Observer-Based Security Fuzzy Control for Nonlinear Networked Systems Under Weighted Try-Once-Discard Protocol

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***Abstract*—This article is concerned with the observer-based security fuzzy control problem for a class of nonlinear networked systems with imperfectly matched membership functions (MFs) under weighted try-once-discard (WTOD) protocol. The nonlinear networked system is constructed based on interval type-2 Takagi–Sugeno model, which can properly handle parameter uncertainties via lower and upper MFs. To mitigate the communication load, WTOD protocol is exploited to schedule the transmission order of the signals, in which those signals may be subjected to randomly occurring deception attacks. The observer is constructed under immeasurable premise variables, and then the controller with imperfect matching MFs is designed according to the estimated states. Moreover, the observer-based controller is derived with Lyapunov stability theory such that the stochastic stability of the augmented closed-loop system with predefined disturbance attenuation performance can be guaranteed. Subsequently, sufficient conditions are provided for the desired observer and controller gain matrices based on linear matrix inequalities technique. Numerical simulation example demonstrates the validity of the proposed observer-based security fuzzy control design scheme.**

***Index Terms*—Deception attacks, interval type-2 (IT2) Takagi–Sugeno (T-S) fuzzy model, imperfect matching membership functions (MFs), observer-based control, weighted try-once-discard (WTOD) protocol.**

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I. Introduction

With the increasing complexity of modern industry, the nonlinearity and uncertainty make it difficult to establish precise mathematical model of nonlinear networked systems [1], [2], such that traditional control theories and methods cannot meet the design requirements of complex control systems well. Therefore, in the past few decades, rapidly growing attention has been witnessed in the investigation of nonlinear networked systems [3], [4], [5]. The Takagi–Sugeno (T-S) fuzzy model which can powerfully describe nonlinear systems via combining a set of linear submodels connected by IF-THEN rules with membership functions (MFs) has become the most intelligent and effective approach for control of nonlinear networked systems since its advent [6], [7], [8], [9]. So far, plentiful results with regard to analysis and synthesis problems for nonlinear networked systems based on interval type-1 (IT1) and interval type-2 (IT2) T-S fuzzy model have received persistent research interest, and substantial stability and stabilization conditions have been derived based on linear matrix inequalities [10], [11], [12], [13].

Note that system states are usually immeasurable in practical systems, the observer-based fuzzy control, which aims to estimate the unavailable states and stabilize unstable systems becomes prevalent and has caused continuous interests [14], [15], [16], [17]. For instance, in [11], a new observer-based fault-tolerant tracking control scheme was designed for a class of T-S fuzzy systems with mismatched faults and disturbances. In [18], the periodic tracking control problem for nonlinear systems on the basis of T-S fuzzy model was considered, which was handled by proposing a novel observer-based repetitive controller. However, these results were all under traditional parallel distribution compensation control framework. In order to facilitate controller design in network environment, the nonparallel distribution compensation control strategy, where the fuzzy controller can be designed with imperfect matching MFs, was proposed [19]. Enlightened by this idea, the problem of the hybrid triggered state feedback controller design problems have been investigated for the T-S fuzzy system with quantization and cyberattacks in our previous works [20] and [21].

Benefiting from the development of communication network, the application, diagnosis, and maintenance of networked control systems have become more flexible and convenient.

Nevertheless, the network also has some defects including constrained communication capacity problems, which may lead to channel congestion and data collisions, thus deteriorating the system performance [22], [23], [24]. Up to now, an active and valid way of alleviating the communication burden is deploying communication protocols to orchestrate the transmission order of signals. These communication protocols include round-robin protocol, stochastic communication protocol, weighted try-once-discard (WTOD) protocol and FlexRay protocol [25], [26], [27]. Among them, the assignment strategy of WTOD protocol is according to the principle of "competition" that is the scheduling is dependent on the importance of different missions [28], [29]. The study for protocol-based nonlinear networked systems have stirred significant attention from researchers [30], [31], [32], [33], [34]. For example, considering round-robin protocol, the H_∞ proportional-integral-derivative control problem for a class of discrete-time T-S fuzzy systems was studied in [12]. The security control problem for a class of IT2 fuzzy systems via the sliding mode control strategy was studied in [35]. The efficient model-predictive control problem for IT2 T-S fuzzy systems under round-robin protocol was conveniently investigated in [25], where a compensation scheme was proposed to analyze the effect of stochastic communication scheduling protocol and cyberattacks. However, the research on WTOD protocol-based nonlinear networked systems has received much less attention, this partially motivates our current investigation.

Network security is also a critical problem in the investigation of nonlinear networked systems due to the openness of communication network [36], [37]. Generally speaking, there are different security threats, such as deception attacks [38], denial-of-service attacks [39], and replay attacks [40], among which the deception attacks are judged as the most malicious ones due to the attackers arbitrarily inject disturbance signals leading to system performance degeneration and instability. However, because of resources limitations of the adversaries or antiattack tactics taking by the defenders, the deception attacks are not always successful. Accordingly, the mathematical models have been established to describe deception attacks, where the randomly occurring characteristic of deception attacks is governed by Bernoulli process [36]. Due to comprehensive consideration of the effects of WTOD protocol and deception attacks, the observer-based security fuzzy control problem for nonlinear networked systems becomes more complex, which has not been adequately addressed, and this is another motivation of this article.

Motivated by the aforementioned analyses, our objective is to obtain the observer-based security fuzzy controller for nonlinear networked systems under WTOD protocol. An IT2 T-S fuzzy system model is first constructed in consideration of WTOD protocol and deception attacks. Although some observer-based fuzzy control methods have been proposed in [19] and [41], these methods cannot be applicable to the scenario when deception attacks occur. In addition, different from the round-robin-based control approach [13] and the event-based control method in [20], [21], a WTOD protocol-based controller design method with imperfect matching MFs depending on estimated system state is addressed in this article. In particular, different Lyapunov functions are selected according to the different scheduling situations under WTOD protocol mechanism. Accordingly, the method of observer-based security fuzzy control for nonlinear networked system is provided. The main contributions of this article can be summarized as follows.

