Observer-Based Dynamic Event-Triggered Robust $H_\infty$ Control of Networked Control Systems Under DoS Attacks

LING HUANG, JING GUO, AND BING LI
School of Automation, Harbin University of Science and Technology, Harbin, Heilongjiang 150080, China
Heilongjiang Provincial Key Laboratory of Complex Intelligent System and Integration, Harbin, Heilongjiang 150080, China
Corresponding author: Jing Guo (182051080@stu.hrbust.edu.cn)
This work was supported by the Natural Science Foundation of Heilongjiang Province under Grant LH2020F035.

ABSTRACT  This paper designs an observer-based controller with a dynamic event-triggered strategy for networked control systems with external disturbance, system uncertainty, and unknown periodic Denial-of-Service (DoS) attacks. First, the system under DoS attacks is modeled as active subsystem and dormant subsystem by using the switching system method. The controller is built based on dynamic event-triggered sequence and observer with the hold-input method used as the control signal for DoS attacks active subsystem. An augmented system is constructed with the time delay method, and the $H_\infty$ performance index of the closed-loop switched system is given. Then, using Lyapunov functional theory and some technical lemmas, the sufficient conditions for the stability of the system are given without the disturbance, and with disturbance, the sufficient conditions for the closed-loop system with $H_\infty$ performance index are deduced. Finally, a numerical example is given to verify the effectiveness of the theory. Through the minimum optimization problem, the $H_\infty$ performance parameter is optimized to increase the disturbance suppression degree of the system.

INDEX TERMS  Dynamic event-triggered scheme, networked control systems, denial-of-service attacks, uncertainty, $H_\infty$ performance.

I. INTRODUCTION

In recent years, due to the rapid development of sensor and communication and computing technology, networked control systems have captured more and more attention. Networked control systems have advantages in information sharing, low installation cost, easy maintenance, and high flexibility. Thus, they are widely applied in many fields, including industrial control, smart grid, petrochemical, automobile device [1].

As introducing a communication network into the traditional system destroys the system’s closure, the open industrial network is vulnerable to network attacks [2]. The studies in [3]–[5] demonstrate that the common security threats of networked control systems are DoS attacks, which attempt to transmit a large amount of invalid data and occupy limited network resources, leading to ineffective data transmission, thus affecting the regular work of the system. However, most of the studies of DoS attacks are focused on researching DoS attacks signal detection [6]–[8] and system security control [9]–[11]. The network attacks could be detected effectively by the attacks detection algorithm in [7], but missed signal detection is inevitable for the change of network attacks. Therefore, it is crucial to design the proper robust control strategy to preserve the stability of networked control systems with network attacks. In fact, the assumption that the energy of DoS attacks is limited is significant for researching the security of networked control systems. For one thing, in [12], based on the asymptotic stability of the system, it is proved that DoS attacks tolerated for the system are limited in energy and duration. For another, it is pointed out that DoS attacks are limited in power from the perspective of attackers in [13].

Actually, the researches of networked control systems are about network security and how to improve the utilization of network bandwidth. Some event-triggered strategies have been intensively worked on [14]–[17] to solve limited network system resources. Only when a specific event occurs can the control rate be updated, or the transmitted signal...
keeps the latest value. Compared with the traditional time-triggered strategy, the event-triggered strategy saves the bandwidth resource of the networked control systems in [15]. Research into event triggering should pay attention to the fact that the minimum interval time between events must be strictly greater than zero to avoid Zeno behavior. One way to overcome this problem is to employ an event-triggered strategy based on sampled data [16]. To further save bandwidth resources, [18] proposes a dynamic event-triggered mechanism. By introducing an additional variable, the event-triggered number is reduced while holding the stability of the system. A new dynamic event-triggered mechanism is designed in [19], and by setting the threshold value of the dynamic parameter, the parameter neither decays prematurely nor increases excessively, which generates fewer transmissions. The analysis and synthesis of networked control systems based on dynamic event triggering have also been discussed in [20]–[23]. Under the same control performance as the static counterpart, the dynamic event-triggered strategies generate fewer events. Besides, [19] researching dynamic event-triggered mechanism based on sampling instant can also avoid the Zeno behavior.

There are growing focus on event triggering and security control of networked control systems. In [24], using the active period and dormant period of DoS attacks, the resilient event-triggered strategy based on output is designed, and the strategy and DoS attacks are integrated into a unified framework by switching system theory. In [25], considering the practical engineering applications, and the state of the system is hard to get all, the networked control systems with periodic DoS attacks based on state observer are studied for resilient event-triggered control, and the observer and controller of the system are designed collaboratively. Although some static event-triggered methods have been developed with the DoS attacks, only a few results considered dynamic event-triggered strategy into account. In [26], resilient dynamic event-triggered strategy is designed to study the control problem of power systems under DoS attacks and transmission delay. Based on [25], to reduce the control update frequency, the parameters of dynamic event triggering, observer, and controller are designed collaboratively in [27]. Considering that the information transmission between the sensor and the controller may be subject to asynchronous DoS attacks, [28] proposes a resilient control method for dynamic event triggering, and the designed dynamic event-triggered strategy generates fewer events than static event-triggered strategy.

To sum up, this paper mainly assumes that DoS attacks energy are limited. Compared with [25], this paper discusses more common attacks with the unknown period, while the above resilient control strategy mainly adopts the zero-input method to compensate for the impact of DoS attacks on the system in [25]–[28]. Considering that the performance of the hold-input method may be better for the compensation of the unstable system, this paper takes the hold-input method to design the controller and studies the secure dynamic event-triggered control of the networked control systems with uncertainty and external disturbance. The novelty of this paper lies in two aspects:

1) Different from [25], [28], [29], considering a more complex networked control systems with DoS attacks, external disturbance, and uncertainty, sufficient conditions are given for robust asymptotic stability of the system without disturbance, and with disturbance, the sufficient condition for the closed-loop system with $H_{\infty}$ performance index is deduced.

2) Comparing with results in [28], by introducing an integral inequality to deal with the integrals with derivatives in Lyapunov-Krasovskii functional, a low conservativeness condition is obtained with an additional parameter, using the hold-input strategy to realize faster and more smoothly the stability of the system.

**Notation:** $\mathbb{R}^n$ denotes the n-dimensional Euclidean space and $\mathbb{R}^{m \times n}$ is the set of $n \times m$ real matrices; the superscript $T$ stands for matrix transposition; the symbol $\bullet$ represents each of the symmetric blocks; $\mathcal{L}_1[0, \infty)$ denotes the space of square-integrable vector functions defined on $[0, \infty)$; $I$ and 0 represent identify matrix and zero matrix with proper dimensions, respectively.

**II. PROBLEM FORMULATION AND MODELING**

Consider a class of networked control systems with uncertainty and disturbance:

$$
\begin{align*}
\dot{x}(t) &= [A + A(t)]x(t) + [B_1 + \Delta B]u(t) + Bw(t), \\
y(t) &= Cx(t),
\end{align*}
$$

where $x(t) \in \mathbb{R}^n$ is the plant state, $y(t) \in \mathbb{R}^q$ is the plant output, $u(t) \in \mathbb{R}^m$ is the control input, $w(t) \in \mathbb{R}^p$ denotes the disturbance input belonging to $\mathcal{L}_1[0, \infty)$, $A$, $B_1$, $B$, $C$ are the known parameter matrices with suitable dimensions, and $\Delta A$, $\Delta B$ are the unknown time-variant matrices representing norm-bounded parameter uncertainties, which are assumed to be of the form $[\Delta A \Delta B] = H(t) [E_1 E_2]$, where $H$, $E_1$ and $E_2$ are known constant matrices with suitable dimensions, and $F(t)$ is an unknown time-varying matrix function, which satisfies the inequality condition $F(t)F(t)^T \leq I$ for all $t$.

