Secure Event-Triggered Control for IT-2 Fuzzy Networked Systems With Stochastic Communication Protocol and FDI Attacks

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***Abstract*—This article is concerned with the secure event-triggered (ET) control issue for interval type-2 (IT-2) fuzzy networked systems under stochastic communication (SC) protocol and random false data injection attacks. On account of the realistic physical sensor constraint, a saturation function is utilized in the measured output. In an effort to mitigate the network burden and reduce the incidence of data collision, a novel dynamic ET SC protocol is proposed by integrating with the major merits of the dynamic ET strategy and SC protocol. Moreover, the fuzzy observer-based controller in the presence of different membership functions is constructed. Subsequently, some sufficient design conditions are put forward for satisfying the asymptotically stable performance of the augmented closed-loop IT-2 fuzzy model. In addition, the gain parameters of fuzzy observer and controller can be obtained by virtue of solvable sufficient criteria without nonlinear terms. Eventually, the effectiveness of the theoretical secure fuzzy control scheme is verified by a numerical example.**

***Index Terms*—Dynamic event-triggered (DET) scheme, false data injection (FDI) attacks, interval type-2(IT-2) fuzzy model, sensor saturation, stochastic communication (SC) protocol.**

NOMENCLATURE

Symbol	Descriptions.
$\mathbb{N}^+$	Set of positive integers.
$\mathbb{R}^t$	t-dimensional Euclidean space.
$\mathbb{R}^{t\times s}$	Set of $t \times s$ real matrices.
$*$	Symmetric term in matrix.
$\|\cdot\|$	Euclidean norm.
$\mathcal{K}^{-1}$	Inverse of $\mathcal{K}$.
$\mathcal{K}^T$	Transpose of $\mathcal{K}$.
$E\{\mathcal{K}\}$	Expectation of $\mathcal{K}$.
$\mathcal{H}e\{\mathcal{K}\}$	Sum of $\mathcal{K}$ and $\mathcal{K}^T$.
Prob$\{\mathcal{K}\}$	Occurrence probability of $\mathcal{K}$.
$\mathbb{L}_2[0,\infty)$	Square-summable vector space.
diag$\{\cdots\}$	Block-diagonal matrix.

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I. INTRODUCTION

OWING to the existence of nonlinearity in physical plant, some severe problems have emerged in the analysis and synthesis of networked control systems (NCSs), which have attracted widespread research interests in recent years [1], [2], [3], [4]. In particular, the so-called Takagi–Sugeno (T-S) fuzzy method, which can divide the original nonlinear systems into a combination of multiple subsystems, has become a powerful tool to cope with the nonlinear issues [5], [6], [7], [8]. In a T-S fuzzy system, a series of linear systems will be effectively connected via membership functions such that the linear analysis strategy can also be applied to the nonlinear problems. It should be noted that the following two forms in fuzzy systems can be presented: The interval type-1 (IT-1) fuzzy model and the interval type-2 (IT-2) fuzzy model. Although the nonlinearities in NCSs can be captured by the IT-1 fuzzy approach [9], [10], which ignores the uncertainty in membership functions posed by the rapidly changing application environment, it is relatively tough to acquire the precise information. For appropriately achieving this requirement, the IT-2 fuzzy model emerges with the application of the lower and upper membership functions. Focusing on the advantages of the IT-2 fuzzy dynamics, abundant theoretical research issues have been extensively addressed. For instance, Chen et al. [11] proposed a fuzzy disturbance observer for the tracking control problem in order to improve the approximation ability of IT-2 fuzzy sets. In [12], the fault-tolerant control strategy for the IT-2 fuzzy model was investigated by applying an event-triggered (ET) scheme and Lyapunov functional theory. From the aforementioned observation, the IT-2 fuzzy method and its merits have achieved preferable effects in different control issues. Thus, it is comparatively deserved that the IT-2 fuzzy model is utilized to investigate the control scheme for nonlinear NCSs.

It should be illustrated that the system states in the IT-2 fuzzy networked model are difficult to be accurately obtained in engineering practice. In order to cope with this problem, the observer-based control approach is utilized to obtain the estimated value of state variables in the plant. In the past decades, abundant attention have been focused on the fuzzy observer-based controller. In [13], a distributed observer has been applied for the fuzzy adaptive consensus control scheme. The authors in [14] addressed a periodic tracking control issue under the combination of a fuzzy repetitive controller and observer. A novel backstepping control framework has been proposed for nonlinear systems by applying the fuzzy observer in [15]. In addition, the premise variables and membership functions of the plant and controller are usually set to the same in existing literature, which refer to the parallel distribution compensation [16]. Owing to the unmanageable data transmission via the open communication channel in NCSs, it is more reasonable to take the different situations corresponding to the actual environment into account, which motivates the current research for incompletely matched membership functions in the IT-2 fuzzy dynamics and observer-based controller.

In a separate field of research, considerably significant attention has been given to the wireless network in NCSs. Taking into account of restrictive bandwidth, a static event-triggered (SET) strategy is exploited to relieve the pressure on communication resources in [17], [18], and [19]. It involves the signal transmission by assessing whether the variation of the sampling data at the current and the latest triggering time instant surpasses a prescribed threshold. Nonetheless, it is relatively hard to select a proper constant threshold to match with the distinct application environments. On the basis of this observation, a dynamic event-triggered (DET) strategy is proposed and it can be obtained that the original static parameter is replaced by an adjustable threshold changing efficiently according to the signal fluctuation. With the popularization of communication technology, plentiful networked problems under the DET scheme have been widely investigated [20], [21], [22], [23]. For example, the authors in [20] proposed a decentralized DET mechanism for an active suspension control issue such that each sensor can be independently scheduled. In addition, Zhang et al. [21] designed an asynchronous fault detection filter for a hidden Markov system in the presence of a mode-dependent DET strategy. To significantly reduce the occupancy of communication resources, the superfluous sampling information is not essential to be transmitted. Thus, the DET-based IT-2 fuzzy control scheme is significant to be discussed at the recent stage.

At the same time, the phenomena of traffic congestion and data conflict frequently occur in the limited-bandwidth wireless network. It has a large possibility that system stability will deteriorate while massive data packages simultaneously get access to the shared communication channel. In an effort to address this unexpected problem, communication protocols, which mainly involve round-robin (RR) protocol [24], [25], try-once-discard (TOD) protocol [26], and stochastic communication (SC) protocol [27], are exploited to schedule the sensor nodes obtaining the chance to transfer their measurement packages. Among them, the SC protocol has been extensively utilized in industrial implementations due to its scheme. In SC protocol, only a sensor node will be assigned to send its data in view of a stochastic sequence, which is regularly modeled by the Markov chain [28] or independent and identical distribution [29]. It is worth noting that the stochastic sequence is partially determined by the preset probability. Thus, the required nodes are more likely to be selected via regulating the corresponding transition probability, which enhance the scheduling flexibility. By virtue of the features above, some research consequences have received continuous attentions in academia [30], [31], [32], [33]. For instance, a novel SC protocol characterized by a nonhomogeneous Markov chain was put forward for the fuzzy control scheme in [30]. Zhang et al. [31] investigated the sliding mode control strategy for IT-2 fuzzy systems with the effect of SC protocol. From the aforementioned content, we can notice that the ET control problem in the observer-based IT-2 fuzzy model under SC protocol has not been adequately addressed. Besides, considering the restrictive network resources and data collision simultaneously, the combination of the DET scheme and SC protocol can comprehensively utilize their respective strengths. To the best of the authors' knowledge, such an idea is a shortage in existing articles, which inspires us to explore further.

In addition to the limited communication capacity, security protection is another hot topic and has aroused widespread concern in the networked circumstance [34], [35]. Recently, a series of research results concentrated on cyberattacks, such as deception attacks [36], [37], denial-of-service (DoS) attacks [38], [39], and replay attacks [40]. Different from the security threats above, the false data injection (FDI) attacks [41] can destroy system performance via modifying the original data packages in order to misdirect the networked systems to unsafe condition. Under the effect of FDI attacks, substantial attentions have been devoted to address the secure control issue [42], [43], [44]. In [42], a secure control strategy with the ET mechanism for a cyber-physical system subject to unknown FDI attacks has been investigated. Li et al. [43] designed an ET consensus controller for multiagent systems subject to FDI attacks and uncertainties. The authors in [44] addressed the resilient load frequency control problem against FDI attacks and DoS attacks. On the ground of these related results, it can be explicitly seen that the fuzzy model-based secure control issue against malicious FDI attacks under communication protocol is rarely mentioned. Therefore, this has become one of the motivations for our exploration.

Inspired by the aforementioned observations, this article investigates the observer-based control strategy for IT-2 fuzzy networked systems subject to stochastic FDI attacks. Its central features are outlined in the following aspects.

1) Due to restricted physical sensors, the saturation constraint [45], [46] usually appears and cannot be easily neglected. In response to this practical problem, a saturation function is applied to the measured output. Under the consideration of the confined physical components, the IT-2 fuzzy dynamics with saturation constraint by applying an observer is established. Taking the incompletely

matched membership functions between the plant and the fuzzy controller into account, an augmented closed-loop IT-2 fuzzy model is constructed.

2) A novel dynamic event-triggered stochastic communication (DETSC) protocol is presented to mitigate the impact of data conflict and limited communication pressure. Different from [47] and [48], the adopted SC protocol concentrates on the scheduling randomness caused by the transition probability in the Markov chain. In addition, the FDI attacks are considered in the communication channel and the security performance of the IT-2 fuzzy system is taken into consideration.
3) Several sufficient design conditions are presented for the fuzzy observer-based controller in a unified analysis framework, and the asymptotic stability of the augmented IT-2 fuzzy networked model with utilization of the DETSC protocol and FDI attacks is guaranteed. Meanwhile, the gain parameters of observer and controller can be simultaneously obtained by the solvable sufficient conditions without nonlinear terms.

The rest of this article is organized as follows. In Section II, IT-2 fuzzy networked dynamics with sensor saturation, DETSC protocol, and randomly occurring FDI attacks are exhibited. Section III derives sufficient design results under the fuzzy observer-based controller. For the purpose of demonstrating the validity of the adopted control strategy, a simulation example is developed in Section IV. Finally, Section V concludes this article.

For the analysis convenience, nomenclature is exploited to demonstrate the mathematical symbols adopted in this article.

II. Problem Formulation

A. IT-2 Fuzzy Model With Saturation Constraint

In this article, the nonlinear NCSs in the presence of sensor saturation and external interference are represented by IT-2 fuzzy dynamics with h rules.

