Event-triggered output feedback dissipative control of nonlinear systems under DoS attacks and actuator saturation

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ABSTRACT
This paper presents a novel event-triggered dynamic output feedback dissipative control of nonlinear systems under intermittent denial-of-service (DoS) attacks and actuator saturation. Firstly, based on attack information, a secure event-triggered mechanism (ETM) is introduced, which not only saves systems resources but also is Zeno-free and resilient to DoS attacks. Secondly, a switched T-S fuzzy closed-loop system model is built, which unifies the parameters of nonlinear plant, noises, ETM, DoS attacks, switched output feedback fuzzy controller, and actuator saturation all in one framework. Thirdly, low conservative exponential stability criteria are derived while guaranteeing strict ($\mathcal{G}$, $\mathcal{H}$, $\mathcal{I}$)-dissipativity, and hence the relationships between system performance and factors such as DoS attacks, secure ETM, noises and actuator saturation are established. Further, sufficient conditions are given for the co-design of the switched output-based fuzzy controller and the secure ETM. Finally, the effectiveness of the proposed method is confirmed by numerical examples, achieving over 92% system resources.

KEYWORDS
Networked control systems; T-S fuzzy systems; secure event-triggered mechanism; intermittent denial-of-service attacks; dynamic output feedback control; dissipative control

1. Introduction

Networked control systems (NCSs) are a kind of complex control systems, wherein the spatially distributed components such as sensors and controllers exchange information through a shared communication network (X. M. Zhang et al., 2020). Due to their advantages of flexible system design, efficient data sharing, minimal wiring, and reduced cost, NCSs have been widely used in smart grids, unmanned vehicles (Gu, Yin, & Ding, 2021), and intelligent agriculture systems, etc.

Although NCSs benefit much from the shared communication network, they are also bearing increasing security problems induced by cyber attacks. These cyber attacks can be mainly classified as DoS attacks and deception attacks (Qu, Tian, & Zhao, 2022). DoS attacks, induced by jamming signals, typically make communication network inaccessible to the intended users (Gu, Sun, Lam, Yue, & Xie, 2021), whereas deception attacks usually tamper communication data packages in order to generate false feedback information (Peng, Sun, Yang, & Wang, 2019). Since DoS attacks can be easily launched even without detailed knowledge of targeted system, they are more likely to occur in NCSs, which motivates the study in this paper.

On the other hand, security control under DoS attacks has been drawing increasing attentions in recent years (D. Zhang, Wang, Feng, Shi, & Vasilakos, 2021). For instance, the work presented in (Qiu et al., 2021) uses model predictive control to ensure the uniform global asymptotic stability of a networked multiple linear motors system under DoS attacks and time delays. In (D. Zhang, Shen, Zhou, Dong, & Yu, 2021), a switched time-delay system model is developed to guarantee the exponential platooning tracking of connected vehicles with DoS attacks and nonuniform sampling. The work in (B. Zhang, Dou, Yue, Park, & Zhang, 2021) presents an evolutionary game-based active defense strategy for consensus-based secondary control of islanded microgrid under DoS attacks. Many existing results use time-triggered control strategy (i.e., periodic control) for easy analysis and implementation. However, time-triggered control may waste scarce system resources such as network bandwidth, since some data do not have to be transmitted while system performance can be maintained.

To better utilize system resources while preserving satisfactory system performance, an event-triggered control (ETC) is proposed (Shi, Tian, Shen, & Zhao, 2021). Due to the distinctive merit that control tasks are only executed when necessary, the ETC has also been introduced in the security control systems. To name a few, the work in (Hossain, Peng, Sun, & Xie, 2022) proposes a dynamic bandwidth allocation based event-triggered load frequency control stragety for smart grids under DoS and deception attacks. The work in (Y. Yang, Li, Yue, Tian, & Ding, 2021) develops a distributed secure consensus control method for multiagent systems (MASs) under DoS attacks and a dual-terminal ETM. In (Xu, Fang, Pan, Shi, & Wu, 2021), an event-triggered control protocol is developed to ensure output synchronization for nonhomogeneous MASs under periodic DoS attacks.

For the ETC systems, a positive minimum inter-event time (MIET) is essential to exclude Zeno behavior (i.e., an infinite number of triggering events in finite time interval), and to enable practical system implementation. However, it is not an easy task to identify a suitable positive MIET, and a positive MIET may even not exist in some real control systems (Peng & Li, 2018). To this end, the periodic ETC is proposed (Yue, Tian, & Han, 2013), where the triggering condition is verified only at periodic sampling instants. Hence a positive MIET can be guaranteed to be sufficiently larger than or at least equal to the sampling period, which directly excludes the Zeno behavior. Recently, the periodic ETC is introduced into security control systems. For instance, the work in (Y. Li, Song, Liu, Xie, & Tian, 2022) presents a decentralized event-triggered synchronization control for complex networks under nonperiodic DoS attacks. The work in (P. Chen, Liu, Chen, & Yu, 2022) uses a multi-agent deep reinforcement learning algorithm to study the decentralized resilient secondary control for multiple heterogeneous battery energy storage systems under DoS attacks. The work in (Peng, Wu, & Tian, 2021) proposes a stochastic ETM and a switching-like H_∞ control strategy for NCSs under stochastic DoS attacks. Most existing works focus on the state feedback ETC for linear systems, while little attention is paid to the output feedback ETC for nonlinear systems. However, many practical systems are nonlinear, and system states are not always available, which motivates this study on the event-triggered dynamic output feedback security control for nonlinear systems under DoS attacks.

Dissipative theory provides a unified framework for input-output energy-based characterization including passivity theorem, circle criterion, bounded real lemma and Kalman-Yakubovich lemma, which has been widely applied in areas such as circuits, systems, networks and control engineering (R. Yang, Ding, & Zheng, 2021). From the energy prospective, dissipativity means that the energy provided from outside is not less than the increase of energy stored in the system. Dissipative control presents a unified method for robust control design, which includes H_∞ control and passive control as its special cases. Recently, dissipativity is introduced into the ETC systems. To name a few, the work in (Song, Zhang, Ahn, & Song, 2021) studies the dissipative synchronization of semi-markov jump complex dynamical networks using adaptive event-triggered sampling control strategy. The work in (Mahmoud & Karaki, 2021) proposes a cooperative event-triggered dissipative approach for output-synchronization of discrete-time heterogenous MASs with time delays. Most existing works study event-triggered dissipative control within ideal system framework, however, there often exist DoS attacks and actuator saturation in NCSs, which motivates this study on dissipative ETC systems under DoS attacks and actuator saturation.

To address the aforementioned issues, this paper investigates event-triggered dynamic output feedback dissipative control of nonlinear systems under DoS attacks and actuator saturation. The main contributions are listed as follows. Firstly, based on the available information of the attacks and the plant, an output-based security periodic event-triggered mechanism is introduced, which can effectively reduce the number of data transmission, increase the resilience to DoS attacks and exclude Zeno behavior naturally. Secondly, a switched T-S fuzzy closed-loop system model is built, which makes it feasible to systematically analyze the effects of the nonlinear plant, the secure ETM, DoS attacks, switched dynamic output feedback fuzzy (SDOFF) controller, noises and actuator saturation all in one unified framework. Thirdly, exponentially stable criteria are derived while guaranteeing ($\mathcal{G}$, $\mathcal{H}$, $\mathcal{I}$)-dissipativity, and its conservativeness is reduced with the aid of combining both the exclusive distribution method and the reciprocally convex approach. Further, sufficient conditions for co-designing the SDOFF controller and the secure ETM are yielded.

Notation: $He\{X\}$ refers to $X + X^T$ for a matrix X. A positive definite matrix X is denoted by $X > 0$. $Col\{X_1, \cdots, X_N\}$, $diag\{X_1, \cdots, X_N\}$ and I indicate column matrix, diagonal matrix and identity matrix, respectively. $\lambda_{min}(X)$ is the minimum eigenvalue of matrix X. $\lfloor x \rfloor$ marks the largest integer no larger than x. $\mathbb{R}$ and $\mathbb{N}$ denote sets of real numbers and positive integers, respectively. $\|\cdot\|$ refers to Euclidean norm.

2. Problem Formulation

2.1. System description

Figure 1 shows the framework of a nonlinear system under DoS attacks, the secure ETM and actuator saturation. The sensors sample the plant outputs periodically. The secure ETM determines whether or not the sampled data packets will be transmitted. The SDOFF controller receives the transmitted data from the secure ETM through a communication network subject to intermittent DoS attacks. The saturated actuator receives the controller output through the shared network under attacks.

The following T-S fuzzy model with r rules is used to describe the nonlinear plant:

Plant rule i: IF $\theta_1(t)$ is M_{i1}, $\theta_2(t)$ is M_{i2} and ... and $\theta_g(t)$ is M_{ig}, THEN

$$\begin{cases} \dot{x}(t) = A_i x(t) + B_i \bar{u}(t) + D_i \omega(t) \\ y(t) = C_i x(t) \\ z(t) = F_i x(t) + G_i \bar{u}(t) \end{cases} \tag{1}$$

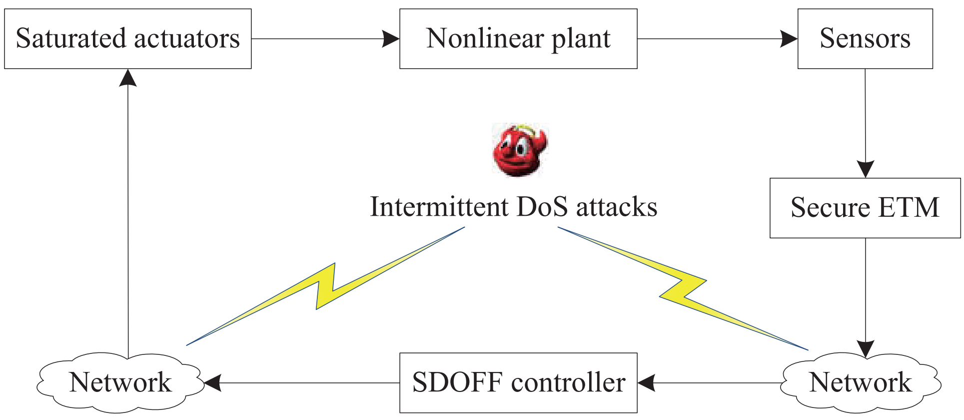

Figure 1. System configuration.

where $x(t) \in \mathbb{R}^{n_x}$ is the plant state vector, $\bar{u}(t) \in \mathbb{R}^{n_u}$ is the saturated control input vector, $y(t) \in \mathbb{R}^{n_y}$ is the measured output vector, $\omega(t) \in \mathbb{R}^{n_\omega}$ is the disturbance vector satisfying $\omega(t) \in \mathcal{L}_2[0, \infty)$, $z(t) \in \mathbb{R}^{n_z}$ is the controlled output vector. r is the number of IF-THEN rules, $\theta(t) = [\theta_1(t), \theta_2(t), \ldots, \theta_g(t)]$ is the premise variable vector, $M_{ij}(i = 1, \ldots, r, j = 1, \ldots, g)$ is the fuzzy set, and A_i, B_i, C_i, D_i, F_i and G_i are gain matrices with appropriate dimensions.

Using the singleton fuzzifier, product fuzzy inference and center-average defuzzifier (Liu, Yin, Cao, Yue, & Karimi, 2021), the system (1) can be rewritten as

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{r} \mu_i(\theta(t))[A_i x(t) + B_i \bar{u}(t) + D_i \omega(t)] \\ y(t) = \sum_{i=1}^{r} \mu_i(\theta(t)) C_i x(t) \\ z(t) = \sum_{i=1}^{r} \mu_i(\theta(t))[F_i x(t) + G_i \bar{u}(t)] \end{cases} \tag{2}$$

where normalized membership function $\mu_i(\theta(t)) = \frac{\varphi_i(\theta(t))}{\sum_{i=1}^{r} \varphi_i(\theta(t))}$ satisfies $\mu_i(\theta(t)) \geq 0$ and $\sum_{i=1}^{r} \mu_i(\theta(t)) = 1$ with $\varphi_i(\theta(t)) = \Pi_{j=1}^{g} M_{ij}(\theta_j(t))$.