In Fig.1, the unknown periodic DoS attacks can be modeled as the following switching signals

$$
D(t) = \begin{cases} 
1, & t \in [g_n, g_n + h_n), \\
0, & t \in [g_n + h_n, g_{n+1}),
\end{cases}
$$

where $[g_n, g_n + h_n)$ denotes the sleep interval of the $n$th DoS attacks with normal transmission, and $[g_n + h_n, g_{n+1})$ denotes the active interval of the $n$th DoS attacks with interrupted transmission. $[h_n)$ represents the time instants when DoS attacks are sleeping, and $[g_n + h_n)$ represents the active start time of the $n$th DoS attacks which end at $g_{n+1}$.

In order to simplify the derivation, let $H_{1,n} = [g_n, g_n + h_n)$, $H_{2,n} = [g_n + h_n, g_{n+1})$, $t_{1,n} = g_n$, $t_{2,n} = g_n + h_n$. 

VOLUME 9, 2021
Assumption 1: Same as [29], \( n(t) \) is the number of the positive edge triggering of DoS attacks in the current period \( [t, \infty) \). There are two real scalars \( \nu \geq 0 \) and \( \Gamma > 0 \) for all \( t \geq 0 \) that satisfy
\[
n(t) \leq \nu + \frac{t}{\Gamma}.
\tag{3}
\]

Assumption 2: Same as [29], \( \Xi(t) \) is the total duration of DoS attacks within \( n(t) \) of the current positive edge triggering. There are two real scalars \( \omega \geq 0 \) and \( \Gamma_D > 0 \) for all \( t \geq 0 \) that satisfy
\[
|\Xi(t)| \leq \omega + \frac{t}{\Gamma_D}.
\tag{4}
\]

Considering the following full-dimensional state observer for system (1)
\[
\begin{align*}
\dot{\hat{x}}(t) &= A\hat{x}(t) + Bu(t) + L(t)[\hat{y}(t) - y(t)], \\
\dot{\hat{y}}(t) &= C\hat{x}(t),
\end{align*}
\tag{5}
\]
where \( \hat{x} \in \mathbb{R}^n \) is the observer state, \( \hat{y} \in \mathbb{R}^q \) is the observer output, and \( L(t) \in \mathbb{R}^{m \times q} \) is the observer gain to be designed as
\[
L(t) = \begin{cases} 
L_1, & t \in H_{1,n}, \\
L_2, & t \in H_{2,n}.
\end{cases}
\]

From Fig.1, \( h > 0 \) is the sampling period, \( t_h \) is the sampling time, and \( t_k h \) is the latest trigger time, \( t_j, t_k \in \mathbb{N} \). During the \( n \)th dormant DoS attacks, the \( j \)th sampling is defined as \( t_j^n, n, j \in \mathbb{N} \), and \( t^n_j \) is the current sampling time. If \( t^n_j \) satisfies (6) as follows
\[
\theta_\eta(t_k h) + \sigma \hat{x}^T(t_k h) \Omega \hat{x}(t_k h)
- \left[ \hat{x}(t^n_j h) - \hat{x}(t_k h) \right]^T \Omega \left[ \hat{x}(t^n_j h) - \hat{x}(t_k h) \right] < 0,
\tag{6}
\]
the data will be transmitted and the trigger time will be undated.

To compensate for the impact of the system from the active DoS attacks, we designed the data transmitted at \( g_{n+1} \) which represents the end of the \( n \)th DoS attacks. Therefore, the transmission instant of observer state \( \hat{x} \) is determined by dynamic event generator which is as follows
\[
t_k,n h \in \left\{ t^n_j h \text{ satisfying (6)} \mid t^n_j h \in H_{1,n} \right\} \bigcup \{g_{n+1}\}. \tag{7}
\]

In (6), \( \theta \geq 0 \), \( \sigma \in (0, 1) \), \( \Omega \) is a positive definite symmetric matrix to be designed, and the dynamic parameter \( \eta(t) \) satisfies
\[
\eta(t) = \begin{cases} 
-\beta(\eta(t)) - \theta \eta(t_k h) + \hat{x}^T(t_k h) \Lambda \hat{x}(t_k h), & \eta(t) < \eta_0, \\
\beta(\eta(t)) - \theta \eta(t_k h), & \eta(t) \geq \eta_0,
\end{cases}
\tag{8}
\]
where \( t \in [t_k h, t_{k+1,n} h) \), \( \Lambda \) is a positive definite weighted matrix to be designed, \( \beta \) is a function of class \( K_\infty \) and satisfies Lipschitz continuity, and \( \eta_0 \) is an adjustable parameter according to the actual condition.

Remark 1: In order to avoid Zeno behavior, the designed trigger condition is based on the sampling time of the system, so the minimum event-triggered interval of the system is an integer multiple of the sampling period.

Lemma 1 [19]: Suppose \( \beta \) is a \( K_\infty \) class function and satisfies Lipschitz continuity, let \( \sigma \in (0, 1), \eta_0 > 0, \theta > 0 \). If \( h, \theta \) satisfy \( \eta \in -\frac{1}{\mu} \ln \frac{T_{h+1}}{\eta}, \eta > 0 \) for any \( t \in [0, \infty) \).

Considering the switching signals of DoS attacks, the controller of the system (1) is designed as follows
\[
u(t)
= \begin{cases} 
K_1 \hat{x}(t_k,n h), & t \in [t_k h, t_{k+1,n} h) \cap H_{1,n}, \\
K_2 \hat{x}(t_k,n h), & t \in [t_k h, t_{k+1,n} h) \cap H_{2,n}.
\end{cases}
\tag{9}
\]
where \( K_1, K_2 \) are the controller gain matrices, the sequence \( t_k,n h \) is determined by iteration of the trigger condition (7), \( t_0,n = g_n, h > 0, k \in [0, 1, \ldots, k(n)] = K(n), k(n) = \sup \{ k \in N \mid t_k,n \leq g_n + h \}, t_{k+1,n} h > g_n + h_n \). From the above definition, it can be known that \( t_k,n h \) is the \( k(n) \)th normal triggering within the time of the \( n \)th dormant DoS attacks.