RULE m: IF $\zeta_1(x(k))$ is W_1^m, $\zeta_2(x(k))$ is $W_2^m, \ldots, \zeta_d(x(k))$ is W_d^m, THEN

$$\begin{aligned} x(k+1) &= A_m x(k) + B_m u(k) + E_{1m}\omega(k) \\ y(k) &= \text{sat}(C_1 x(k)) + E_2\omega(k) \\ z(k) &= C_{2m}x(k) + D_m u(k) + F_m\omega(k) \end{aligned} \tag{1}$$

where $x(k) \in \mathbb{R}^{n_x}$, $u(k) \in \mathbb{R}^{n_u}$, $y(k) \in \mathbb{R}^{n_y}$, $z(k) \in \mathbb{R}^{n_z}$, and $\omega(k) \in \mathbb{L}_2[0,\infty)$ are the state vector, the control signal, the measurement output, the control output, and the disturbance input, respectively. $\text{sat}(s) = [\text{sat}_1^T(s_1), \text{sat}_2^T(s_2), \ldots, \text{sat}_{n_y}^T(s_{n_y})]^T$ is the saturation function satisfying $\text{sat}_i(s_i) = \text{sign}(s_i)\min\{s_{i,\max}, |s_i|\}$ $(i = 1, 2, \ldots, n_y)$, in which $s_{i,\max}$ is the ith element of saturation level $s_{\max}$. A_m, B_m, C_1, C_{2m}, D_m, E_{1m}, E_2, and F_m are constant coefficient matrices with appropriate dimensions. W_q^m denotes the mth fuzzy sets in accordance with the premise variable $\zeta_q(x(k))$ with $q = 1, 2, \ldots, d$ and $m = 1, 2, \ldots, h$. The interval sets indicate the firing strength of the mth rule in the following form:

$$\varpi_m(x(k)) = [\underline{\vartheta}_m(x(k)), \overline{\vartheta}_m(x(k))] \tag{2}$$

where

$$\underline{\vartheta}_m(x(k)) = \prod_{q=1}^{d} \underline{W}_q^m(\zeta_q(x(k))) \geq 0$$

$$\overline{\vartheta}_m(x(k)) = \prod_{q=1}^{d} \overline{W}_q^m(\zeta_q(x(k))) \geq 0.$$

$\underline{\vartheta}_m(x(k))$ and $\overline{\vartheta}_m(x(k))$ denote the lower and upper grades with $\overline{\vartheta}_m(x(k)) \geq \underline{\vartheta}_m(x(k))$. $\underline{W}_q^m(\zeta_q(x(k)))$ and $\overline{W}_q^m(\zeta_q(x(k)))$ are the lower and upper membership functions with $\overline{W}_q^m(\zeta_q(x(k))) \geq \underline{W}_q^m(\zeta_q(x(k))) \geq 0$. Subsequently, the IT-2 fuzzy dynamics in (1) can be derived as

$$\begin{aligned} x(k+1) &= \sum_{m=1}^{h} \vartheta_m(x(k))[A_m x(k) + B_m u(k) + E_{1m}\omega(k)] \\ y(k) &= \text{sat}(C_1 x(k)) + E_2\omega(k) \\ z(k) &= \sum_{m=1}^{h} \vartheta_m(x(k))[C_{2m}x(k) + D_m u(k) + F_m\omega(k)] \end{aligned} \tag{3}$$

where $\vartheta_m(x(k)) = \varsigma_m(x(k))/\sum_{m=1}^{h}\varsigma_m(x(k))$, $\varsigma_m(x(k)) = \underline{a}_m(x(k))\underline{\vartheta}_m(x(k)) + \overline{a}_m(x(k))\overline{\vartheta}_m(x(k))$. $\vartheta_m(x(k))$ is the membership value with $\sum_{m=1}^{h}\vartheta_m(x(k)) = 1$. $\underline{a}_m(x(k)) \in [0,1]$ and $\overline{a}_m(x(k)) \in [0,1]$ stand for nonlinear weighting functions satisfying $\underline{a}_m(x(k)) + \overline{a}_m(x(k)) = 1$.

Definition 1 (See [49]): A nonlinear function $\psi(\cdot) : \mathbb{R}^{n_y} \longmapsto \mathbb{R}^{n_y}$ belongs to the sector $[G_1, G_2]$ if there exist real matrices G_1 and G_2, and a positive-definite matrix $G = G_2 - G_1$ such that the following condition holds:

$$(\psi(s) - G_1 s)^T(\psi(s) - G_2 s) \leq 0. \tag{4}$$

In order to characterize the effect of sensor saturation, we suppose that the diagonal matrices H_1 and H_2 satisfy the strict limitation $0 \leq H_1 < I \leq H_2$ and the saturation function $\text{sat}(\cdot)$ in (1) can be formulated as

$$sat(C_1 x(k)) = H_1 C_1 x(k) + \psi(C_1 x(k)) \tag{5}$$

where $\psi(C_1 x(k))$ is a nonlinear vector-valued function related to the system state. On the basis of Definition 1, $\psi(C_1 x(k))$ satisfies the following inequality by considering $G_1 = 0$ and $G_2 = H$ in (4):

$$\psi^T(C_1 x(k))(\psi(C_1 x(k)) - HC_1 x(k)) \leq 0 \tag{6}$$

where $H = H_2 - H_1$.

Remark 1: Under the comprehensive consideration of external disturbance and process noise, the IT-2 T–S fuzzy system can preferably focus on the actual factors in engineering implementation. However, for the convenience and uniformity of the derivation, we denote the same notation $\omega(k)$ on process noise and external disturbance in this article. It should be noted that the distinctive impacts of $\omega(k)$ have not been neglected and have been mainly reflected in different coefficient matrices. In addition, by applying the augmentation technique, the situation can be similarly handled when external disturbance and process noise are different.

B. DETSC Protocol

Due to the restricted network resource, some unexpected phenomena in a shared communication channel between sensors and observer will frequently appear, such as data conflict and network traffic congestion. Focusing on resolving the aforementioned problems, a novel scheduling protocol is utilized to determine whether the measured signal will be transferred at each sampling instant and dynamically select sensor nodes through the communication network with bandwidth constraint. In other words, the measurement output $y(k)$ can be released if the adopted DET condition is satisfied and an SC protocol is applied to ensure the transmission sequence of all sensor nodes at each triggered time instant.

To effectively lessen the communication occupancy, a DET strategy is exploited. For notational simplicity, the ET instant sequences are denoted as $\mathbb{T} = \{t_n | n = 0, 1, 2, \cdots \text{ and } 0 \leq t_0 < t_1 < \cdots < t_n < \cdots\}$. Then, the adopted event execution function can be described as

$$\Xi(k, \mu, \theta) = \mu y^T(k)y(k) - q^T(k)q(k) + \frac{1}{\theta}\chi(k) \tag{7}$$

where $q(k) = y(k) - y(t_n)$ $(k \in [t_n, t_{n+1}))$ represents the gap of the sampled signal at the current time and the latest triggering time. $\mu \in (0, 1)$ and $\theta > 0$ are two predetermined scalars. $\chi(k)$ is an internal variable to symbolize the dynamic threshold in DET scheme and it can be obtained as follows:

$$\begin{cases} \chi(k+1) = \lambda\chi(k) - q^T(k)q(k) + \mu y^T(k)y(k) \\ \quad\chi(0) = \chi_0 \end{cases} \tag{8}$$

in which χ_0 denotes a prescribed positive initial condition and $\lambda \in (0, 1)$ is a given constant.

Furthermore, the measurement output can be transmitted to the communication network if and only if the condition $\Xi(k, \mu, \theta) < 0$ holds. Therefore, the ET instants are determined by

$$t_{n+1} = \inf_{k\in\mathbb{N}^+} \{k | k > t_n,\ \Xi(k, \mu, \theta) < 0\}. \tag{9}$$

Without loss of feasibility, we assume that only one sensor node will be scheduled to send its data package at the triggered time instant t_n and other unselected nodes will be redeemed by the zero-order holder (ZOH) technique. Let $\bar{y}(t_n) = [\bar{y}_1^T(t_n), \bar{y}_2^T(t_n), \ldots, \bar{y}_{n_y}^T(t_n)]^T$ denote the measured signal transferred through the shared network. Hence, the updating standard for the ith sensor can be expressed as

$$\bar{y}_i(t_n) = \begin{cases} y_i(t_n), & \text{if } i = \varphi_{t_n} \\ \bar{y}_i(t_{n-1}), & \text{otherwise} \end{cases} \tag{10}$$

where $\varphi_{t_n} \in \mathbb{S} = \{1, 2, \ldots, n_y\}$ denotes the sensor node scheduled to the communication channel when the considered DET condition is satisfied. In light of [28], a Markov chain with the transition probability matrix $\mathcal{P} = [p_{ts}] \in \mathbb{R}^{n_y\times n_y}$ is applied to regulate the variable φ_{t_n} in this article, from which the transition probability p_{ts} can be decided by

$$p_{ts} = \text{Prob}\{\varphi_{t_{n+1}} = s | \varphi_{t_n} = t\} \tag{11}$$

where $p_{ts} \in [0, 1]$ and $\sum_{s=1}^{n_y} p_{ts} = 1$ for all $t, s \in \mathbb{S}$.

According to (9) and (10), we can conclude that

$$t_n = \begin{cases} k, & \text{if the measured output is released} \\ t_{n-1}, & \text{otherwise.} \end{cases} \tag{12}$$

By applying the Kronecker delta function $\delta(a - b) \in \{0, 1\}$ and denoting $y(t_n) = [y_1^T(t_n), y_2^T(t_n), \ldots, y_{n_y}^T(t_n)]^T$, it can be easily obtained that

$$\bar{y}(t_n) = \Phi_{\varphi_{t_n}} y(t_n) + (I - \Phi_{\varphi_{t_n}})\bar{y}(t_{n-1}) \tag{13}$$

where $\Phi_{\varphi_{t_n}}$=diag$\{\delta(\varphi_{t_n}-1), \delta(\varphi_{t_n} - 2), \ldots, \delta(\varphi_{t_n} - n_y)\}$ stands for the updating matrix.

Remark 2: In an effort to effectively reduce the communication load and the occurrence of data collision, a novel DETSC protocol emerges on the ground of DET scheme and SC protocol. To be specific, the DET condition (9) will be judged in the first place. Without satisfying this condition, no information will be transmitted and the input of observer-based controller $\bar{y}(t_n)$ becomes the latest triggered data stored in the buffer. It is seen clearly that the communication resources can be further economized. On the other hand, the triggered signal will be scheduled by the SC protocol, which can tackle the problem of data conflict in a network medium. Attributed to the close integration of the DET mechanism and SC protocol, the system performance can be commendably stabilized under the bandwidth constraint, where the validity of the DETSC protocol will be illustrated in the simulation.

Remark 3: The proposed DETSC protocol in this article is different from the existing articles [47], [48] and the related details will be analyzed as follows. In [47], a new DETRR protocol with the combination of DET scheme and static RR protocol, from which the scheduled sequence is characterized by periodicity, was presented for Markov switching systems. The authors in [48] put forward an ETTOD protocol, which regulates the sensor signals on the basis of the preset condition. However, it is worth mentioning that the randomly scheduling sequence with certain probability is emerged in the proposed DETSC protocol according to the Markov chain such that transmitted nodes can be selected in a stochastic form when the DET condition is satisfied. Hence, the DETSC protocol has its own regulating characteristic compared with the aforementioned protocol.

Remark 4: In (10), the ZOH technique, which can store the previously transmitted signal, is employed to compensate the unscheduled sensor nodes. Comparatively, the zero-input (ZI) strategy [31] is also frequently applied in the updating standard of SC protocol. Under the ZI strategy, the condition (13) can be derived as $\bar{y}(t_n) = \Phi_{\varphi_{t_n}} y(t_n)$. It is apparently observed that the measurement data of unscheduled nodes are replaced by zero. Obviously, the ZI strategy is easier to implement, whereas the ZOH technique can be considered as the more reliable method from the perspective of control performance.