2.2. *Intermittent DoS attacks*

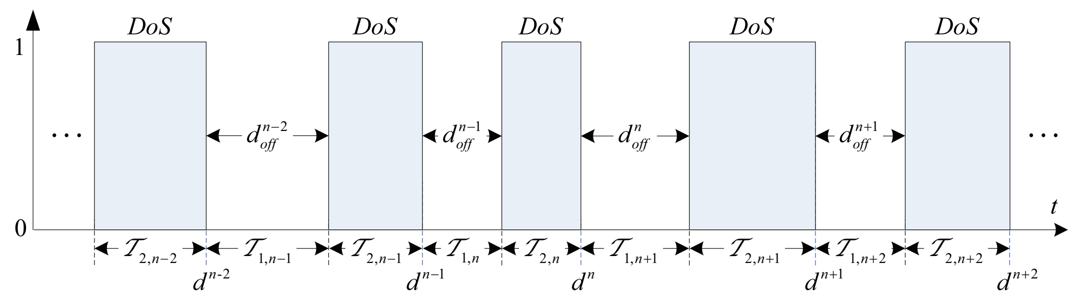

Figure 2. Intermittent DoS attacks.

Consider the intermittent DoS attacks in (Dolk, Tesi, De Persis, & Heemels, 2017) (as shown in Figure 2)

$$\mathscr{D}(t)=\begin{cases}0, & t\in\mathcal{T}_{1,n}=[d^{n-1},d^{n-1}+d_{off}^{n-1})\\ 1, & t\in\mathcal{T}_{2,n}=[d^{n-1}+d_{off}^{n-1},d^{n}),n\in\mathbb{N}\end{cases} \tag{3}$$

where $\mathcal{T}_{1,n}$ and $\mathcal{T}_{2,n}$ denote attack-sleeping and attack-active intervals, respectively. In the following analysis, $d_{off}^{min}=min\{\mathcal{T}_{1,n}\}$ and $d_{on}^{max}=max\{\mathcal{T}_{2,n}\}$ denote the attack's minimum sleeping interval and maximum active interval, respectively.

Definition 2.1. (DoS frequency): A sequence of DoS attacks satisfies DoS frequency constraint, if there exist real scalars $\varkappa\geq 0,\varrho>0$ such that

$$n_f(t)=card\{n\in\mathbb{N}|d^{n-1}+d_{off}^{n-1}<t\}\leq\varkappa+\frac{t}{\varrho},\ \forall t\geq 0 \tag{4}$$

where $n_f(t)$ indicates the number of DoS off/on transitions occurring within the interval $[0,t]$, and *card* denotes the number of elements in the set.

Definition 2.2. (DoS duration): A sequence of DoS attacks satisfies DoS duration constraint, if there exist real scalars $\psi\geq 0,\Gamma>0$ such that

$$|\Xi(t)|\leq\psi+\frac{t}{\Gamma},\ \forall t\geq 0 \tag{5}$$

where $\Xi(t)=[\cup_{i=1}^{n_f(t)-1}[d^{i-1}+d_{off}^{i-1},d^{i})]\cup[d^{n_f(t)-1}+d_{off}^{n_f(t)-1},min\{d^{n_f(t)},t\}]$, and $|\Xi(t)|$ indicates the sum of the lengths of all intervals in $\Xi(t)$ (i.e., the total length of DoS attacks during the interval [0,t]).

Remark 1. During the attack-active intervals $\mathcal{T}_{2,n}$, network is jammed and thus data can not be transmitted. If the frequency and/or duration of DoS attacks can be arbitrarily large, the data communication will be blocked all the time, and thus the system runs in open-loop mode. Fortunately, there exist several techniques to mitigate jamming attacks, e.g. high-pass filtering and spreading techniques (Hu et al., 2020). These provisions can be exploited to decrease the success chance of DoS attacks aiming at limiting in practice the attack's frequency and duration.

Remark 2. If setting $d^{n-1}=(n-1)T$ and $d_{off}^{n-1}=T_{off}$ with given attacking period T and sleeping period T_{off}, the intermittent DoS attack model (3) becomes a periodic DoS attack model, which implies the periodic DoS attacks are a special case of the intermittent DoS attacks (3).

2.3. Secure event-triggered mechanism

To save constrained system resources in NCSs under DoS attacks, a security event-triggered mechanism is introduced as

$$\begin{cases} t_{k+1,n}h = \{min\{t^j_{k,n}h | \mathscr{T} \geq 0, t^j_{k,n}h \in \mathcal{T}_{1,n}\}\} \cup d^n \\ \mathscr{T} = \|\Omega^{\frac{1}{2}}[y(t_{k,n}h) - y(t^j_{k,n}h)]\|^2 - \delta\|\Omega^{\frac{1}{2}}y(t_{k,n}h)\|^2 \\ t_{1,n}h = d^{n-1} \in \mathcal{T}_{1,n} \end{cases} \tag{6}$$

where triggering threshold parameter $\delta \in (0,1)$, matrix $\Omega > 0$, $t_{k,n}h$ is the triggering instant, h is the sampling period, and $t^j_{k,n}h = t_{k,n}h + jh$, $j, k, t_{k,n} \in \mathbb{N}$.

During the attack-sleeping intervals $\mathcal{T}_{1,n}$, the secure ETM checks the triggering condition in (6) at each sampling instant. If the condition is satisfied, the secure ETM releases the sampled data. Otherwise, the data packet will be discarded. During the attack-active intervals $\mathcal{T}_{2,n}$, the secure ETM does not transmit any data. Thus, the triggering-instant set $\{t_{1,1}h, t_{2,1}h, \ldots\}$ is a subset of the sampling-instant set $\{h, 2h, \ldots\}$, which makes it possible to save systems resources.

Remark 3. Unlike the continuous time ETM, the secure ETM has the following features. First, the secure ETM only checks the triggering condition at periodic sampling instants, which excludes Zeno behavior naturally. Second, at the beginning of each attack-sleeping interval, an event is triggered, which guarantees at least one successful communication after each attack-active interval. Third, the secure ETM does not transmit data during attack-active intervals, which avoids attack induced dropouts.

2.4. Actuator saturation

Consider the following saturation function (Zhao, Shi, Xing, & Agarwal, 2021)

$$sat(u_i) = \begin{cases} u^s_i, & u_i > u^s_i \\ u_i, & -u^s_i \leq u_i \leq u^s_i, \ i = 1, 2, \ldots, n_u \\ -u^s_i, u_i < -u^s_i \end{cases} \tag{7}$$

where u^s_i is the maximum allowable output of the i^{th} element in actuator.

Given (7), the saturated control input in (2) can be expressed as

$$\bar{u}(t) = sat(u(t)) = u(t) - \mathscr{S}(u(t)) \tag{8}$$

where $sat(u(t)) = [sat(u_1), \ldots, sat(u_{n_u})]$, $\mathscr{S}(u(t)) = [\mathscr{S}(u_1), \ldots, \mathscr{S}(u_{n_u})]$ is the nonlinear dead-zone function and $u(t)$ is control input without saturation. Then, there exists a real number $\varepsilon \in (0,1)$ such that

$$\mathscr{S}^T(u(t))\mathscr{S}(u(t)) \leq \varepsilon u^T(t)u(t) \tag{9}$$

Remark 4. When DoS attacks are active, control input is blocked, and thus system often moves away from equilibrium. Once the attacks turn to sleep mode, a larger control input needs to be exerted in order to stabilize the system, which often results in actuator saturation. Considering the saturation function (7), the saturated control input may not equal to the original control input, which often degrades system performance. Thus, it is necessary to consider actuator saturation in security control.

2.5. Closed-loop switched system model

Divide the triggering interval of the secure ETM as (as shown in Figure 3)

$$[t_{k,n}h, t_{k+1,n}h) = \bigcup_{\ell_{k,n}=0}^{\varepsilon_{k,n}} \phi_{\ell_{k,n}}^{t_{k,n}}, \quad \phi_{\ell_{k,n}}^{t_{k,n}} = [t_{k,n}h + \ell_{k,n}h, t_{k,n}h + (\ell_{k,n}+1)h) \tag{10}$$

where $\varepsilon_{k,n} = t_{k+1,n} - t_{k,n} - 1$.

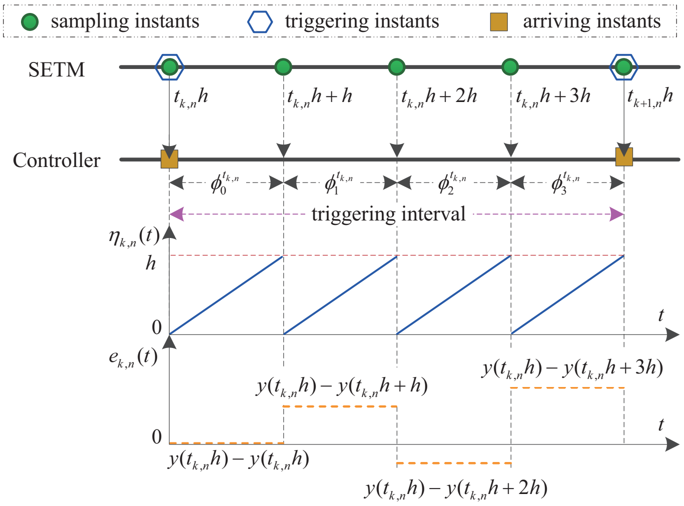

Figure 3. Dividing triggering intervals of the secure ETM and defining $\eta_{k,n}$ and $e_{k,n}$.

Using definitions of the DoS attack (3) and the ETM (6), we have

$$\mathcal{T}_{1,n} = \bigcup_{k=1}^{k_n^m} \bigcup_{\ell_{k,n}=0}^{\varepsilon_{k,n}} \bar{\phi}_{\ell_{k,n}}^{t_{k,n}} \subseteq \bigcup_{k=1}^{k_n^m} [t_{k,n}h, t_{k+1,n}h) \tag{11}$$

where $\bar{\phi}_{\ell_{k,n}}^{t_{k,n}} = \phi_{\ell_{k,n}}^{t_{k,n}} \cap \mathcal{T}_{1,n}$, $k_n^m = max\{k \in \mathbb{N} |\ t_{k,n}h \le d^{n-1} + d_{off}^{n-1}\}$, $t_{k_n^m+1,n}h = d^n$, and $t_{k_n^m,n}h$ denotes the last triggering instant in $\mathcal{T}_{1,n}$.

Define the following piecewise functions (as shown in Figure 3)

$$\begin{cases} e_{k,n}(t) = y(t_{k,n}h) - y(t_{k,n}h + \ell_{k,n}h) \\ \eta_{k,n}(t) = t - (t_{k,n}h + \ell_{k,n}h), \ t \in \bar{\phi}_{\ell_{k,n}}^{t_{k,n}} \end{cases} \tag{12}$$

where $\eta_{k,n}(t) \in [0, h)$ and $\dot{\eta}_{k,n}(t) = 1$ $(t \in \bar{\phi}_{\ell_{k,n}}^{t_{k,n}} \backslash \{t_{k,n}h + \ell_{k,n}h\})$.

Using (12), the released data of the secure ETM can be rewritten as

$$y(t_{k,n}h) = e_{k,n}(t) + y(t - \eta_{k,n}(t)), \ t \in \bar{\phi}_{\ell_{k,n}}^{t_{k,n}} \tag{13}$$

Define the following switched dynamic output feedback fuzzy controller with dual indexed rules:

Controller rule ij: IF $\theta_1(t)$ is M_{i1}, and $\theta_1(t)$ is M_{j1}, ..., $\theta_g(t)$ is M_{ig} and $\theta_g(t)$ is

M_{jg}, THEN

$$\begin{cases} \dot{x}_c(t) = A^{\zeta}_{c_{ij}} x_c(t) + B^{\zeta}_{c_{ij}} x_c(t-\eta_i(t)) + C^{\zeta}_{c_j} \hat{y}(t) \\ u(t) = D^{\zeta}_{c_j} x_c(t), \quad t \in \mathcal{T}_{\zeta,n}, \zeta = 1,2 \end{cases} \tag{14}$$

where $x_c(t) \in \mathbb{R}^{n_c}$ is controller state, $\eta_1(t) = \eta_{k,n}(t)$, $\eta_2(t) = t - \left\lfloor \frac{t}{h} \right\rfloor h$, $A^{\zeta}_{c_{ij}}$, $B^{\zeta}_{c_{ij}}$, $C^{\zeta}_{c_j}$ and $D^{\zeta}_{c_j}$ are gain matrices. When the attack is active, no signal can be received by the plant or controller, so $C^2_{c_j}$ and $D^2_{c_j}$ are set to be zero. The controller input signal $\hat{y}(t)$ is described as

$$\hat{y}(t) = \begin{cases} y(t_{k,n}h), & t \in \mathcal{T}_{1,n} \\ 0, & t \in \mathcal{T}_{2,n} \end{cases} \tag{15}$$

Then the controller (14) can be expressed as

$$\begin{cases} \dot{x}_c(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} \mu_i \mu_j [A^{\zeta}_{c_{ij}} x_c(t) + B^{\zeta}_{c_{ij}} x_c(t-\eta_\zeta(t)) + C^{\zeta}_{c_j} \hat{y}(t)] \\ u(t) = \sum_{j=1}^{r} \mu_j D^{\zeta}_{c_j} x_c(t), \quad t \in \mathcal{T}_{\zeta,n}, \zeta = 1,2 \end{cases} \tag{16}$$

where $\mu_i = \mu_i(\theta(t))$ and $\mu_j = \mu_j(\theta(t))$ are employed to simplify representation.