In order to simplify the derivation, similar to [25], let \( R_{k,n} = [t_k,n h, t_{k+1,n} h] \). Substitute (9) into (1), we can obtain
\[
\begin{align*}
\dot{x}(t) &= [A + \Delta A]x(t) + [B_1 + \Delta B]K_1 \hat{x}(t_k,n h) + B_2 w(t), \\
\dot{x}(t) &= [A + \Delta A]x(t) + [B_1 + \Delta B]K_2 \hat{x}(t_k,n h) + B_2 w(t),
\end{align*}
\tag{10}
\]
\( R_{k,n} \) is divided into inter cell according to sampling interval as follows
\[
R_{k,n} = \bigcup_{m=1}^{\rho_{k,n}} [t_k,n h + (m - 1)h, t_k,n h + mh],
\tag{11}
\]
where \( k \in K(n), n \in N, \rho_{k,n} = \inf \{ m \in N \mid t_k,n h + mh \geq t_{k+1,n} h \}. \)
For \( k \in K(n), n \in N \), same as [29], two piecewise functions are defined,

\[
\tau_k,n(t) = \begin{cases} 
    t - \tau_{k,n} h, & t \in [t_k,n, h, t_k,n + h), \\
    t - \tau_{k,n} h - h, & t \in [t_k,n + h, t_k,n + 2h), \\
    \vdots & \\
    t - \tau_{k,n} h - (\rho_{k,n-1}) h, & t \in [t_k,n + h + \rho_{k,n-1} h, t_{k,n-1} + h), \\
    \vdots & \\
    t - \tau_{k,n} h - (\rho_{k,n-1}) h, & t \in [t_k,n + h + \rho_{k,n-1} h, t_{k,n-1} + h), \\
    \vdots & \\
\end{cases}
\]

(12)

\[
e_{k,n}(t) = \begin{cases} 
    \hat{x} (t_k,n) - \hat{x} (t_{k,n-1}, h) h + h, & t \in [t_k,n + h, t_k,n + 2h), \\
    \vdots & \\
\end{cases}
\]

(13)

it can be concluded that \( \tau_k,n(t) \in [0, h), t \in R_k,n \), and \( \hat{x} (t_k,n) = \hat{x} (t - \tau_k,n(t)) + e_k,n(t), t \in R_k,n \).

The error state is defined as \( e(t) = \hat{x}(t) - x(t) \), and the augmented state is \( \xi(t) = [x^T(t) e^T(t)] \), then the augmented system is derived as follows:

\[
\dot{\xi}(t) = A_1 \xi(t) + B_1 \xi(t - \tau_k,n(t)) + \ddot{B}_1 e_k,n(t) + \ddot{B}_1 w(t), \quad t \in R_k,n \cap H_1,n, \\
\dot{\xi}(t) = A_2 \hat{\xi}(t) + B_2 \hat{\xi}(t - \tau_k,n(n)) + \ddot{B}_2 e_k,n(t) + \ddot{B}_2 w(t), \quad t \in R_k(n), n \cap H_2,n, \\
\dot{\xi}(t) = \phi(t), \quad t \in [-h, 0),
\]

where

\[
A_1 = \begin{bmatrix} A + \Delta A & 0 \\ -\Delta A & -A - L_1 C \end{bmatrix},
A_2 = \begin{bmatrix} A + \Delta A & 0 \\ -\Delta A & -A - L_2 C \end{bmatrix},
B_1 = \begin{bmatrix} B \hat{K}_1 + \Delta B \hat{K}_1  \\ \Delta B \hat{K}_1 \end{bmatrix},
B_2 = \begin{bmatrix} B \hat{K}_2 + \Delta B \hat{K}_2 \\ \Delta B \hat{K}_2 \end{bmatrix},
\]

III. MAIN RESULTS

In order to facilitate, the lemmas are given for the treatment of uncertainty and integral item in Lyapunov functional.

Lemma 2 [30]: If there are two known matrices \( D \) and \( E \) of proper dimensions and \( F(t) \) satisfies \( F^T(t)F(t) \leq I \), there is a scalar \( \lambda > 0 \) such that the following inequality holds

\[
DF(t)E + E^T F(t)D^T \leq \lambda DDT + \chi^{-1} E^TE.
\]

Lemma 3 [31]: For constant matrices \( T, R = R^T > 0 \), scalars \( d_1 \leq d(t) \leq d_2 \), a vector function \( \hat{x} : [-d_2, -d_1] \rightarrow R^n \) such that the integration in the following inequality is well defined, then it holds that

\[
\int_{-d_2}^{t-d_1} \hat{x}^T(\alpha)R\hat{x}(\alpha)d\alpha \leq \theta^T(t) \begin{bmatrix} I - I & 0 \\ 0 - I & -I \end{bmatrix} W \begin{bmatrix} I - I & 0 \\ 0 - I & -I \end{bmatrix} \theta(t),
\]

where \( \theta(t) = \begin{bmatrix} x^T(t - d_1) & x^T(t - d(t)) & x^T(t - d_2) \end{bmatrix} \), \( W = \begin{bmatrix} -R & T \\ 0 & -R \end{bmatrix} \leq 0 \).

Lemma 4: Given fixed DoS attacks parameters \( \nu \geq 0, \Gamma \geq 0, \omega \geq 0, \Gamma_D \geq 0 \), the feedback control gain matrices \( K_1, K_2 \), the observer gain matrices \( L_1, L_2 \), and the parameters \( \alpha_1 > 0, \alpha_2 > 0, \sigma > 0, h > 0, \epsilon_1 > 0, \epsilon_2 > 0 \), if there exist positive definite symmetric matrices \( P_1 > 0, Q_1 > 0, R_1 > 0, P_2 > 0, Q_2 > 0, R_2 > 0, \Omega_1 > 0, \Lambda > 0, \Omega_2 > 0 \) and matrices \( T_1, T_2 \) of appropriate dimensions, such that the following matrix inequalities

\[
\Phi_1 = \begin{bmatrix} \hat{F}_1 & * & * & * \\ h\hat{R}_1 \hat{F}_1 & \hat{R}_1 & * & * \\ \hat{E}_1 & 0 & -\epsilon_1 I & * \\ 0 & 0 & \hat{H} - \epsilon_1 I & -\epsilon_1 I \end{bmatrix} < 0,
\]

(17)

\[
\Phi_2 = \begin{bmatrix} \hat{F}_2 & * & * & * \\ h\hat{R}_2 \hat{F}_2 & \hat{R}_2 & * & * \\ \hat{E}_2 & 0 & -\epsilon_2 I & \hat{H} \\ 0 & 0 & \hat{H} - \epsilon_2 I & -\epsilon_2 I \end{bmatrix} < 0,
\]

(18)

where

\[
\hat{F}_1 = \begin{bmatrix} \hat{F}_{11} & \hat{F}_{12} & B_1 K_1 & B_1 K_2 & 0 & 0 & B_1 K_1 \\ \hat{F}_{13} & \hat{F}_{14} & 0 & 0 & 0 & 0 \end{bmatrix}, \\
\hat{F}_{11} = A + \epsilon_1 H\hat{H}^T P_1, \quad \hat{F}_{12} = \epsilon_1 \hat{H}^T P_1, \\
\hat{F}_{13} = \epsilon_1 \hat{H}^T P_1, \quad \hat{F}_{14} = A - L_1 C + \epsilon_1 \hat{H}^T P_1, \\
\hat{E}_1 = \begin{bmatrix} E_1 & 0 \end{bmatrix} E_2 K_1 E_2 K_2 \begin{bmatrix} 0 & 0 \end{bmatrix}, \\
\hat{F}_2 = \begin{bmatrix} \hat{F}_{21} & \hat{F}_{22} & B_2 K_2 & B_2 K_2 & 0 & 0 & B_2 K_2 \\ \hat{F}_{23} & \hat{F}_{24} & 0 & 0 & 0 & 0 \end{bmatrix}, \\
\hat{F}_{21} = A + \epsilon_2 H\hat{H}^T P_1, \quad \hat{F}_{22} = \epsilon_2 H\hat{H}^T P_2, \\
\hat{F}_{23} = \epsilon_2 H\hat{H}^T P_2, \quad \hat{F}_{24} = A - L_2 C + \epsilon_2 H\hat{H}^T P_2,
\]

\[
\hat{H} = [H^T H]^T,
\]
it can be obtained
\[
W(t) \leq \begin{cases} 
    e^{-2\alpha_1(t-t_{1,n})}W_1\left(t_{1,n}\right), & t \in R_{k,n} \cap H_{1,n}, \\
    e^{2\alpha_2(t-t_{2,n})}W_2\left(t_{2,n}\right), & t \in R_{k(n),n} \cap H_{2,n}.
\end{cases} \tag{19}
\]