C. FDI Attack Model

Owing to the open communication environment in NCSs, the measurement output is vulnerable to FDI attacks from sensors to observer, which can destroy the integrity of the original transmitted signal. Nevertheless, since the energy limitation of the adversaries exists in practical application, it is actually difficult for attackers to launch continuous malignant signals. In light of [50] and [51], a Bernoulli variable $\alpha(k)$ with $E\{\alpha(k)\} = \bar{\alpha} \in [0, 1]$, which is a prescribed scalar, has been considered to indicate the random behavior of FDI attacks. Then, we assume that the false data $\Gamma(k)$ generated by the attackers is restricted by

$$\|\Gamma(t_n)\| \leq \|Ry(t_n)\| \tag{14}$$

where R is a given matrix with a suitable dimension.

To comprehensively describe the effect of the DETSC protocol and stochastic FDI attacks, the updating standard in (10) can be rewritten as

$$\bar{y}_i(t_n) = \begin{cases} y_i(t_n) + \alpha(t_n)\Gamma(t_n), & \text{if } i = \varphi_{t_n} \\ \bar{y}_i(t_{n-1}), & \text{otherwise.} \end{cases} \tag{15}$$

Hence, the received measurement $\bar{y}(t_n)$ by the observer can be inferred as follows:

$$\bar{y}(t_n) = \Phi_{\varphi_{t_n}} y(t_n) + \alpha(t_n)\bar{\Phi}_{\varphi_{t_n}}\Gamma(t_n) + \tilde{\Phi}_{\varphi_{t_n}}\bar{y}(t_{n-1}) \tag{16}$$

where $\bar{\Phi}_{\varphi_{t_n}} = \Phi_{\varphi_{t_n}} E_I$, $E_I = [I, \ldots, I]^T$, $\tilde{\Phi}_{\varphi_{t_n}} = I - \Phi_{\varphi_{t_n}}$.

Remark 5: In recent existing results, some ET secure control issues have been addressed. In [50], the limited magnitude of FDI attacks was designed to have a bearing on the system output. In [51], the authors investigated the DET scheme-based security tracking controller design approach for NCSs under randomly occurring network attacks with given probability. Therefore, it is sensible to model FDI attacks with a stochastic method and assume the restriction in the form of (14). Moreover, if $\alpha(t_n) = 1$, it denotes the transferred data subject to FDI attacks. $\alpha(t_n) = 0$ means the malicious attacks do not occur and the measured signal will be normally transmitted as we expected. On the basis of the above observations, the destructive behavior of the adversary has been considered, which is not mentioned in [47].

D. Observer-Based Fuzzy Controller Design

In an effort to deal with the unmeasurable system state, the fuzzy observer model with h rules is constructed as

RULE r: IF $\zeta_1(\hat{x}(k))$ is W_1^r, $\zeta_2(\hat{x}(k))$ is $W_2^r, \ldots, \zeta_d(\hat{x}(k))$ is W_d^r, THEN

$$\begin{aligned} \hat{x}(k+1) &= A_r\hat{x}(k) + B_r u(k) + L_{r,\varphi_{t_n}}(\bar{y}(t_n) - \hat{y}(k)) \\ \hat{y}(k) &= C_1\hat{x}(k) \end{aligned} \tag{17}$$

where $\hat{x}(k) \in \mathbb{R}^{n_x}$, $\hat{y}(k) \in \mathbb{R}^{n_y}$, and $L_{r,\varphi_{t_n}} \in \mathbb{R}^{n_x \times n_y}$ $(r = 1, 2, \ldots, h)$ represent the estimated state vector, the measured signal of the observer, and the fuzzy observer gain matrices to be devised, respectively. Then, the global fuzzy observer is derived as

$$\begin{aligned} \hat{x}(k+1) = \sum_{r=1}^{h} \vartheta_r(\hat{x}(k))[&A_r\hat{x}(k) + B_r u(k) \\ &+ L_{r,\varphi_{t_n}}(\bar{y}(t_n) - \hat{y}(k))] \\ \hat{y}(k) = C_1\hat{x}(k).& \end{aligned} \tag{18}$$

The jth observer-based fuzzy control law can be obtained as follows:

RULE j: IF $\tau_1(\hat{x}(k))$ is N_1^j, $\tau_2(\hat{x}(k))$ is N_2^j,..., $\tau_\iota(\hat{x}(k))$ is N_ι^j, THEN

$$u(k) = K_{j,\varphi_{t_n}}\hat{x}(k) \tag{19}$$

where $K_{j,\varphi_{t_n}} \in \mathbb{R}^{n_u \times n_x}$ denotes the fuzzy controller parameter to be solved later. N_p^j stands for the jth fuzzy sets related to the premise variable $\tau_p(\hat{x}(k))$ with $p = 1, 2, \ldots, \iota$ and $j = 1, 2, \ldots, h$. Whereafter, the firing strength of the jth rule can be elicited as

$$\tilde{\varepsilon}_j(\hat{x}(k)) = [\underline{\varepsilon}_j(\hat{x}(k)), \overline{\varepsilon}_j(\hat{x}(k))] \tag{20}$$

in which

$$\underline{\varepsilon}_j(\hat{x}(k)) = \prod_{p=1}^{\iota} \underline{N}_p^j(\tau_p(\hat{x}(k))) \geq 0$$

$$\overline{\varepsilon}_j(\hat{x}(k)) = \prod_{p=1}^{\iota} \overline{N}_p^j(\tau_p(\hat{x}(k))) \geq 0.$$

$\underline{\varepsilon}_j(\hat{x}(k))$ and $\overline{\varepsilon}_j(\hat{x}(k))$ are the lower and upper grades with $\overline{\varepsilon}_j(\hat{x}(k)) \geq \underline{\varepsilon}_j(\hat{x}(k))$. $\underline{N}_p^j(\tau_p(\hat{x}(k)))$ and $\overline{N}_p^j(\tau_p(\hat{x}(k)))$ are the lower and upper membership functions with $\overline{N}_p^j(\tau_p(\hat{x}(k))) \geq \underline{N}_p^j(\tau_p(\hat{x}(k))) \geq 0$. The IT-2 fuzzy controller is described as follows:

$$u(k) = \sum_{j=1}^{h} \varepsilon_j(\hat{x}(k))K_{j,\varphi_{t_n}}\hat{x}(k) \tag{21}$$

where $\varepsilon_j(\hat{x}(k)) = \kappa_j(\hat{x}(k)) / \sum_{j=1}^{h} \kappa_j(\hat{x}(k))$, $\kappa_j(\hat{x}(k)) = \underline{b}_j(\hat{x}(k))\underline{\varepsilon}_j(\hat{x}(k)) + \overline{b}_j(\hat{x}(k))\overline{\varepsilon}_j(\hat{x}(k))$, $\sum_{j=1}^{h} \varepsilon_j(\hat{x}(k)) = 1$. $\underline{b}_j(\hat{x}(k))) \in [0, 1]$ and $\overline{b}_j(\hat{x}(k))) \in [0, 1]$ are nonlinear weighting functions in the presence of $\underline{b}_j(\hat{x}(k))) + \overline{b}_j(\hat{x}(k))) = 1$.

Remark 6: Due to the disturbances of the external mutable environment and the communication network, the signal transmission process is said to be unreliable [16]. Hence, the IT-2 fuzzy networked dynamics with different premise variables and membership functions can be worth further discussing. The authors in [52] addressed an optimization fuzzy control issue in the absence of network attacks, DET scheme, and communication protocol, which cannot respond to the requirements of reducing the network pressure and avoiding the data conflict phenomenon. Under the DETSC protocol and stochastic FDI attacks, the secure control problem for the IT-2 fuzzy model with sensor saturation is investigated in this article.

For presentation convenience, t, s, and ψ_k denote the notation of φ_{t_n}, $\varphi_{t_{n+1}}$, and $\psi(C_1 x(k))$ in the subsequent derivation, respectively. Combining the formulas (3) and (21), and defining the estimation error $e(k) = x(k) - \hat{x}(k)$, the following condition can be obtained:

$$x(k+1) = \sum_{m=1}^{h}\sum_{j=1}^{h} \vartheta_m(x(k))\varepsilon_j(\hat{x}(k))[(A_m + B_m K_{j,t})\hat{x}(k) + A_m e(k) + E_m \omega(k)]. \tag{22}$$

Owing to the gap $q(k) = y(k) - y(t_n)$, it can be explicitly derived by the conditions (3), (5), and (13) that

$$\begin{aligned}\bar{y}(t_n) &= \Phi_t(y(k) - q(k)) + \alpha(t_n)\bar{\Phi}_t\Gamma(t_n) + \tilde{\Phi}_t\bar{y}(t_{n-1})\\ &= \Phi_t H_1 C_1 \hat{x}(k) + \Phi_t H_1 C_1 e(k) + \Phi_t \psi_k + \Phi_t E_2 \omega(k)\\ &\quad - \Phi_t q(k) + \alpha(t_n)\bar{\Phi}_t\Gamma(t_n) + \tilde{\Phi}_t\bar{y}(t_{n-1}).\end{aligned} \tag{23}$$

According to the fuzzy observer dynamics (18) and (23), one has

$$\begin{aligned}\hat{x}(k+1) = \sum_{r=1}^{h}\sum_{j=1}^{h} \vartheta_r(\hat{x}(k))\varepsilon_j(\hat{x}(k))[(A_r + B_r K_{j,t}\\ + L_{r,t}\Phi_t H_1 C_1 - L_{r,t}C_1)\hat{x}(k) + L_{r,t}\Phi_t E_2\omega(k)\\ + L_{r,t}\Phi_t H_1 C_1 e(k) + L_{r,t}\Phi_t\psi_k - L_{r,t}\Phi_t q(k)\\ + \alpha(t_n)L_{r,t}\bar{\Phi}_t\Gamma(t_n) + L_{r,t}\tilde{\Phi}_t\bar{y}(t_{n-1})].\end{aligned} \tag{24}$$

Hence, the estimation error is calculated as

$$\begin{aligned}e(k+1) = \sum_{m=1}^{h}\sum_{r=1}^{h}\sum_{j=1}^{h} \vartheta_m(x(k))\vartheta_r(\hat{x}(k))\varepsilon_j(\hat{x}(k))\\ \times [(A_m - A_r + B_m K_{j,t} - B_r K_{j,t} + L_{r,t}C_1\\ - L_{r,t}\Phi_t H_1 C_1)\hat{x}(k) + (A_m - L_{r,t}\Phi_t H_1 C_1)e(k)\\ + E_{1m}\omega(k) + L_{r,t}\Phi_t q(k) - \alpha(t_n)L_{r,t}\bar{\Phi}_t\Gamma(t_n)\\ - L_{r,t}\Phi_t\psi_k - L_{r,t}\Phi_t E_2\omega(k) - L_{r,t}\tilde{\Phi}_t\bar{y}(t_{n-1})].\end{aligned} \tag{25}$$

Meanwhile, the control output in (3) can be rewritten as

$$z(k) = \sum_{m=1}^{h}\sum_{j=1}^{h} \vartheta_m(x(k))\varepsilon_j(\hat{x}(k))[(C_{2m} + D_m K_{j,t})\hat{x}(k) + C_{2m}e(k) + F_m\omega(k)]. \tag{26}$$