1) A novel model of augmented closed-loop IT2 T-S fuzzy system is constructed, in which signals are orchestrated in order under WTOD protocol to avoid data collision.
2) Under the concurrent consideration of protocol and deception attacks, the fuzzy controller is designed with imperfect matching MFs depending on estimated system state to increase its flexibility.
3) The sufficient conditions for ensuring the augmented closed-loop system is stochastically stable with the prescribed disturbance attenuation performance index are derived, then an observer-based fuzzy control method is designed to guarantee such system performance.

The rest of this article is organized as follows. Section II describes the IT-2 T-S fuzzy model, observer-based controller, and gives some preliminaries on the WTOD protocol-based communication network subject to deception attacks. Section III demonstrates the observer-based security fuzzy controller design results of this article. Simulation results are shown in Section IV. Finally, Section V concludes this article.

Notations: $\mathbb{R}^n$ denotes the n-dimensional Euclidean space, and $\mathbb{R}^{m\times n}$ is real matrices of dimension $m \times n$. $\mathbb{L}_2[0,\infty)$ is the space of square summable sequences. $\mathbb{N}^*$ is a set of positive integers. Prob$\{X\}$ stands for the occurrence probability of the event X. $\mathbb{E}\{X|Y\}$ and $\mathbb{E}\{X\}$ means expectation of X conditional on Y and expectation of X. diag$\{\cdots\}$ represents a blockdiagonal matrix. The symbol $*$ is utilized to represent a symmetric term in matrices. I and 0 denotes the identity matrix and zero matrix with proper dimensions. X^T, X^{-1} represent transpose and inverse of X. $\|\cdot\|$ is the Euclidean norm of a vector and its induced norm of a matrix. $\mathcal{H}_e\{Y\} = Y + Y^T$ means the sum of matrix Y and its transpose.

II. Problem Formulation and Preliminaries

The diagram of a nonlinear networked system described by IT2 T-S fuzzy model subject to deception attacks under WTOD protocol is shown in Fig. 1. In what follows, the IT2 T-S fuzzy model and some preliminaries related to WTOD protocol and deception attacks are introduced.

A. IT2 T-S Fuzzy Model

Consider the following nonlinear networked system described by IT2 T-S fuzzy model with s rules.

Plant Rule i: **IF** $f_1(x(k))$ is M_1^i, $f_2(x(k))$ is M_2^i, $\ldots$, $f_q(x(k))$ is M_q^i, **THEN**

$$\begin{aligned} x(k+1) &= A_i x(k) + B_i u(k) + E_i \omega(k) \\ z(k) &= C_{1i} x(k) + D_i u(k) + F_i \omega(k) \\ y(k) &= C_{2i} x(k), \quad i = 1,2,\ldots,s \end{aligned} \tag{1}$$

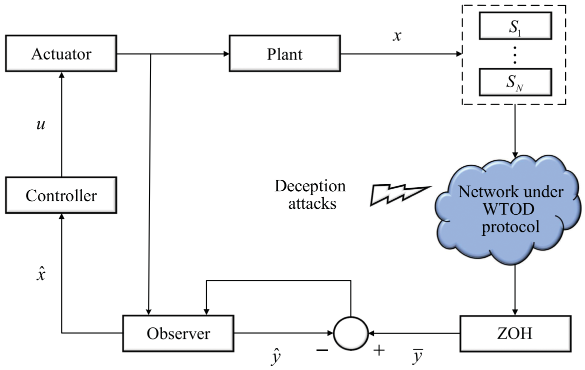

Fig. 1. Diagram of a nonlinear networked system subject to deception attacks under WTOD protocol.

where, $f_d(x(k))$ $(d = 1, 2, \ldots, q)$ stands for the premise variables, M_d^i $(i = 1, 2, \ldots, s)$ denotes the fuzzy sets, q and s represent the number of the premise variables and the IF-THEN rules of the system. $x(k) \in \mathbb{R}^{n_x}$ is the system state, $u(k) \in \mathbb{R}^{n_u}$ is control input, $z(k) \in \mathbb{R}^{n_z}$ is control output, and $y(k) \in \mathbb{R}^{n_y}$ is measured output, respectively. $\omega(k) \in \mathbb{R}^{n_\omega}$ represents the disturbance input, which belongs to $\mathbb{L}_2[0, \infty)$. $A_i, B_i, C_{1i}, C_{2i}, D_i, E_i$, and F_i are constant matrices with appropriate dimensions. For expression convenience, we denote $f(x(k)) = [f_1(x(k)), f_2(x(k)), \ldots, f_q(x(k))]^T$.

Remark 1: It is noted that the process noise and the control output measurement noise in this article are denoted as the same notation (i.e., $\omega(k)$) just for the ease of derivation. However, the effects of $\omega(k)$ on $x(k)$ and $z(k)$ are different due to the difference of coefficient matrices E_i and F_i. It should be clarified that the proposed method in this article can extend to the case when the process noise and the control output measurement noise are different by similar investigation method of this article.

The firing strength of to the ith rule can be defined as the following interval sets:

$$S_i(x(k)) = [\underline{\vartheta}_i(x(k)), \overline{\vartheta}_i(x(k))]$$

where

$$\underline{\vartheta}_i(x(k)) = \prod_{d=1}^{q} \underline{M}_d^i f_d(x(k))$$

$$\overline{\vartheta}_i(x(k)) = \prod_{d=1}^{q} \overline{M}_d^i f_d(x(k)).$$

$\underline{M}_d^i f_d(x(k))$ and $\overline{M}_d^i f_d(x(k))$ stand for the lower and upper MFs, and $\overline{M}_d^i f_d(x(k)) \geq \underline{M}_d^i f_d(x(k)) \geq 0$. $\underline{\vartheta}_i(x(k))$ and $\overline{\vartheta}_i(x(k))$ represent the lower and upper grades of membership, and $\overline{\vartheta}_i(x(k)) \geq \underline{\vartheta}_i(x(k)) > 0$.

