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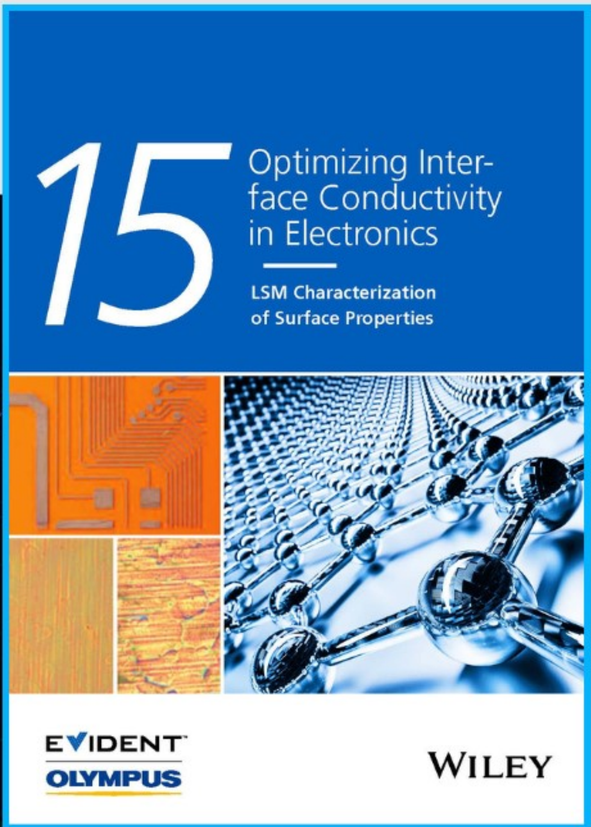

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INTERNATIONAL JOURNAL OF ROBUST AND NONLINEAR CONTROL
Int. J. Robust Nonlinear Control 2017; **27**:236–251
Published online 26 May 2016 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/rnc.3570

An adaptive event-triggering scheme for networked interconnected control system with stochastic uncertainty

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SUMMARY

This paper investigates the problem of adaptive event-triggering scheme for networked interconnected systems to relieve the burden of the network bandwidth. The data releasing is triggered by an adaptive event-triggering device. The triggering condition depends on the state information at both the latest releasing instant and the current sampling instant. The threshold of the triggering parameter is achieved online rather than a predetermined constant. Taking the network-induced delays and the coupling delays of the subsystems into account, together with the hybrid adaptive event-triggering scheme and the stochastic uncertainty, we propose an unified model of the networked interconnected system. Sufficient conditions for the mean square stability and stabilization of the interconnected systems are developed by using Lyapunov–Krasovskii functional approach. A co-designed method is put forward to obtain the controller gains and the weight of the triggering condition simultaneously. Finally, an example is provided to demonstrate the design method.

Received 9 April 2015; Revised 31 March 2016; Accepted 2 May 2016

KEY WORDS: adaptive event triggering scheme; networked interconnected control system; stochastic uncertainty

1. INTRODUCTION

Large-scale systems are often modelled as dynamic equations composed of interconnections of lower-dimensional subsystems, which are called interconnected systems [1, 2]. Many real-life practical applications, such as electric power systems, economic systems, urban traffic networks, process control systems, and computer networks, can be regarded as interconnected system [3–5]. The stability analysis of the interconnected system is performed to linear matrix inequalities (LMIs)-based conditions under which every local subsystem is asymptotically stable (see [6–8] and references therein). A common characteristic of these systems is that they are often widely distributed in space. The information interaction among the components of subsystems may be via physical connection or communication network. In recent years, networked control systems (NCSs) have become the focus of study because of their attractive advantages, such as reduced system wiring, low weight, ease of system diagnosis and maintenance[9–11], and the reference therein. However, the insertion of networks in control systems also introduces new challenges, such as network-induced delays, packet dropouts, limited bandwidth, which should inevitably be considered in the stability analysis and controller synthesis. This has motivated a lot of interesting research; see, for example, [12–20] and references therein.

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More recently, much attention has also been paid to save the limited communication resource for NCSs by designing a reasonable communication scheme. As an alternative of the periodic time-triggered communication scheme for NCSs, event-triggered schemes have been proposed in the published literature to decrease the quantity of the data transmission while preserving the control performance. In this way, the transmissions are adapted to the state of the system. In [21], an event-triggered dynamic output feedback control design for linear time invariant systems was proposed to render the closed-loop system input-to-state stable with respect to exogenous disturbances. In order to accommodate system uncertainties, an $\mathcal{L}_1$ adaptive control technique is developed for the design and analysis of the event-triggered system in [22]. Yu and Antsaklis provided a static output feedback-based event-triggered control scheme of NCSs, where the triggering condition and the static output feedback gain are derived based on the output feedback passivitxy indices of the plant. However, the results only apply to passive and output feedback passive systems. The authors in [23] proposed an adaptive scheme to estimate the state of the discrete-time system while the event is not triggered. It should be noted that the event-triggering schemes depending on continuous-time states of the system (see, for example,[21, 24–26] and the references therein) imply that an extra hardware is required to monitor the states of the system in anytime so as to achieve the next triggering instant.

Discrete event-triggering communication (DETC) schemes for NCSs were developed in [27–32] and the references therein. Different from the periodic time-trigged control, the packet of the sampled data is released into the network only when it violates the triggering condition at sampling instant under DETC scheme. Comparing with the event-triggering schemes depending on the continuous-time states, the problem of over-sampling due to the violation of the triggering condition heaps of times within a short period can be avoided by using DETC scheme. In [31, 32], the authors proposed a periodic event-triggering control for linear sampled-data systems and NCSs, respectively, by using a piecewise linear system approach, however, the results are independent on the network-induced delay. Based on the DETC scheme, the authors investigated an event-triggered control for a class of network-based interconnected system with consideration of the probabilistic nonlinear disturbance in [29], wherein a co-design method for controller and the triggering parameters is proposed. A distributed event-triggered sampled-data transmission strategy is proposed for distributed multi-agent systems with directed graph in [33]. The authors in [28] proposed a design method for networked T-S fuzzy system. It should be noted that the controller of the designed system by using DETC schemes is not required to be known *a priori*.

The weight of the event-triggering condition of the DETC scheme in the existing literature was achieved by using Lyapunov theory and LMI technology, while the threshold of the triggering condition is a predetermined constant, which is hard to adapt varying conditions. In recent years, there are some research results on adaptive scheme for event-triggered system. In [34, 35], the authors developed a price-based adaptive mechanism to adjust the threshold according to the estimated price, by which the event-triggers adapted the request rate to accommodate a global resource constraint. In [36], Medium access control is introduced to improve the event-based scheduling design by an adaptive method to choose the error threshold for transmission. Note that the triggering parameters are optimized; however, the controller of the plant are unavailable by using the aforementioned adaptive method. Few results present co-design methods for the networked interconnected system by using adaptive event-triggering scheme, which motivates the present study.

The uncertainty in the model of control systems is considered to describe the systematic parameters varying with the time. The conventional model of the uncertainty is assumed to be with a norm-bound format [37–39] or polytope [40] format. In some cases, the varying of the perturbation parameter follows a certain distribution that can be obtained in advance. However, few attention is focused on the distribution of the uncertainty. Therefore, to model the uncertainty of the system with statistic is another motivation of our study.