Proof: An candidate Lyapunov-Krasovskii functional for the closed-loop switched system (14) is constructed as follows
\[
W_i(t) = \begin{cases} 
    V_i(t) + \eta(t), & t \in R_{k,n} \cap H_{1,n}, i = 1, \\
    V_i(t), & t \in R_{k(n),n} \cap H_{2,n}, i = 2.
\end{cases} \tag{20}
\]
\(\eta(t)\) is defined by (8), \(\beta(\eta(t)) = -2\alpha_1\eta(t)\), and \(V_i(t)\) is constructed as
\[
\begin{align*}
    V_i &= \xi^T(t)P_i\xi(t) \\
    + &\int_{t-h}^{t} \xi^T(s)e^{2(1-\alpha_1(t-s))Q_i}\xi(s)ds \\
    &+ h\int_{t-h}^{t} \xi^T(s)e^{2(1-\alpha_1(t-s))R_i}\xi(s)ds d\theta, \tag{21}
\end{align*}
\]
where
\(P_i > 0, Q_i > 0, R_i > 0, i \in \{1, 2\}\).
When \(i = 1\), \(w(t) = 0\),
\[W(t) = W_1(t), \tag{22}\]
by taking the derivative of \(V_1(t)\) along the trajectory of the system (14) at \(t \in R_{k,n} \cap H_{1,n}\),
\[
\dot{V}_1(t) \leq \dot{\xi}^T(t)P_1\xi(t) + \xi^T(t)P_1\dot{\xi}(t) + \xi^T(t)Q_1\xi(t) \\
- \dot{\xi}^T(t-h)e^{-2\alpha_1h}\xi(t-h) + h^2\dot{\xi}^T(t)R_1\dot{\xi}(t) \\
- h\int_{t-h}^{t} \dot{\xi}^T(s)e^{-2\alpha_1hR_1}\dot{\xi}(s)ds, \tag{23}
\]
applying Lemma 3 to the integral term
\[\int_{t-h}^{t} \dot{\xi}^T(s)e^{-2\alpha_1hR_1}\dot{\xi}(s)ds \leq \partial^T(t)Z_i\partial(t), \tag{24}\]
we can get
\[\int_{t-h}^{t} \dot{\xi}^T(s)e^{-2\alpha_1hR_1}\dot{\xi}(s)ds \leq \partial^T(t)Z_i\partial(t), \tag{24}\]
where
\[
Z_1 = \begin{bmatrix} 
    -e^{-2\alpha_1hR_1} & * & * \\
    Z_{11} & Z_{12} & * \\
    T_1^T & e^{-2\alpha_1hR_1} & -T_1^T & -e^{-2\alpha_1hR_1} \\
\end{bmatrix},
\]
\[
Z_{11} = e^{-2\alpha_1hR_1} - T_1^T, \\
Z_{12} = \begin{bmatrix} 
    \xi^T(t) \\
    \xi^T(t-h) \\
\end{bmatrix}, \\
\partial^T(t) = \begin{bmatrix} 
    \xi^T(t) \\
    \xi^T(t-h) \\
\end{bmatrix}.
\]
Substituting (24) for (23), we can get
\[
\dot{V}_1(t) \leq -2\alpha_1V_1(t) + 2\alpha_1\xi^T(t)P_1\xi(t) + \xi^T(t)P_1\xi(t) \\
+ \xi^T(t)Q_1\xi(t) + h^2\dot{\xi}^T(t)R_1\dot{\xi}(t) \\
- \dot{\xi}^T(t-h)e^{-2\alpha_1hQ_1}\xi(t-h) + \partial^T(t)Z_i\partial(t). \tag{25}
\]
Define
\[
\xi^T(t) = \begin{bmatrix} 
    \xi^T(t) \\
    \xi^T(t-h) \\
\end{bmatrix},
\]
\[
\eta(t) = \begin{bmatrix} 
    \xi^T(t) \\
    \xi^T(t-h) \\
\end{bmatrix} e_T^{k(n)}(t).
\]
According to (8) and (25) we can obtain
\[ W_1(t) \leq -2\alpha_1 V_1(t) - 2\alpha_1 \eta(t) \]
\[ + \xi^T(t) [\Phi_1^1 + h^2 F^T R_1 F_1] \xi(t), \]
where \( \Phi_1 = \Phi_{11}^1 + h^2 F^T R_1 F_1 \), and \( \Phi_{11} \prec 0 \). To apply Schur’s Complement Lemma [30], we can obtain
\[
\Phi_1 = \begin{bmatrix}
\Phi_{11}^1 & * \\
* & hR_1 F_1 - R_1 
\end{bmatrix} < 0,
\]  
(26)

where \( F_1 = [A_1 \bar{B}_1 \ 0 \ \bar{B}_1] \) and
\[
\Phi_{11} = \begin{bmatrix}
\Gamma_{11}^1 & * & * & * \\
\Gamma_{12}^1 & \Gamma_{13}^1 & * & * \\
T_{11} & T_{12} & T_{13} & T_{14} \\
T_{21} & T_{22} & \Gamma_{23}^1 & \Gamma_{24}^1
\end{bmatrix} < 0,
\]

where
\[
\Gamma_{11} = 2\alpha_1 P_1 + A_1^T P_1 + P_1 A_1 + Q_1 - e^{-2\alpha_1 h} R_1,
\]
\[
\Gamma_{12} = \bar{B}_1^T P_1 - T_{11} + e^{-2\alpha_1 h} R_1,
\]
\[
\Gamma_{13} = \sigma G^T \Omega_1 G + \Lambda + H e \left[T_1 - e^{-2\alpha_1 h} R_1 \right],
\]
\[
\Gamma_{14} = e^{-2\alpha_1 h} R_1 - T_{11},
\]
\[
\Gamma_{15} = -e^{-2\alpha_1 h} Q_1 - e^{-2\alpha_1 h} R_1,
\]
\[
G = [I \ I].
\]

To eliminate the uncertainty in \( \Phi_1 \), we obtain \( \Phi_{11} \prec \Phi_1 \), and the form of \( \Phi_1 \) is shown in (17) of Lemma 4.