By use of the method of singleton fuzzifier, product inference and center-average defuzzifier, the nonlinear networked system (1) can be represented as

$$x(k+1) = \sum_{i=1}^{s} \vartheta_i(x(k))[A_i x(k) + B_i u(k) + E_i \omega(k)]$$

$$z(k) = \sum_{i=1}^{s} \vartheta_i(x(k))[C_{1i} x(k) + D_i u(k) + F_i \omega(k)]$$

$$y(k) = \sum_{i=1}^{s} \vartheta_i(x(k)) C_{2i} x(k), \quad i = 1, 2, \ldots, s \tag{2}$$

where

$$\vartheta_i(x(k)) = \frac{\epsilon_i(x(k))}{\sum_{i=1}^{s} \epsilon_i(x(k))}$$

$$\epsilon_i(x(k)) = \underline{a}_i(x(k))\underline{\vartheta}_i(x(k)) + \overline{a}_i(x(k))\overline{\vartheta}_i(x(k)). \tag{3}$$

$\vartheta_i(x(k))$ is the normalized membership satisfying $\vartheta_i(x(k)) \geq 0$ and $\sum_{i=1}^{s} \vartheta_i(x(k)) = 1$. $\underline{a}_i(x(k))$ and $\overline{a}_i(x(k))$ denote the nonlinear weighting functions which satisfy $0 \leq \underline{a}_i(x(k)) \leq 1$, $0 \leq \overline{a}_i(x(k)) \leq 1$ and $\underline{a}_i(x(k)) + \overline{a}_i(x(k)) = 1$.

Remark 2: In general, the T-S fuzzy model can be categorized into two types as follows. The IT1 T-S fuzzy model and the IT2 T-S fuzzy model. In IT1 T-S fuzzy model, fuzzy sets are employed with the MFs containing no uncertainty information [42], and the accurate MF, which is utilized to approximate nonlinear networked system is usually difficult to obtain in practice [43]. In contrast, the IT2 T-S fuzzy model can preferably capture the nonlinear system subject to uncertainties in practical engineering, by utilizing the lower and the upper MFs [35], [44], [45].

Remark 3: The lower and upper MFs together with weighting functions are defined as nonlinear functions related to system state in IT2 T-S fuzzy model. It is noted that the normalized membership regulated by the nonlinear weighting functions $\underline{a}_i(x(k))$ and $\overline{a}_i(x(k))$ can be obtained by a combination of $\underline{\vartheta}_i(x(k))$ and $\overline{\vartheta}_i(x(k))$, that is, the desired normalized membership can be determined by adjusting these functions.

B. Description of Communication Network

In the considered nonlinear networked system, the measured output $y(k)$ is supposed to be transmitted through the communication network. The signal transmission process is described in Fig. 1. For analysis simplify, we assume that the sensors can be divided into N groups, which are denoted as $S_1, \ldots, S_N$. In what follows, let $y(k) = [y_1^T(k), y_2^T(k), \ldots, y_N^T(k)]^T$, and $y_m(k)$ $(m = 1, 2, \ldots, N)$ represents the measured output of the mth group of sensors.

Since the communication network between sensor groups and observer is of limited bandwidth, WTOD protocol is employed to schedule the transmission order of the sensor groups and avoid data collisions in this channel. Based on existing literature on WTOD protocol [28], we define

$$\varphi(k) = \arg \max_{1 \leq m \leq N} (y_m(k) - y_m^*(k))^T W_m((y_m(k) - y_m^*(k)) \tag{4}$$

as the selected sensor group that has the opportunity to transmit its signal at time instant k, where $y_m^*(k)$ stands for the last transmitted signal from sensor group m before time instant k. W_m is the given positive-definite weight matrix of sensor group m. Obviously, only one sensor group is allowed to transmit its measured output at each sampling instant under WTOD protocol mechanism, that is, $\varphi(k) \in \mathbb{L} \triangleq \{1, 2, \ldots, N\}$. For another, similar to [36], Bernoulli process is utilized to characterize the randomly occurring malicious deception attacks that only affect the transmitted signals in this article.

Considering the effect of protocol and attacks on system performance, a comprehensive model for the updating rule of $\bar{y}_m(k)$ is formulated as

$$\bar{y}_m(k) = \begin{cases} y_m(k) + \alpha(k)\varpi(k), & \text{if } m = \varphi(k) \\ \bar{y}_m(k-1), & \text{otherwise} \end{cases} \tag{5}$$

where, $\bar{y}_m(k)$ represents the measured output received by the observer with a zero-order holder from the mth sensor group. $\alpha(k)$ is a stochastic variable subject to Bernoulli distribution with the following probabilities:

$$\begin{aligned} \text{Prob}\{\alpha(k) = 1\} &= E\{\alpha(k)\} = \bar{\alpha} \\ \text{Prob}\{\alpha(k) = 0\} &= 1 - \bar{\alpha} \end{aligned} \tag{6}$$

and $\bar{\alpha} \in [0, 1]$ is a known constant. $\varpi(k)$ is the false signal sent by the adversary to the mth sensor group, which is assumed as $\varpi(k) = -y_m(k) + v(k)$, where $v(k)$ is the energy signal related to system state $x(k)$. Besides, for $\forall\ k \in \mathbb{N}^*$, $v(k)$ is assumed to satisfy

$$v^T(k)v(k) \leq x^T(k)G^T Gx(k) \tag{7}$$

where G is a known matrix with appropriate dimension.