Based on (23)–(26), let $\xi(k) = [\hat{x}^T(k)\ e^T(k)\ \bar{y}^T(t_{n-1})]^T$, the augmented IT-2 fuzzy system is formulated as follows:

$$\begin{aligned}\xi(k+1) &= \sum_{m=1}^{h}\sum_{r=1}^{h}\sum_{j=1}^{h} \vartheta_m(x(k))\vartheta_r(\hat{x}(k))\varepsilon_j(\hat{x}(k))\\ &\quad\times [\mathcal{M}^1_{mrjt}\xi(k) + (\mathcal{M}^2_{rt} + \mathcal{M}^3_{rt})\Gamma(t_n)\\ &\quad + \mathcal{M}^4_{rt}q(k) + \mathcal{M}^5_{rt}\psi_k + \bar{E}_{mrt}\omega(k)]\\ z(k) &= \sum_{m=1}^{h}\sum_{j=1}^{h} \vartheta_m(x(k))\varepsilon_j(\hat{x}(k))[\bar{C}_{mjt}\xi(k) + F_m\omega(k)]\end{aligned} \tag{27}$$

where

$$\mathcal{M}^1_{mrjt} = \begin{bmatrix} \mathcal{M}^1_{11} & \mathcal{M}^1_{12} & L_{r,t}\tilde{\Phi}_t \\ \mathcal{M}^1_{21} & \mathcal{M}^1_{22} & -L_{r,t}\tilde{\Phi}_t \\ \Phi_t H_1 C_1 & \Phi_t H_1 C_1 & \tilde{\Phi}_t \end{bmatrix}$$

$$\mathcal{M}^2_{rt} = \begin{bmatrix} \bar{\alpha}\bar{\Phi}_t^T L_{r,t}^T & -\bar{\alpha}\bar{\Phi}_t^T L_{r,t}^T & \bar{\alpha}\bar{\Phi}_t^T \end{bmatrix}^T$$

$$\mathcal{M}^3_{rt} = \begin{bmatrix} \hat{\alpha}(t_n)\bar{\Phi}_t^T L_{r,t}^T & -\hat{\alpha}(t_n)\bar{\Phi}_t^T L_{r,t}^T & \hat{\alpha}(t_n)\bar{\Phi}_t^T \end{bmatrix}^T$$

$$\mathcal{M}^4_{rt} = \begin{bmatrix} -\Phi_t^T L_{r,t}^T & \Phi_t^T L_{r,t}^T & -\Phi_t^T \end{bmatrix}^T,\ \mathcal{M}^5_{rt} = -\mathcal{M}^4_{rt}$$

$$\bar{E}_{mrt} = \begin{bmatrix} E_2^T\Phi_t^T L_{r,t}^T & E_{1m}^T - E_2^T\Phi_t^T L_{r,t}^T & E_2^T\Phi_t^T \end{bmatrix}^T$$

$$\bar{C}_{mjt} = \begin{bmatrix} C_{2m} + D_m K_{j,t} & C_{2m} & 0 \end{bmatrix},\ \hat{\alpha}(t_n) = \alpha(t_n) - \bar{\alpha}$$

$$\mathcal{M}^1_{11} = A_r + B_r K_{j,t} + L_{r,t}\Phi_t H_1 C_1 - L_{r,t}C_1$$

$$\mathcal{M}^1_{21} = A_m - A_r + (B_m - B_r)K_{j,t} + L_{r,t}(I - \Phi_t H_1)C_1$$

$$\mathcal{M}^1_{12} = L_{r,t}\Phi_t H_1 C_1,\ \mathcal{M}^1_{22} = A_m - L_{r,t}\Phi_t H_1 C_1.$$

The object of this article is to develop an observer-based security controller for the IT-2 fuzzy system with saturation constraint under the proposed DETSC protocol and random FDI attacks. For the cause of facilitating the next analysis, the following lemma is introduced.

Lemma 1 (See [16], [53]): The singular value decomposition for matrix $\mathcal{H} \in \mathbb{R}^{m\times n}$ with rank$(\mathcal{H}) = m$ can be represented as $\mathcal{H} = T[V\ 0]S^T$, where T and S are the orthogonal matrices. With matrices $Y > 0$, $Y^1 \in \mathbb{R}^{m\times m}$, and $Y^2 \in \mathbb{R}^{(n-m)\times(n-m)}$, there exists a matrix $\bar{Y} = TVY^1V^{-1}T^T$ such that $\bar{Y}\mathcal{H} = \mathcal{H}Y$ holds if the following condition holds:

$$Y = S\begin{bmatrix} Y^1 & 0 \\ 0 & Y^2 \end{bmatrix}S^T. \tag{28}$$

III. Main Results

In the position, the asymptotic stability with H_∞ performance for the augmented IT-2 fuzzy model (27) will be analyzed. Meanwhile, some sufficient design conditions will be presented by considering the DETSC protocol and FDI attacks. Then, the parameters of the fuzzy observer and controller will be attained in virtue of linear matrix inequalities (LMIs).

Theorem 1: Given positive parameters $\theta > 0, \rho > 0, \gamma > 0, \bar{\alpha} \in (0,1), \lambda \in (0,1), \mu \in (0,1)$, and matrices $K_{j,t}, L_{r,t}$ $(t \in \mathbb{S})$, $\varepsilon_j(\hat{x}(k)) - l_j\vartheta_j(\hat{x}(k)) > 0$ $(l_j > 0)$, the augmented IT-2 fuzzy system (27) is asymptotically stable in the sense of H_∞ performance if there exist positive definite matrices $P_t > 0$ and slack matrix Δ with suitable dimension such that

$$\lambda - \frac{1}{\theta} \geq 0, \tag{29}$$

$$\bar{\Omega}_{mrjt} + \bar{\Omega}_{mjrt} - 2\Delta < 0, r \leq j \tag{30}$$

$$l_j\bar{\Omega}_{mrjt} + l_r\bar{\Omega}_{mjrt} - l_j\Delta - l_r\Delta + 2\Delta < 0, r \leq j \tag{31}$$

where

$$\bar{\Omega}_{mrjt} = \Omega_{mrjt} + \Sigma_{mjt},\ \Sigma_{mjt} = \begin{bmatrix} \Theta_{mjt} & * \\ 0 & 0 \end{bmatrix}$$

$$\Theta_{mjt} = \begin{bmatrix} \bar{C}_{mjt}^T \bar{C}_{mjt} & * & * \\ 0 & 0 & * \\ F_m^T \bar{C}_{mjt} & 0 & F_m^T F_m - \gamma^2 I \end{bmatrix}$$

$$\Omega_{mrjt} = \begin{bmatrix} \Upsilon_{11} & * & * & * & * & * \\ \Upsilon_{21} & \Upsilon_{22} & * & * & * & * \\ \Upsilon_{31} & \Upsilon_{32} & \Upsilon_{33} & * & * & * \\ \Upsilon_{41} & \Upsilon_{42} & \Upsilon_{43} & \Upsilon_{44} & * & * \\ 0 & 0 & 0 & 0 & \Upsilon_{55} & * \\ \Upsilon_{61} & \Upsilon_{62} & \Upsilon_{63} & \Upsilon_{64} & 0 & \Upsilon_{66} \end{bmatrix}$$

$$\Upsilon_{11} = \mathcal{M}_{mrjt}^{1T} \bar{P}_t \mathcal{M}_{mrjt}^1 - P_t + \tilde{H}^T R^T R \tilde{H} + \beta \tilde{H}^T \tilde{H}$$

$$\Upsilon_{21} = \mathcal{M}_{rt}^{2T} \bar{P}_t \mathcal{M}_{mrjt}^1,\ \beta = \mu(\frac{1}{\theta} + \rho)$$

$$\Upsilon_{22} = \mathcal{M}_{rt}^{2T} \bar{P}_t \mathcal{M}_{rt}^2 + \bar{\mathcal{M}}_{rt}^{3T} \bar{P}_t \bar{\mathcal{M}}_{rt}^3 - I$$

$$\Upsilon_{31} = \bar{E}_{mrt}^T \bar{P}_t \mathcal{M}_{mrjt}^1 + \beta E_2^T \tilde{H} + E_2^T R^T R \tilde{H}$$

$$\Upsilon_{32} = \bar{E}_{mrt}^T \bar{P}_t \mathcal{M}_{rt}^2,\ \tilde{H} = \begin{bmatrix} H_1 C_1 & H_1 C_1 & 0 \end{bmatrix}$$

$$\Upsilon_{33} = \bar{E}_{mrt}^T \bar{P}_t \bar{E}_{mrt} + \beta E_2^T E_2 + E_2^T R^T R E_2$$

$$\Upsilon_{41} = \mathcal{M}_{rt}^{4T} \bar{P}_t \mathcal{M}_{mrjt}^1 - R^T R \tilde{H},\ \Upsilon_{42} = \mathcal{M}_{rt}^{4T} \bar{P}_t \mathcal{M}_{rt}^2$$

$$\Upsilon_{43} = \mathcal{M}_{rt}^{4T} \bar{P}_t \bar{E}_{mrt} - R^T R E_2,\ \bar{P}_t = \sum_{s=1}^{n_y} p_{ts} P_s$$

$$\Upsilon_{44} = \mathcal{M}_{rt}^{4T} \bar{P}_t \mathcal{M}_{rt}^4 - \left(\frac{1}{\theta} + \rho\right) I + R^T R$$

$$\Upsilon_{55} = -\frac{1}{\theta}(1 - \lambda - \rho) I,\ \bar{H} = \begin{bmatrix} H C_1 & H C_1 & 0 \end{bmatrix}$$

$$\Upsilon_{61} = \mathcal{M}_{rt}^{5T} \bar{P}_t \mathcal{M}_{mrjt}^1 + \beta \tilde{H} + \bar{H} + R^T R \tilde{H}$$

$$\Upsilon_{62} = \mathcal{M}_{rt}^{5T} \bar{P}_t \mathcal{M}_{rt}^2,\ \Upsilon_{63} = \mathcal{M}_{rt}^{5T} \bar{P}_t \bar{E}_{mrt} + \beta E_2 + R^T R E_2$$

$$\Upsilon_{64} = \mathcal{M}_{rt}^{5T} \bar{P}_t \mathcal{M}_{rt}^4 - R^T R,\ \vec{\alpha} = 1 - \bar{\alpha}$$

$$\Upsilon_{66} = \mathcal{M}_{rt}^{5T} \bar{P}_t \mathcal{M}_{rt}^5 - (1 - \beta) I + R^T R$$

$$\bar{\mathcal{M}}_{rt}^3 = \left[\sqrt{\bar{\alpha}\vec{\alpha}} \bar{\Phi}_t^T L_{r,t}^T \quad -\sqrt{\bar{\alpha}\vec{\alpha}} \bar{\Phi}_t^T L_{r,t}^T \quad \sqrt{\bar{\alpha}\vec{\alpha}} \bar{\Phi}_t^T\right]^T.$$

Proof 1: According to the formulas (7) and (9), for $k \in [t_n, t_{n+1})$, it is not difficult to obtain that

$$\frac{1}{\theta}\chi(k) - q^T(k)q(k) + \mu y^T(k)y(k) \geq 0. \tag{32}$$

By means of combining the iterative expression (8), the conditions (29) and (32), one can derive based on the method in [54] that

$$\chi(k+1) = \lambda\chi(k) - q^T(k)q(k) + \mu y^T(k)y(k) \geq \lambda\chi(k) - \frac{1}{\theta}\chi(k) \geq \cdots \geq (\lambda - \frac{1}{\theta})^{k+1}\chi(0) \geq 0. \tag{33}$$