The rest of the paper is organized as follows. Section 2 presents a unified model of the networked interconnected system with a stochastic uncertainty under the AETS. On the basis of a novel Lyapunov–Krasovskii functional, sufficient conditions of robust asymptotically stable in the mean-square sense for the interconnected system under AETS are proposed in Sections 3. In Section 4, we design the controller for the interconnected system under AETS. A simulation example is given in

DOI: 10.1002/rnc

Section 5 to demonstrate the advantage of our adaptive event-triggering scheme. Finally, Section 6 concludes the paper.

Notation: $\mathbb{R}^n$ denotes the n-dimensional Euclidean space, $\mathbb{R}^{n\times m}$ is the set of real $n \times m$ matrices, I is the identity matrix of appropriate dimensions, and $\|\cdot\|$ stands for the Euclidean vector norm or spectral norm as appropriate. The notation $X > 0$ (respectively, $X < 0$) for $X \in \mathbb{R}^{n\times n}$ means that the matrix X is a real symmetric positive definite (respectively, negative definite). $\mathbb{E}\{x\}$ is the expectation of x. The asterisk $*$ in a matrix is used to denote term that is induced by symmetry, Matrices, if they are not explicitly stated , are assumed to have compatible dimensions.

2. PROBLEM FORMULATION

For presentation convenience, we introduce the following notations:

- **S** denotes the overall interconnected system with n_s subsystems;
- $\mathbf{S}_i$ denotes the i-th subsystem ($i = 1, \ldots, n_s$);
- $s_k h$ denotes the sampling instant, and $r_k^i h$ denotes the releasing instant of the subsystem $\mathbf{S}_i$;
- $\mathscr{N} = \{1, 2, \ldots, n_s\}$ denotes the whole sets of the system;
- $\mathscr{N}_i \triangleq \mathscr{N}/\{i\} = \{1, 2, \ldots, i-1, i+1, \ldots, n_s\}$;
- $\mathscr{L}_i = \{1, 2, \ldots, \bar{\ell}_i\}$;
- $\wp_{r_k^i}^{\ell_i} = [r_k^i h + \ell_i h - h + d_{\ell_i - 1}, r_k^i h + \ell_i h + d_{\ell_i})$;

Consider a nonlinear interconnected system **S** composed of n_s subsystems with the dynamics of the i-th subsystem $\mathbf{S}_i$ ($i \in \mathscr{N}$), being described by the following differential equation

$$\dot{x}_i(t) = (A_i + \Delta A_i(t))x_i(t) + \sum_{j\in\mathscr{N}_i} A_{dij} x_j(t - \eta_{ij}(t)) + B_i u_i(t) + f_i(x_i(t), t) \tag{1}$$

where $x_i(t) \in \mathbb{R}^{n_i}$ and $u_i \in \mathbb{R}^{m_i}$ are the subsystem state and input vectors, respectively. $f_i(x_i(t), t)$ is the vector-valued time-varying nonlinear perturbations with $f_i(0, t) = 0$. $\bar{A}_i$, A_{dij} and B_i are the matrices with appropriate dimensions; $\eta_{ij}(t)$ is the coupled delay within the subsystems with $\dot{\eta}_{ij}(t) \leqslant \bar{\eta}_{ij}$, $\Delta A_i(t) = \alpha_i(t)\mathring{A}_i$, and $\alpha_i(t)$ is a rand variable with expectation $\bar{\alpha}_i$ and variance $\tilde{\alpha}_i^2$. Similar to [41, 42], we assume that it satisfies

$$\|f_i(x_i(t), t)\| \leqslant \beta_i^2 \|F_i x_i(t)\| \tag{2}$$

where β_i are interconnection bounds and F_i are bounding matrices.

Remark 1
The uncertainty of the system is modeled by $\Delta A_i(t) = \alpha_i(t)\mathring{A}_i$ in (1), whose statistic information is assumed to be available beforehand. The nominal part can be regarded as a theoretical model that can be obtained by a series of physical constrains without consideration of the perturbation parameter of the system. Different from the conventional way about the uncertainty with a format of $\Delta A(t) = DF(t)E$ whose boundary needs to be known exactly, we mainly pay attention to the statistic of the uncertainty deviating from the nominal part in this study. In fact, the system can also be stabilized by a suitable controller when the uncertainty with a big deviation from the nominal part has a small probability. However, a feasible solution is hard to find by using the model with a condition of the boundary of the uncertainty because of the uncertainty with a big boundary at few instants. Therefore, it will lead to a less conservative result by using the statistic information of the uncertainty comparing with the conventional way.

The framework of the proposed adaptive event-triggering scheme for decentralized interconnected control system is shown in Figure 1, from which one can see an AETD is introduced in the closed loop of each subsystem. The AETD is responsible for making a decision on wether the data release or not. If the designed triggering condition depending on both the states at the latest releasing instant and the current sampling instant is violated, the state information is then broadcast to the network. To do this, we do the following assumptions: The sensors are clock-driven, and controllers

DOI: 10.1002/rnc

and actuators are event-driven; the control signal is hold by ZOH before the new data updates. Moreover, the data are transmitted over the network by a single packet in every control period.

Based on the previous work [43, 44], the following decentralized networked state feedback controller is considered for subsystem $\mathbf{S}_i$ by

$$u_i\left(t^+\right) = K_i x_i\left(r_k^i h\right), \qquad t \in \left[r_k^i h + \tau_k^i, r_{k+1}^i h + \tau_{k+1}^i\right) \tag{3}$$

where $u_i(t^+) = \lim\limits_{\hat{t}\to t+0} u_i(\hat{t})$, K_i $(i \in \mathscr{N})$ is a controller gain of each subsystem to be designed; r_k^i $(k = 1, 2, \cdots)$ are some integers such that $\{r_1^i, r_2^i \cdots\} \subset \{0, 1, 2, \cdots\}$; h is a sampling period; $r_k^i h$ denotes the k-th releasing instant of the subsystem $\mathbf{S}_i$; τ_k^i is a transmission delay at the k-th releasing instant; and $[r_k^i h + \tau_k^i, r_{k+1}^i h + \tau_{k+1}^i)$ is the hold interval of zero order hold (ZOH) (Figure 2).

As shown in Figure 1, an AETD is introduced in the closed loop of the subsystem to determine wether or not to release the state information. The decision depends on the triggering condition and the instruction from the network-detector, which is responsible for detecting the status of the current node. Therefore, the sampled information failing to reach the other side of the network is primarily the results of the following: (i) the adaptive event-triggering condition is not violated; (ii) it is not the i-th node turn to release the sampling data at that instant; and (iii) the packet is lost.

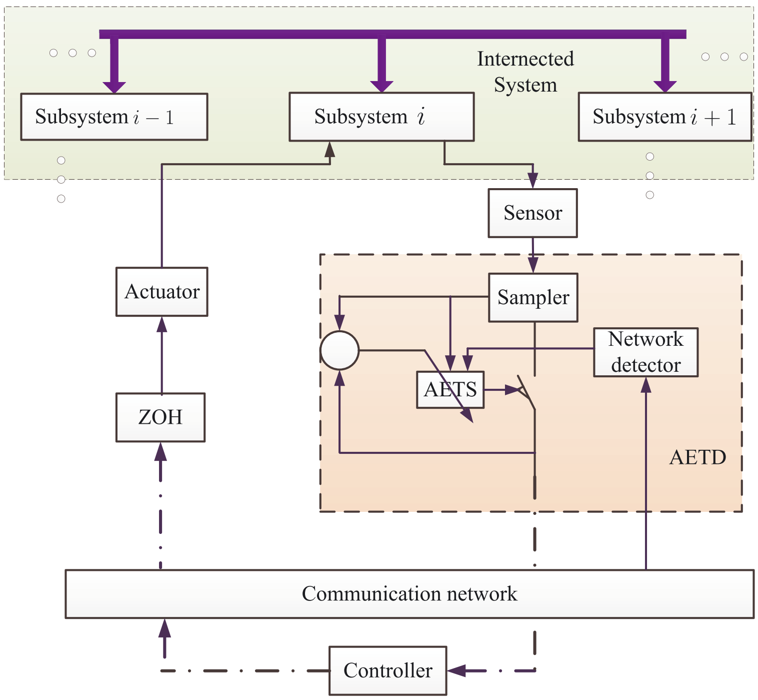

Figure 1. The framework of the networked interconnected system with adaptive event-triggering device.

