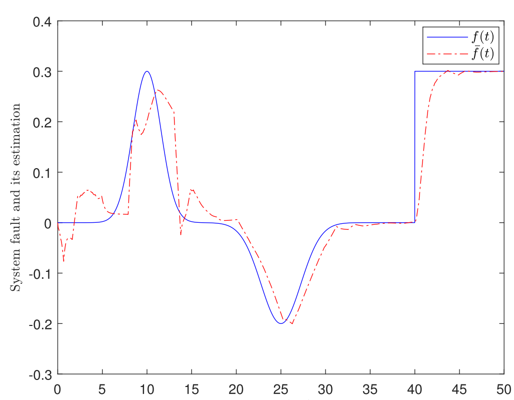


Fig. 7. The fault and its estimation.

To test the performance of the proposed memory-based ETM respect to disturbance with RJ, we set the disturbance as shown in Fig. 3.

Fig. 4 - Fig. 6 present the plant trajectories and their estimations, from which one can see that the system with the fault (depicted in Fig. 7) and the disturbance (shown in Fig. 3) performs well by using the proposed approach. Also, from Fig. 7, it can be known that the fault estimation signal can well observe the injected fault signal. As such a reason, the injected fault signal of the plant can be better compensated (see the control strategy in (10)) by the estimated fault signal, thereby leading to good control performance.

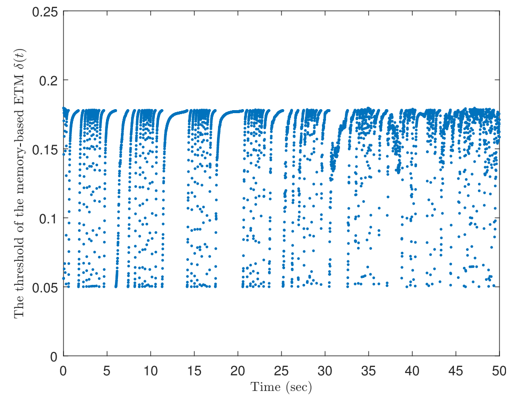


Fig. 8. Adaptive threshold $\delta(t)$.

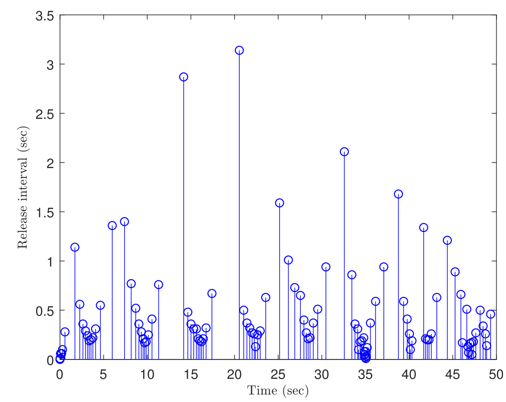


Fig. 9. Triggering instants and releasing intervals with $\alpha_1 = 0.7$.

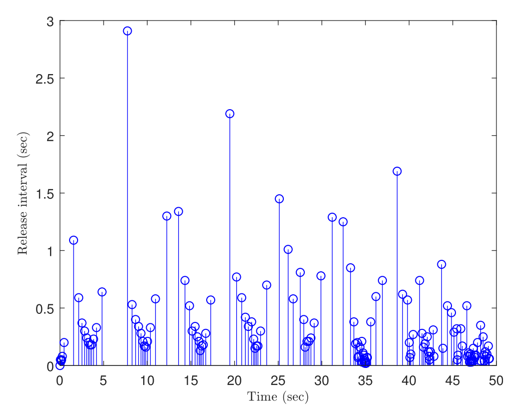


Fig. 10. Triggering instants and releasing intervals with $\alpha_1 = 0$.