In line with the aforesaid analysis and the DETSC protocol, we choose the Lyapunov functional candidate as

$$V(k) = \xi^T(k) P_t \xi(k) + \frac{1}{\theta}\chi(k). \tag{34}$$

On the basis of (6), (9), and (14), by defining the difference $\Delta V(k) = V(k+1) - V(k)$, the following condition can be simply formulated that:

$$\begin{aligned} E\{\Delta V(k)\} &= E\{\xi^T(k+1) P_s \xi(k+1) + \frac{1}{\theta}\chi(k+1) \\ &\quad - \xi^T(k) P_t \xi(k) - \frac{1}{\theta}\chi(k)\} \\ &\leq E\{\xi^T(k+1) \bar{P}_t \xi(k+1) - \xi^T(k) P_t \xi(k) + \frac{1}{\theta} \\ &\quad \times [(\lambda - 1)\chi(k) - q^T(k)q(k) + \mu y^T(k)y(k)]\} \\ &\quad + y^T(t_n) R^T R y(t_n) - \Gamma^T(t_n)\Gamma(t_n) \\ &\quad + \rho\Xi(k, \mu, \theta) + \psi_k^T H C_1 x(k) - \psi_k^T \psi_k. \end{aligned} \tag{35}$$

Let $\eta(k) = [\xi^T(k)\ \Gamma^T(t_n)\ \omega^T(k)\ q^T(k)\ \sqrt{\chi(k)}^T\ \psi_k^T]^T$ represent the augmented state vector. Then, considering the constructed closed-loop system (27), it yields that

$$\begin{aligned} E\{\Delta V(k)\} &\leq E\left\{\sum_{m=1}^{h}\sum_{r=1}^{h}\sum_{j=1}^{h} \vartheta_m(x(k))\vartheta_r(\hat{x}(k))\varepsilon_j(\hat{x}(k))\right. \\ &\quad \times [\mathcal{M}_{mrjt}^1 \xi(k) + (\mathcal{M}_{rt}^2 + \mathcal{M}_{rt}^3)\Gamma(t_n) \\ &\quad + \mathcal{M}_{rt}^4 q(k) + \mathcal{M}_{rt}^5 \psi_k + \bar{E}_{mrt}\omega(k)]^T \bar{P}_t \\ &\quad \times [\mathcal{M}_{mrjt}^1 \xi(k) + (\mathcal{M}_{rt}^2 + \mathcal{M}_{rt}^3)\Gamma(t_n) \\ &\quad + \mathcal{M}_{rt}^4 q(k) + \mathcal{M}_{rt}^5 \psi_k + \bar{E}_{mrt}\omega(k)] \\ &\quad - \xi^T(k) P_t \xi(k) + \frac{1}{\theta}[(\lambda - 1)\chi(k) - q^T(k)q(k) \\ &\quad \left. + \mu y^T(k)y(k)]\right\} + y^T(t_n) R^T R y(t_n) \\ &\quad - \Gamma^T(t_n)\Gamma(t_n) + \rho\Xi(k, \mu, \theta) + \psi_k^T H C_1 x(k) \\ &\quad - \psi_k^T \psi_k \\ &= \sum_{m=1}^{h}\sum_{r=1}^{h}\sum_{j=1}^{h} \vartheta_m(x(k))\vartheta_r(\hat{x}(k))\varepsilon_j(\hat{x}(k)) \\ &\quad \times \eta^T(k)\Omega_{mrjt}\eta(k). \end{aligned} \tag{36}$$

Based on the conditions (27) and (36), we can readily have that

$$\begin{aligned} &E\{\Delta V(k) + z^T(k)z(k) - \gamma^2\omega^T(k)\omega(k)\} \\ &\leq \sum_{m=1}^{h}\sum_{r=1}^{h}\sum_{j=1}^{h} \vartheta_m(x(k))\vartheta_r(\hat{x}(k))\varepsilon_j(\hat{x}(k))\eta^T(k)\bar{\Omega}_{mrjt}\eta(k). \end{aligned} \tag{37}$$

In light of [55], the slack matrix Δ is applied and it can be witnessed that

$$\begin{aligned}&\sum_{m=1}^{h}\sum_{r=1}^{h}\sum_{j=1}^{h}\vartheta_m(x(k))\vartheta_r(\hat{x}(k))[(\vartheta_j(\hat{x}(k))-\varepsilon_j(\hat{x}(k)))\Delta]\\&=\sum_{m=1}^{h}\sum_{r=1}^{h}\vartheta_m(x(k))\vartheta_r(\hat{x}(k))\\&\quad\times\left[\left(\sum_{j=1}^{h}\vartheta_j(\hat{x}(k))-\sum_{j=1}^{h}\varepsilon_j(\hat{x}(k))\right)\Delta\right]=0.\end{aligned}\tag{38}$$

Subsequently, the formula (37) can be written as

$$\begin{aligned}&E\{\Delta V(k)+z^T(k)z(k)-\gamma^2\omega^T(k)\omega(k)\}\\&\leq\sum_{m=1}^{h}\sum_{r=1}^{h}\sum_{j=1}^{h}\vartheta_m(x(k))\vartheta_r(\hat{x}(k))\varepsilon_j(\hat{x}(k))\eta^T(k)\bar{\Omega}_{mrjt}\eta(k)\\&\leq\sum_{m=1}^{h}\sum_{r=1}^{h}\sum_{j=1}^{h}\vartheta_m(x(k))\vartheta_r(\hat{x}(k))\eta^T(k)\\&\quad\times[\vartheta_j(\hat{x}(k))(l_j\bar{\Omega}_{mrjt}-l_j\Delta+\Delta)\\&\quad+(\varepsilon_j(\hat{x}(k))-l_j\vartheta_j(\hat{x}(k)))(\bar{\Omega}_{mrjt}-\Delta)]\eta(k)\\&=\frac{1}{2}\sum_{m=1}^{h}\sum_{r=1}^{h}\sum_{j=1}^{h}\vartheta_m(x(k))\vartheta_r(\hat{x}(k))\eta^T(k)\\&\quad\times[\vartheta_j(\hat{x}(k))(l_j\bar{\Omega}_{mrjt}+l_r\bar{\Omega}_{mjrt}-l_j\Delta-l_r\Delta+2\Delta)\\&\quad+(\varepsilon_j(\hat{x}(k))-l_j\vartheta_j(\hat{x}(k)))(\bar{\Omega}_{mrjt}+\bar{\Omega}_{mjrt}-2\Delta)]\eta(k).\end{aligned}\tag{39}$$

Noticing the conditions (29)–(31) in Theorem 1, we can obtain that

$$E\{\Delta V(k)+z^T(k)z(k)-\gamma^2\omega^T(k)\omega(k)\}\leq 0.\tag{40}$$

Hence, when the external disturbance $\omega(k)\equiv 0$, it can be observed clearly that the condition $E\{\Delta V(k)\}\leq 0$ can be derived by using the Schur complement and it means that the augmented IT-2 fuzzy dynamics is asymptotically stable. Meanwhile, by means of summing both sides of (40) for the time instant k from 0 to ∞, one can see that

$$E\left\{\sum_{k=0}^{\infty}\|z(k)\|^2\right\}\leq\gamma^2\sum_{k=0}^{\infty}\|\omega(k)\|^2\tag{41}$$

from which the H_∞ performance index has been satisfied and the proof is completed. ■

Remark 7: It can be mentioned that the proposed DETSC protocol should be properly reflected in the selected Lyapunov function $V(k)$ in (34) such that the stability analysis can consider the impacts of DETSC protocol, which ensure the asymptotic stability of the augmented IT-2 fuzzy system under the DETSC protocol. To be specific, taking account of the scheduling behaviors led by the SC protocol, the first term $\xi^T(k)P_t\xi(k)$ in $V(k)$ has been utilized in relation to the scheduled node φ_{t_n}. On the other hand, similar to [56], the second term $\frac{1}{\theta}\chi(k)$ is introduced to characterize the dynamic adjustment of $\chi(k)$ in the DET scheme.

Theorem 2: For predetermined scalars $\theta>0$, $\rho>0$, $\gamma>0$, $\bar{\alpha}\in(0,1)$, $\lambda\in(0,1)$, $\mu\in(0,1)$, and the condition $\varepsilon_j(\hat{x}(k))-l_j\vartheta_j(\hat{x}(k))>0$ $(l_j>0)$, the asymptotic stability with H_∞ performance index of the augmented IT-2 fuzzy system (27) under the DETSC protocol can be ensured if there exist positive-definite matrices $P_t=\text{diag}\{P_{1,t},P_{2,t},P_{3,t}\}>0$, $Y_t>0$, $U_{r,t}$, $U_{j,t}$ $(t\in\mathbb{S})$, and slack matrix Δ such that

$$\lambda-\frac{1}{\theta}\geq 0\tag{42}$$

$$\begin{bmatrix}2\tilde{Q}_t & *\\ \tilde{\Pi}_{mrjt}+\tilde{\Pi}_{mjrt} & 2\Lambda\end{bmatrix}<0,\ r\leq j\tag{43}$$

$$\begin{bmatrix}2\tilde{Q}_t & *\\ \sqrt{l_j}\tilde{\Pi}_{mrjt}+\sqrt{l_r}\tilde{\Pi}_{mjrt} & \Psi\end{bmatrix}<0,\ r\leq j\tag{44}$$

where

$$\tilde{Q}_t=\text{diag}\{\vec{P}_t,\vec{P}_t,-I,-I,-I,-I\}$$

$$\vec{P}_t=\text{diag}\{\bar{P}_{1,t}-\mathcal{H}e\{Y_t\},\bar{P}_{2,t}-\mathcal{H}e\{Y_t\},\bar{P}_{3,t}-\mathcal{H}e\{Y_t\}\}$$

$$\tilde{\Pi}_{mrjt}=\begin{bmatrix}\tilde{\mathcal{M}}^{1T}_{mrjt} & 0 & \bar{C}^T_{mjt} & 0 & \tilde{H}^TR^T & \sqrt{\beta}\tilde{H}^T\\ \tilde{\mathcal{M}}^{2T}_{rt} & \tilde{\mathcal{M}}^{3T}_{rt} & 0 & 0 & 0 & 0\\ \tilde{E}^T_{mrt} & 0 & F^T_m & 0 & E^T_2R^T & \sqrt{\beta}E^T_2\\ \tilde{\mathcal{M}}^{4T}_{rt} & 0 & 0 & 0 & -R^T & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ \tilde{\mathcal{M}}^{5T}_{rt} & 0 & 0 & 0 & R^T & \sqrt{\beta}I\end{bmatrix}$$

$$\tilde{\mathcal{M}}^{1T}_{mrjt}=\begin{bmatrix}\tilde{\mathcal{M}}^1_{11} & \tilde{\mathcal{M}}^1_{12} & C^T_1H^T_1\Phi^T_tY^T_t\\ C^T_1H^T_1\Phi^T_tU_{r,t} & \tilde{\mathcal{M}}^1_{22} & C^T_1H^T_1\Phi^T_tY^T_t\\ \tilde{\Phi}^T_tU_{r,t} & -\tilde{\Phi}^T_tU_{r,t} & \tilde{\Phi}^T_tY^T_t\end{bmatrix}$$