Obviously, if \( \Phi_1 < 0 \) then \( \Phi_{11} < 0 \), \( W_1(t) < -2\alpha_1 W_1(t) \), when \( t \in R_{k,n}, H_{1}, n \), we can obtain
\[
W(t) \leq e^{2\alpha_1 (t-t_{1,n})} W_1(t_{1,n}).
\]
When \( i = 2, w(t) = 0 \),
\[
W(t) = W_2(t),
\]
(27)
in the same way by taking the derivative of \( V_2(t) \) along the trajectory of the system (14) at \( t \in R_{k,n}, H_{2}, n \), we can obtain
\[
W_2(t) = \dot{W}_2(t) \leq 2\alpha_2 V_2(t) + \xi^T(t) \left[ \Phi_{22}^2 + h^2 F^T R_2 F_2 \right] \xi(t),
\]
where \( \Phi_2 = \Phi_{11}^2 + h^2 F^T R_2 F_2 \), taking Schur complement of \( \Phi_2 < 0 \), and it can be obtained to
\[
\Phi_{22} = \begin{bmatrix}
\Gamma_{21}^2 & * & * & * \\
\Gamma_{22}^2 & \Gamma_{23}^2 & * & * \\
T_{21} & \Gamma_{24}^2 & \Gamma_{25}^2 & \Gamma_{26}^2 \\
T_{22} & \Gamma_{27}^2 & \Gamma_{28}^2 & \Gamma_{29}^2
\end{bmatrix} < 0,
\]

where
\[
\Gamma_{21} = 2\alpha_2 P_2 + A_2^T P_2 + P_2 A_2 + Q_2 - e^{2\alpha_2 h} R_2,
\]
\[
\Gamma_{22} = \bar{B}_2^T P_2 - T_{22} + e^{2\alpha_2 h} R_2,
\]
\[
\Gamma_{23} = \sigma G^T \Omega_2 G + He \left[T_2 - e^{2\alpha_2 h} R_2 \right],
\]
\[
\Gamma_{24} = e^{2\alpha_2 h} R_2 - T_{22},
\]
\[
\Gamma_{25} = -e^{2\alpha_2 h} Q_2 - e^{2\alpha_2 h} R_2.
\]

Similarly, the uncertainty of (28) is eliminated to obtain \( \Phi_2 \preceq \Phi_2 \), and the form of \( \Phi_2 \) is shown in (18) of Lemma 4.

Obviously, if \( \Phi_2 < 0 \) then \( \Phi_2 < 0 \), \( \dot{W}_2(t) < 2\alpha_2 W_2(t) \), when \( t \in R_{k,n}, H_{2}, n \), we can obtain
\[
W(t) \leq e^{2\alpha_2 (t-t_{2,n})} W_2(t_{2,n}).
\]

The proof is now completed.

Remark 2: Since the closed-loop switched system has time delay, Lyapunov-Krasovskii functional with the integral term is designed to deal with the delay effect of the system. In [25], the integral term is processed by the free weight matrix, and an additional constraint is introduced. In this paper, the integral term is processed by Lemma 3 in [31], and no redundant constraint is introduced, thus providing a low conservative condition.

(19) is a sufficient condition that will be used to prove the asymptotic stability of (14) in Theorem 1.

Theorem 1: Given fixed DoS attacks parameters \( \nu \geq 0, \omega \geq 0, \Gamma_D \geq 0, \) feedback controller gain matrices \( K_1, K_2, \) observer gain matrices \( L_1, L_2, \) and parameters \( \alpha_1 > 0, \alpha_2 > 0, \sigma > 0, \nu > 0, \xi_1 > 0, \xi_2 > 0, \mu_1 > 0, \mu_2 > 0, \) if there exist positive definite symmetric matrices \( P_1 > 0, Q_1 > 0, R_1 > 0, \) \( P_2 > 0, Q_2 > 0, R_2 > 0, \) \( \Omega_1 > 0, \) \( \Lambda > 0, \) \( 2 \alpha > 0 > 0, \) and matrices \( T_1, T_2 \) of appropriate dimensions satisfying the inequalities (17) and (18), and satisfying the following conditions
\[
\begin{align*}
P_1 - \mu_2 P_2 & \preceq 0, \\
Q_1 - \mu_2 Q_2 & \preceq 0, \\
R_1 - \mu_2 R_2 & \preceq 0, \\
P_2 - \mu_1 e^{2(\alpha_1 + \alpha_2) h} P_1 & \preceq 0, \\
Q_2 - \mu_1 Q_1 & \preceq 0, \\
R_2 - \mu_1 R_1 & \preceq 0,
\end{align*}
\]
and
\[
\frac{\ln \left( \mu_1 \mu_2 / 2 (\alpha_1 + \alpha_2) + h \right)}{\Gamma} + \frac{1}{\Gamma_D} < \frac{\alpha_1}{\alpha_1 + \alpha_2},
\]
then the closed-loop switched system (14) is robust asymptotically stable under unknown periodic DoS attacks (2).

Proof: From (29) and (30) we can get
\[
\begin{align*}
\mu_2 W_2 \left(t_{1,n} \right) + \eta \left(t_{1,n} \right) & \geq W_1 \left(t_{1,n} \right), & t \in \left[t_{1,n}, t_{2,n} \right), \\
e^{2(\alpha_1 + \alpha_2) h} \mu_1 W_1 \left(t_{2,n} \right) & \geq W_2 \left(t_{2,n} \right), & t \in \left[t_{2,n}, t_{1,n+1} \right).
\end{align*}
\]
(32)

When \( t \in \left[t_{1,n}, t_{2,n} \right] \), from the DoS attacks assumptions (3) and (4) we can obtained
\[
\begin{align*}
W(t) & \leq e^{-2\alpha_1 (t-t_{1,n})} W_1 \left(t_{1,n} \right) \\
& \leq \ldots \leq e^{\nu t} \left[ 2 (\alpha_1 + \alpha_2) + \ln (\mu_1 \mu_2) + (2 \alpha_1 + 2 \alpha_2) \varepsilon (t-2 \alpha_1) \right] W_1 (0)
\end{align*}
\]
Given fixed DoS attacks parameters

\[ \mu_1, \mu_2, t \in H_{1,n} \]

we can get

\[ W(t) = \frac{1}{2} \left[ X_1^T \Sigma(t) X_1 + X_2^T \Sigma(t) X_2 \right] \]

where

\[ \Sigma(t) = \begin{bmatrix} \alpha_1 & \alpha_2 \\ \alpha_2 & \alpha_1 \end{bmatrix}, \quad \alpha_1, \alpha_2 > 0 \]

From (31) and (35), when \( t \to \infty \) we can get \( \beta_2 \to 0 \), and from (8) we can get \( \eta(pT) \to \infty \). To sum up, when \( t \to \infty \), we can get \( W(t) \to 0 \). It can be known from Lyapunov functional theory that closed-loop switched system (14) is robust asymptotically stable.

The proof is now completed.