Remark 5. Due to the introduction of the delay term $x_c(t-\eta_\zeta(t))$, the controller (16) is a memory controller. In general, a memory controller can obtain better performance than a memoryless controller (Gao, Li, & Fu, 2020).

Using the T-S fuzzy plant (2) and the SDOFF controller (16), the switched T-S fuzzy closed-loop system is obtained as

$$\begin{cases} \dot{\mathcal{X}}(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} \mu_i \mu_j [\bar{A}_\zeta \mathcal{X}(t) + \bar{A}^d_\zeta \mathcal{X}(t-\eta_i(t)) + \bar{B}^e_\zeta e_{k,n}(t) + \bar{B}^\omega_\zeta \omega(t) + \bar{B}^s_\zeta \mathscr{S}(u(t))] \\ z(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} \mu_i \mu_j [\bar{F}_\zeta \mathcal{X}(t) + \bar{G}_\zeta \mathscr{S}(u(t))], \quad t \in \mathcal{T}_{\zeta,n}, \zeta = 1,2 \end{cases} \tag{17}$$

where $\mathcal{X}(t) = \begin{bmatrix} x(t) \\ x_c(t) \end{bmatrix}$, $\bar{A}_1 = \begin{bmatrix} A_i & B_i D^1_{c_j} \\ 0 & A^1_{c_{ij}} \end{bmatrix}$, $\bar{A}^d_1 = \begin{bmatrix} 0 & 0 \\ C^1_{c_j} C_i & B^1_{c_{ij}} \end{bmatrix}$, $\bar{B}^e_1 = \begin{bmatrix} 0 \\ C^1_{c_j} \end{bmatrix}$, $\bar{B}^\omega_1 = \begin{bmatrix} D_i \\ 0 \end{bmatrix}$, $\bar{B}^s_1 = \begin{bmatrix} -B_i \\ 0 \end{bmatrix}$, $\bar{F}_1 = \begin{bmatrix} F_i & G_i D^1_{c_j} \end{bmatrix}$, $\bar{G}_1 = -G_i$, $\bar{A}_2 = \begin{bmatrix} A_i & 0 \\ 0 & A^2_{c_{ij}} \end{bmatrix}$, $\bar{A}^d_2 = \begin{bmatrix} 0 & 0 \\ 0 & B^2_{c_{ij}} \end{bmatrix}$, $\bar{B}^e_2 = 0$, $\bar{B}^\omega_2 = \begin{bmatrix} D_i \\ 0 \end{bmatrix}$, $\bar{B}^s_2 = 0$, $\bar{F}_2 = \begin{bmatrix} F_i & 0 \end{bmatrix}$ and $\bar{G}_2 = 0$.

Remark 6. As shown in Figure 1, communication networks are employed in both of sensor and controller channels. Network-induced factors such as delays or dropouts usually have negative effects on system performance such as instability or quenching phenomena. However, delays sometimes have positive effects on systems such as steel jacket offshore platforms (X. M. Zhang, Han, & Ge, 2021). Unlike our previous work (F. Li, Gao, Dou, & Zheng, 2018) using data processing units to handle different network delays in both channels, we focus on event-triggered security control of nonlinear system without delays here. By virtually dividing triggering intervals in (10), the resultant subintervals can be used for system modelling in both channels. In future, we will consider network-induced factors in security control of nonlinear systems.

3. Stability and dissipative analysis

3.1. Exponential stability analysis

Lemma 3.1. *(X. Wang, Park, Yang, & Zhong, 2021) Parameterized linear matrix inequality* $\sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\mathscr{M}_{ij}<0$ *is fulfilled, if the following conditions hold:*

$$\begin{cases}\mathscr{M}_{ii}<0,\ i=1,2,\ldots,r\\ \frac{1}{r-1}\mathscr{M}_{ii}+\frac{1}{2}(\mathscr{M}_{ij}+\mathscr{M}_{ji})<0,\ 1\le i\ne j\le r\end{cases}\tag{18}$$

For simplification of expression, let

$$\begin{cases}\chi_i(t)=col\{\dot{\mathcal{X}}(t),\mathcal{X}(t),\mathcal{X}(t-\eta_i(t)),\mathcal{X}(t-\frac{h}{2}),\mathcal{X}(t-h),\\ \qquad e_{k,n}(t),\mathscr{S}(u(t)),\omega(t)\},\ i=1,2\\ e_j=[\underbrace{0,\ldots,0}_{j-1},I,\underbrace{0,\ldots,0}_{8-j}],\ j=1,\ldots,8\end{cases}\tag{19}$$

Theorem 3.2. For given attack parameters $d_{off}^{min}>0$, $d_{on}^{max}>0$, sampling period $h<d_{off}^{min}$, triggering threshold parameter $\delta\in(0,1)$, saturation parameter $\varepsilon\in(0,1)$, and scalars $a_i>0$, $\xi_i>1(i=1,2)$, if there exist positive matrices $\Omega>0,P_i>0,Q_i>0,R_i>0,S_i>0(i=1,2)$, and matrices M_1,M_2,N_1,N_2 such that

$$\begin{bmatrix}R_i & *\\ M_i & R_i\end{bmatrix}>0,\begin{bmatrix}S_i & *\\ N_i & S_i\end{bmatrix}>0,i=1,2\tag{20}$$

$$\begin{cases}\mathscr{M}_{ii}^{l}<0,\ l=2,3,i=1,2,\ldots,r\\ \frac{1}{r-1}\mathscr{M}_{ii}^{l}+\frac{1}{2}(\mathscr{M}_{ij}^{l}+\mathscr{M}_{ji}^{l})<0,\ 1\le i\ne j\le r\end{cases}\tag{21}$$

$$\begin{cases}\mathscr{N}_{ii}^{l}<0,\ l=2,3,i=1,2,\ldots,r\\ \frac{1}{r-1}\mathscr{N}_{ii}^{l}+\frac{1}{2}(\mathscr{N}_{ij}^{l}+\mathscr{N}_{ji}^{l})<0,\ 1\le i\ne j\le r\end{cases}\tag{22}$$

$$\begin{cases}P_1\le\xi_2P_2,Q_1\le\xi_2Q_2,R_1\le\xi_2R_2,S_1\le\xi_2S_2\\ P_2\le e^{2(a_1+a_2)h}\xi_1P_1,Q_2\le\xi_1Q_1,R_2\le\xi_1R_1,S_2\le\xi_1S_1\end{cases}\tag{23}$$

$$\rho=\frac{1}{\varrho}(2a_1d_{off}^{min}-2a_2d_{on}^{max}-2(a_1+a_2)h-ln(\xi_1\xi_2))>0\tag{24}$$

where $\mathscr{M}_{ij}^{l}=\begin{bmatrix}\Phi_{11}^{l} & * & *\\ \Phi_{21} & \Phi_{22} & *\\ \Phi_{31} & 0 & \Phi_{33}\end{bmatrix}$,
$\mathscr{N}_{ij}^{l}=\Psi_{ij}^{l}+He\{(e_1^T+e_2^T+e_3^T)U_2[\bar{A}_2e_2+\bar{A}_2^de_3+\bar{B}_2^ee_6+\bar{B}_2^se_7+\bar{B}_2^{\omega}e_8-e_1]\}$,
$\Phi_{11}^{l}=\Upsilon_{ij}^{l}+He\{(e_1^T+e_2^T+e_3^T)U_1[\bar{A}_1e_2+\bar{A}_1^de_3+\bar{B}_1^ee_6+\bar{B}_1^se_7+\bar{B}_1^{\omega}e_8-e_1]\}-e_6^T\Omega e_6-e_7^Te_7$,
$\Phi_{21}=C_iE_1e_3+e_6,\Phi_{22}=-\delta^{-1}\Omega^{-1},\Phi_{31}=D_{c_j}E_2e_2,\Phi_{33}=-\varepsilon^{-1}$,
$\Upsilon_{ij}^{l}=2a_1e_2^TP_1e_2+He\{e_1^TP_1e_2\}+[e_2^T\ e_4^T]Q_1[e_2^T\ e_4^T]^T-e^{-a_1h}[e_4^T\ e_5^T]Q_1[e_4^T\ e_5^T]^T+(\frac{h}{2})^2e_1^T(R_1+S_1)e_1-(3-l)e^{-a_1h}(e_2-e_3)^TR_1(e_2-e_3)-(3-l)e^{-a_1h}(e_3-e_4)^TR_1(e_3-e_4)-(3-l)e^{-a_1h}He((e_3-e_4)^TM_1(e_2-e_3))-(3-l)e^{-2a_1h}(e_4-e_5)^TS_1(e_4-e_5)-(l-2)e^{-2a_1h}(e_4-e_3)^TS_1(e_4-e_3)-(l-2)e^{-2a_1h}(e_3-e_5)^TS_1(e_3-e_5)-(l-2)e^{-2a_1h}He((e_3-e_5)^TN_1(e_4-e_3))-(l-2)e^{-a_1h}(e_2-e_4)^TR_1(e_2-e_4)$,

$\Psi_{ij}^{l} = -2a_2 e_2^T P_2 e_2 + He\{e_1^T P_2 e_2\} + [e_2^T \;\; e_4^T]Q_2[e_2^T \;\; e_4^T]^T - e^{a_2 h}[e_4^T \;\; e_5^T]Q_2[e_4^T \;\; e_5^T]^T + (\frac{h}{2})^2 e_1^T(R_2+S_2)e_1 - (3-l)(e_2-e_3)^T R_2(e_2-e_3) - (3-l)(e_3-e_4)^T R_2(e_3-e_4) - (3-l)He((e_3-e_4)^T M_2(e_2-e_3)) - (3-l)e^{a_2 h}(e_4-e_5)^T S_2(e_4-e_5) - (l-2)e^{a_2 h}(e_4-e_3)^T S_2(e_4-e_3) - (l-2)e^{a_2 h}(e_3-e_5)^T S_2(e_3-e_5) - (l-2)e^{a_2 h}He((e_3-e_5)^T N_2(e_4-e_3)) - (l-2)(e_2-e_4)^T R_2(e_2-e_4)$, $E_1 = [I \; 0]$, $E_2 = [0 \; I]$,
then, the system (17) under DoS attacks, the secure ETM and actuator saturation is exponentially stable with a decay rate $\bar{\rho} = \frac{\rho}{2}$.

Proof. Construct the following piecewise Lyapunov-Krasovskii functional (LKF) as

$$\begin{aligned} V_\zeta(t) =& \mathcal{X}^T(t)P_\zeta\mathcal{X}(t) + \frac{h}{2}\int_{-\frac{h}{2}}^{0}\int_{t+\theta}^{t}\dot{\mathcal{X}}^T(\iota)\mathscr{G}_\zeta(\iota)R_\zeta\dot{\mathcal{X}}(\iota)d\iota d\theta \\ &+ \int_{t-\frac{h}{2}}^{t}[\mathcal{X}^T(\iota)\;\mathcal{X}^T(\iota-\frac{h}{2})]\mathscr{G}_\zeta(\iota)Q_\zeta[\mathcal{X}^T(\iota)\;\mathcal{X}^T(\iota-\frac{h}{2})]^T d\iota \\ &+ \frac{h}{2}\int_{-h}^{-\frac{h}{2}}\int_{t+\theta}^{t}\dot{\mathcal{X}}^T(\iota)\mathscr{G}_\zeta(\iota)S_\zeta\dot{\mathcal{X}}(\iota)d\iota d\theta,\; t\in\mathcal{T}_{\zeta,n}, \zeta=1,2 \end{aligned} \tag{25}$$

where positive matrices $P_\zeta > 0, Q_\zeta > 0, R_\zeta > 0, S_\zeta > 0$, scalars $a_\zeta > 0$, and $\mathscr{G}_\zeta(\iota) = e^{2(-1)^\zeta a_\zeta(t-\iota)}$.

Two cases are considered as follows.