By introducing Kronecker delta function $\delta(\cdot) \in \{0, 1\}$, the overall measured output $\bar{y}(k) = [\bar{y}_1^T(k), \bar{y}_2^T(k), \ldots, \bar{y}_N^T(k)]^T$ arrived at the observer can be presented as

$$\begin{aligned} \bar{y}(k) = &(1 - \alpha(k))\Phi_{\varphi(k)} y(k) + \bar{\Phi}_{\varphi(k)} \bar{y}(k-1) \\ &+ \alpha(k)\tilde{\Phi}_{\varphi(k)} v(k) \end{aligned} \tag{8}$$

where

$$\Phi_{\varphi(k)} = \text{diag}\{\delta(\varphi(k) - 1)I, \ldots, \delta(\varphi(k) - N)I\}$$

$$\bar{\Phi}_{\varphi(k)} = I - \Phi_{\varphi(k)}, \quad \tilde{\Phi}_{\varphi(k)} = \Phi_{\varphi(k)} E_y, \quad E_y = [I \cdots I]^T.$$

Without loss of generality, it is assumed that $\bar{y}(k) = 0$ for any $k < 0$.

Remark 4: Compared with the approach for WTOD protocol in [28], the zero-order holder is considered in this article. In this case, the signal sent at previous time can be used to replace the signal at the current time without considering deception attacks when one signal is not granted the privilege to transmit through communication network. From (5), it can be seen that the signal transmission is subject to deception attacks. To be specific, $\alpha(k) = 0$ represents the signal does not experience deception attacks, and the input of the observer is $y_m(k)$, $\alpha(k) = 1$ means the signal is subject to deception attacks, and the real measured output arrived at the observer is $v(k)$.

Remark 5: Security control, which deals with the control problem for networked system in the presence of malicious attacks, is acknowledged as the important research branch in current control field [46]. In the existing studies, various attack models have been proposed, such as Markov process models [47], constraint models [28], and Bernoulli models [36], [48]. Due to limitation of resources and difficulty in obtaining the information of system for adversaries, the deception attacks are not always successful, and usually occur in an intermittently or randomly way. Among these proposed models, the Bernoulli stochastic process can exactly and expediently describe the probabilistic nature of deception attacks, and then $\alpha(k)$ is introduced.

C. Observer and Controller Model

Based on the aforementioned WTOD protocol and deception attacks, the observer with s fuzzy rules is given as follows.

Observer Rule j: **IF** $f_1(\hat{x}(k))$ is M_1^j, $f_2(\hat{x}(k))$ is M_2^j,..., $f_q(\hat{x}(k))$ is M_q^j, **THEN**

$$\begin{aligned} \hat{x}(k+1) &= A_j\hat{x}(k) + B_j u(k) + L_{j,\varphi(k)}(\bar{y}(k) - \hat{y}(k)) \\ \hat{y}(k) &= C_{2j}\hat{x}(k), \quad j = 1, 2, \ldots, s \end{aligned} \tag{9}$$

where, $\hat{x}(k) \in \mathbb{R}^{n_x}$ is the estimated system state, $\bar{y}(k) \in \mathbb{R}^{n_y}$ is the measured output through communication network arrived at the observer, and $\hat{y}(k) \in \mathbb{R}^{n_y}$ is the measured output of the observer. $L_{j,\varphi(k)}$ are observer gains to be determined. The global dynamics of the fuzzy observer can be inferred as follows:

$$\begin{aligned} \hat{x}(k+1) = &\sum_{j=1}^{s} \vartheta_j(\hat{x}(k))[A_j\hat{x}(k) + B_j u(k) \\ &+ L_{j,\varphi(k)}(\bar{y}(k) - \hat{y}(k))] \\ \hat{y}(k) = &\sum_{j=1}^{s} \vartheta_j(\hat{x}(k)) C_{2j}\hat{x}(k), \quad j = 1, 2, \ldots, s. \end{aligned} \tag{10}$$

An IT2 fuzzy controller with s fuzzy rules is presented in the following format.

Controller Rule l: **IF** $g_1(\hat{x}(k))$ is W_1^l, $g_2(\hat{x}(k))$ is W_2^l,..., $g_p(\hat{x}(k))$ is W_p^l, **THEN**

$$u(k) = K_{l,\varphi(k)}\hat{x}(k), \quad l = 1, 2, \ldots, s \tag{11}$$

where, $g_c(\hat{x}(k))$ $(c = 1, 2, \ldots, p)$ stands for the premise variables, W_c^l $(l = 1, 2, \ldots, s)$ denotes the fuzzy sets, p and s represent the number of the premise variables and the IF-THEN rules. $K_{l,\varphi(k)}$ are controller gains with appropriate dimensions to be designed. For the sake of simplicity, we denote $g(\hat{x}(k)) = [g_1(\hat{x}(k)), g_2(\hat{x}(k)), \ldots, g_p(\hat{x}(k))]^T$.

The following interval sets define the firing strength of the lth rule:

$$T_l(\hat{x}(k)) = [\underline{\sigma}_l(\hat{x}(k)), \overline{\sigma}_l(\hat{x}(k))]$$

where

$$\underline{\sigma}_l(\hat{x}(k)) = \prod_{c=1}^{p} \underline{W}_c^l g_c(\hat{x}(k))$$

$$\overline{\sigma}_l(\hat{x}(k)) = \prod_{c=1}^{p} \overline{W}_c^l g_c(\hat{x}(k)).$$

$\underline{W}_c^l g_c(\hat{x}(k))$ and $\overline{W}_c^l g_c(\hat{x}(k))$ stand for the lower and upper MFs, and $\overline{W}_c^l g_c(\hat{x}(k)) \geq \underline{W}_c^l g_c(\hat{x}(k)) \geq 0$. $\underline{\sigma}_l(\hat{x}(k))$ and $\overline{\sigma}_l(\hat{x}(k))$ represent the lower and upper grades of membership, and $\overline{\sigma}_l(\hat{x}(k)) \geq \underline{\sigma}_l(\hat{x}(k)) > 0$.