**Theorem 2:** Given fixed DoS attacks parameters \( \nu \geq 0 \), \( \Gamma \geq 0, \omega \\geq 0, \Gamma_D \geq 0 \), if for some parameters \( \alpha_1 > 0, \alpha_2 > 0, \sigma > 0, h > 0, e_1 > 0, e_2 > 0, \mu_1 > 0, \mu_2 > 0 \), there exist positive definite symmetric matrices \( X_1 \in \mathbb{R}^{2n \times 2n} > 0 \), \( \tilde{Q}_1 \in \mathbb{R}^{2n \times 2n} > 0 \), \( \tilde{R}_1 \in \mathbb{R}^{2n \times 2n} > 0 \), \( \tilde{Q}_2 \in \mathbb{R}^{2n \times 2n} > 0 \), \( \tilde{R}_2 \in \mathbb{R}^{2n \times 2n} > 0 \), \( \tilde{Q}_1 \in \mathbb{R}^{n \times n} > 0 \), \( \tilde{Q}_2 \in \mathbb{R}^{n \times n} > 0 \) and matrices \( T_1, T_2 \) of appropriate dimensions satisfying the inequality (31), and satisfying the following LMIs

**\( \Phi_1 \)**

\[
\begin{bmatrix}
\Phi_1^1 & \Phi_1^2 \\
\Phi_1^2 & \Phi_1^4
\end{bmatrix}
\] = 0,

**\( \Phi_2 \)**

\[
\begin{bmatrix}
\Phi_2^1 & \Phi_2^2 \\
\Phi_2^2 & \Phi_2^4
\end{bmatrix}
\] = 0,

**\( \Phi_1 \)**

\[
\begin{bmatrix}
\tilde{Q}_1 & \tilde{R}_1 \\
\tilde{R}_1^T & \tilde{Q}_1
\end{bmatrix}
\] = 0,

**\( \Phi_2 \)**

\[
\begin{bmatrix}
\tilde{Q}_2 & \tilde{R}_2 \\
\tilde{R}_2^T & \tilde{Q}_2
\end{bmatrix}
\] = 0,
\[ \begin{align*} 
\Phi_1 &= \begin{bmatrix} \hat{\Phi}_{11} & 0 & 0 & 0 \\
hr R_1 F_1 - R_1 & 0 & 0 & 0 \\
E_1 & -x_1 I & 0 & 0 \\
0 & H^T T & 0 & -x_1^{-2} I \end{bmatrix}, 
\end{align*} \]

where

\[ \begin{align*} 
\hat{\Phi}_{11} &= \begin{bmatrix} \hat{\Phi}_{11} & 0 & 0 & 0 \\
\hat{\Phi}_{11} & 0 & 0 & 0 \\
\hat{\Phi}_{11} & 0 & 0 & 0 \\
\hat{\Phi}_{11} & 0 & 0 & 0 \end{bmatrix}, 
\end{align*} \]

Then, the closed-loop switched system (14) satisfies \( H_\infty \)
performance. The gain matrices of controller are \( K_1 = Y_1 X_1^{-1} \) and \( K_2 = Y_2 X_2^{-1} \), and the gain matrices of observer are \( L_1 = S_1 \tilde{X}_1^{-1} \) and \( L_2 = S_2 \tilde{X}_2^{-1} \).

**Proof:** When \( w(t) \neq 0 \), the \( H_\infty \) performance index is constructed as

\[ J_{yw} = \int_0^\infty \left[ y^T(t)y(t) - y^2 w^T(t)w(t) \right] dt, \]

initial state \( x(t) = 0 \), the Lyapunov-Krasovskii functional satisfies \( W(0) = 0, W(\infty) = 0 \), then

\[ J_{yw} = \int_0^\infty \left[ y^T(t)y(t) - y^2 w^T(t)w(t) \right] dt - W(\infty) = \int_0^\infty \left[ x^T(t)C^T C x(t) - y^2 w^T(t)w(t) + \hat{W}(\xi(t)) \right] dt \]

where \( \hat{W}(\xi(t)) \) is \( \hat{W}(\xi) \) in Lemma 4, if

\[ x^T(t)C^T C x(t) - y^2 w^T(t)w(t) + \hat{W}(\xi(t)) < 0 \]

we can obtain \( y^T(t)y(t) < y^2 w^T(t)w(t) \).

When \( i = 1 \), the alternative Lyapunov-Krasovskii functional form same as Lemma 4 is selected. Define the augmented state \( \tilde{\xi}^T(t) = [ \xi^T(t) \ w^T(t) ] \), the same proof process as Lemma 4 can be obtained

\[ x^T(t)C^T C x(t) - y^2 w^T(t)w(t) + \hat{W}(\xi(t)) < \tilde{\xi}^T(t) \hat{\Phi}_1 \tilde{\xi}(t), \]

and

\[ \hat{\Phi}_2 = \begin{bmatrix} \hat{\Phi}_{2}^1 & 0 & 0 & 0 \\
hr R_2 F_2 - R_2 & 0 & 0 & 0 \\
E_2 & -x_2 I & 0 & 0 \\
0 & H^T T & 0 & -x_2^{-2} I \end{bmatrix}, \]

Similarly, when \( i = 2 \), we can obtain

\[ x^T(t)C^T C x(t) - y^2 w^T(t)w(t) + \hat{W}(\xi(t)) < \tilde{\xi}^T(t) \hat{\Phi}_2 \tilde{\xi}(t), \]
where
\[
\Phi_1^2 = \begin{bmatrix}
\tilde{F}_1 & 0 & 0 & \cdots & 0 \\
\tilde{F}_2 & \tilde{F}_3 & \tilde{F}_4 & \cdots & \tilde{F}_n \\
\tilde{F}_2 & 0 & \tilde{F}_3 & \tilde{F}_4 & \cdots & \tilde{F}_n \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
\tilde{F}_2 & \tilde{F}_3 & \tilde{F}_4 & \cdots & 0 \\
\end{bmatrix}
\]

\[
F_2 = \begin{bmatrix}
\tilde{F}_1 & \tilde{F}_2 & \tilde{F}_3 & \tilde{F}_4 & \cdots & \tilde{F}_n \\
\end{bmatrix}
\]

\[
E_2 = \begin{bmatrix}
E_1 & 0 & 0 & \cdots & 0 \\
\end{bmatrix}
\]

where
\[
\tilde{F}_1 = 2\alpha_2 P_21 + He(P_21 A) + Q_21 - e^{2\alpha_2 h} R_21 + e^{2\alpha_2 h} R_21 \\
\tilde{F}_2 = \epsilon P_22 H H^T P_21 + C^T C,
\]

\[
\tilde{F}_3 = \sigma \Omega + He(T_{21} - e^{2\alpha_2 h} R_{21}).
\]

\[
\tilde{F}_4 = \sigma \Omega + T_{21} + T_{22}.
\]

\[
\tilde{F}_5 = e^{2\alpha_2 h} R_{21} - T_{21} - T_{22} + T_{21}.
\]

\[
\tilde{F}_6 = \sigma \Omega + e^{2\alpha_2 h} R_{22} + e^{2\alpha_2 h} R_{22}.
\]

\[
\tilde{F}_7 = -e^{2\alpha_2 h} Q_{21} - e^{2\alpha_2 h} R_{21}.
\]

\[
\tilde{F}_8 = \gamma^2 I.
\]

By repeatedly deriving the stability theory of the augmented system in Theorem 1, the conditions (29) - (31) are obtained. Multiply \( J_1 \) by the left and right sides of (45), and \( J_1 = \text{diag}(X_1, \ldots, X_1) \), multiply \( X_1 \) by the left and right sides of (29), let \( X_1 = P^{-1}, R_1 = X_1 R X_1, Q_1 = X_1 Q X_1, T_1 = J_3 T_1 X_1, \Omega_1 = X_1 \Omega X_1, \Lambda = X_1 \Lambda X_1, S_1 = L_1 X_1, Y_1 = K_1 X_1 \), through the inequality \( R_1^{-1} X_1 R_1^{-1} X_1 \geq 2 \lambda_1 X_1 - \lambda_1^2 R_1 \), finally we can obtain (36), (39), (42) and (43). Similarly, we can obtain (37), (38), (40) and (41).