Case 1: if $t \in \mathcal{T}_{1,n}$, taking time derivative of $V_1(t)$ in (25) yields

$$\begin{aligned} \dot{V}_1(t) \le& \sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\{-2a_1V_1(t) + 2a_1\mathcal{X}^T(t)P_1\mathcal{X}(t) \\ &+ 2\dot{\mathcal{X}}^T(t)P_1\mathcal{X}(t) + (\frac{h}{2})^2\dot{\mathcal{X}}^T(t)(R_1+S_1)\dot{\mathcal{X}}(t) \\ &- e^{-a_1h}[\mathcal{X}^T(t-\frac{h}{2})\;\mathcal{X}^T(t-h)]Q_1[\mathcal{X}^T(t-\frac{h}{2})\;\mathcal{X}^T(t-h)]^T \\ &+ [\mathcal{X}^T(t)\;\mathcal{X}^T(t-\frac{h}{2})]Q_1[\mathcal{X}^T(t)\;\mathcal{X}^T(t-\frac{h}{2})]^T + \vartheta_R + \vartheta_S\} \end{aligned} \tag{26}$$

where

$$\vartheta_R = -\frac{h}{2}\int_{t-\frac{h}{2}}^{t}\dot{\mathcal{X}}^T(\theta)e^{-a_1h}R_1\dot{\mathcal{X}}(\theta)d\theta,\;\; \vartheta_S = -\frac{h}{2}\int_{t-h}^{t-\frac{h}{2}}\dot{\mathcal{X}}^T(\theta)e^{-2a_1h}S_1\dot{\mathcal{X}}(\theta)d\theta \tag{27}$$

If $\eta_1(t) \in [0, \frac{h}{2})$, applying Jensen inequality to ϑ_R and ϑ_S, and then using reciprocally convex approach (Park, Ko, & Jeong, 2011) with $\begin{bmatrix} R_1 & * \\ M_1 & R_1 \end{bmatrix} > 0$ to ϑ_R, we have

$$\begin{aligned} \vartheta_R \le& -e^{-a_1h}(\varphi_1^T R_1\varphi_1 + \varphi_2^T R_1\varphi_2 + He(\varphi_2^T M_1\varphi_1)) \\ \vartheta_S \le& -e^{-2a_1h}(\mathcal{X}(t-\frac{h}{2}) - \mathcal{X}(t-h))^T S_1(\mathcal{X}(t-\frac{h}{2}) - \mathcal{X}(t-h)) \end{aligned} \tag{28}$$

where $\varphi_1 = \mathcal{X}(t) - \mathcal{X}(t-\eta_1(t))$ and $\varphi_2 = \mathcal{X}(t-\eta_1(t)) - \mathcal{X}(t-\frac{h}{2})$.

If $\eta_1(t) \in [\frac{h}{2}, h)$, using Jensen inequality to ϑ_R and ϑ_S, and then applying reciprocally convex approach with $\begin{bmatrix} S_1 & * \\ N_1 & S_1 \end{bmatrix} > 0$ to ϑ_S, we have

$$\begin{aligned} \vartheta_R \leq& -e^{-a_1 h}(\mathcal{X}(t) - \mathcal{X}(t-\frac{h}{2}))^T R_1(\mathcal{X}(t) - \mathcal{X}(t-\frac{h}{2})) \\ \vartheta_S \leq& -e^{-2a_1 h}(\varphi_3^T S_1 \varphi_3 + \varphi_4^T S_1 \varphi_4 + He(\varphi_4^T N_1 \varphi_3)) \end{aligned} \tag{29}$$

where $\varphi_3 = \mathcal{X}(t-\frac{h}{2}) - \mathcal{X}(t-\eta_1(t))$ and $\varphi_4 = \mathcal{X}(t-\eta_1(t)) - \mathcal{X}(t-h)$.

Using (28) and (29), it follows from (26) that

$$\dot{V}_1(t) \leq -2a_1 V_1(t) + \sum_{i=1}^{r}\sum_{j=1}^{r} \mu_i \mu_j \{\chi_1^T(t) \Upsilon_{ij}^l \chi_1(t)\},\ l = 2, 3 \tag{30}$$

Using the system (17), define the following zero terms

$$\begin{aligned} \mathscr{Z}_\zeta =& (\dot{\mathcal{X}}^T(t) + \mathcal{X}^T(t) + \mathcal{X}^T(t-\eta_\zeta(t)))U_\zeta\{\sum_{i=1}^{r}\sum_{j=1}^{r} \mu_i\mu_j[\bar{A}_\zeta \mathcal{X}(t) + \bar{A}_\zeta^d \mathcal{X}(t-\eta_\zeta(t)) \\ &+ \bar{B}_\zeta^e e_{k,n}(t) + \bar{B}_\zeta^\omega \bar{\omega}(t) + \bar{B}_\zeta^s \mathscr{S}(u(t))] - \dot{\mathcal{X}}(t)\},\ t \in \mathcal{T}_{\zeta,n}, \zeta = 1, 2 \end{aligned} \tag{31}$$

Using event-triggered conditions in (6), we have

$$e_{k,n}^T(t)\Omega e_{k,n}(t) \leq \delta(e_{k,n}(t) + y(t-\eta_1(t)))^T \Omega(e_{k,n}(t) + y(t-\eta_1(t))) \tag{32}$$

Using (31), (32) and (9), it follows from (30) that

$$\begin{aligned} \dot{V}_1(t) \leq& -2a_1 V_1(t) + \sum_{i=1}^{r}\sum_{j=1}^{r} \mu_i\mu_j\{\chi_1^T(t)\Upsilon_{ij}^l \chi_1(t) - e_{k,n}^T(t)\Omega e_{k,n}(t) \\ &- \mathscr{S}^T(u(t))\mathscr{S}(u(t)) + e_{k,n}^T(t)\Omega e_{k,n}(t) + \mathscr{S}^T(u(t))\mathscr{S}(u(t)) + He\{\mathscr{Z}_1\}\} \\ \leq& -2a_1 V_1(t) + \sum_{i=1}^{r}\sum_{j=1}^{r} \mu_i\mu_j\{\chi_1^T(t)\bar{\Upsilon}_{ij}^l \chi_1(t)\},\ l = 2, 3 \end{aligned} \tag{33}$$

where $\bar{\Upsilon}_{ij}^l = \Upsilon_{ij}^l + He\{(e_1^T + e_2^T + e_3^T)U_1[\bar{A}_1 e_2 + \bar{A}_1^d e_3 + \bar{B}_1^e e_6 + \bar{B}_1^s e_7 + \bar{B}_1^\omega e_8 - e_1]\} - e_6^T \Omega e_6 - e_7^T e_7 + (C_i E_1 e_3 + e_6)^T \delta\Omega(C_i E_1 e_3 + e_6) + \varepsilon e_2^T E_2^T D_{c_j}^T D_{c_j} E_2 e_2$.

Using Schur complement to (21) yields

$$\begin{cases} \bar{\Upsilon}_{ii}^l < 0,\ l = 2, 3, i = 1, 2, \ldots, r \\ \frac{1}{r-1}\bar{\Upsilon}_{ii}^l + \frac{1}{2}(\bar{\Upsilon}_{ij}^l + \bar{\Upsilon}_{ji}^l) < 0,\ 1 \leq i \neq j \leq r \end{cases} \tag{34}$$

Using Lemma 3.1 to (34) yields $\sum_{i=1}^r \sum_{j=1}^r \mu_i\mu_j\{\chi_1^T(t)\bar{\Upsilon}_{ij}^l \chi_1(t)\} < 0$. Substituting this inequality into (33), we have

$$\dot{V}_1(t) \leq -2a_1 V_1(t) \ \Rightarrow\ V_1(t) \leq e^{-2a_1(t-\tau_n)} V_1(\tau_n), \tau_n = d^{n-1} \tag{35}$$

Case 2: if $t \in \mathcal{T}_{2,n}$, taking time derivative of $V_2(t)$ in (25) yields

$$\dot{V}_2(t) \leq 2a_2V_2(t) + \sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\{\chi_2^T(t)\Psi_{ij}^l\chi_2(t)\},\ l=2,3 \tag{36}$$

Using the zero term $\mathscr{Z}_2$ in (31), it follows from (36) that

$$\dot{V}_2(t) \leq 2a_2V_2(t) + \sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\{\chi_2^T(t)\bar{\Psi}_{ij}^l\chi_2(t)\},\ l=2,3 \tag{37}$$

where $\bar{\Psi}_{ij}^l = \Psi_{ij}^l + He\{(e_1^T+e_2^T+e_3^T)U_2[\bar{A}_2e_2+\bar{A}_2^de_3+\bar{B}_2^ee_6+\bar{B}_2^se_7+\bar{B}_2^\omega e_8-e_1]\}$.

Using Lemma 3.1 to (22) yields $\sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\{\chi_2^T(t)\bar{\Psi}_{ij}^l\chi_2(t)\}<0$, where $\mathscr{N}_{ij}^l = \bar{\Psi}_{ij}^l$. Substituting this inequality into (37), we have

$$\dot{V}_2(t) \leq 2a_2V_2(t) \ \Rightarrow\ V_2(t) \leq e^{2a_2(t-\bar{\tau}_n)}V_2(\bar{\tau}_n), \bar{\tau}_n = d^{n-1}+d_{off}^{n-1} \tag{38}$$

Using (35) and (38), the piecewise LKF (25) satisfies

$$V(t) \leq \begin{cases} e^{-2a_1(t-\tau_n)}V_1(\tau_n),\ t\in\mathcal{T}_{1,n} \\ e^{2a_2(t-\bar{\tau}_n)}V_2(\bar{\tau}_n),\quad t\in\mathcal{T}_{2,n}\end{cases} \tag{39}$$

Using the condition (23), the LKF (25) satisfies

$$V_1(\tau_n) \leq \xi_2V_2(\tau_n^-),\quad V_2(\bar{\tau}_n) \leq e^{2(a_1+a_2)h}\xi_1V_1(\bar{\tau}_n^-) \tag{40}$$

If $t\in\mathcal{T}_{1,n}$, using (39) and (40), we have

$$\begin{aligned} V(t) &\leq e^{-2a_1(t-\tau_n)}V_1(\tau_n) \leq \xi_2e^{-2a_1(t-\tau_n)}e^{2a_2(\tau_n-\bar{\tau}_{n-1})}V_2(\bar{\tau}_{n-1}) \\ &\leq \ldots \leq e^{b_1}V_1(0) \leq e^{\bar{b}_1}V_1(0) \leq e^{\tilde{b}_1}V_1(0)e^{-\rho t}\end{aligned} \tag{41}$$

where $b_1 = 2(n_f(t)-1)(a_1+a_2)h + (n_f(t)-1)ln(\xi_1\xi_2) + 2a_2\sum_{i=2}^{n_f(t)}(\tau_i-\bar{\tau}_{i-1}) - 2a_1\sum_{i=2}^{n_f(t)}(\bar{\tau}_{i-1}-\tau_{i-1})$, $\bar{b}_1 = (n_f(t)-1)(2(a_1+a_2)h+ln(\xi_1\xi_2)+2a_2d_{on}^{max}-2a_1d_{off}^{min})$, $\tilde{b}_1 = (\varkappa-1)(2(a_1+a_2)h+ln(\xi_1\xi_2)+2a_2d_{on}^{max}-2a_1d_{off}^{min})$, and ρ is shown in (24).

If $t\in\mathcal{T}_{2,n}$, using (39) and (40), we have

$$V(t) \leq e^{2a_2(t-\bar{\tau}_n)}V_2(\bar{\tau}_n) \leq \ldots \leq \frac{e^{\bar{b}_2}}{\xi_2}V_1(0) \leq \frac{e^{\tilde{b}_2}}{\xi_2}V_1(0)e^{-\rho t} \tag{42}$$

where $\bar{b}_2 = n_f(t)(2(a_1+a_2)h+ln(\xi_1\xi_2)+2a_2d_{on}^{max}-2a_1d_{off}^{min})$ and $\tilde{b}_2 = \varkappa(2(a_1+a_2)h+ln(\xi_1\xi_2)+2a_2d_{on}^{max}-2a_1d_{off}^{min})$.

Using (41), (42) and (25), we have

$$\varsigma_1\|\mathcal{X}(t)\|^2 \leq V(t) \leq \varsigma_2V_1(0)e^{-\rho t},\ \forall\ t\geq 0 \quad\Rightarrow\quad \|\mathcal{X}(t)\| \leq \varsigma_3e^{-\bar{\rho}t},\ \forall\ t\geq 0 \tag{43}$$

where $\varsigma_1 = min\{\lambda_{min}(P_1),\lambda_{min}(P_2)\}$, $\varsigma_2 = max\{e^{\tilde{b}_1},\frac{e^{\tilde{b}_2}}{\xi_2}\}$, $\varsigma_3 = (\frac{\varsigma_2}{\varsigma_1}V_1(0))^{\frac{1}{2}}$ and $\bar{\rho}=\frac{\rho}{2}$.