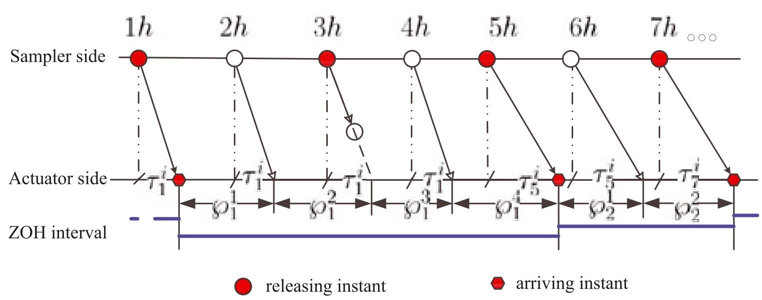

Figure 2. An example of time sequence under adaptive event-triggering scheme.

DOI: 10.1002/rnc

Remark 2
The aforementioned three facts have no essential difference for they can be regarded as packet loss, wherein the first two reasons are the case of active dropping packet.

Remark 3
The maximum allowable number of successive packet losses will be given by the criteria derived in the next section to guarantee the system stable, which is a crucial basis of network scheduling.

Here, we consider the following adaptive triggering condition

$$\varphi_i^T(t)\Phi_i\varphi_i(t) - \sigma_i(t)x_i^T\left(r_k^i h + \ell_i h\right)\Phi_i x_i\left(r_k^i h + \ell_i h\right) \leqslant 0 \tag{4}$$

where $\varphi_i(t) = x_i(r_k^i h) - x_i(r_k^i h + \ell_i h)$, $\ell_i \in \mathscr{L}_i$ and $\Phi_i > 0$ is a positive definite matrix to be designed and $\sigma_i(t)$ is an adaptive-triggered parameter, which satisfies

$$\dot{\sigma}_i(t) = -\kappa_i\sigma_i^2(t)\varphi_i^T(t)\Phi_i\varphi_i(t) \tag{5}$$

with $\sigma_i(0) \leqslant 1$ and $\kappa_i > 0$.

For convenience of analysis, next we will partition the hold interval of ZOH $\bar{\ell}_i$ parts, where $\bar{\ell}_i = r_{k+1}^i - r_k^i$. Define $d_0^i = \tau_k^i$ and $d_{\bar{\ell}_i}^i = \tau_{k+1}^i$. Obviously, there exist artificial delays $d_{\ell_i}^i > 0$ $(\ell_i \in \mathscr{L}_i)$ such that $d_{\ell_i-1}^i < h + d_{\ell_i}^i$. Defining a set $\wp_{r_k^i}^{\ell_i} = [r_k^i h + \ell_i h - h + d_{\ell_i-1}, r_k^i h + \ell_i h + d_{\ell_i})$ for any $\ell_i \in \mathscr{L}_i$ yields $\wp_k = \left[r_k^i h + \tau_k^i, r_{k+1}^i h + \tau_{k+1}^i\right) = \cup_{\ell_i=1}^{\bar{\ell}_i}\wp_{r_k^i}^{\ell_i}$.

To explain the AETS clearly, an illustrative example is given in Figure 2 wherein the sampling data at $1h, 3h, 5h$ violate the triggering condition; however, the other node of subsystem $\mathbf{S}_j$ $(j \in \mathscr{N}_i)$ is scheduled to access the network at instant $3h$; therefore, the sampling data at $3h$ is discarded actively. Then the sampling information at instant $r_1^1 h = 1h, r_2^1 h = 5h, r_3^1 h = 7h, \cdots$ reaches the actuator side finally, and the data at sampling instant $s_k^1 h = 2h, 4h, 7h, \cdots$ are discarded. In Figure 2, the interval $\wp_1$ is partitioned 4 $(r_2^1 - r_1^1 = 4)$ parts: $\wp_1^1, \wp_1^2, \wp_1^3, \wp_1^4$, and $\wp_1 = \cup_{i=1}^4\wp_1^i$. Similarly, $\wp_2 = \cup_{i=1}^2\wp_2^i, \cdots$.

From the aforementioned analysis, we can know that the maximum allowable number of successive packet losses

$$\bar{\ell}_i = \max_{\ell_i \in \mathscr{L}_i}\left\{\ell_i|\varphi_i^T(t)\Phi_i\varphi_i(t) - \sigma_i(t)x_i^T\left(r_k^i h + \ell_i h\right)\Phi_i x_i\left(r_k^i h + \ell_i h\right) \leqslant 0\right\} \tag{6}$$

Remark 4
The event-triggering condition in (4) is different from the one in [27] where the threshold σ is a predetermined constant, which plays a balancing role between the control performance and network condition. For example, if σ tends to zero, then the scheme will approach to the one with a time-triggered scheme. With the increase of σ, the chance of the condition being violated decreases, which leads to a poor control performance for the reasons of less control information being transmitted over the network. Therefore, it is a trade-off between the control performance and network QoS to choose a suitable value of σ. In this study, $\sigma_i(t)$ is varying adaptively with hybrid state $\varphi_i(t)$. From the adaptive law shown in (5), one can know that $\sigma_i(t)$ is an attenuation function. It implies that $\sigma_i(t)$ tends to be a certain value finally, that is, $\sigma_i(t)$ is an optimal result adjusted by the states of both the controlled plant and the communication network. Furthermore, one can know that the interval of $\sigma_i(t)$ belongs to [0 1] from the fundamental theorem of calculus with its initial state $\sigma_i(0) \leqslant 1$.

Remark 5
If one chooses $\kappa_i = 0$ in (5) with $0 < \sigma_i(0) \leqslant 1$, the trigger condition in (4) becomes the case in [27]. Specially, letting $\sigma_i(0) = 0$, then the condition in (5) turns to be a time-triggered transmitting scheme.

DOI: 10.1002/rnc

Define $\varrho_i(t) = t - (r_k^i h + \ell_i h)$ for $t \in \wp_{r_k^i}^{\ell_i}$. Recalling the definition of $\wp_{r_k^i}^{\ell_i}$, one can know that

$$0 \leqslant \underline{\tau}_k^i \leqslant \varrho_i(t) \leqslant h + \bar{\tau}_k^i \leqslant \bar{\rho}_i \tag{7}$$

From the definition of $\varphi_i(t)$, we can know that $x_i(r_k^i h) = \varphi_i(t) + x_i(t - \varrho_i(t))$, which leads to

$$u_i(t) = K_i \varphi_i(t) + K_i x_i(t - \varrho_i(t)), \quad t \in \wp_{r_k^i}^{\ell_i} \tag{8}$$

and thus the adaptive event-triggering condition in (4) can be rewritten as

$$\varphi_i^T(t)\Phi_i\varphi_i(t) - \sigma_i(t)x_i^T(t - \varrho(t))\Phi_i x_i(t - \varrho(t)) \leqslant 0 \tag{9}$$

Combining with (1) and (8) leads to the following closed-loop NCS model

$$\dot{x}_i(t) = \mathscr{A}_i(t) + (\alpha_i - \bar{\alpha}_i)\mathring{A}_i x_i(t) \tag{10}$$

for $t \in \wp_{r_k^i}^{\ell_i}$, where $\mathscr{A}_i(t) = (A_i + \bar{\alpha}_i\mathring{A}_i)x_i(t) + \sum_{j \in \mathscr{N}_i} A_{dij}x_j(t - \eta_{ij}(t)) + B_i K_i \varphi_i(t) + B_i K_i x_i (t - \varrho_i(t)) + f_i(x_i(t), t)$.