$$\tilde{\mathcal{M}}^{2T}_{rt}=\begin{bmatrix}\bar{\alpha}\bar{\Phi}^T_tU_{r,t} & -\bar{\alpha}\bar{\Phi}^T_tU_{r,t} & \bar{\alpha}\bar{\Phi}^T_tY^T_t\end{bmatrix}$$

$$\tilde{\mathcal{M}}^{3T}_{rt}=\begin{bmatrix}\sqrt{\bar{\alpha}\vec{\alpha}}\bar{\Phi}^T_tU_{r,t} & -\sqrt{\bar{\alpha}\vec{\alpha}}\bar{\Phi}^T_tU_{r,t} & \sqrt{\bar{\alpha}\vec{\alpha}}\bar{\Phi}^T_tY^T_t\end{bmatrix}$$

$$\tilde{\mathcal{M}}^{4T}_{rt}=\begin{bmatrix}-\Phi^T_tU_{r,t} & \Phi^T_tU_{r,t} & -\Phi^T_tY^T_t\end{bmatrix},\ \tilde{\mathcal{M}}^{5T}_{rt}=-\tilde{\mathcal{M}}^{4T}_{rt}$$

$$\tilde{E}^T_{mrt}=\begin{bmatrix}E^T_2\Phi^T_tU_{r,t} & E^T_{1m}Y^T_t-E^T_2\Phi^T_tU_{r,t} & E^T_2\Phi^T_tY^T_t\end{bmatrix}$$

$$\tilde{\mathcal{M}}^1_{11}=A^T_rY^T_t+\tilde{V}_{jtr}B^T_r+C^T_1H^T_1\Phi^T_tU_{r,t}-C^T_1U_{j,t}$$

$$\begin{aligned}\tilde{\mathcal{M}}^1_{12}&=A^T_mY^T_t-A^T_rY^T_t+\tilde{V}_{jtm}B^T_m-\tilde{V}_{jtr}B^T_r\\&\quad-C^T_1H^T_1\Phi^T_tU_{r,t}+C^T_1U_{r,t},\ U_{r,t}=L^T_{r,t}Y^T_t\end{aligned}$$

$$\tilde{\mathcal{M}}^1_{22}=A^T_mY^T_t-C^T_1H^T_1\Phi^T_tU_{r,t},\ U_{j,t}=L^T_{j,t}Y^T_t$$

$$\Lambda=\begin{bmatrix}\Lambda_1 & \Lambda_2 & \Lambda_3\\ \Lambda_4 & \Lambda_5 & \Lambda_6\\ \Lambda_7 & \Lambda_8 & \Lambda_9\end{bmatrix},\ \Lambda_1=\begin{bmatrix}\Lambda^1_{11} & -\Delta_{12} & -\Delta_{13}\\ -\Delta_{21} & \Lambda^1_{22} & -\Delta_{23}\\ -\Delta_{31} & -\Delta 32 & \Lambda^1_{33}\end{bmatrix}$$

$$\Lambda_2 = \begin{bmatrix} -\Delta_{14} & -\Delta_{15} & -\Delta_{16} \\ -\Delta_{24} & -\Delta_{25} & -\Delta_{26} \\ -\Delta_{34} & -\Delta_{35} & -\Delta_{36} \end{bmatrix}, \ \Lambda_3 = \begin{bmatrix} -\Delta_{17} & \Lambda^3_{12} \\ -\Delta_{27} & \Lambda^3_{22} \\ -\Delta_{37} & -\Delta_{38} \end{bmatrix}$$

$$\Lambda_4 = \begin{bmatrix} -\Delta_{41} & -\Delta_{42} & -\Delta_{43} \\ -\Delta_{51} & -\Delta_{52} & -\Delta_{53} \\ -\Delta_{61} & -\Delta_{62} & -\Delta_{63} \end{bmatrix}, \ \Lambda_6 = \begin{bmatrix} -\Delta_{47} & -\Delta_{48} \\ -\Delta_{57} & -\Delta_{58} \\ -\Delta_{67} & -\Delta_{68} \end{bmatrix}$$

$$\Lambda_5 = \begin{bmatrix} -I-\Delta_{44} & -\Delta_{45} & -\Delta_{46} \\ -\Delta_{54} & -\gamma^2 I - \Delta_{55} & -\Delta_{56} \\ -\Delta_{64} & -\Delta_{65} & -(\frac{1}{\theta}+\rho)I - \Delta_{66} \end{bmatrix},$$

$$\Lambda_7 = \begin{bmatrix} -\Delta_{71} & -\Delta_{72} & -\Delta_{73} \\ HC_1 - \Delta_{81} & HC_1 - \Delta_{82} & -\Delta_{83} \end{bmatrix},$$

$$\Lambda_8 = \begin{bmatrix} -\Delta_{74} & -\Delta_{75} & -\Delta_{76} \\ -\Delta_{84} & -\Delta_{85} & -\Delta_{86} \end{bmatrix},$$

$$\Lambda_9 = \begin{bmatrix} -\frac{1}{\theta}(1-\lambda-\rho)I - \Delta_{77} & -\Delta_{78} \\ -\Delta_{87} & -I-\Delta_{88} \end{bmatrix},$$

$$\Lambda^1_{11} = -P_{1,t} - \Delta_{11}, \ \Lambda^1_{22} = -P_{2,t} - \Delta_{22},$$

$$\Lambda^1_{33} = -P_{3,t} - \Delta_{33}, \ \Lambda^3_{12} = C_1^T H_1^T - \Delta_{18}$$

$$\Lambda^3_{22} = C_1^T H_1^T - \Delta_{28}$$

$$\Psi = \begin{bmatrix} \Psi_1 & \Psi_2 & \Psi_3 \\ \Psi_4 & \Psi_5 & \Psi_6 \\ \Psi_7 & \Psi_8 & \Psi_9 \end{bmatrix}, \ \Psi_1 = \begin{bmatrix} \Psi^1_{11} & \bar{l}_{jr}\Delta_{12} & \bar{l}_{jr}\Delta_{13} \\ \bar{l}_{jr}\Delta_{21} & \Psi^1_{22} & \bar{l}_{jr}\Delta_{23} \\ \bar{l}_{jr}\Delta_{31} & \bar{l}_{jr}\Delta_{32} & \Psi^1_{33} \end{bmatrix}$$

$$\Psi_2 = -\bar{l}_{jr}\Lambda_2, \ \Psi_4 = -\bar{l}_{jr}\Lambda_4, \ \Psi_6 = -\bar{l}_{jr}\Lambda_6, \ \Psi_8 = -\bar{l}_{jr}\Lambda_8$$

$$\Psi_3 = \begin{bmatrix} \bar{l}_{jr}\Delta_{17} & \Psi^3_{12} \\ \bar{l}_{jr}\Delta_{27} & \Psi^3_{22} \\ \bar{l}_{jr}\Delta_{37} & \bar{l}_{jr}\Delta_{38} \end{bmatrix}, \Psi_5 = \begin{bmatrix} \Psi^5_{11} & \bar{l}_{jr}\Delta_{45} & \bar{l}_{jr}\Delta_{46} \\ \bar{l}_{jr}\Delta_{54} & \Psi^5_{22} & \bar{l}_{jr}\Delta_{56} \\ \bar{l}_{jr}\Delta_{64} & \bar{l}_{jr}\Delta_{65} & \Psi^5_{33} \end{bmatrix}$$

$$\Psi_7 = \begin{bmatrix} \bar{l}_{jr}\Delta_{71} & \bar{l}_{jr}\Delta_{72} & \bar{l}_{jr}\Delta_{73} \\ l_{jr}HC_1 + \bar{l}_{jr}\Delta_{81} & l_{jr}HC_1 + \bar{l}_{jr}\Delta_{82} & \bar{l}_{jr}\Delta_{83} \end{bmatrix}$$

$$\Psi_9 = \begin{bmatrix} -l_{jr}\frac{1}{\theta}(1-\lambda-\rho)I + \bar{l}_{jr}\Delta_{77} & \bar{l}_{jr}\Delta_{78} \\ \bar{l}_{jr}\Delta_{87} & -l_{jr}I + \bar{l}_{jr}\Delta_{88} \end{bmatrix}$$

$$\Psi^1_{11} = -l_{jr}P_{1,t} + \bar{l}_{jr}\Delta_{11}, \ \Psi^1_{22} = -l_{jr}P_{2,t} + \bar{l}_{jr}\Delta_{22}$$

$$\Psi^1_{33} = \bar{l}_{jr}\Delta_{33} - l_{jr}P_{3,t}, \ \Psi^3_{12} = \bar{l}_{jr}\Delta_{18} + l_{jr}C_1^T H_1^T$$

$$\Psi^3_{22} = \bar{l}_{jr}\Delta_{28} + l_{jr}C_1^T H_1^T, \ \Psi^5_{11} = -l_{jr}I + \bar{l}_{jr}\Delta_{44}$$

$$\Psi^5_{22} = -l_{jr}\gamma^2 I + \bar{l}_{jr}\Delta_{55} \ \Psi^5_{33} = -l_{jr}(\frac{1}{\theta}+\rho)I + \bar{l}_{jr}\Delta_{66}$$

$$l_{jr} = l_j + l_r, \ \bar{l}_{jr} = 2 - l_{jr}.$$

Proof 2: By applying the Schur complement, the equalities (30) and (31) are converted to the following conditions:

$$\begin{bmatrix} 2Q_t & * \\ \Pi_{mrjt} + \Pi_{mjrt} & 2\Lambda \end{bmatrix} < 0, \ r \le j \qquad (45)$$

$$\begin{bmatrix} 2Q_t & * \\ \sqrt{l_j}\Pi_{mrjt} + \sqrt{l_r}\Pi_{mjrt} & \Psi \end{bmatrix} < 0, \ r \le j \qquad (46)$$

where

$$Q_t = \mathrm{diag}\{-\bar{P}_t^{-1}, -\bar{P}_t^{-1}, -I, -I, -I, -I\}$$
$$\bar{P}_t = \mathrm{diag}\{\bar{P}_{1,t}, \bar{P}_{2,t}, \bar{P}_{3,t}\}$$

$$\Pi_{mrjt} = \begin{bmatrix} \mathcal{M}^{1T}_{mrjt} & 0 & \bar{C}^T_{mjt} & 0 & \tilde{H}^T R^T & \sqrt{\beta}\tilde{H}^T \\ \mathcal{M}^{2T}_{rt} & \mathcal{M}^{3T}_{rt} & 0 & 0 & 0 & 0 \\ \bar{E}^T_{mrt} & 0 & F^T_m & 0 & E_2^T R^T & \sqrt{\beta}E_2^T \\ \mathcal{M}^{4T}_{rt} & 0 & 0 & 0 & -R^T & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \mathcal{M}^{5T}_{rt} & 0 & 0 & 0 & R^T & \sqrt{\beta}I \end{bmatrix}.$$