Therefore, if the conditions in Theorem 3.2 are satisfied, the system (17) under DoS attacks, the secure ETM and actuator saturation is exponentially stable with a decay rate $\bar{\rho}$. This completes the proof. □

Remark 7. To handle the second-order integral terms in the LKF (25), exclusive distribution method (Y. L. Wang, Shi, Lim, & Liu, 2016) is introduced by dividing the interval $\eta_1(t) \in [0, h)$ into $[0, \frac{h}{2})$ and $[\frac{h}{2}, h)$. Moreover, reciprocally convex approach is employed to achieve a lower bound of the integral inequalities. By combining these two methods, more relaxed results can be derived. Recently, some methods are proposed to reduce conservatism such as Wirtinger-based inequality, Bessel-Legendre inequality together with augmented Lyapunov-Krasovskii functionals (X. M. Zhang et al., 2021). In future, we will introduce these methods in security control.

3.2. Dissipative analysis

Definition 3.3. (Gu, Yan, Ahn, Yue, & Xie, 2021) For given scalar $\alpha > 0$, symmetric matrices $\mathcal{G}$, $\mathcal{I}$, and matrix $\mathcal{H}$, if the following inequality holds under zero initial condition:

$$\int_0^t z^T(\iota)\mathcal{G}z(\iota)d\iota + \int_0^t 2z^T(\iota)\mathcal{H}\omega(\iota)d\iota + \int_0^t \omega^T(\iota)\mathcal{I}\omega(\iota)d\iota \geq \alpha \int_0^t \omega^T(\iota)\omega(\iota)d\iota \quad (44)$$

then the system (17) is said to be strictly $(\mathcal{G}, \mathcal{H}, \mathcal{I})$-dissipative.

Remark 8. The notion of strict $(\mathcal{G}, \mathcal{H}, \mathcal{I})$-dissipativity includes the following special cases: (i) if setting $\mathcal{G} = -\gamma^{-1}I$, $\mathcal{H} = 0$ and $\mathcal{I} = (\gamma + \alpha)I$ with $\gamma > 0$, the notion becomes H_∞ control. (ii) if setting $\mathcal{G} = 0$, $\mathcal{H} = I$ and $\mathcal{I} = (\gamma+\alpha)I$, the notion reduces to passive control. (iii) if setting $\mathcal{G} = -\gamma^{-1}\sigma I$, $\mathcal{H} = (1-\sigma)I$ and $\mathcal{I} = (\gamma + \alpha)I$ with $\sigma \in (0, 1)$, the notion changes into mixed H_∞ and passive control, where the weighting parameter σ provides a tradeoff between H_∞ control and passive control.

Theorem 3.4. For given attack parameters $d_{off}^{min} > 0$, $d_{on}^{max} > 0$, sampling period $h < d_{off}^{min}$, triggering threshold parameter $\delta \in (0, 1)$, saturation parameter $\varepsilon \in (0, 1)$, scalars $a_i > 0$, $\xi_i > 1 (i = 1, 2)$, symmetric matrices $\mathcal{G}$, $\mathcal{I}$, and matrix $\mathcal{H}$, if there exist positive matrices $\Omega > 0, P_i > 0, Q_i > 0, R_i > 0, S_i > 0 (i = 1, 2)$, and matrices M_1, M_2, N_1, N_2 satisfying (20), (23), (24) and

$$\begin{cases} \tilde{\mathscr{M}}_{ii}^l < 0,\ l = 2, 3, i = 1, 2, \ldots, r \\ \frac{1}{r-1}\tilde{\mathscr{M}}_{ii}^l + \frac{1}{2}(\tilde{\mathscr{M}}_{ij}^l + \tilde{\mathscr{M}}_{ji}^l) < 0,\ 1 \leq i \neq j \leq r \end{cases} \quad (45)$$

$$\begin{cases} \tilde{\mathscr{N}}_{ii}^l < 0,\ l = 2, 3, i = 1, 2, \ldots, r \\ \frac{1}{r-1}\tilde{\mathscr{N}}_{ii}^l + \frac{1}{2}(\tilde{\mathscr{N}}_{ij}^l + \tilde{\mathscr{N}}_{ji}^l) < 0,\ 1 \leq i \neq j \leq r \end{cases} \quad (46)$$

where $\tilde{\mathscr{M}}_{ij}^l = \begin{bmatrix} \tilde{\Phi}_{11}^l & * & * & * \\ \Phi_{21} & \Phi_{22} & * & * \\ \Phi_{31} & 0 & \Phi_{33} & * \\ \Phi_{41} & 0 & 0 & \Phi_{44} \end{bmatrix}, \tilde{\mathscr{N}}_{ij}^l = \begin{bmatrix} \Pi_{11}^l & * \\ \Pi_{12} & \Pi_{22} \end{bmatrix}$,
$\Phi_{41} = \bar{F}_1 e_2 + \bar{G}_1 e_7, \Phi_{44} = \mathcal{G}^{-1}$, $\tilde{\Phi}_{11}^l = \Phi_{11}^l - He\{(\bar{F}_1 e_2 + \bar{G}_1 e_7)^T \mathcal{H} e_8\} - e_8^T(\mathcal{I} - \alpha)e_8$, $\Pi_{11}^l = \mathscr{N}_{ij}^l - He\{(\bar{F}_2 e_2 + \bar{G}_2 e_7)^T \mathcal{H} e_8\} - e_8^T(\mathcal{I} - \alpha)e_8$, $\Pi_{21} = \bar{F}_2 e_2 + \bar{G}_2 e_7, \Pi_{22} = \mathcal{G}^{-1}$, and other terms are same as that in Theorem 3.2,

then, the system (17) under DoS attacks, the secure ETM and actuator satuation is exponentially stable and strictly ($\mathcal{G}$, $\mathcal{H}$, $\mathcal{I}$)-dissipative.

Proof. Firstly, define $\mathcal{F}(t) = z^T(t)\mathcal{G}z(t) + 2z^T(t)\mathcal{H}\omega(t) + \omega^T(t)\mathcal{I}\omega(t) - \alpha\omega^T(t)\omega(t)$. If $t \in \mathcal{T}_{1,n}$, subtracting $\mathcal{F}(t)$ at both sides of (33) yields

$$\dot{V}_1(t) + 2a_1V_1(t) - \mathcal{F}(t) \leq \sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\{\chi_1^T(t)\tilde{\Upsilon}_{ij}^l\chi_1(t)\},\ l = 2,3 \tag{47}$$

where $\tilde{\Upsilon}_{ij}^l = \bar{\Upsilon}_{ij}^l - (\bar{F}_1e_2 + \bar{G}_1e_7)^T\mathcal{G}(\bar{F}_1e_2 + \bar{G}_1e_7) - He\{(\bar{F}_1e_2 + \bar{G}_1e_7)^T\mathcal{H}e_8\} - e_8^T(\mathcal{I} - \alpha)e_8$.

Using Schur complement and Lemma 3.1 to (45), we have $\sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\{\chi_1^T(t)\tilde{\Upsilon}_{ij}^l\chi_1(t)\} < 0$. Substituting this inequality into (47) yields

$$\dot{V}_1(t) + 2a_1V_1(t) \leq \mathcal{F}(t) \tag{48}$$

If $t \in \mathcal{T}_{2,n}$, subtracting $\mathcal{F}(t)$ at both sides of (37) yields

$$\dot{V}_2(t) - 2a_2V_2(t) - \mathcal{F}(t) \leq \sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\{\chi_2^T(t)\tilde{\Psi}_{ij}^l\chi_2(t)\},\ l = 2,3 \tag{49}$$

where $\tilde{\Psi}_{ij}^l = \bar{\Psi}_{ij}^l - (\bar{F}_2e_2 + \bar{G}_2e_7)^T\mathcal{G}(\bar{F}_2e_2 + \bar{G}_2e_7) - He\{(\bar{F}_2e_2 + \bar{G}_2e_7)^T\mathcal{H}e_8\} - e_8^T(\mathcal{I} - \alpha)e_8$.

Using Schur complement and Lemma 3.1 to (46), we have $\sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\{\chi_2^T(t)\tilde{\Psi}_{ij}^l\chi_2(t)\} < 0$. Substituting this inequality into (49) yields

$$\dot{V}_2(t) - 2a_2V_2(t) \leq \mathcal{F}(t) \tag{50}$$

For any $t > 0$, either $t \in \mathcal{T}_{1,n}$ or $t \in \mathcal{T}_{2,n}$ holds.

Case 1: if $t \in \mathcal{T}_{1,n}$, we have

$$\begin{aligned}
\mathscr{D}_1 =& \sum_{i=0}^{n-2}\int_{d^i}^{d^i+d_{off}^i} s_i^1(\iota)[\dot{V}_1(\iota) + 2a_1V_1(\iota)]d\iota \\
&+ \sum_{i=0}^{n-2}\int_{d^i+d_{off}^i}^{d^{i+1}} s_i^2(\iota)[\dot{V}_2(\iota) - 2a_2V_2(\iota)]d\iota + \int_{d^{n-1}}^{t} s_{n-1}^1(\iota)[\dot{V}_1(\iota) + 2a_1V_1(\iota)]d\iota \\
=& \sum_{i=0}^{n-2}\Big[\frac{1}{\xi_2}e^{2a_1d_{off}^i}V_1(d^i + d_{off}^i) - \frac{1}{\xi_2}V_1(d^i) + V_2(d^{i+1}) \\
&- e^{2a_2(d^{i+1}-d^i-d_{off}^i)}V_2(d^i + d_{off}^i)\Big] + \frac{1}{\xi_2}e^{2a_1(t-d^{n-1})}V_1(t) - \frac{1}{\xi_2}V_1(d^{n-1})
\end{aligned} \tag{51}$$

where $s_i^1(\iota) = e^{2a_1(\iota-d^i)}/\xi_2$ and $s_i^2(\iota) = e^{2a_2(d^{i+1}-\iota)}$.

Using (40), it follows from (51) that

$$
\begin{aligned}
\mathscr{D}_1 \geq & \sum_{i=0}^{n-2} \left[\frac{1}{\xi_2} e^{2a_1 d_{off}^i} V_1(d^i + d_{off}^i) - e^{2a_2(d^{i+1} - d^i - d_{off}^i) + 2(a_1+a_2)h} \xi_1 V_1(d^i + d_{off}^i) \right. \\
& \left. - \frac{1}{\xi_2} V_1(d^i) + \frac{1}{\xi_2} V_1(d^{i+1}) \right] + \frac{1}{\xi_2} e^{2a_1(t-d^{n-1})} V_1(t) - \frac{1}{\xi_2} V_1(d^{n-1}) \\
= & \sum_{i=0}^{n-2} \left[\frac{1}{\xi_2} e^{2a_1 d_{off}^i} - e^{2a_2(d^{i+1} - d^i - d_{off}^i) + 2(a_1+a_2)h} \xi_1 \right] V_1(d^i + d_{off}^i) \\
& + \frac{1}{\xi_2} e^{2a_1(t-d^{n-1})} V_1(t) - \frac{1}{\xi_2} V_1(0)
\end{aligned}
\tag{52}
$$

Using (24), we have $2a_1 d_{off}^{min} > 2a_2 d_{on}^{max} + 2(a_1 + a_2)h + ln(\xi_1 \xi_2)$. Applying this inequality to (52) yields

$$
\begin{aligned}
\mathscr{D}_1 \geq & \sum_{i=0}^{n-2} \left[\frac{1}{\xi_2} e^{2a_1 d_{off}^{min}} - e^{2a_2 d_{on}^{max} + 2(a_1+a_2)h} \xi_1 \right] V_1(d^i + d_{off}^i) \\
& + \frac{1}{\xi_2} e^{2a_1(t-d^{n-1})} V_1(t) - \frac{1}{\xi_2} V_1(0) \geq 0
\end{aligned}
\tag{53}
$$

Using (48), (50) and (53), it follows from (51) that

$$
\begin{aligned}
& \sum_{i=0}^{n-2} \int_{d^i}^{d^i + d_{off}^i} s_i^1(\iota) \mathcal{F}(\iota) d\iota + \sum_{i=0}^{n-2} \int_{d^i + d_{off}^i}^{d^{i+1}} s_i^2(\iota) \mathcal{F}(\iota) d\iota \\
& + \int_{d^{n-1}}^{t} s_{n-1}^1(\iota) \mathcal{F}(\iota) d\iota \geq \mathscr{D}_1 \geq 0, \ \forall \ t \in \mathcal{T}_{1,n}
\end{aligned}
\tag{54}
$$

Case 2: if $t \in \mathcal{T}_{2,n}$, using similar methods above, we have

$$
\begin{aligned}
\mathscr{D}_2 = & \sum_{i=0}^{n-1} \int_{d^i}^{d^i + d_{off}^i} s_i^1(\iota) [\dot{V}_1(\iota) + 2a_1 V_1(\iota)] d\iota + \sum_{i=0}^{n-2} \int_{d^i + d_{off}^i}^{d^{i+1}} s_i^2(\iota) [\dot{V}_2(\iota) - 2a_2 V_2(\iota)] d\iota \\
& + \int_{d^{n-1} + d_{off}^{n-1}}^{t} s_{n-1}^2(\iota) [\dot{V}_2(\iota) - 2a_2 V_2(\iota)] d\iota \\
\geq & \sum_{i=0}^{n-1} \left[\frac{1}{\xi_2} e^{2a_1 d_{off}^{min}} - e^{2a_2 d_{on}^{max} + 2(a_1+a_2)h} \xi_1 \right] V_1(d^i + d_{off}^i) \\
& + e^{2a_2(d^n - t)} V_2(t) - \frac{1}{\xi_2} V_1(0) \geq 0
\end{aligned}
\tag{55}
$$