The main purpose of this study is to co-design the decentralized controllers and event-triggered parameters for the network-based interconnected systems under the proposed adaptive event-triggering scheme to relieve the burden of the network bandwidth.

3. STABILITY ANSYSIS

In this section, we will derive a stability criterion for the networked interconnected system under AETS. For this purpose, the following lemma and definition are needed.

Lemma 1

[45] For any constant matrix $R \in \mathbb{R}^{n\times n}$, $R > 0$, scalars $0 \leqslant \rho(t) \leqslant \bar{\rho}$, and vector function $\dot{x} : [-\bar{\rho}, 0] \to \mathbb{R}^n$ such that the following integration is well defined, it holds that

$$-\bar{\rho}\int_{t-\bar{\rho}}^{t} \dot{x}^T(t)R\dot{x}(t) \leqslant \begin{bmatrix} x(t) \\ x(t-\rho(t)) \\ x(t-\bar{\rho}) \end{bmatrix}^T \begin{bmatrix} -R & * & * \\ R & -2R & * \\ 0 & R & -R \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\rho(t)) \\ x(t-\bar{\rho}) \end{bmatrix}$$

Definition 1

[46] For a given function $V : C_{F_0}^b([-\eta_M, 0], \mathbb{R}^n) \times S$, its infinitesimal operator $\mathcal{L}$ is defined as

$$\mathcal{L}V(x_t) = \lim_{\Delta\to 0^+} \frac{1}{\Delta}[\mathscr{E}(V(x_{t+\Delta}|x_t) - V(x_t))] \tag{11}$$

Theorem 1

For given parameters $\bar{\eta}_{ij}, \bar{\rho}_i, \vartheta_i$ and ϵ_i and matrix K_i, under the adaptive event-triggering condition (4), the closed-loop system (10) with stochastic uncertainty is robust asymptotically stable in mean square sense if there exist matrices $P_i > 0$, $Q_i > 0$, $Q_{ij} > 0$, $R_i > 0$ and $\Phi_i > 0$ ($i \in \mathscr{N}$, $j \in \mathscr{N}_i$) with appropriate dimensions such that

$$\Xi_i = \begin{bmatrix} \Pi^i{}_{11} & * & * & * & * \\ \Pi^i{}_{21} & \Pi_{22}^i & * & * & * \\ \Pi^i{}_{31} & 0 & -\Pi_{33}^i & * & * \\ \Pi^i{}_{41} & 0 & \Pi_{43}^i & -\Pi_{44}^i & * \\ \Pi^i{}_{51} & 0 & 0 & 0 & -\Pi_{55}^i \end{bmatrix} < 0, \qquad i \in \mathscr{N} \tag{12}$$

where

$$
\Pi_{11}^i = \begin{bmatrix} \Lambda_1^i & * & * & * \\ K_i^T B_i^T P_i + R_i & -2R_i + \Phi_i & * & * \\ K_i^T B_i^T P_i & 0 & -\vartheta_i \Phi_i & * \\ P_i & 0 & 0 & -\epsilon_i I \end{bmatrix};
$$

$$
\Lambda_1^i = P_i(A_i + \bar{\alpha}_i \mathring{A}_i) + (A_i + \bar{\alpha}_i \mathring{A}_i)^T P_i + Q_i - R_i + \sum_{j \in \mathscr{N}_i} Q_{ij};
$$

$$
\Pi_{21}^i = \begin{bmatrix} 0 & R_i & 0 & 0 & 0 \end{bmatrix}; \Pi_{22}^i = -Q_i - R_i
$$

$$
\Pi_{31}^i = \begin{bmatrix} P_i A_{di1} & \cdots & P_i A_{di,i-1} & P_i A_{di,i+1} & \cdots & P_i A_{diN} \\ 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix}^T;
$$

$$
\Pi_{33}^i = \mathrm{diag}\{(1-\bar{\eta}_{i1})Q_{i1}, \cdots, (1-\bar{\eta}_{i,i-1})Q_{i,i-1}, (1-\bar{\eta}_{i,i+1})Q_{i,i+1}, \cdots, (1-\bar{\eta}_{in_s})Q_{in_s}\};
$$

$$
\Pi_{41}^i = \begin{bmatrix} \tilde{\alpha}_i \bar{\rho}_i P_i \mathring{A}_i & 0 & 0 & 0 \\ \bar{\rho}_i P_i (A_i + \alpha_i \mathring{A}_i) & \bar{\rho}_i P_i B_i K_i & \bar{\rho}_i P_i B_i K_i & \bar{\rho}_i P_i \end{bmatrix};
$$

$$
\Pi_{43}^i = \begin{bmatrix} 0 & \cdots & 0 & 0 & \cdots & 0 \\ \bar{\rho}_i P_i A_{di1} & \bar{\rho}_i \cdots & P_i A_{di,i-1} & \bar{\rho}_i P_i A_{di,i+1} & \cdots & \bar{\rho}_i P_i A_{diN} \end{bmatrix};
$$

$$
\Pi_{44}^i = diag\{P_i R_i^{-1} P_i, P_i R_i^{-1} P_i\};
$$

$$
\Pi_{51}^i = \begin{bmatrix} \epsilon_i \beta_i F_i & 0 & 0 & 0 \end{bmatrix}; \Pi_{55}^i = \epsilon_i I
$$

Proof

Construct a new Lyapunov–Krasovskii functional candidate for the system (10) as

$$
V(t) = \sum_{i \in \mathscr{N}_i} (V_{1i}(t) + V_{2i}(t) + V_{3i}(t) + V_{4i}(t)) \tag{13}
$$

where

$$
\begin{aligned}
V_{1i}(t) &= x_i^T(t) P_i x_i(t) \\
V_{2i}(t) &= \int_{t-\bar{\rho}_i}^{t} x_i^T(s) Q_i x_i(s) ds + \sum_{j \in \mathscr{N}_i} \int_{t-\eta_{ij}(t)}^{t} x_j^T(s) Q_{ij} x_j(s) ds \\
V_{3i}(t) &= \bar{\rho}_i \int_{\bar{\rho}_i}^{0} \int_{t-s}^{t} \dot{x}_i^T(v) R_i \dot{x}_i(v) dv ds \\
V_{4i}(t) &= \frac{1}{2\kappa_i} \left(\frac{1}{\sigma_i(t)} - \vartheta_i \right)^2
\end{aligned}
$$

□

Remark 6

The item $V_{4i}(t)$ plays an important role to introduce the proposed AETS in the deriving of the results.