Then, the fuzzy controller is formulated as follows:

$$u(k)=\sum_{l=1}^{s}\sigma_l(\hat{x}(k))K_{l,\varphi(k)}\hat{x}(k),\quad l=1,2,\ldots,s \tag{12}$$

where

$$\sigma_l(\hat{x}(k))=\frac{\kappa_l(\hat{x}(k))}{\sum_{l=1}^{s}\kappa_l(\hat{x}(k))}$$
$$\kappa_l(\hat{x}(k))=\underline{b}_l(\hat{x}(k))\underline{\sigma}_l(\hat{x}(k))+\overline{b}_l(\hat{x}(k))\overline{\sigma}_l(\hat{x}(k)).$$

$\sigma_l(\hat{x}(k))$ is the normalized membership satisfying $\sigma_l(\hat{x}(k))\geq 0$ and $\sum_{l=1}^{s}\sigma_l(\hat{x}(k))=1$. $\underline{b}_l(\hat{x}(k))$ and $\overline{b}_l(\hat{x}(k))$ denote the nonlinear weighting functions which satisfy $0\leq\underline{b}_l(\hat{x}(k))\leq 1$, $0\leq\overline{b}_l(\hat{x}(k))\leq 1$, and $\underline{b}_l(\hat{x}(k))+\overline{b}_l(\hat{x}(k))=1$.

Remark 6: Although some observer-based fuzzy control and security fuzzy control have been conducted in [13], [19], [41], but the addressed problem in this article is different from the existing ones. Security control problem for the T-S fuzzy systems with the effects of quantization, communication protocol, and deception attacks was solved in [13] under conventional parallel distribution compensation control strategy. In [19], the problem of an event-triggered nonparallel distribution compensation control was addressed for networked T-S fuzzy systems. The authors in [41] investigated the observer-based fuzzy control for nonlinear networked system in the absence of malicious attack and communication protocol, and therefore it cannot be applied to scenario when deception attacks occur in the transmission channel scheduled by WTOD protocol. However, the abovementioned references are based on one of the assumption that the MFs are perfect matched and the addressed systems work in safe environments, which is actually unrealistic. To be more realistic, in this article, with consideration of nonparallel distribution compensation control strategy, WTOD protocol and deception attacks, we present an observer-based security fuzzy controller design approach for nonlinear networked system.

D. Augmented Closed-Loop IT2 T-S Fuzzy System

For expression convenience, we define $t\triangleq\varphi(k)$, $h\triangleq\varphi(k+1)$. In addition, according to (2), (10), and (12), defining $e(k)=x(k)-\hat{x}(k)$ to represent estimation error, one has

$$\begin{aligned}x(k+1)&=\sum_{i=1}^{s}\vartheta_i(x(k))[A_ix(k)+B_iu(k)+E_i\omega(k)]\\&=\sum_{i=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\sigma_l(\hat{x}(k))\\&\quad[(A_i+B_iK_{l,t})\hat{x}(k)+A_ie(k)+E_i\omega(k)]\end{aligned}\tag{13}$$

$$\begin{aligned}\hat{x}(k+1)&=\sum_{j=1}^{s}\vartheta_j(\hat{x}(k))[A_j\hat{x}(k)+B_ju(k)\\&\quad+L_{j,t}(\bar{y}(k)-\hat{y}(k))]\\&=\sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\sigma_l(\hat{x}(k))\\&\quad(A_j+B_jK_{l,t}+(1-\alpha(k))L_{j,t}\Phi_tC_{2i}\\&\quad-L_{j,t}C_{2j})\hat{x}(k)+(1-\alpha(k))L_{j,t}\Phi_tC_{2i}e(k)\\&\quad+L_{j,t}\bar{\Phi}_t\bar{y}(k-1)+\alpha(k)L_{j,t}\tilde{\Phi}_tv(k)\end{aligned}\tag{14}$$

$$\begin{aligned}e(k+1)&=\sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\sigma_l(\hat{x}(k))\\&\quad(A_i-A_j+(B_i-B_j)K_{l,t}-(1-\alpha(k))\\&\quad\times L_{j,t}\Phi_tC_{2i}+L_{j,t}C_{2j})\hat{x}(k)\\&\quad+(A_i-(1-\alpha(k))L_{j,t}\Phi_tC_{2i})e(k)+E_i\omega(k)\\&\quad-L_{j,t}\bar{\Phi}_t\bar{y}(k-1)-\alpha(k)L_{j,t}\tilde{\Phi}_tv(k)\end{aligned}\tag{15}$$

$$\begin{aligned}z(k)&=\sum_{i=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\sigma_l(\hat{x}(k))\\&\quad[(C_{1i}+D_iK_{l,t})\hat{x}(k)+C_{1i}e(k)+F_i\omega(k)].\end{aligned}\tag{16}$$

Based on (8), (14)–(16), let $\xi(k)=[\hat{x}^T(k)\quad e^T(k)\quad \bar{y}^T(k-1)]^T$, the augmented closed-loop IT2 T-S fuzzy system can be inferred as follows:

$$\begin{aligned}\xi(k+1)&=\sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\sigma_l(\hat{x}(k))\\&\quad[(\digamma_{1ijlt}+\digamma_{2ijlt})\xi(k)+\bar{E}_i\omega(k)\\&\quad+(\digamma_{3ijlt}+\digamma_{4ijlt})v(k)]\\z(k)&=\sum_{i=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\sigma_l(\hat{x}(k))[C_{ilt}\xi(k)+F_i\omega(k)]\end{aligned}\tag{17}$$