Using (48) and (50), it follow from (55) that

$$\begin{aligned}&\sum_{i=0}^{n-1}\int_{d^i}^{d^i+d^i_{off}} s_i^1(\iota)\mathcal{F}(\iota)d\iota+\sum_{i=0}^{n-2}\int_{d^i+d^i_{off}}^{d^{i+1}} s_i^2(\iota)\mathcal{F}(\iota)d\iota\\&+\int_{d^{n-1}+d^{n-1}_{off}}^{t} s^2_{n-1}(\iota)\mathcal{F}(\iota)d\iota\geq\mathscr{D}_2\geq 0,\ \forall\ t\in\mathcal{T}_{2,n}\end{aligned}\tag{56}$$

Using (54) and (56), we have

$$\int_0^t\mathscr{C}\mathcal{F}(\iota)d\iota\geq\mathscr{D}_\zeta\geq 0,\ \forall\ t\in\mathcal{T}_{\zeta,n}(\zeta=1,2)\quad\Rightarrow\quad\int_0^t\mathcal{F}(\iota)d\iota\geq 0,\ \forall\ t>0\tag{57}$$

where $\mathscr{C} = max\{s_i^1(t), s_i^2(t)\} = max\{e^{2a_1 d^{max}_{off}}/\xi_2, e^{2a_2 d^{max}_{on}}\} > 0$, and $d^{max}_{off} = max\{d^n_{off}\}$ denotes the maximum sleeping interval of DoS attacks.

Using Definition 3.3, we derive from (57) that the system (17) under DoS attacks, the secure ETM and actuator saturation is strictly $(\mathcal{G},\mathcal{H},\mathcal{I})$-dissipative. Besides, exponential stability has been proved in Theorem 3.2. The proof is thus completed. □

4. Co-design of the SDOFF controller and resilient ETM

Lemma 4.1. *(Liu, Wang, Cao, Yue, & Xie, 2021) For scalar $\epsilon > 0$, positive matrix $\Omega > 0$ and symmetric matrix $\mathscr{P}$, the following inequality holds*

$$-\mathscr{P}\Omega^{-1}\mathscr{P}<\epsilon^2\Omega-2\epsilon\mathscr{P}\tag{58}$$

Theorem 4.2. For given attack parameters $d^{min}_{off} > 0$, $d^{max}_{on} > 0$, sampling period $h < d^{min}_{off}$, saturation parameter $\varepsilon \in (0, 1)$, scalars $a_i > 0$, $\xi_i > 1(i = 1, 2), \epsilon > 0$, symmetric matrices $\mathcal{G}$, $\mathcal{I}$, and matrix $\mathcal{H}$, if there exist positive matrices $\Omega > 0, \bar{P}_i > 0, \bar{Q}_i > 0, \bar{R}_i > 0, \bar{S}_i > 0(i = 1, 2)$, symmetric matrix Y, matrices $X_i, \bar{M}_i, \bar{N}_i(i = 1, 2)$, and scalar $\bar{\delta} > 1$ satisfying (24) and

$$\begin{bmatrix}\bar{R}_i & *\\ \bar{M}_i & \bar{R}_i\end{bmatrix}>0,\ \begin{bmatrix}\bar{S}_i & *\\ \bar{N}_i & \bar{S}_i\end{bmatrix}>0,\ i=1,2\tag{59}$$

$$\begin{cases}\bar{\mathscr{M}}^l_{ii}<0,\ l=2,3,i=1,2,\ldots,r\\ \frac{1}{r-1}\bar{\mathscr{M}}^l_{ii}+\frac{1}{2}(\bar{\mathscr{M}}^l_{ij}+\bar{\mathscr{M}}^l_{ji})<0,\ 1\leq i\neq j\leq r\end{cases}\tag{60}$$

$$\begin{cases}\bar{\mathscr{N}}^l_{ii}<0,\ l=2,3,i=1,2,\ldots,r\\ \frac{1}{r-1}\bar{\mathscr{N}}^l_{ii}+\frac{1}{2}(\bar{\mathscr{N}}^l_{ij}+\bar{\mathscr{N}}^l_{ji})<0,\ 1\leq i\neq j\leq r\end{cases}\tag{61}$$

$$\begin{cases}\bar{P}_1\leq\xi_2\bar{P}_2,\bar{Q}_1\leq\xi_2\bar{Q}_2,\bar{R}_1\leq\xi_2\bar{R}_2,\bar{S}_1\leq\xi_2\bar{S}_2\\ \bar{P}_2\leq e^{2(a_1+a_2)h}\xi_1\bar{P}_1,\bar{Q}_2\leq\xi_1\bar{Q}_1,\bar{R}_2\leq\xi_1\bar{R}_1,\bar{S}_2\leq\xi_1\bar{S}_1\end{cases}\tag{62}$$

where $\bar{\mathscr{M}}^l_{ij} = \begin{bmatrix} \bar{\Phi}^l_{11} & * & * & * \\ \bar{\Phi}_{21} & \bar{\Phi}_{22} & * & * \\ \bar{\Phi}_{31} & 0 & \Phi_{33} & * \\ \bar{\Phi}_{41} & 0 & 0 & \Phi_{44} \end{bmatrix}$, $\bar{\mathscr{N}}^l_{ij} = \begin{bmatrix} \bar{\Pi}^l_{11} & * \\ \bar{\Pi}_{21} & \Pi_{22} \end{bmatrix}$,
$\bar{\Phi}^l_{11} = 2a_1 e_2^T \bar{P}_1 e_2 + He\{e_1^T \bar{P}_1 e_2\} + [e_2^T \ e_4^T]\bar{Q}_1[e_2^T \ e_4^T]^T - e^{-a_1 h}[e_4^T \ e_5^T]\bar{Q}_1[e_4^T \ e_5^T]^T + (\frac{h}{2})^2 e_1^T(\bar{R}_1 + \bar{S}_1)e_1 - (3-l)e^{-a_1 h}(e_2 - e_3)^T \bar{R}_1(e_2 - e_3) - (3-l)e^{-a_1 h}(e_3 - e_4)^T \bar{R}_1(e_3 - e_4) - (3-l)e^{-a_1 h} He((e_3 - e_4)^T \bar{M}_1(e_2 - e_3)) - (3-l)e^{-2a_1 h}(e_4 - e_5)^T \bar{S}_1(e_4 - e_5) - (l-2)e^{-2a_1 h}(e_4 - e_3)^T \bar{S}_1(e_4 - e_3) - (l-2)e^{-2a_1 h}(e_3 - e_5)^T \bar{S}_1(e_3 - e_5) - (l-2)e^{-2a_1 h} He((e_3 - e_5)^T \bar{N}_1(e_4 - e_3)) - (l-2)e^{-a_1 h}(e_2 - e_4)^T \bar{R}_1(e_2 - e_4) + He\{(e_1^T + e_2^T + e_3^T)[\hat{A}_1 e_2 + \hat{A}^d_1 e_3 + \hat{B}^e_1 e_6 + \hat{B}^s_1 e_7 + \hat{B}^\omega_1 e_8 - \mathscr{U}_1 e_1]\} - e_6^T \Omega e_6 - e_7^T e_7 - He\{(\hat{F}_1 e_2 + \bar{G}_1 e_7)^T \mathcal{H} e_8\} - e_8^T(\mathcal{I} - \alpha)e_8$,
$\bar{\Phi}_{21} = [C_i Y \ C_i]e_3 + e_6, \bar{\Phi}_{22} = \epsilon^2\Omega - 2\epsilon\bar{\delta}I, \bar{\delta} = \delta^{-\frac{1}{2}}, \bar{\Phi}_{31} = [\mathscr{L}^1_j \ 0]e_2,\ \Phi_{33} = -\varepsilon^{-1}$,
$\bar{\Phi}_{41} = \hat{F}_1 e_2 + \bar{G}_1 e_7,\ \Phi_{44} = \mathcal{G}^{-1}$,
$\hat{A}_1 = \begin{bmatrix} A_i Y + B_i \mathscr{L}^1_j & A_i \\ \mathscr{L}^4_{ij} & X_1 A_i \end{bmatrix}$, $\hat{A}^d_1 = \begin{bmatrix} 0 & 0 \\ \mathscr{L}^3_{ij} & \mathscr{L}^2_j C_i \end{bmatrix}$, $\hat{B}^e_1 = \begin{bmatrix} 0 \\ \mathscr{L}^2_j \end{bmatrix}$, $\hat{B}^\omega_1 = \begin{bmatrix} D_i \\ X_1 D_i \end{bmatrix}$, $\hat{B}^s_1 = \begin{bmatrix} -B_i \\ -X_1 B_i \end{bmatrix}$, $\mathscr{U}_1 = \begin{bmatrix} Y & I \\ I & X_1 \end{bmatrix}$, $\hat{F}_1 = \begin{bmatrix} F_i Y + G_i \mathscr{L}^1_j & F_i \end{bmatrix}$, $\mathscr{L}^1_j = D^1_{c_j} Y$, $\mathscr{L}^2_j = (Y^{-1} - X_1)C^1_{c_j}$, $\mathscr{L}^3_{ij} = \mathscr{L}^2_j C_i Y + (Y^{-1} - X_1)B^1_{c_{ij}} Y$, $\mathscr{L}^4_{ij} = X_1 A_i Y + X_1 B_i \mathscr{L}^1_j + (Y^{-1} - X_1)A^1_{c_{ij}} Y$,
$\bar{\Pi}^l_{11} = -2a_2 e_2^T \bar{P}_2 e_2 + He\{e_1^T \bar{P}_2 e_2\} + [e_2^T \ e_4^T]\bar{Q}_2[e_2^T \ e_4^T]^T - e^{a_2 h}[e_4^T \ e_5^T]\bar{Q}_2[e_4^T \ e_5^T]^T + (\frac{h}{2})^2 e_1^T(\bar{R}_2 + \bar{S}_2)e_1 - (3-l)(e_2 - e_3)^T \bar{R}_2(e_2 - e_3) - (3-l)(e_3 - e_4)^T \bar{R}_2(e_3 - e_4) - (3-l)He((e_3 - e_4)^T \bar{M}_2(e_2 - e_3)) - (3-l)e^{a_2 h}(e_4 - e_5)^T \bar{S}_2(e_4 - e_5) - (l-2)e^{a_2 h}(e_4 - e_3)^T \bar{S}_2(e_4 - e_3) - (l-2)e^{a_2 h}(e_3 - e_5)^T \bar{S}_2(e_3 - e_5) - (l-2)e^{a_2 h} He((e_3 - e_5)^T \bar{N}_2(e_4 - e_3)) - (l-2)(e_2 - e_4)^T \bar{R}_2(e_2 - e_4) + He\{(e_1^T + e_2^T + e_3^T)[\hat{A}_2 e_2 + \hat{A}^d_2 e_3 + \hat{B}^e_2 e_6 + \hat{B}^s_2 e_7 + \hat{B}^\omega_2 e_8 - \mathscr{U}_2 e_1]\} - He\{(\hat{F}_2 e_2 + \bar{G}_2 e_7)^T \mathcal{H} e_8\} - e_8^T(\mathcal{I} - \alpha)e_8$,
$\bar{\Pi}_{21} = \hat{F}_2 e_2 + \bar{G}_2 e_7,\ \Pi_{22} = \mathcal{G}^{-1},\ \hat{F}_2 = \begin{bmatrix} F_i Y & F_i \end{bmatrix}$,
$\hat{A}_2 = \begin{bmatrix} A_i Y & A_i \\ \mathscr{L}^5_{ij} & X_2 A_i \end{bmatrix}$, $\hat{A}^d_2 = \begin{bmatrix} 0 & 0 \\ \mathscr{L}^6_{ij} & 0 \end{bmatrix}$, $\hat{B}^\omega_2 = \begin{bmatrix} D_i \\ X_2 D_i \end{bmatrix}$, $\hat{B}^e_2 = \hat{B}^s_2 = 0$, $\mathscr{U}_2 = \begin{bmatrix} Y & I \\ I & X_2 \end{bmatrix}$,
$\mathscr{L}^5_{ij} = X_2 A_i Y + (Y^{-1} - X_2)A^2_{c_{ij}} Y$, $\mathscr{L}^6_{ij} = (Y^{-1} - X_2)B^2_{c_{ij}} Y$, $\bar{P}_i = \mu_1^T P_i \mu_1$, $\bar{Q}_i = \mu_2^T Q_i \mu_2$, $\bar{R}_i = \mu_1^T R_i \mu_1$, $\bar{S}_i = \mu_1^T S_i \mu_1$, $\bar{M}_i = \mu_1^T M_i \mu_1$, $\bar{N}_i = \mu_1^T N_i \mu_1 (i = 1, 2)$,
then, the system (17) under DoS attacks, the secure ETM and actuator saturation is exponentially stable and strictly ($\mathcal{G}$, $\mathcal{H}$, $\mathcal{I}$)-dissipative. Besides, parameters of the secure ETM (6) and the SDOFF controller (16) are obtained as ($\delta = \bar{\delta}^{-2}, \Omega$) and

$$\begin{cases} A^1_{c_{ij}} = (Y^{-1} - X_1)^{-1}(\mathscr{L}^4_{ij} - X_1 A_i Y - X_1 B_i \mathscr{L}^1_j)Y^{-1},\ D^1_{c_j} = \mathscr{L}^1_j Y^{-1} \\ B^1_{c_{ij}} = (Y^{-1} - X_1)^{-1}(\mathscr{L}^3_{ij} - \mathscr{L}^2_j C_i Y)Y^{-1},\ C^1_{c_j} = (Y^{-1} - X_1)^{-1}\mathscr{L}^2_j \\ A^2_{c_{ij}} = (Y^{-1} - X_2)^{-1}(\mathscr{L}^5_{ij} - X_2 A_i Y)Y^{-1}, B^2_{c_{ij}} = (Y^{-1} - X_2)^{-1}\mathscr{L}^6_{ij} Y^{-1} \end{cases} \tag{63}$$