From the definition of α_i, one can know that $\mathbb{E}\{\alpha_i - \bar{\alpha}_i\} = 0$ and $\mathbb{E}\{(\alpha_i - \bar{\alpha}_i)^2\} = \tilde{\alpha}_i^2$.

For $t \in \wp_{r_k^i}^{\ell_i}$, the mathematical expectation of the generator $\mathcal{L}V_{li}(t), l = 1, 2, 3, 4$ for the evolution of $V_{li}(t), l = 1, 2, 3, 4$ along the solutions of (10) are given by

$$
\mathbb{E}\{\mathcal{L}V_{1i}(t)\} = \mathbb{E}\left\{2x_i^T(t) P_i \mathscr{A}_i(t)\right\} \tag{14}
$$

$$\begin{aligned}\mathbb{E}\{\mathcal{L}V_{2i}(t)\} = \mathbb{E}\Bigg\{ & x_i^T(t)Q_i x_i(t) + \sum_{j\in\mathcal{N}_i} x_j^T(t)Q_{ij}x_j(t) - x_i^T(t-\bar{\rho}_i)Q_i x_i(t-\bar{\rho}_i) \\ & - \sum_{j\in\mathcal{N}_i}(1-\dot{\eta}_{ij}(t))x_j^T(t-\eta_{ij}(t))Q_{ij}x_j(t-\eta_{ij}(t))\Bigg\}\end{aligned} \tag{15}$$

$$\mathbb{E}\{\mathcal{L}V_{3i}(t)\} = \mathbb{E}\left\{\bar{\rho}_i^2\dot{x}_i^T(t)R_i\dot{x}_i(t) - \bar{\rho}_i\int_{t-\bar{\rho}_i}^{t}\dot{x}_i^T(s)R_i\dot{x}_i(s)ds\right\} \tag{16}$$

From (5), it follows

$$\mathbb{E}\left\{\mathcal{L}\left(\frac{1}{\sigma_i(t)}\right)\right\} = \mathbb{E}\left\{\kappa_i\varphi_i^T(t)\Phi_i\varphi_i(t)\right\} \tag{17}$$

Then, we have

$$\begin{aligned}\mathbb{E}\{\mathcal{L}V_{4i}(t)\} &= \mathbb{E}\left\{\frac{1}{\kappa_i}\left(\frac{1}{\sigma_i(t)} - \vartheta_i\right)\mathcal{L}\left(\frac{1}{\sigma_i(t)}\right)\right\} \\ &= \mathbb{E}\left\{\frac{1}{\sigma_i(t)}\varphi_i^T\Phi_i\varphi_i(t) - \varphi_i^T\vartheta_i\Phi_i\varphi_i(t)\right\}\end{aligned} \tag{18}$$

Recalling the triggering condition in (9), it is equivalent to

$$\frac{1}{\sigma_i(t)}\varphi_i^T\Phi_i\varphi_i(t) \leqslant x_i^T(t-\varrho(t))\Phi_i x_i(t-\varrho(t)) \tag{19}$$

for $t \in \wp_{r_k^i}^{\ell_i}$.

Then, we have

$$\mathbb{E}\{\mathcal{L}V_{4i}(t)\} \leqslant \mathbb{E}\left\{x_i^T(t-\varrho(t))\Phi_i x_i(t-\varrho(t)) - \varphi_i^T\vartheta_i\Phi_i\varphi_i(t)\right\} \tag{20}$$

Notice that

$$\mathbb{E}\left\{\dot{x}_i^T(t)\left(\bar{\varrho}_i^2R_i\right)\dot{x}_i(t)\right\} = \mathbb{E}\left\{\mathscr{A}_i^T(t)\bar{\varrho}_i^2R_i\mathscr{A}_i(t)\right\} + \mathbb{E}\left\{\tilde{\alpha}_i^2x_i^T(t)\mathring{A}_i^T\bar{\varrho}_i^2R_i\mathring{A}_i x_i(t)\right\} \tag{21}$$

For the class of interconnected systems (10), the following structural identity holds:

$$\sum_{i\in\mathcal{N}_i}\sum_{j\in\mathcal{N}_i} x_j^T(t)Q_{ij}x_j(t) = \sum_{i\in\mathcal{N}_i}\sum_{j\in\mathcal{N}_i} x_i^T(t)Q_{ji}x_i(t) \tag{22}$$

Combining (14)–(16) and (20)–(22) and using Lemma 1 together with (2), we can obtain

$$\begin{aligned}\mathbb{E}\{\mathcal{L}V(t)\} \leqslant \mathbb{E}\Bigg\{ & \sum_{i\in\mathcal{N}}\big(2x_i^T(t)P_i\mathscr{A}_i(t) + x_i^T(t)Q_i x_i(t) - x_i^T(t-\bar{\rho}_i)Q_i x_i(t-\bar{\rho}_i) \\ & + \sum_{j\in\mathcal{N}_i} x_i^T(t)Q_{ji}x_i(t) - \sum_{j\in\mathcal{N}_i}(1-\bar{\eta}_{ij}(t))x_j^T(t-\eta_{ij}(t))Q_{ij}x_j(t-\eta_{ij}(t)) \\ & + \mathscr{A}_i^T(t)\bar{\rho}_i^2R_i\mathscr{A}_i(t) + \tilde{\alpha}_i^2x_i^T(t)\mathring{A}_i^T\bar{\rho}_i^2R_i\mathring{A}_i x_i(t) \\ & + \begin{bmatrix} x_i(t) \\ x_i(t-\varrho_i(t)) \\ x_i(t-\bar{\varrho}_i(t)) \end{bmatrix}^T \begin{bmatrix} -R_i & * & * \\ R_i & -2R_i & * \\ 0 & R_i & -R_i \end{bmatrix} \begin{bmatrix} x_i(t) \\ x_i(t-\varrho_i(t)) \\ x_i(t-\bar{\varrho}_i(t)) \end{bmatrix} \\ & + x_i^T(t-\varrho_i(t))\Phi_i x_i(t-\varrho_i(t)) - \varphi_i^T\vartheta_i\Phi_i\varphi_i(t) \\ & - \epsilon_i f_i^T(x_i(t),t)f_i(x_i(t),t) + x_i^T(t)\epsilon_i\beta_i^2F_i^TF_i x_i(t)\big)\Bigg\}\end{aligned}$$

DOI: 10.1002/rnc

For presentation convenience, we define

$$\zeta_{1i}^T(t) = \left[\, x_i^T(t)\ x_i^T(t-\varrho_i(t))\ \varphi_i^T(t)\ f_i^T(x_i(t),t)\ \omega_i^T(t), \,\right]$$
$$\zeta_{2i}^T(t) = \left[\, x_1^T(t-\eta_{i1}(t)) \cdots x_{i-1}^T(t-\eta_{i,i-1}(t))\ x_{i+1}^T(t-\eta_{i,i+1}(t)) \cdots x_N^T(t-\eta_{in_s}(t)) \,\right]$$