Denoting the matrix $X = \mathrm{diag}\{\mathcal{J}, \mathcal{J}, I, \dots, I\}$ with $\mathcal{J} = \mathrm{diag}\{Y_t, Y_t, Y_t\}$, we multiply the left and right-hand sides of (45) and (46) by X and X^T. Then, it is easily derived that

$$\begin{bmatrix} 2\bar{Q}_t & * \\ \bar{\Pi}_{mrjt} + \bar{\Pi}_{mjrt} & 2\Lambda \end{bmatrix} < 0, \ r \le j \qquad (47)$$

$$\begin{bmatrix} 2\bar{Q}_t & * \\ \sqrt{l_j}\bar{\Pi}_{mrjt} + \sqrt{l_r}\bar{\Pi}_{mjrt} & \Psi \end{bmatrix} < 0, \ r \le j \qquad (48)$$

in which

$$\bar{Q}_t = \mathrm{diag}\{-Y_t\bar{P}_t^{-1}Y_t^T, -Y_t\bar{P}_t^{-1}Y_t^T, -I, -I, -I, -I\}$$

$$\bar{\Pi}_{mrjt} = \begin{bmatrix} \vec{\mathcal{M}}^{1T}_{mrjt} & 0 & \bar{C}^T_{mjt} & 0 & \tilde{H}^T R^T & \sqrt{\beta}\tilde{H}^T \\ \tilde{\mathcal{M}}^{2T}_{rt} & \tilde{\mathcal{M}}^{3T}_{rt} & 0 & 0 & 0 & 0 \\ \tilde{E}^T_{mrt} & 0 & F^T_m & 0 & E_2^T R^T & \sqrt{\beta}E_2^T \\ \tilde{\mathcal{M}}^{4T}_{rt} & 0 & 0 & 0 & -R^T & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \tilde{\mathcal{M}}^{5T}_{rt} & 0 & 0 & 0 & R^T & \sqrt{\beta}I \end{bmatrix}$$

$$\vec{\mathcal{M}}^{1T}_{mrjt} = \begin{bmatrix} \vec{\mathcal{M}}^1_{11} & \vec{\mathcal{M}}^1_{12} & C_1^T H_1^T \Phi_t^T Y_t^T \\ C_1^T H_1^T \Phi_t^T U_{r,t} & \tilde{\mathcal{M}}^1_{22} & C_1^T H_1^T \Phi_t^T Y_t^T \\ \tilde{\Phi}_t^T U_{r,t} & -\tilde{\Phi}_t^T U_{r,t} & \tilde{\Phi}_t^T Y_t^T \end{bmatrix}$$

$$\vec{\mathcal{M}}^1_{11} = A_r^T Y_t^T + K^T_{j,t} B_r^T Y_t^T + C_1^T H_1^T \Phi_t^T U_{r,t} - C_1^T U_{r,t}$$

$$\vec{\mathcal{M}}^1_{12} = A_m^T Y_t^T - A_r^T Y_t^T + K^T_{j,t} B_m^T Y_t^T - K^T_{j,t} B_r^T Y_t^T - C_1^T H_1^T \Phi_t^T U_{r,t} + C_1^T U_{r,t}.$$

Owing to the condition $(\bar{P}_{i,t} - Y_t)\bar{P}_{i,t}^{-1}(\bar{P}_{i,t} - Y_t)^T \ge 0$ $(i \in \{1,2,3\})$, one has

$$-Y_t\bar{P}_{i,t}^{-1}Y_t^T \le \bar{P}_{i,t} - \mathcal{H}e\{Y_t\}. \qquad (49)$$

According to Lemma 1, we can notice that $B_m^T \in \mathbb{R}^{n_u \times n_x}$ with $B_m^T = T_m[V_m \ 0]S_m^T$, from which T_m and S_m are orthogonal matrices. Thus, for $Y_t^T = S_m \begin{bmatrix} Y^1_{mt} & 0 \\ 0 & Y^2_{mt} \end{bmatrix} S_m^T$, it can be conclude that $\bar{Y}^T_{tm} B_m^T = B_m^T Y_t^T$ with $\bar{Y}^T_{tm} = T_m V_m Y^1_{mt} V_m^{-1} T_m^T$. Similarly, we can get that $\bar{Y}^T_{tr} B_r^T = B_r^T Y_t^T$ with $\bar{Y}^T_{tr} = T_r V_r Y^1_{rt} V_r^{-1} T_r^T$ and $\bar{Y}^T_{tj} B_j^T = B_j^T Y_t^T$ with $\bar{Y}^T_{tj} = T_j V_j Y^1_{jt} V_j^{-1} T_j^T$.

By substituting the above formulas with (49) into (47) and (48), defining $\tilde{V}_{jtr} = K_{j,t}^T \bar{Y}_{tr}^T$, $\tilde{V}_{jtm} = K_{j,t}^T \bar{Y}_{tm}^T$, $\tilde{V}_{rtj} = K_{r,t}^T \bar{Y}_{tj}^T$, and $\tilde{V}_{rtm} = K_{r,t}^T \bar{Y}_{tm}^T$, the condition (43) and (44) can be derived. Under the analysis above, the conditions (29)–(31) in Theorem 1 can be guaranteed by (42)–(44) in Theorem 2. Meanwhile, it is clearly seen that the nonlinear terms are properly tackled and the parameters of fuzzy observer and controller can be attained by solving the LMIs. The proof of Theorem 2 has been finished.

IV. Numerical Illustrative Example

In order to demonstrate the feasibility of the proposed DETSC protocol and the fuzzy observer-based secure control scheme under sensor saturation, a simulation example will be subsequently presented. The coefficient matrices of the IT-2 fuzzy system (1) with two rules are outlined as

$$A_1 = \begin{bmatrix} 0.2902 & 0.5543 \\ -0.5463 & 0.6851 \end{bmatrix}, \ B_1 = \begin{bmatrix} 0.3021 \\ 0.1197 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 0.1978 & 0.4326 \\ -0.1527 & 0.5841 \end{bmatrix}, \ B_2 = \begin{bmatrix} 0.1207 \\ 0.1543 \end{bmatrix}$$

$$C_{21} = \begin{bmatrix} -0.3797 & -0.0563 \end{bmatrix}, \ E_{11} = \begin{bmatrix} 0.0004 \\ 0.0135 \end{bmatrix}$$

$$C_{22} = \begin{bmatrix} -0.4877 & -0.0875 \end{bmatrix}, \ E_{12} = \begin{bmatrix} 0.0139 \\ 0.0278 \end{bmatrix}$$

$$C_1 = \begin{bmatrix} -0.1788 & 0 \\ 0 & -0.1439 \end{bmatrix}, \ E_2 = \begin{bmatrix} 0.1058 \\ 0.0964 \end{bmatrix}$$

$$D_1 = -1.4899, \ D_2 = -0.4765$$

$$F_1 = -0.0133, \ F_2 = -0.1242$$

and the saturation function is derived as

$$\text{sat}(s_i) = \begin{cases} s_i, & \text{if } -s_{i,\max} < s_i < s_{i,\max} \\ \text{sign}(s_i) s_{i,\max}, & \text{otherwise}, \ (i = 1, 2). \end{cases} \tag{50}$$

In this example, the interference input is chosen as $\omega(k) = 0.01e^{-0.02k}\sin(0.21k)$ and other saturation parameters are set to be $s_{1,\max} = 0.014$, $s_{2,\max} = 0.025$, $H_1 = 0.7$, and $H = 0.3$.

In addition, the lower and upper membership functions of the plant are listed as follows:

$$\underline{W}_1^1(x_1(k)) = 1 - e^{-\frac{x_1^2(k)}{1.45}}, \ \overline{W}_1^1(x_1(k)) = 0.2e^{-\frac{x_1^2(k)}{0.35}}$$

$$\underline{W}_2^1(x_1(k)) = 1 - 0.2e^{-\frac{x_1^2(k)}{0.35}}, \ \overline{W}_2^1(x_1(k)) = e^{-\frac{x_1^2(k)}{1.45}}$$

$$\underline{W}_1^2(x_1(k)) = 0.35e^{-\frac{x_1^2(k)}{0.25}}, \ \overline{W}_1^2(x_1(k)) = e^{-\frac{x_1^2(k)}{2.55}}$$

$$\underline{W}_2^2(x_1(k)) = 1 - e^{-\frac{x_1^2(k)}{2.55}}, \ \overline{W}_2^2(x_1(k)) = 1 - 0.35e^{-\frac{x_1^2(k)}{0.25}}.$$

TABLE I
Nonlinear Weighting Functions

Lower bound weight	Upper bound weight
$\underline{a}_m(x(k)) = cos^2(x_1(k))$	$\overline{a}_m(x(k)) = 1 - cos^2(x_1(k))$
$\underline{b}_j(\hat{x}(k)) = sin^2(\hat{x}_1(k))$	$\overline{b}_j(\hat{x}(k)) = 1 - sin^2(\hat{x}_1(k))$

Meanwhile, the lower and upper membership functions of the fuzzy controller can be also given as

$$\underline{N}_1^1(\hat{x}_1(k)) = e^{-\frac{\hat{x}_1^2(k)}{0.35}}, \ \overline{N}_1^1(\hat{x}_1(k)) = e^{-\frac{\hat{x}_1^2(k)}{0.45}}$$

$$\underline{N}_2^1(\hat{x}_1(k)) = e^{-\frac{\hat{x}_1^2(k)}{0.45}}, \ \overline{N}_2^1(\hat{x}_1(k)) = e^{-\frac{\hat{x}_1^2(k)}{0.55}}$$

$$\underline{N}_1^2(\hat{x}_1(k)) = 1 - 0.45e^{-\frac{\hat{x}_1^2(k)}{0.42}}, \ \overline{N}_1^2(\hat{x}_1(k)) = e^{-\frac{\hat{x}_1^2(k)}{0.32}}$$

$$\underline{N}_2^2(\hat{x}_1(k)) = e^{-\frac{\hat{x}_1^2(k)}{0.32}}, \ \overline{N}_2^2(\hat{x}_1(k)) = 1 - 0.45e^{-\frac{\hat{x}_1^2(k)}{0.42}}.$$

To calculate $\varsigma_m(x(k))$ and $\kappa_j(\hat{x}(k))$, the selected nonlinear weighting functions are given in Table I. Under the restrictive consideration of $\varepsilon_j(\hat{x}(k)) - l_j\vartheta_j(\hat{x}(k)) > 0$ $(l_j > 0)$ and $\lambda\theta \geq 1$, we adopt the parameters $l_1 = 0.95$, $l_2 = 0.56$, $\lambda = 0.62$, and $\theta = 5$. Then, the scheduled senor signal under the DETSC protocol is denoted as $\varphi_k \in \mathbb{S} = \{1, 2\}$ with the following transition probability matrix:

$$\mathcal{P} = \begin{bmatrix} 0.35 & 0.65 \\ 0.45 & 0.55 \end{bmatrix}.$$

Moreover, let the FDI attacks signal $\Gamma(k) = 0.1\sin(k)x_i(k)$ with energy restriction $R = \text{diag}\{0.1, 0.1\}$ and its probability $\bar{\alpha} = 0.25$. The remaining parameters related to the DETSC protocol are given as $\mu = 0.75$ and $\rho = 0.35$. By applying the LMI toolbox in MATLAB, the gain matrices of the observer and controller in the H_∞ sense with index $\gamma = 0.35$ can be solved as follows:

$$K_{11} = \begin{bmatrix} -0.5612 & -0.0876 \end{bmatrix}, \ K_{12} = \begin{bmatrix} -0.4800 & -0.0418 \end{bmatrix}$$

$$K_{21} = \begin{bmatrix} -0.6308 & -0.0761 \end{bmatrix}, \ K_{22} = \begin{bmatrix} -0.5719 & -0.0520 \end{bmatrix}$$

$$L_{11} = \begin{bmatrix} -0.0226 & 0.0015 \\ -0.0084 & -0.0022 \end{bmatrix}, \ L_{12} = \begin{bmatrix} -0.0001 & -0.1109 \\ 0.0020 & -0.0568 \end{bmatrix}$$

$$L_{21} = \begin{bmatrix} -0.0645 & -0.0023 \\ 0.0228 & 0.0053 \end{bmatrix}, \ L_{22} = \begin{bmatrix} 0.0009 & -0.0231 \\ 0.0009 & -0.1324 \end{bmatrix}.$$