Proof. Define the following matrices

$$U_i = \begin{bmatrix} X_i & Y^{-1} - X_i \\ Y^{-1} - X_i & X_i - Y^{-1} \end{bmatrix} (i = 1, 2),\ \mu_1 = \begin{bmatrix} Y & I \\ Y & 0 \end{bmatrix} \tag{64}$$

where X_1, X_2, Y are real matrices with Y symmetric.

Using $\mu_2 = \text{diag}\{\mu_1, \mu_1\}$, $\mu_3 = \text{diag}\{\mu_4, I, I\}$ and $\mu_4 = \text{diag}\{\underbrace{\mu_1, \ldots, \mu_1}_{5}, \underbrace{I, \ldots, I}_{4}\}$, transform the conditions in Theorem 3.4 as

$$\begin{bmatrix}\bar{R}_i & * \\ \bar{M}_i & \bar{R}_i\end{bmatrix} = \mu_2^T \begin{bmatrix}R_i & * \\ M_i & R_i\end{bmatrix}\mu_2 > 0, \begin{bmatrix}\bar{S}_i & * \\ \bar{N}_i & \bar{S}_i\end{bmatrix} = \mu_2^T \begin{bmatrix}S_i & * \\ N_i & S_i\end{bmatrix}\mu_2 > 0, i = 1, 2 \tag{65}$$

$$\begin{bmatrix}\bar{\Phi}_{11}^l & * & * & * \\ \bar{\Phi}_{21} & \Phi_{22} & * & * \\ \bar{\Phi}_{31} & 0 & \Phi_{33} & * \\ \bar{\Phi}_{41} & 0 & 0 & \Phi_{44}\end{bmatrix} = \mu_3^T \begin{bmatrix}\tilde{\Phi}_{11}^l & * & * & * \\ \Phi_{21} & \Phi_{22} & * & * \\ \Phi_{31} & 0 & \Phi_{33} & * \\ \Phi_{41} & 0 & 0 & \Phi_{44}\end{bmatrix}\mu_3 < 0,\ l = 2, 3 \tag{66}$$

$$\begin{bmatrix}\bar{\Xi}_{11}^l & * \\ \bar{\Xi}_{21} & \Xi_{22}\end{bmatrix} = \mu_4^T \begin{bmatrix}\Xi_{11}^l & * \\ \Xi_{21} & \Xi_{22}\end{bmatrix}\mu_4 < 0,\ l = 2, 3 \tag{67}$$

$$\begin{cases}\mu_1^T P_1 \mu_1 \le \xi_2 \mu_1^T P_2 \mu_1, \mu_2^T Q_1 \mu_2 \le \xi_2 \mu_2^T Q_2 \mu_2, \mu_1^T R_1 \mu_1 \le \xi_2 \mu_1^T R_2 \mu_1, \\ \mu_1^T S_1 \mu_1 \le \xi_2 \mu_1^T S_2 \mu_1, \mu_1^T P_2 \mu_1 \le e^{2(a_1+a_2)h} \xi_1 \mu_1^T P_1 \mu_1, \mu_2^T Q_2 \mu_2 \le \xi_1 \mu_2^T Q_1 \mu_2 \\ \mu_1^T R_2 \mu_1 \le \xi_1 \mu_1^T R_1 \mu_1, \mu_1^T S_2 \mu_1 \le \xi_1 \mu_1^T S_1 \mu_1\end{cases} \tag{68}$$

Using Lemma 4.1 to Φ_{22} in (66) yields $\bar{\Phi}_{22}$ in (60). Thus, if the conditions in Theorem 4.2 are satisfied, the system (17) under DoS attacks, the secure ETM and actuator satuation is exponentially stable and strictly $(\mathcal{G}, \mathcal{H}, \mathcal{I})$-dissipative. Moreover, the SDOFF controller (16) and the secure ETM (6) can be co-designed by (63). This completes the proof. □

Algorithm 1. Co-design algorithm of the ETM and the SDOFF controller.

Step 1. Using Theorem 4.2, find out the maximum allowable triggering threshold parameter δ_m satisfying system performance. Set the desired indexes of communication and control performances such as an expected triggering rate $r_t = n_t/n_s$ of the ETM where n_t and n_s denote numbers of triggering data and sampling data, respectively.

Step 2. For given initial value δ_0 and step value Δ_δ, using a loop with $\delta = \delta_0 : \Delta_\delta : \delta_m$, calculate parameters of the ETM and controller based on Theorem 4.2. Using the resultant ETM and controller, run the system and check the communication and control performances. Keep the loop running until satisfactory communication and control performances are obtained.

Remark 9. Unlike the two-step emulation approach where a controller is first designed in the absence of communication constraints, and then an event trigger is designed using the known controller (W. Wang, Postoyan, Nesic, & Heemels, 2020), Algorithm 1 can co-design the required ETM and controller simultaneously, which is more convenient. Besides, Algorithm 1 establishes relationships between system performance and the factors including the nonlinear plant, noises, secure ETM, DoS attacks, SDOFF controller and saturated actuator. By choosing suitable parameters of these factors, the desired system performance can be achieved.

5. Examples

Consider the T-S fuzzy system in (Guan & Chen, 2004) with the following parameters $A_1 = \begin{bmatrix}0 & 1 \\ 0.1 & -2\end{bmatrix}, A_2 = \begin{bmatrix}0 & 1 \\ 0.1 & -0.5\end{bmatrix}, B_1 = B_2 = \begin{bmatrix}0 \\ 1\end{bmatrix}, D_1 = D_2 = \begin{bmatrix}0.01 \\ 0.01\end{bmatrix}, C_1 = C_2 = \begin{bmatrix}-0.1 & -0.2\end{bmatrix}, F_1 = F_2 = \begin{bmatrix}0.02 & -0.03\end{bmatrix}, G_1 = G_2 = 0.01$. The membership

functions are $\mu_2 = 1 - \mu_1$ and $\mu_1 = \left(1 - \frac{1}{1+exp\{-3(\frac{x_2(t)}{0.5} - \frac{\pi}{2})\}}\right) \times \frac{1}{1+exp\{-3(\frac{x_2(t)}{0.5} + \frac{\pi}{2})\}}$
Other parameters are given as: sampling period $h = 0.01s$, attack parameters $d_{off}^{min} = 2s$, $d_{on}^{max} = 1.12s$, $\mathcal{G} = -0.2$, $\mathcal{H} = 0.5$, $\mathcal{I} = 2$, $a_1 = 0.113, a_2 = 0.19$, $\xi_1 = \xi_2 = 1.01, \epsilon = 0.001$, actuator saturation parameters $u_i^s = 1.52, \varepsilon = 0.051$, disturbance signal $\omega(t) = sin(8\pi t)$, and initial states are $x_0 = col\{1.8, 0.5\}$.

Using Theorem 4.2, parameters of the secure ETM and SDOFF controller are obtained as ($\delta = 0.025, \Omega = 819.1611$) and

$$\begin{cases} A_{c_{11}}^1 = \begin{bmatrix} -0.2323 & 0.9810 \\ -2.8922 & -6.4851 \end{bmatrix}, & A_{c_{12}}^1 = \begin{bmatrix} -0.2707 & 0.6622 \\ -3.0737 & -9.4861 \end{bmatrix} \\ A_{c_{21}}^1 = \begin{bmatrix} -0.2779 & 1.0564 \\ -3.0599 & -3.6901 \end{bmatrix}, & A_{c_{22}}^1 = \begin{bmatrix} -0.2489 & 0.9768 \\ -3.1608 & -6.2918 \end{bmatrix} \\ B_{c_{11}}^1 = \begin{bmatrix} -1.3016 & -2.9454 \\ -4.4333 & -10.4458 \end{bmatrix}, & B_{c_{12}}^1 = \begin{bmatrix} -4.9673 & -6.7224 \\ -4.2462 & -11.4877 \end{bmatrix} \\ B_{c_{21}}^1 = \begin{bmatrix} 2.4342 & 1.0975 \\ -5.2389 & -10.5955 \end{bmatrix}, & B_{c_{22}}^1 = \begin{bmatrix} -1.2978 & -2.9312 \\ -5.1193 & -11.9809 \end{bmatrix} \\ C_{c_1}^1 = \begin{bmatrix} -14.0543 & -47.2686 \end{bmatrix}^T, & D_{c_1}^1 = \begin{bmatrix} -1.4626 & -2.1189 \end{bmatrix} \\ C_{c_2}^1 = \begin{bmatrix} -13.9273 & -56.5449 \end{bmatrix}^T, & D_{c_2}^1 = \begin{bmatrix} -1.4580 & -3.2952 \end{bmatrix} \\ A_{c_{11}}^2 = \begin{bmatrix} -0.0070 & 1.0127 \\ 0.1631 & -2.1601 \end{bmatrix}, & A_{c_{12}}^2 = \begin{bmatrix} -7.4742 & -4.1487 \\ 1.8775 & -1.0228 \end{bmatrix} \\ A_{c_{21}}^2 = \begin{bmatrix} 7.4664 & 6.3399 \\ -1.6056 & -1.7958 \end{bmatrix}, & A_{c_{22}}^2 = \begin{bmatrix} -0.0394 & 1.1975 \\ 0.1697 & -0.5730 \end{bmatrix} \\ B_{c_{11}}^2 = \begin{bmatrix} 0.0190 & -0.0021 \\ -0.0750 & -0.0214 \end{bmatrix}, & B_{c_{12}}^2 = \begin{bmatrix} -0.0162 & 0.0204 \\ -0.0418 & -0.0611 \end{bmatrix} \\ B_{c_{21}}^2 = \begin{bmatrix} -0.0166 & 0.0042 \\ -0.0421 & -0.0569 \end{bmatrix}, & B_{c_{22}}^2 = \begin{bmatrix} -0.0063 & -0.0210 \\ -0.0220 & -0.0142 \end{bmatrix} \end{cases} \tag{69}$$

Figure 4 shows that the open-loop system is unstable. As shown in Figure 5, although the unstable system is also affected by DoS attacks, the secure ETM and actuator saturation, it can still be stabilized by the designed controller with gain matrices (69). Figure 6 illustrates the saturated control input $\bar{u}(t)$ and control input $u(t)$. During the attack's active intervals, since the actuator can not receive signals, both of saturated input $\bar{u}(t)$ and control input $u(t)$ become zero. The zoomed plot shows that, due to actuator saturation, values of control input $u(t)$ smaller than $-u_i^s$ are bounded by the corresponding saturated control input $\bar{u}(t) = -1.52$. In these figures, the white bands denote the attack's sleeping intervals, while the gray bands indicate the attack's active intervals $[2.1s\ 3.1s), [5.1s\ 5.9s), [8.1s\ 9.2s), [11.3s\ 11.7s)$, $[14.0s\ 14.9s)$ and $[17.3s\ 18.0s)$.