Fig. 8 shows the adaptive threshold of the memory-based ETM. Under such a threshold, the next triggering instant is decided by the event-triggering condition in (8). Fig. 9 presents the time sequence of triggering instants and their releasing intervals. Combining Fig. 8 and Fig. 9, one can see that the threshold is time-varying and the triggering threshold increases after the latest triggering event, which is an attempt of decreasing the amount of data-releasing till the triggering condition is invoked. To verify the necessity of using adaptive threshold, we choose $\delta(t) \equiv (\underline{\delta} + \bar{\delta})/2$. Under this fixed threshold, the amount of releasing data (ARD) within 50 s is 127, while the AMD is 99 when using the adaptive threshold in (7) whose curve is depicted in Fig. 8.

TABLE I
THE AMOUNT OF RELEASING DATA WITHIN 50 S

| | ARD (with RJ) | ARD (without RJ) |
|---|---|---|
| Adaptive TETM | 137 | 91 |
| Our method | 99 | 83 |

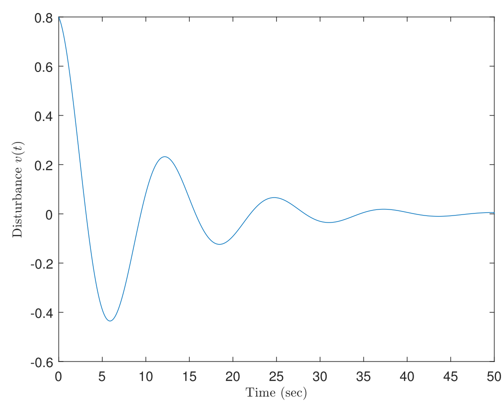


Fig. 11. The disturbance without random jitter.

Next, we choose $\alpha_1 = 0$ as stated in Remark 3. In this case, the ETM does not include the historical information, and it turns to be an adaptive traditional event-triggered mechanism (TETM). Fig. 10 shows the time sequence of triggering events under this scenario. Table I gives the ARDs of adaptive TETM and our proposed adaptive memory-based ETM. Combining Table I, Fig. 9 and Fig. 10, one can see that the ARD by using our method is obviously less than the one by using adaptive TETM when the system is subject to RJ disturbance. That is to say, the performance of avoiding the occurrence of bad events by using our method is better than using the technique of TETM for the system with RJ, as mentioned in Remark 4. To further show the advantage of our proposed adaptive memory-based ETM, the disturbance is assumed to be smooth, which is shown in Fig. 11. In Table I, it is clear that our method is still better than the TETM in the condition of the disturbance without RJ. Therefore, one can conclude that the network bandwidth can be greatly saved when using our proposed method for networked FE and FTC problems.

## V. CONCLUSION

In this paper, the problem of networked FE and FTC has been addressed. To mitigate the usage of limited network resources, a new adaptive memory-based event-triggered mechanism has been proposed. By introducing a certain length of historical information to the ETM and matching the historical information with different weights to different past times, the unexpected triggering events generated by disturbance or some random noises can be decreased. Moreover, a reasonable threshold can be obtained online by the proposed adaptive approach, which depends on the current and the past output rather than a fixed constant. Under this proposed ETM, a new FE and FTC design method for networked systems has been developed. Finally, an example of the F-404 AES is used to show the effectiveness and advantages of the proposed approaches. In the future study, the networked fault detection problem with the proposed memory-based ETM will be considered. Also, a full hardware experimental platform will be constructed.

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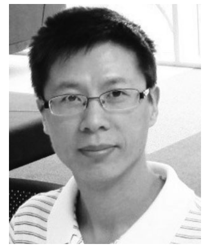

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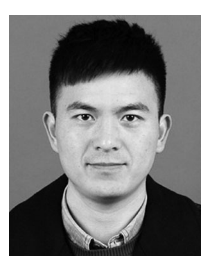

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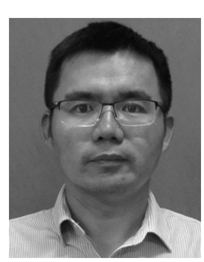

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