By setting the initialization $x(0) = [0.2 \quad -0.2]^T$, $\hat{x}(0) = [0.3 \quad -0.3]^T$, and $\chi(0) = 1$, the responses of state values $x_1(k)$ and $x_2(k)$, and the estimated values $\hat{x}_1(k)$ and $\hat{x}_2(k)$ are depicted in Fig. 1. It is witnessed explicitly that the state vector in the plant has converged to zero about 13 time instant, which reveal the phenomenon that IT-2 fuzzy dynamics under the observer-based controller with the gain matrices solved above is asymptotically stable. At the same time, the curves of estimated states generated by the designed fuzzy observer are gradually

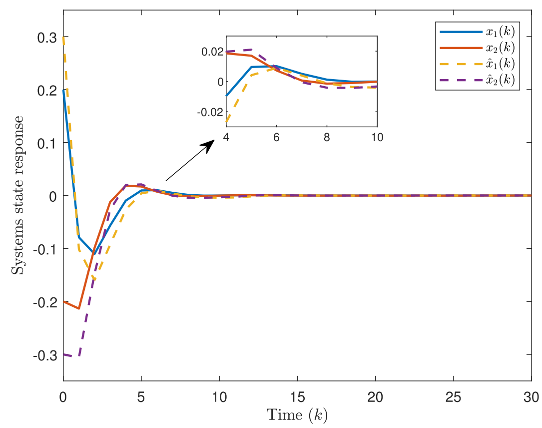

Fig. 1. Trajectories of the system state and its estimation.

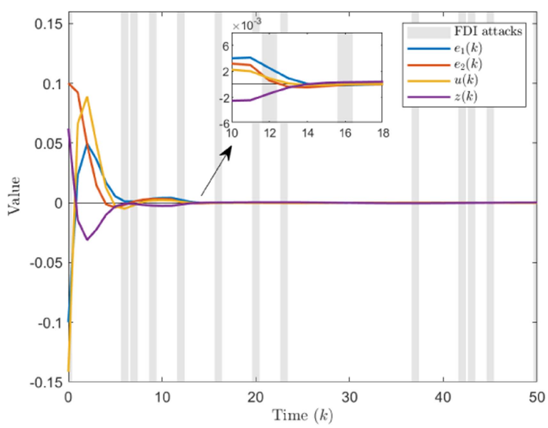

Fig. 2. Responses of $e_1(k)$, $e_2(k)$, $u(k)$, and $z(k)$ under FDI attacks.

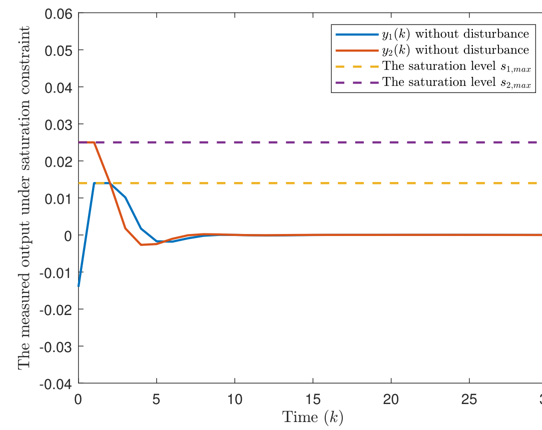

Fig. 3. Responses of the measured output with saturation constraint.

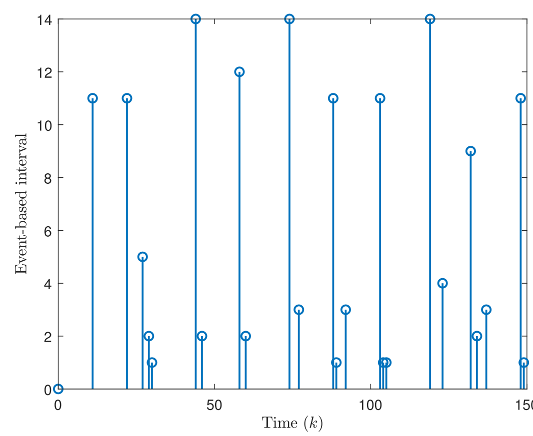

Fig. 4. Release instants of the DET strategy.

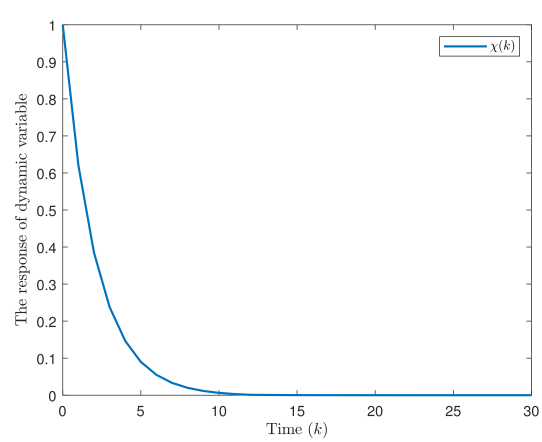

Fig. 5. Trajectory of the dynamic internal variable.

approaching the real states. Based on the aforementioned observation, we can readily conclude that the fuzzy controller scheme (21) is valid.

The trajectories of the control signal $u(k)$, the control output $z(k)$, and the estimation error $e(k)$ under the stochastic FDI attacks are depicted in Fig. 2. It is commendably discovered that these curves can eventually arrive at the expected stable situation despite the large fluctuations in the early simulation. In addition, in order to evidently observe the results, the measured output without considering the external disturbance is shown in Fig. 3. From it, we can obviously witness that the real measured output does not exceed the saturation level, which indicates the existence of the sensor saturation in line with the practical application.

In the proposed DETSC protocol, the ET instants and the response of dynamic internal variable $\chi(k)$ are presented in Figs. 4 and 5, respectively. It can be apparently reflected that the redundant data without satisfying the condition (9) is not transmitted through the communication channel, from which the limited network resource can be further saved under the effect of dynamic triggering threshold posed by the internal variable. Particularly, the applied DET mechanism will be transformed to the SET condition in [57] by letting the parameter $\theta \to \infty$ in this article. In comparison with the SET scheme, whose released time instants are plotted in Fig. 6, the more efficient transmission appears in the DET mechanism according to Table II. Define transmission ratio as the ratio of the total triggered time and runtime (i.e., 150 time instant in this simulation). It is not hard to notice that only 16.7% of sampling data can be released, while

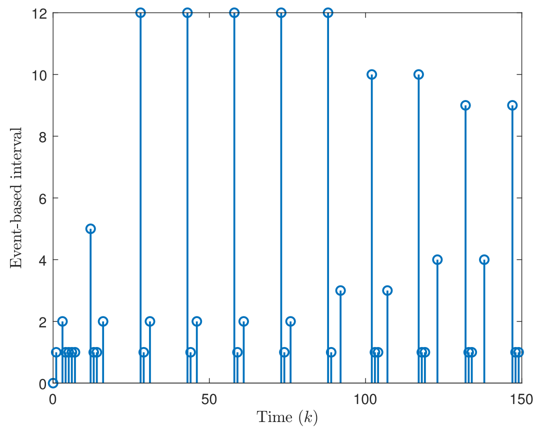

Fig. 6. Released instants of the SET strategy.

TABLE II
COMPARISON OF TWO ET MECHANISMS

	DET scheme ($\theta = 5$)	SET scheme ($\theta \to \infty$)
Release package	25	41
Transmission ratio	16.7%	27.3%

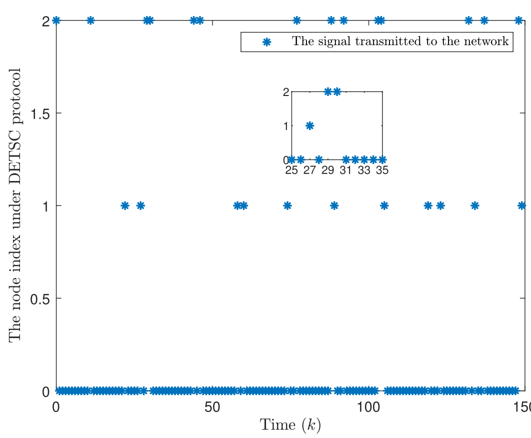

Fig. 7. Distribution of the scheduled signal under the DETSC protocol.

the transmission ratio in SET scheme becomes 27.3%. Thus, the considered DETSC protocol has the preferable capacity to alleviate the communication burden in terms of the SET scheme.

On the other hand, it is the traditional assumption that all sensor signals can be released at the current time instant when the DET condition is met. By reason of the restrictive bandwidth, only one sensor data selected by the SC protocol will obtain the chance to the shared network medium at each t_n step. Then, the scheduling sequences of sensor signal under the DETSC protocol are depicted in Fig. 7. In accordance with Figs. 4 and 7, it should be explicitly mentioned that only 25 data packages are released by the DET scheme. Moreover, sensor nodes are denoted to be index 1 and 2, whereas index 0 represents that the DET condition (9) not holds at the current time instant. In addition, the different node indexes have not simultaneously appeared at any t_nth step and it means that the phenomenon of data collision in a channel has been avoided. Hence, the practicability of the proposed DETSC protocol has been verified again from another perspective.

V. CONCLUSION

In this article, a secure fuzzy controller design for nonlinear NCSs in the presence of the stochastic FDI attacks has been presented. From a practical perspective, a saturation function, which ensures the measured output constrained within a predetermined range, is employed to account for the limited capacity of physical sensors. Moreover, the proposed DETSC protocol has been put forward for decreasing the incidence of data collision and lessening the communication pressure by comprehensively utilizing with the advantages of the DET scheme and SC protocol. Under the consideration of immeasurable system state in practical application, a fuzzy observer-based controller is designed in a unified framework and the augmented IT-2 fuzzy system is presented. On the basis of the Lyapunov functional technique, a range of sufficient conditions guaranteeing the asymptotic stability for the constructed augmented dynamics are derived. Furthermore, the gain parameters of the IT-2 fuzzy observer-based controller can be solved under the utilization of LMIs approach. Eventually, compared with the SET strategy, a simulation example is given to illustrate the practicability of the proposed theoretical fuzzy control scheme.

In future research works, the occurrence of multiple network attacks for the IT-2 fuzzy system with saturation constraint will be investigated. It is worth mentioning that the measurement outliers usually arise in communication transmission, which give rise to controller performance degeneration. Thus, the fuzzy model-based outlier-resistant control method under communication protocols and the ET scheme are worthy of discussion.

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