Then, we have

$$\mathbb{E}\{\mathcal{L}V(t)\} \leqslant \sum_{i\in\mathscr{N}} \left(\mathbb{E}\left\{ \begin{bmatrix} \zeta_{1i}(t) \\ x_i(t-\bar{\rho}) \\ \zeta_{2i}(t) \end{bmatrix}^T \begin{bmatrix} \Pi_{11}^i + \epsilon_i^{-1}\Pi_{51}^{iT}\Pi_{51}^i & * & * \\ \Pi_{21}^i & \Pi_{22}^i & * \\ \Pi_{31}^i & 0 & -\Pi_{33}^i \end{bmatrix} \begin{bmatrix} \zeta_{1i}(t) \\ x_i(t-\bar{\rho}) \\ \zeta_{2i}(t) \end{bmatrix} \right\} \right.$$
$$\left. + \ \mathbb{E}\left\{ \begin{bmatrix} \zeta_{1i}(t) \\ \zeta_{2i}(t) \end{bmatrix}^T \begin{bmatrix} \Pi_{41}^{i\ T} \\ \Pi_{43}^{i\ T} \end{bmatrix} \Pi_{44}^{i\ -1} \left[\, \Pi_{41}^i\ \ \Pi_{43}^i \,\right] \begin{bmatrix} \zeta_{1i}(t) \\ \zeta_{2i}(t) \end{bmatrix} \right\} \right)$$

By using Schur complement, we can conclude that (12) is a sufficient condition to guarantee $\mathbb{E}\{\mathcal{L}V(t)\} \leqslant 0$ for $t \in \wp_{r_k^i}^{\ell_i}$. Notice that $\cup_{k=0}^{\infty} \cup_{\ell_i=1}^{\bar{\ell}_i} \wp_{r_k^i}^{\ell_i} = [0,\infty)$. The proof is completed.

Remark 7
From Theorem 1, it seems that κ_i in adaptive law (5) has no contribution to the stability of the interconnected system. However, it has an influence on the the rate of decay. To ensure the existence of $\sigma_i(t)$, the value of κ_i cannot be selected too much in the design.

4. AETS-BASED ROBUST CONTROLLER DESIGN

Based on Theorem 1, we are in a position to give a sufficient condition on the existence of AETS-based decentralized robust controller of the networked interconnected system.

Theorem 2
For given parameters $\bar{\eta}_{ij}$, $\bar{\rho}_i$, ϑ_i, and ϵ_i, under the adaptive event-triggering condition (4), the closed-loop networked interconnected system (10) with stochastic uncertainty is robust asymptotically stable in mean square sense if there exist matrices $X_i > 0$, $\tilde{Q}_i > 0$, $\tilde{Q}_{ij} > 0$, $\tilde{R}_i > 0$, $\tilde{\Phi}_i > 0$ and Y_i $(i \in \mathscr{N}, j \in \mathscr{N}_i)$ with appropriate dimensions such that the following LMI holds

$$\begin{bmatrix} \tilde{\Pi}_{11}^i & * & * & * & * \\ \tilde{\Pi}_{21}^i & \tilde{\Pi}_{22}^i & * & * & * \\ \tilde{\Pi}_{31}^i & 0 & -\tilde{\Pi}_{33}^i & * & * \\ \tilde{\Pi}_{41}^i & 0 & \tilde{\Pi}_{43}^i & -\tilde{\Pi}_{44}^i & * \\ \tilde{\Pi}_{51}^i & 0 & 0 & 0 & -\epsilon_i I \end{bmatrix} < 0, \qquad i \in \mathscr{N} \tag{23}$$

Moreover, the controller gain in (3) and the weight of the event-triggering condition Φ_i in (4) are $K_i = Y_i X_i^{-1}$ and $\Phi_i = X_i^{-1}\tilde{\Phi}_i X_i^{-1}$, respectively, where

$$\tilde{\Pi}_{11}^i = \begin{bmatrix} \tilde{\Lambda}_1^i & * & * & * \\ Y_i^T B_i^T + \tilde{R}_i & -2\tilde{R}_i + \tilde{\Phi}_i & * & * \\ Y_i^T B_i^T & 0 & -\vartheta_i \tilde{\Phi}_i & * \\ I & 0 & 0 & -\epsilon_i I \end{bmatrix};$$
$$\tilde{\Lambda}_1^i = He(A_i X_i + \bar{\alpha}_i \mathring{A}_i X_i) + \tilde{Q}_i - \tilde{R}_i + \sum_{j\in\mathscr{N}_i} \tilde{Q}_{ij};$$
$$\tilde{\Pi}_{21}^i = \left[\, 0\ \tilde{R}_i\ 0\ 0\ 0 \,\right]; \tilde{\Pi}_{22}^i = -\tilde{Q}_i - \tilde{R}_i;$$
$$\tilde{\Pi}_{31}^i = \begin{bmatrix} A_{di1}X_i & \cdots & A_{di,i-1}X_i & A_{di,i+1}X_i & \cdots & A_{diN}X_i \\ 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix}^T;$$

$$\tilde{\Pi}_{33}^{i} = \text{diag}\{(1-\bar{\eta}_{i1})\tilde{Q}_{i1}, \cdots, (1-\bar{\eta}_{i,i-1})\tilde{Q}_{i,i-1}, (1-\bar{\eta}_{i,i+1})\tilde{Q}_{i,i+1}, \cdots, (1-\bar{\eta}_{ij})\tilde{Q}_{in_s}\};$$
$$\tilde{\Pi}_{41}^{i} = \begin{bmatrix} \tilde{\alpha}_i\bar{\rho}_i\mathring{A}_iX_i & 0 & 0 & 0 \\ \bar{\rho}_iA_iX_i + \bar{\rho}_i\alpha_i\mathring{A}_iX_i & \bar{\rho}_iB_iY_i & \bar{\rho}_iB_iY_i & \bar{\rho}_iI \end{bmatrix};$$
$$\tilde{\Pi}_{43}^{i} = \begin{bmatrix} 0 & \cdots & 0 & 0 & \cdots & 0 \\ A_{di1}X_i & \cdots & A_{di,i-1}X_i & A_{di,i+1}X_i & \cdots & A_{diN}X_i \end{bmatrix};$$
$$\tilde{\Pi}_{44}^{i} = diag\{-2\varepsilon_iX_i + \varepsilon_i^2\tilde{R}_i, -2\varepsilon_iX_i + \varepsilon_i^2\tilde{R}_i\};$$
$$\tilde{\Pi}_{51}^{i} = \begin{bmatrix} \epsilon_i\beta_iF_iX_i & 0 & 0 & 0 \end{bmatrix}$$

Proof
Because of

$$(\varepsilon_iR_i - P_i)R_i^{-1}(\varepsilon_iR_i - P_i) \geqslant 0 \tag{24}$$

Then, it is true that

$$-P_iR_i^{-1}P_i \leqslant -2\varepsilon_iP_i + \varepsilon_i^2R_i \tag{25}$$

It can be concluded that

$$\tilde{\Xi}_i < 0 \tag{26}$$

is a sufficient condition to guarantee (12) holds, where $\tilde{\Xi}_i$ is Ξ_i in (12) by substituting the item $-\Pi_{44}^i$ with $\hat{\Pi}_{44}^i = diag\{-2\varepsilon_iP_i + \varepsilon_i^2R_i, -2\varepsilon_iP_i + \varepsilon_i^2R_i\}$.