IV. ILLUSTRATIVE EXAMPLES AND SIMULATION

Consider an unstable batch reactor system [32], whose system parameters are as follows
\[
A = \begin{bmatrix}
1.38 & -0.2007 & 6.715 & -5.676 \\
-0.5814 & -4.29 & 0 & 0.675 \\
1.067 & 4.273 & -6.654 & 5.893 \\
0.048 & 4.273 & 1.343 & -2.104
\end{bmatrix}
\]

In order to verify the effectiveness of Theorem 2, the closed-loop switched system (14) is simulated as shown in Fig. 2 - Fig. 5. As shown in Fig. 2 and Fig. 3, when there is no disturbance, the state of the closed-loop batch reactor system with unknown periodic DoS attacks converges to zero in finite time. When there is a disturbance, the states of the closed-loop system converge to zero in finite time as well as the system still can effectively restrain disturbance with \( H_{\infty} \).
FIGURE 2. Response of closed-loop system without disturbance.

FIGURE 3. Response of closed-loop system with disturbance.

FIGURE 4. Response of closed-loop system observation error.

FIGURE 5. Dynamic event-triggered sequence.

FIGURE 6. Responses of state $x$ with the method in Theorem 1 (upper) and the method in [28](lower).

According to Fig. 4, the observation errors converge to zero before the state of the closed-loop system is stable, which verifies the effectiveness of the full-dimensional state observer designed in this paper.

In addition, instants and intervals of dynamic event triggering are shown in Fig. 5, and we can derive that the average triggering interval is 0.14s, which is much longer than the sampling period 0.001s. Thus, system resources such as networked bandwidth can be saved. The minimum triggering interval equals to the sampling period 0.001s, which excludes Zeno behavior. These observations above confirm Remark 1.

Significantly, by comparing Fig. 2 and Fig. 3, the system can suppress the disturbance with short-term DoS attacks, such as the 5s to 15s. However, the disturbance suppression ability of the system is reduced with long-term DoS attacks, such as the 30s to 40s. It can be known that high energy DoS attacks will worsen the adverse effects of disturbance on the system and interfere with the normal operation of the system.

Here we compare the results of the proposed method with [26]. The responses of state show in Fig.6 employ the two different control strategies without disturbance and uncertainty. Apparently, Theorem 1 can achieve satisfactory control performance faster and more smoothly. This result is mainly because the hold-input strategy adopted in this paper compensates for the impact of DoS attacks on the system. In contrast, the zero-input strategy is adopted in [28] to compensate for the impact of DoS attacks on the system.

To further optimize the $H_{\infty}$ performance of the system, we use MATLAB to solve the following optimization problem

$$\begin{align*}
\min \gamma \\
s.t. (31), (36) - (43)
\end{align*}$$

(47)
The optimal value $\gamma = 0.36$ of $H_\infty$ performance parameter is obtained through $\text{mincx}$ solver of the LMI toolbox, and the simulation result is shown in Fig. 7. By comparing Fig. 3 and Fig. 7, it can be seen that the disturbance suppression degree of the closed-loop system increases after the $H_\infty$ performance parameter $\gamma$ is optimized. According to (15), the $H_\infty$ performance parameter $\gamma$ determines the degree of disturbance suppression, and the smaller $\gamma$ is, the greater the degree of disturbance suppression. However, if the given $\gamma$ is smaller, the LMIs in Theorem 2 will be more challenging to solve. In this article, the control parameters of the closed-loop system and minimum $\gamma$ can be effectively found through solving optimization problem (47).

V. CONCLUSION

This paper studied an observer-based dynamic event-triggered control for networked control systems with unknown periodic DoS attacks, external disturbance, and uncertainty. Firstly, we have analyzed the case without the disturbance and obtained sufficient conditions for the robust asymptotic stability of the closed-loop switched system by using Lyapunov functional theory, improved Jensen’s inequality, Schur’s Complement Lemma, etc. Secondly, we have considered the case with the disturbance. By introducing the $H_\infty$ performance index, we obtained the sufficient conditions that the closed-loop switched system has the $H_\infty$ performance with the disturbance. Finally, an example of batch reactor has been used to verify the correctness of the control parameters of the closed-loop system for PS-poll DoS attack in 802.11 networks using real time discrete event system, and the smaller $\gamma$ is, the greater the degree of disturbance suppression.