where

$$\digamma_{1ijlt}=\begin{bmatrix}\Pi_{1ijlt}&\vec{\alpha}L_{j,t}\Phi_tC_{2i}&L_{j,t}\bar{\Phi}_t\\\Pi_{2ijlt}&\Pi_{3ijlt}&-L_{j,t}\bar{\Phi}_t\\\vec{\alpha}\Phi_tC_{2i}&\vec{\alpha}\Phi_tC_{2i}&\bar{\Phi}_t\end{bmatrix}$$

$$\digamma_{2ijlt}=\begin{bmatrix}-\tilde{\alpha}(k)L_{j,t}\Phi_tC_{2i}&-\tilde{\alpha}(k)L_{j,t}\Phi_tC_{2i}&0\\\tilde{\alpha}(k)L_{j,t}\Phi_tC_{2i}&\tilde{\alpha}(k)L_{j,t}\Phi_tC_{2i}&0\\-\tilde{\alpha}(k)\Phi_tC_{2i}&-\tilde{\alpha}(k)\Phi_tC_{2i}&0\end{bmatrix}$$

$$\digamma_{3ijlt}=\begin{bmatrix}\bar{\alpha}L_{j,t}\tilde{\Phi}_t\\-\bar{\alpha}L_{j,t}\tilde{\Phi}_t\\\bar{\alpha}\tilde{\Phi}_t\end{bmatrix},\quad\digamma_{4ijlt}=\begin{bmatrix}\tilde{\alpha}(k)L_{j,t}\tilde{\Phi}_t\\-\tilde{\alpha}(k)L_{j,t}\tilde{\Phi}_t\\\tilde{\alpha}(k)\tilde{\Phi}_t\end{bmatrix}$$

$$\begin{aligned}\Pi_{1ijlt}&=A_j+B_jK_{l,t}+\vec{\alpha}L_{j,t}\Phi_tC_{2i}-L_{j,t}C_{2j}\\\Pi_{2ijlt}&=A_i-A_j+(B_i-B_j)K_{l,t}-\vec{\alpha}L_{j,t}\Phi_tC_{2i}+L_{j,t}C_{2j}\\\Pi_{3ijlt}&=A_i-\vec{\alpha}L_{j,t}\Phi_tC_{2i},\ \bar{E}_i=[0\quad E_i^T\quad 0]^T\\\vec{\alpha}&=1-\bar{\alpha},\ \ \tilde{\alpha}(k)=\alpha(k)-\bar{\alpha}\\C_{ilt}&=[C_{1i}+D_iK_{l,t}\quad C_{1i}\quad 0].\end{aligned}$$

In addition, from (6), it is not hard to obtain that

$$E\{\tilde{\alpha}(k)\}=0,\quad E\{\tilde{\alpha}(k)\tilde{\alpha}(k)\}=\bar{\alpha}\vec{\alpha}.$$

Based on the content elaborated previously, we aim to investigate the observer-based security fuzzy control problem for the nonlinear networked system (1) under WTOD protocol subject to deception attacks. Before ending this section, the following definition and lemma which will be utilized to derive the sufficient conditions for the fuzzy observer and controller are introduced.

Definition 1: (See [44]) Under initial condition $\xi(0)$, when $\omega(k) \equiv 0$, the stochastical stability of the augmented closed-loop IT2 T-S fuzzy system (17) can be derived if there is a matrix $\Theta > 0$ such that

$$E\left\{\sum_{k=0}^{r} \|\xi(k)\|^2\right\} \leq \xi^T(0)\Theta\xi(0). \tag{18}$$

Lemma 1: (See [36]) For given $B \in \mathbb{R}^{n_x \times n_u}$ with $\mathrm{rank}(B) = n_u$, the singular value decomposition (SVD) for B can be described as

$$B = U\begin{bmatrix} S \\ 0 \end{bmatrix} V^T$$

where, U and V are orthogonal matrices, with $U^TU = I$ and $V^TV = I$. Let matrices $Y > 0, D \in \mathbb{R}^{n_x \times n_x}$, and $E \in \mathbb{R}^{n_u \times n_x}$, there exists matrix $\bar{Y}$ such that $\bar{Y}B = BY$ holds if and only if the following condition holds:

$$Y = U\begin{bmatrix} D & 0 \\ 0 & E \end{bmatrix} U^T. \tag{19}$$

III. Observer-Based Security Fuzzy Controller Design

In this section, the sufficient conditions for the stochastically stability of system (17) with given disturbance attenuation level are analyzed in the presence of WTOD protocol and deception attacks. Then, the observer gains and controller gains are derived by solving a set of LMIs.

A. Stability Analysis and Performance Guarantee

The following theorem gives the sufficient conditions that ensure the stochastical stability of system (17) with the predefined disturbance attenuation performance index.

Theorem 1: For given observer gains $L_{j,t}$ $(t \in \mathbb{L})$, controller gains $K_{l,t}, \sigma_l(\hat{x}(k)) - \tau_l\vartheta_l(\hat{x}(k)) > 0$ $(\tau_l > 0)$, predefined disturbance attenuation performance index γ and positive scalar $\bar{\alpha}$, the stochastically stability of the augmented closed-loop IT2 T-S fuzzy system (17) can be obtained if there exist positive-define matrices $P_t > 0$ and Λ with appropriate dimensions satisfying the following inequalities:

$$\bar{\Omega}_{ijlth} + \bar{\Omega}_{iljth} - 2\Lambda < 0,\ j \leq l \tag{20}$$

$$\tau_l\bar{\Omega}_{ijlth} + \tau_j\bar{\Omega}_{iljth} - \tau_l\Lambda - \tau_j\Lambda + 2\Lambda < 0,\ j \leq l \tag{21}$$

where

$$\bar{\Omega}_{ijlth} = \Omega_{ijlth} + \Theta_{ilt}$$

$$\Omega_{ijlth} = \begin{bmatrix} \Upsilon_{1ijlth} & * & * \\ \Upsilon_{2ijlth} & \Upsilon_{3ijlth} & * \\ \bar{E}_i^T P_h \digamma_{1ijlt} & \bar{E}_i^T P_h \digamma_{3ijlt} & \bar{E}_i^T P_h \bar{E}_i \end{bmatrix}$$