Define $X_i = P_i^{-1}$, $J_1 = diag\{X_i, X_i, X_i, I\}$, $J_2 = diag\{\underbrace{X_i, \ldots, X_i}_{N}\}$, $\tilde{Q}_i = X_iQ_iX_i$, $\tilde{R}_i = X_iR_iX_i$, $\tilde{Q}_{i,j} = X_iQ_{ij}X_i$, $\tilde{\Phi}_i = X_i\Phi_iX_i$ and $Y_i = K_iX_i$, then pre-multiply and post-multiply both side of (26) with $diag\{J_1, X_i, J_2, X_i, X_i, I\}$ and its transpose, respectively. One can obviously see that $\tilde{\Xi}_i < 0$ is equivalent to (23). This completes the proof. □

5. A SIMULATION EXAMPLE

In this section, we give a numerical example to show the validity of AETS designed for networked interconnected system. This example is concerned with an interconnected model [47] composed of two machine subsystems $\mathbf{S}_1$ and $\mathbf{S}_2$ with the structure of (1), where the parameters of the system are given by

$$A_1 = \begin{bmatrix} 1 & 0.5 \\ 1 & -0.5 \end{bmatrix}, A_2 = \begin{bmatrix} 2 & 1 \\ 0.5 & 1 \end{bmatrix}, \mathring{A}_1 = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix}, \mathring{A}_2 = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.3 \end{bmatrix},$$
$$A_{d12} = \begin{bmatrix} -0.001 & 0.02 \\ 0.025 & -0.04 \end{bmatrix}, A_{d21} = \begin{bmatrix} -0.03 & 0.03 \\ 0.01 & -0.05 \end{bmatrix}, B_1 = \begin{bmatrix} 2 \\ 1 \end{bmatrix}, B_2 = \begin{bmatrix} 3 \\ 2 \end{bmatrix},$$
$$\beta_1 = 0.02, \beta_2 = 0.01, F_1 = F_2 = I$$

In this example, the system is composed of two subsystems. The coupled delays between the subsystems are supposed by $\eta_{12}(t) = 0.6 + 0.5sin(t)$ and $\eta_{21}(t) = 0.9 + 0.8sin(t)$. For the sake of unknown disturbance upon the system, we assume the statistic of some parameters can be obtained a *priori*. The expectation and variance of the random variable $\alpha_i (i = 1, 2)$ are listed in Table I.

Table I. The statistical property of the random variable α_i $(i = 1, 2)$.

Random variable	Expectation	Variance
α_1	0.95	0.50
α_2	0.96	0.15

The control signal is transmitted over the communicated network. Suppose the upper-bound of the network-induced delay $\bar{\rho} = 0.5$.

By using Theorem 2, we can obtain the controller gain K_i in (3) and triggering matrices Φ_i in (4)

$$K_1 = \begin{bmatrix} -0.2112 & -0.1486 \end{bmatrix}, \Phi_1 = \begin{bmatrix} 1.5329 & 0.3272 \\ 0.3272 & 1.6106 \end{bmatrix},$$
$$K_2 = \begin{bmatrix} 0.0166 & -0.0662 \end{bmatrix}, \Phi_2 = \begin{bmatrix} 1.2139 & 0.0106 \\ 0.0106 & 1.3261 \end{bmatrix}$$

Remark 8

The eigenvalues of A_1 are -1.5 and 0. The maximum eigenvalues of $A_1 + \alpha_1(t)\AA_1$ are up to -0.05 and 0.2 by simulating 5000 discrete time instant, respectively, which means a great perturbation are interfered with the system at a certain instant, However, the probability of this happening is quit small from the simulation. But still, the system can be asymptotically stable in mean square sense by using the aforementioned controller and triggering parameters.

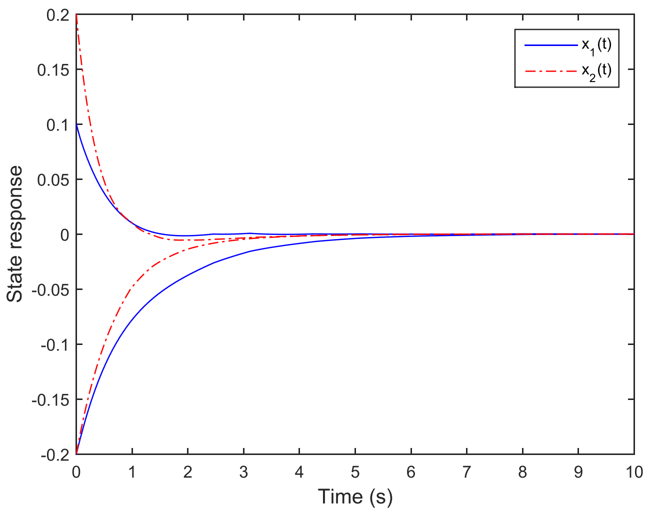

Figure 3. The state responses of the subsystems.

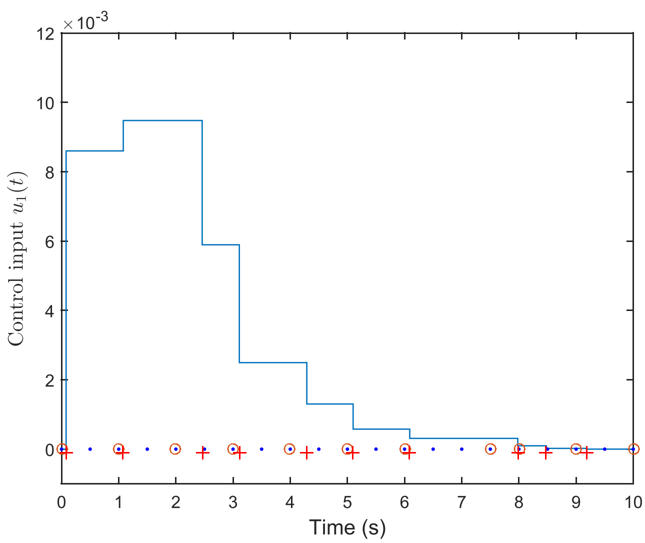

Figure 4. The control input of the subsystem 1.

DOI: 10.1002/rnc

Selecting the initial parameters of the adaptive trigger $\kappa_1 = 10$ and $\kappa_2 = 20$ in (5), and initial conditions $x_1(t) = [0.1 \ -0.2]^T, x_2(t) = [0.2 \ -0.2]^T, \sigma_1(0) = 0.9$ and $\sigma_2(0) = 0.6$ for $t \in [-\max\{\bar{\varrho}_i, \bar{\eta}_{ij}\}, 0)$, we can get the following results which are shown in Figures 3– 9.

Figure 3 presents the state responses of the each subsystem, which demonstrates that the AETS-based interconnected system with stochastic uncertainty is robust asymptotically stable in the mean-square sense by using the proposed method. The control inputs of the subsystems are shown in Figures 4 and 5, where the blue dot '·' represents the periodic sampling instant, the circle '$\odot$' denotes the data releasing instant, and the red plus '$+$' means the data arriving instant. The distance from '$\odot$' to '$+$' denotes the network-induced delay τ_k^i. From Figures 4– 5, we can see that (i) the control value is hold by ZOH at each interval $[r_k^i h + \tau_k^i, r_{k+1}^i h + \tau_{k+1}^i)$, which begins to '$+$' and ends to the next '$+$' in Figures 4 and 5, that is, the control input keep the previous released value till the triggering condition in (4) is violated and the data are transmitted over the network; (ii) the variation of the distance from $\odot$ to $+$ in the figure means the network-induced delay is time-varying and; (iii) the distance between the adjacent $+$s is different in the figure, which indicates the releasing period changes with the triggering condition and scheduling instruction. Furthermore, releasing period is much bigger than the sampling period, which reduces the amount of the data releasing greatly.