Figure 7 shows the triggering instants and triggering intervals of the secure ETM (6). During the attack's sleeping intervals, there are 1510 sampled data packets, however, only 118 data packets are released. That is, transmission rate of the ETM is 7.81%, and thus 92.19% system resources can be saved. Besides, the minimum triggering interval $0.02s$ is larger than sampling period and hence it excludes Zeno behavior.

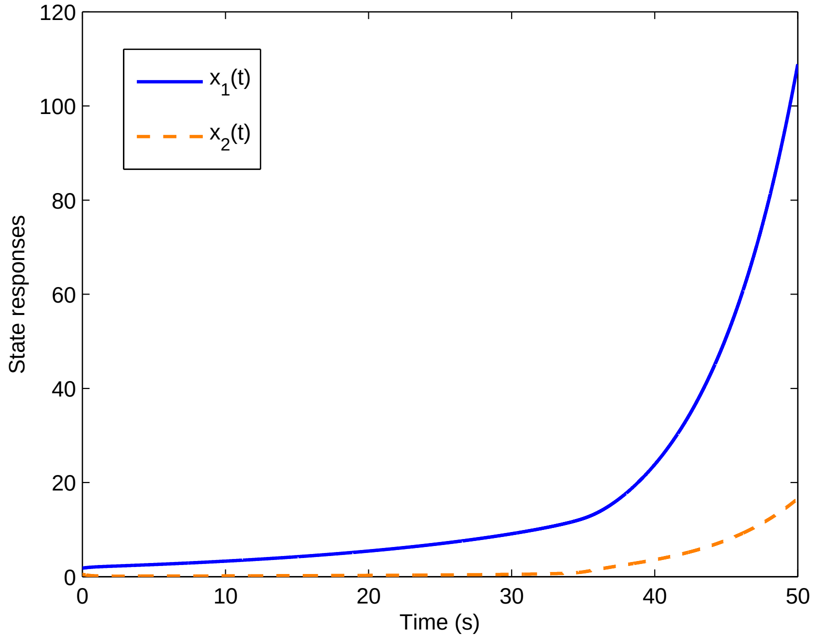

Figure 4. State responses of open-loop system

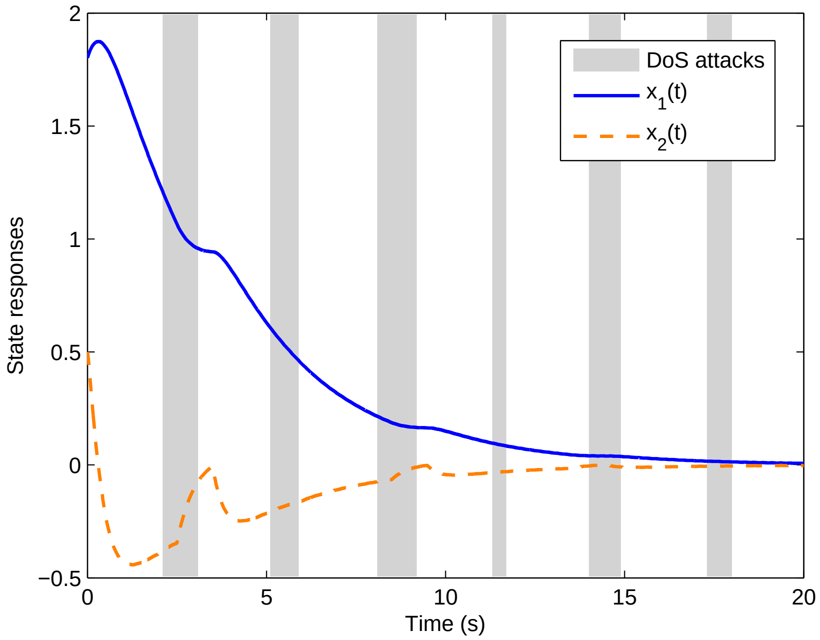

Figure 5. State responses of closed-loop system

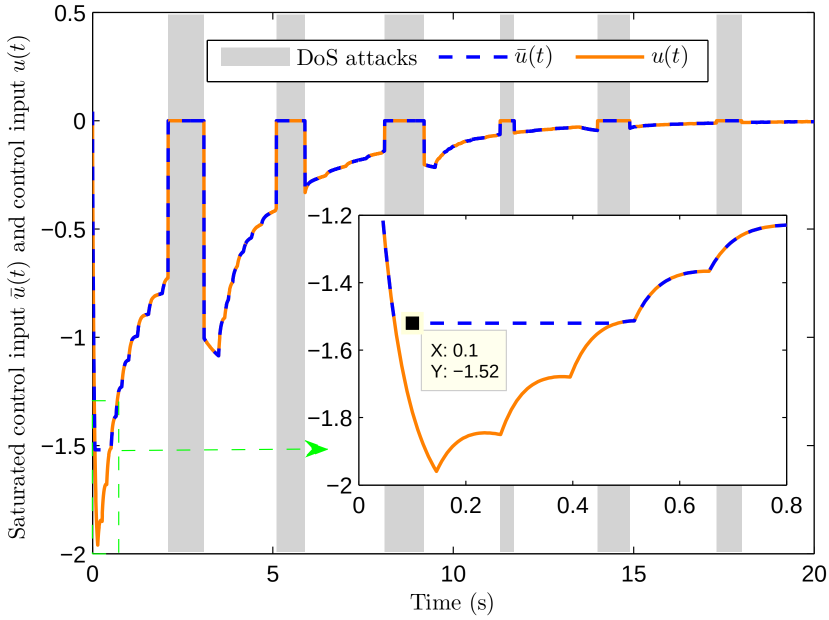

Figure 6. Saturated control input $\bar{u}(t)$ and control input $u(t)$.

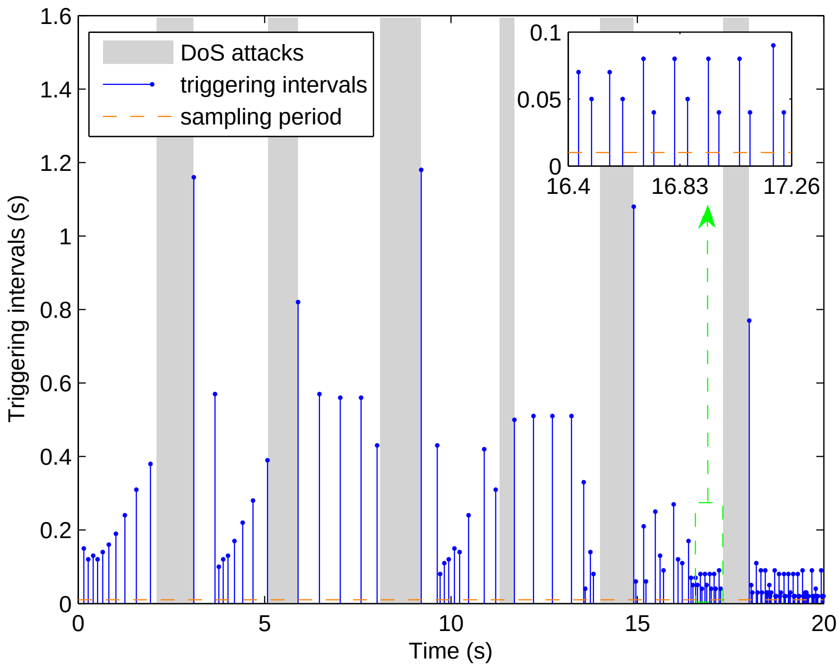

Figure 7. Triggering intervals and triggering instants of the secure ETM.

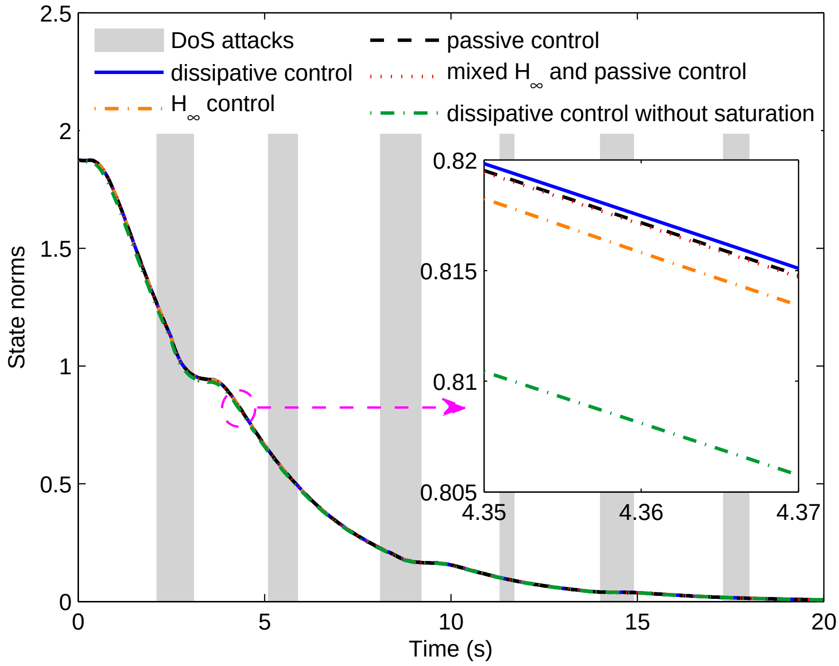

Figure 8. State norms under different cases

There exists a triggering instant (e.g. $3.1s, 5.9s, 9.2s, 11.7s, 14.9s, 18.0s$) immediately after each attack-active interval, which helps offset the attack's adverse impact. During each attack-active interval, no triggering instant exists, which excludes attack induced dropouts. These observations confirm Remark 3.

Remark 10. Based on Definition 3.3, using Remark 8 with $\gamma = 10$ and $\alpha = 0.8$, H_∞ controller, passive controller, and mixed H_∞ and passive controller can be designed by Theorem 4.2, respectively. As shown in Figure 8, the system can all be stabilized by H_∞ controller (yellow dashdot line), passive controller (black dashed line), and mixed H_∞ and passive controller (red dotted line), respectively. Besides, using dissipative controller, state norms of system without actuator saturation (green dashdot line) converge faster than that of system with actuator saturation (blue solid line).

Remark 11. As shown in Table 1, under different triggering threshold parameter δ, Theorem 4.2 achieves a bigger maximum allowable sampling period h_{max} than the methods in (X. Chen, Wang, & Hu, 2018; Hu, Yue, Xie, Chen, & Yin, 2019) and (Liu, Wang, et al., 2021), which confirms the advantages of combining both the exclusive distribution method and the reciprocally convex approach in Remark 7. For fair comparison in Table 1, we use the same system with DoS attacks, actuator saturation and noises.

Remark 12. Table 2 shows that as the triggering threshold parameter increases, the triggering rate of the secure ETM decreases. Namely, a larger triggering threshold parameter can save more communication resources. On the other hand, Table 1 indicates that a larger triggering threshold parameter results in a smaller maximum allowable

Table 1. The maximum allowable sampling period h_{max} under triggering threshold parameter δ.

δ	0.004	0.008	0.012	0.016	0.020	0.024
Theorem 4.1	0.189s	0.126s	0.082s	0.055s	0.033s	0.014s
method in Liu, Wang, et al. (2021)	0.161s	0.108s	0.077s	0.050s	0.029s	0.012s
method in X. Chen et al. (2018); Hu et al. (2019)	0.139s	0.101s	0.068s	0.048s	0.023s	0.010s

Table 2. The triggering rate of the secure ETM under triggering threshold parameter δ.

δ	0.004	0.008	0.012	0.016	0.020	0.024
triggering rate of the ETM (%)	12.19	10.46	9.34	9.01	8.21	7.95

sampling period, which implies control performance is degraded. Thus, by choosing triggering threshold parameter of the secure ETM, tradeoffs can be made between communication and control performances.

6. Conclusion

This paper has investigated the event-triggered dynamic output feedback dissipative control of T-S fuzzy systems under intermittent DoS attacks, secure ETM and actuator saturation. First, based on the information of DoS attacks and output measurements of the plant, an output-based secure periodic event-triggered communication scheme is introduced, which is attack-tolerant, Zeno-free, and effective to save system resources. Then, based on time-delay system theory, a switched T-S fuzzy closed-loop system is built, which provides a uniform model to further study the effects of DoS attacks, secure ETM and actuator saturation. Next, using piecewise LKF, we have derived a set of sufficient conditions for exponential stability while ensuring strict ($\mathcal{G}$, $\mathcal{H}$, $\mathcal{I}$)-dissipativity. The combination of exclusive distribution method and reciprocally convex approach is employed to reduce conservativeness. Further, a co-design method has been developed to obtain both the parameters of the secure ETM and the gain matrices of the SDOFF controller simultaneously. Finally, simulation studies confirm the effectiveness of the proposed method, achieving 92.19% saving of system resources.

Disclosure statement

No potential conict of interest was reported by the authors.

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Data Availability Statement

Data available on request from the authors.

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