REFERENCES

[1] A. Sargolzaei, K. K. Yen, M. N. Abdelghani, S. Sargolzaei, and B. Carballar, “Resilient design of networked control systems under time delay switch attacks. application in smart grid,” IEEE Access, vol. 5, pp. 15901–15912, 2017.
[2] J. P. Farwell and R. Rohozinski, “Stuxnet and the future of cyber war,” Survival, vol. 53, no. 1, pp. 23–40, 2011.
[3] H. S. Foroush and S. Martinez, “On event-triggered control of linear systems under periodic denial-of-service jamming attacks,” in Proc. IEEE 51st IEEE Conf. Decis. Control (CDC), Dec. 2012, pp. 2551–2556.
[4] Y. Tan, Q. Liu, J. Liu, X. Xie, and S. Fei, “Observer-based security control for interconnected semi-Markovian jump systems with unknown transition probabilities,” IEEE Trans. Cybern., early access, Feb. 26, 2021, doi: 10.1109/tcyb.2021.3052752.
[5] Y. Tan, Q. Liu, D. Du, B. Niu, and S. Fei, “Observer-based finite-time $H_\infty$ control for interconnected fuzzy systems with quantization and random network attacks,” IEEE Trans. Fuzzy Syst., vol. 29, no. 3, pp. 674–685, Mar. 2021.
[6] M. Agarwal, S. Purwar, S. Biswas, and S. Nandi, “Intrusion detection system for PS-poll DoS attack in 802.11 networks using real time discrete event system,” IEEE/CAA J. Automatica Sinica, vol. 4, no. 4, pp. 792–808, Nov. 2017.
[7] D. Zhang, Q.-G. Wang, G. Feng, Y. Shi, and A. V. Vasilakos, “A survey on attack detection, estimation and control of industrial cyber–physical systems,” ISA Trans., vol. 116, pp. 1–16, Oct. 2021, doi: 10.1016/j.isatra.2021.01.036.
[8] D. Tang, S. Zhang, J. Chen, and X. Wang, “The detection of low-rate DoS attacks using the SADBSCAN algorithm,” Inf. Sci., vol. 565, pp. 229–247, Jul. 2021.
[9] X.-M. Zhang, Q.-L. Han, G. E. Xie, and L. Ding, “Resilient control design based on a sampled-data model for a class of networked control systems under denial-of-service attacks,” IEEE Trans. Cybern., vol. 50, no. 8, pp. 3616–3626, Aug. 2020.
[10] Y. Ma, Z. Nie, S. Hu, Z. Li, R. Malekian, and M. Sotelo, “Fault detection filter and controller co-design for unmanned surface vehicles under DoS attacks,” IEEE Trans. Intell. Transp. Syst., vol. 22, no. 3, pp. 1422–1434, Mar. 2021.
[11] S. Hu, D. Yue, C. Dou, X. Xie, Y. Ma, and L. Ding, “Attack-resilient event-triggered fuzzy interval type-2 filter design for networked nonlinear systems under sporadic denial-of-service jamming attacks,” IEEE Trans. Fuzzy Syst., early access, Oct. 26, 2020, doi: 10.1109/TFUZZ.2020.3033851.
[12] C. D. Persis and P. Tesi, “Input-to-state stabilizing control under denial-of-service,” IEEE Trans. Autom. Control, vol. 60, no. 11, pp. 2930–2944, Nov. 2015.
[13] S. Hu, D. Yue, X. Xie, X. Chen, and X. Yin, “Resilient event-triggered controller synthesis of networked control systems under periodic DoS jamming attacks,” IEEE Trans. Cybern., vol. 49, no. 12, pp. 4271–4281, Dec. 2019.
[14] E. Hendrickx, M. Jensen, A. Chevalier, and T. Vesterholm, “Problems in event based engine control,” in Proc. Amer. Control Conf. (ACC), Jun. 1994, pp. 1585–1587.
[15] R. Yang and W. X. Zheng, “Output-based event-triggered predictive control for networked control systems,” IEEE Trans. Ind. Electron., vol. 67, no. 12, pp. 10631–10640, Dec. 2020.
[16] D. Yue, E. Tian, and Q.-L. Han, “A delay system method for designing event-triggered controllers of networked control systems,” IEEE Trans. Autom. Control, vol. 58, no. 2, pp. 475–481, Feb. 2013.
[17] X. Liu, X. Su, P. Shi, and C. Shen, “Observer-based sliding mode control for uncertain fuzzy systems via event-triggered strategy,” IEEE Trans. Fuzzy Syst., vol. 27, no. 11, pp. 2190–2201, Nov. 2019.
[18] A. Girard, “Dynamic triggering mechanisms for event-triggered control,” IEEE Trans. Autom. Control, vol. 60, no. 7, pp. 1992–1997, Jul. 2015.
[19] D. Liu and G. Yang, “Dynamic event-triggered control for linear time-invariant systems with $L_2$-gain performance,” Int. J. Robust Nonlinear Control, vol. 29, no. 2, pp. 507–518, Jan. 2019.
[20] X. Ge, Q.-L. Han, X.-M. Zhang, and D. Ding, “Dynamic event-triggered control and estimation: A survey,” Int. J. Autom. Comput., Jun. 2021, doi: 10.1007/s11633-021-1306-z.
[21] X. Ge, Q.-L. Han, L. Ding, Y.-L. Wang, and X.-M. Zhang, “Dynamic event-triggered distributed coordination control and its applications: A survey of trends and techniques,” IEEE Trans. Syst., Man, Cybern. Syst., vol. 50, no. 9, pp. 3616–3626, Aug. 2020.
[22] W. Wan, T. Han, J. An, and M. Wu, “Fault diagnosis for networked switched systems: An improved dynamic event-based scheme,” IEEE Trans. Cybern., early access, Oct. 26, 2020, doi: 10.1109/TCYB.2021.3049838.
[23] X. Liu, X. Su, P. Shi, C. Shen, and Y. Peng, “Event-triggered sliding mode control of nonlinear dynamic systems,” Automatica, vol. 116, pp. 1–16, Oct. 2021, doi: 10.1016/j.automatica.2021.109488.
[25] S. Hu, Y. Gu, X. Chen, and H. Ge, “Observer-based event-triggered control for cyber-physical systems under unknown periodic DoS jamming attacks,” in Proc. Chin. Control Decis. Conf. (CCDC), Jun. 2018, pp. 1422–1427.

[26] Z. Cheng, D. Yue, S. Hu, C. Huang, C. Dou, and X. Ding, “Resilient dynamic event-triggered control for multi-area power systems with renewable energy penetration under dos attacks,” IET Contr. Theory Appl., vol. 14, no. 16, pp. 2267–2279, Nov. 2020.

[27] Z.-H. Zhang, D. Liu, C. Deng, and Q.-Y. Fan, “A dynamic event-triggered resilient control approach to cyber-physical systems under asynchronous DoS attacks,” Inf. Sci., vol. 519, pp. 260–272, May 2020.

[28] S. Hu, D. Yue, Z. Cheng, E. Tian, X. Xie, and X. Chen, “Co-design of dynamic event-triggered communication scheme and resilient observer-based control under aperiodic DoS attacks,” IEEE Trans. Cybern., vol. 51, no. 9, pp. 4591–4601, Sep. 2021, doi: 10.1109/TCYB.2020.3001187.

[29] L. Huang, G. Jing, and H. Zhang, “Observer-based dynamic event-triggering control for networked systems with periodic denial-of-service attack,” Control Theory Technol., vol. 38, no. 6, pp. 851–861, Jun. 2021.

[30] I. R. Petersen, “A stabilization algorithm for a class of uncertain linear systems,” Syst Control Lett., vol. 8, no. 4, pp. 351–357, Mar. 1987.

[31] F. Yang, H. Zhang, G. Hui, and S. Wang, “Mode-independent fuzzy fault-tolerant variable sampling stabilization of nonlinear networked systems with both time-varying and random delays,” Fuzzy Sets Syst., vol. 207, pp. 45–63, Nov. 2012.

[32] G. C. Walsh and H. Ye, “Scheduling of networked control systems,” IEEE Control Syst. Mag., vol. 21, no. 1, pp. 57–65, Feb. 2001.

LING HUANG was born in Xinyang, China, in 1975. She received the B.E. and M.S. degrees from the Harbin University of Science and Technology, Harbin, in 1999 and 2002, respectively, and the Ph.D. degree in control science and engineering from the Harbin Institute of Technology, Heilongjiang, China, in 2007. From 2005 to 2009, she was a Lecturer with the Harbin University of Science and Technology, where she is a Professor with the School of Automation, in 2013. Her research interests include analysis and synthesis of networked control systems, the signal processing and recognition, the theory and application of intelligent control, and robust control.

JING GUO was born in Datong, China, in 1996. She received the B.E. and M.E. degrees in control from the Harbin University of Science and Technology, Heilongjiang, China, in 2018 and 2021, respectively, where she is currently pursuing the Ph.D. degree. Her research interests include the analysis and synthesis of networked control systems and robust control.

BING LI was born in Heihe, China, in 1977. She received the B.E. degree in automation, the M.S. degree in control theory and control engineer, and the Ph.D. degree in measurement technology and instruments from the Harbin University of Science and Technology, Harbin, Heilongjiang, in 1999, 2005, and 2016, respectively. From 2005 to 2013, she was a Lecturer with the Harbin University of Science and Technology, where she is an Associate Professor with the School of Automation, in 2013. Her research interests include analysis and synthesis of networked control systems, robust control, and medical image processing.