$$\Theta_{ilt} = \begin{bmatrix} C_{ilt}^T C_{ilt} & * & * \\ 0 & 0 & * \\ F_i^T C_{ilt} & 0 & F_i^T F_i - \gamma^2 I \end{bmatrix}$$

$$\Upsilon_{1ijlth} = \digamma_{1ijlt}^T P_h \digamma_{1ijlt} + \bar{\digamma}_{2ijlt}^T P_h \bar{\digamma}_{2ijlt} - P_t + \bar{G}$$

$$\Upsilon_{2ijlth} = \digamma_{3ijlt}^T P_h \digamma_{1ijlt} + \bar{\digamma}_{4ijlt}^T P_h \bar{\digamma}_{2ijlt}$$

$$\Upsilon_{3ijlth} = \digamma_{3ijlt}^T P_h \digamma_{3ijlt} + \bar{\digamma}_{4ijlt}^T P_h \bar{\digamma}_{4ijlt} - I$$

$$\bar{\digamma}_{2ijlt} = \begin{bmatrix} -\sqrt{\bar{\alpha}\vec{\alpha}}L_{j,t}\Phi_t C_{2i} & -\sqrt{\bar{\alpha}\vec{\alpha}}L_{j,t}\Phi_t C_{2i} & 0 \\ \sqrt{\bar{\alpha}\vec{\alpha}}L_{j,t}\Phi_t C_{2i} & \sqrt{\bar{\alpha}\vec{\alpha}}L_{j,t}\Phi_t C_{2i} & 0 \\ -\sqrt{\bar{\alpha}\vec{\alpha}}\Phi_t C_{2i} & -\sqrt{\bar{\alpha}\vec{\alpha}}\Phi_t C_{2i} & 0 \end{bmatrix}$$

$$\bar{\digamma}_{4ijlt} = \begin{bmatrix} \sqrt{\bar{\alpha}\vec{\alpha}}L_{j,t}\tilde{\Phi}_t \\ -\sqrt{\bar{\alpha}\vec{\alpha}}L_{j,t}\tilde{\Phi}_t \\ \sqrt{\bar{\alpha}\vec{\alpha}}\tilde{\Phi}_t \end{bmatrix},\quad \bar{G} = \begin{bmatrix} G^TG & * & * \\ G^TG & G^TG & * \\ 0 & 0 & 0 \end{bmatrix}.$$

Proof: Construct the following Lyapunov function:

$$V(k) = \xi^T(k)P_t\xi(k) \tag{22}$$

and define the forward difference of $V(k)$ as $\Delta V(k) \triangleq V(k+1) - V(k)$.

Denote $\zeta(k) = [\xi^T(k) \quad v^T(k) \quad \omega^T(k)]^T$. Considering the effects of WTOD protocol and deception attacks, recalling (7) and (22), it can be derived that

$$\begin{aligned} E\{\Delta V(k)\} &\leq E\{\xi^T(k+1)P_h\xi(k+1) - \xi^T(k)P_t\xi(k)\} \\ &\quad + x^T(k)G^TGx(k) - v^T(k)v(k) \\ &= E\Bigg\{\sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\sigma_l(\hat{x}(k)) \\ &\quad \times [(\digamma_{1ijlt} + \digamma_{2ijlt})\xi(k) + \bar{E}_i\omega(k) \\ &\quad + (\digamma_{3ijl} + \digamma_{4ijl})v(k)]^T P_h \\ &\quad \times [(\digamma_{1ijlt} + \digamma_{2ijlt})\xi(k) + \bar{E}_i\omega(k) \\ &\quad + (\digamma_{3ijlt} + \digamma_{4ijlt})v(k)] \\ &\quad - \xi^T(k)P_t\xi(k)\Bigg\} + x^T(k)G^TGx(k) \\ &\quad - v^T(k)v(k) \\ &= \sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\sigma_l(\hat{x}(k)) \\ &\quad \times \zeta^T(k)\Omega_{ijlth}\zeta(k). \end{aligned} \tag{23}$$

Similar to [41], a slack matrix is introduced

$$\sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))[(\vartheta_l(\hat{x}(k)) - \sigma_l(\hat{x}(k)))\Lambda]$$

$$= \sum_{i=1}^{s}\sum_{j=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k)) \times \left[\left(\sum_{l=1}^{s}\vartheta_l(\hat{x}(k)) - \sum_{l=1}^{s}\sigma_l(\hat{x}(k))\right)\Lambda\right] = 0. \quad (24)$$

Then, we have

$$\begin{aligned} E\{\Delta V(k)\} \leq & \sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\zeta^T(k) \\ & [\sigma_l(\hat{x}(k))\Omega_{ijlth} + (\vartheta_l(\hat{x}(k)) - \sigma_l(\hat{x}(k)))\Lambda]\zeta(k) \\ = & \sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\zeta^T(k) \\ & [\vartheta_l(\hat{x}(k))(\tau_l\Omega_{ijlth} - \tau_l\Lambda + \Lambda) \\ & + (\sigma_l(\hat{x}(k)) - \tau_l\vartheta_l(\hat{x}(k)))(\Omega_{ijlth} - \Lambda)]\zeta(k). \end{aligned} \quad (25)$$

According to (20) and (21), when $\omega(k) \equiv 0$, we can get

$$\begin{aligned} \Psi \triangleq & \sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\zeta^T(k) \\ & [\vartheta_l(\hat{x}(k))(\tau_l\Sigma_{1ijlth} - \tau_l\Lambda_1 + \Lambda_1) \\ & + (\sigma_l(\hat{x}(k)) - \tau_l\vartheta_l(\hat{x}(k)))(\Sigma_{1ijlth} - \Lambda_1)]\zeta(k) < 0 \end{aligned}$$

where

$$\Sigma_{1ijlth} = \begin{bmatrix} \Upsilon_{1ijlth} & * \\ \Upsilon_{2ijlth} & \Upsilon_{3ijlth} \end{bmatrix}, \quad \Lambda = \begin{bmatrix} \Lambda_1 & \Lambda_3 \\ \Lambda_2 & \Lambda_4 \end{bmatrix}$$

and Λ_1 is the upper left block of Λ.