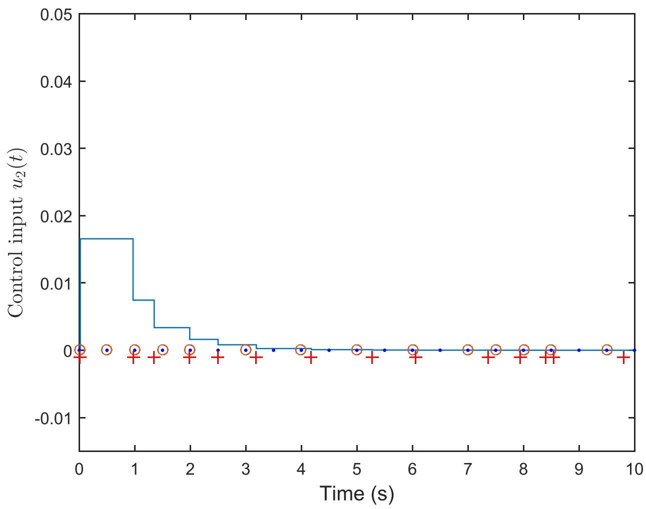

Figure 5. The control input of the subsystem 2.

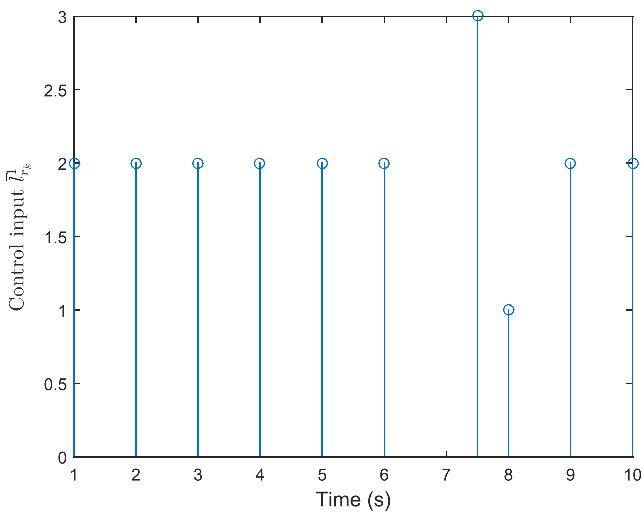

Figure 6. The spacing of subsystem 1 between the adjacent released instants.

DOI: 10.1002/rnc

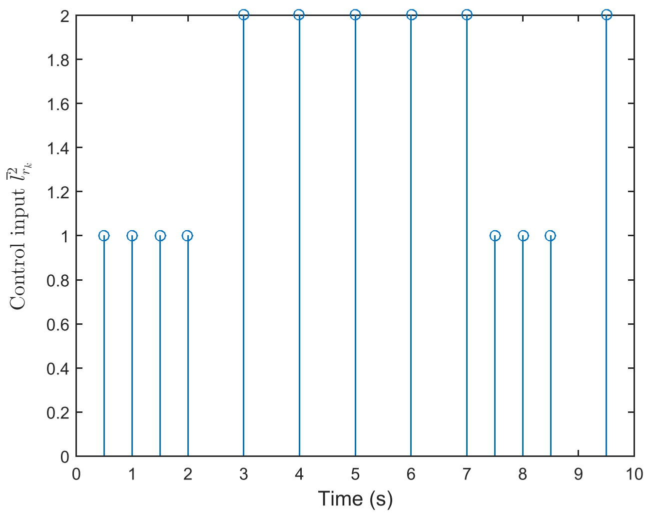

Figure 7. The spacing of subsystem 2 between the adjacent released instants.

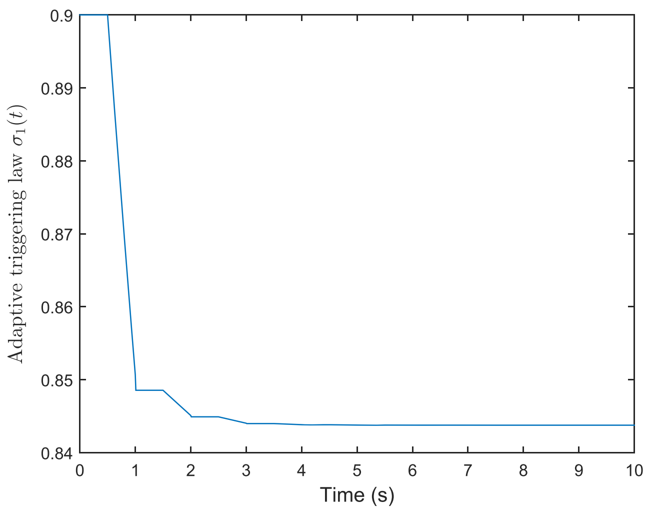

Figure 8. The adaptive law of $\sigma_1(t)$.

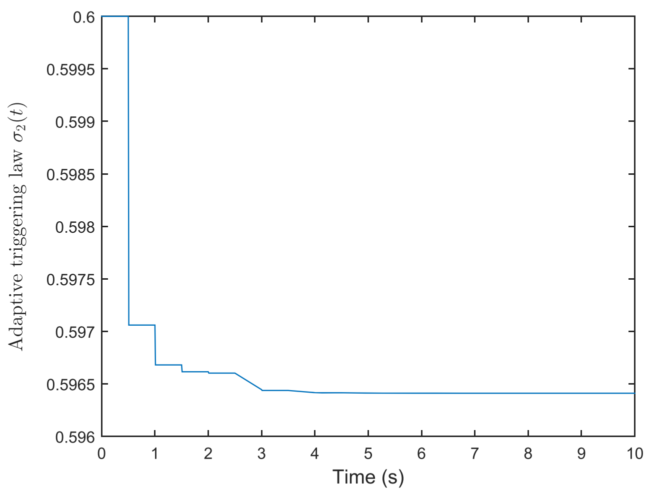

Figure 9. The adaptive law of $\sigma_2(t)$.

DOI: 10.1002/rnc

The spacing between the adjacent released instants are shown in Figures 6 and 7, from which one can conclude that not all the sampling data are necessary to stabilize the interconnected system by comparing the sate responses in Figure 3 with the results in [47]. In this example, the releasing rate of subsystem 1 is 52.38%, while the releasing rate of subsystem 2 is 66.67%, many 'unnecessary' data are discarded by ATED. Therefore, by using the triggering condition (4) to 'filter' the sampling data, the network bandwidth can be saved effectively.

Figures 8 and 9 show the curves of the adaptive triggering parameters $\sigma_i(t)$ $(i = 1, 2)$. Different from the method in [27], the triggering parameter σ is a predetermined constant. In this study, the threshold is a result of self-optimization, which depends on the state variables value at releasing instant, sampling instant and their error. In this example, the $\sigma_1(t)$ and $\sigma_2(t)$ converges to 0.844 and 0.596, respectively, under the initial conditions $\kappa_1 = 10$, $\kappa_2 = 20$ and $\sigma_1(0) = 0.9, \sigma_2(0) = 0.6$.

6. CONCLUSION

In this study, the adaptive event-triggering scheme for a class of networked interconnected system with stochastic uncertainty has been investigated. In the modeling process, a random variable is introduced to model the uncertainty. To reduce the network traffic, a new adaptive event-triggering scheme is proposed. Based on the Lyapunov stability theory and LMIs technology, the decentralized controllers and the weight of the triggering condition are co-designed. Furthermore, the threshold of the triggering condition is obtained by an adaptive method, which can guarantee every subsystems robustly asymptotically stable in the mean-square sense. Simulation results show the effectiveness of the proposed method. Moreover, the case of the network communication between the subsystems under the scheme of AETS will be investigated in our future work.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Grant Nos. 61473156, 61573112), Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20133204120018).

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