Then, summarize the abovementioned discussions, we have

$$E\{\Delta V(k)\} \leq -\lambda_{\min}(-\Psi)\xi^T(k)\xi(k) \quad (26)$$

that is

$$\begin{aligned} E\left\{\sum_{k=0}^{r}\|\xi(k)\|^2\right\} \leq & (\lambda_{\min}(-\Psi))^{-1}\{\xi^T(0)P_t\xi(0) \\ & - E\{\xi^T(r+1)P_h\xi(r+1)\}\} \\ \leq & (\lambda_{\min}(-\Psi))^{-1}\xi^T(0)P_t\xi(0) \\ = & \xi^T(0)\Theta\xi(0) \end{aligned} \quad (27)$$

where, $\xi(0)$ is the initial value, $\Theta = (\lambda_{\min}(-\Psi))^{-1}P_t > 0$. Therefore, according to Definition 1, the augmented closed-loop IT2 T-S fuzzy system (17) is stochastically stable. Following the problem investigated, we consider the disturbance rejection performance of this system under zero initial condition subsequently.

According to (17) and (25), it can be obtain that

$$\begin{aligned} & E\{\Delta V(k)|\zeta(k)\} + E\{z^T(k)z(k)|\zeta(k)\} - \gamma^2\omega^T(k)\omega(k) \\ & \leq \sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\sigma_l(\hat{x}(k))\zeta^T(k)\bar{\Omega}_{ijlth}\zeta(k) \\ & = \sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\zeta^T(k) \\ & [\vartheta_l(\hat{x}(k))(\tau_l\bar{\Omega}_{ijlth} - \tau_l\Lambda + \Lambda) \\ & + (\sigma_l(\hat{x}(k)) - \tau_l\vartheta_l(\hat{x}(k)))(\bar{\Omega}_{ijlth} - \Lambda)]\zeta(k) \\ & = \frac{1}{2}\sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{l=1}^{s}\vartheta_i(x(k))\vartheta_j(\hat{x}(k))\zeta^T(k) \\ & [\vartheta_l(\hat{x}(k))(\tau_l\bar{\Omega}_{ijlth} + \tau_j\bar{\Omega}_{iljth} - \tau_l\Lambda - \tau_j\Lambda + 2\Lambda) \\ & + (\sigma_l(\hat{x}(k)) - \tau_l\vartheta_l(\hat{x}(k)))(\bar{\Omega}_{ijlth} + \bar{\Omega}_{iljth} - 2\Lambda)]\zeta(k). \end{aligned} \quad (28)$$

In light of (20) and (21), one has

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

then, it is derived that

$$E\left\{\sqrt{\sum_{k=0}^{\infty}z^T(k)z(k)}\right\} \leq \gamma\|\omega(k)\|_2$$

and the proof of Theorem 1 is completed. ■

Remark 7: The Lyapunov function in (22) is identified with t which is induced by WTOD protocol. In this case, the corresponding Lyapunov function is guaranteed for different scheduling situations under WTOD protocol mechanism. Accordingly, this method can reduce the conservation compared to the common Lyapunov function proposed in [12].

Remark 8: The asynchronous premise variables and imperfectly matched MFs make the handling approach under conventional parallel distribution compensation strategy [13] inapplicable. To tackle this problem, the slack matrix employed by [41] and [44] is adopted in Theorem 1.

B. Observer and Controller Design

The sufficient conditions that guarantee the stochastic stability of the system (17) with predefined disturbance attenuation performance level are derived based on the given observer and controller gain matrices in Theorem 1, then the following theorem that provides a design method for the desired observer-based controller is presented consequently.

Theorem 2: Under $\sigma_l(\hat{x}(k)) - \tau_l\vartheta_l(\hat{x}(k)) > 0$ $(\tau_l > 0)$, for given positive scalar $\bar{\alpha}$, the augmented closed-loop IT2 T-S fuzzy system (17) is stochastically stable with predefined disturbance attenuation performance index γ if there exist positive-define matrices $P_t > 0$, $Y_t > 0, U_{j,t}$ $(t \in \mathbb{L})$ and Λ with appropriate dimensions such that the following LMIs hold:

$$\begin{bmatrix} 2\vec{P}_{th} & * \\ \vec{\Xi}_{ijlt} + \vec{\Xi}_{iljt} & 2\aleph \end{bmatrix} < 0, \quad j \leq l \quad (29)$$

$$\begin{bmatrix} 2\vec{P}_{th} & * \\ \sqrt{\tau_l}\vec{\Xi}_{ijlt} + \sqrt{\tau_j}\vec{\Xi}_{iljt} & \Delta \end{bmatrix} < 0, \quad j \leq l \quad (30)$$

with $L_{j,t} = (U_{j,t}(Y_t^T)^{-1})^T, L_{l,t} = (U_{l,t}(Y_t^T)^{-1})^T$, and in which

$$\vec{P}_{th} = \mathrm{diag}\{P_{1,h} - \mathcal{H}_e\{Y_t\}, P_{2,h} - \mathcal{H}_e\{Y_t\}, P_{3,h} - \mathcal{H}_e\{Y_t\}, P_{1,h} - \mathcal{H}_e\{Y_t\}, P_{2,h} - \mathcal{H}_e\{Y_t\} P_{3,h} - \mathcal{H}_e\{Y_t\}, -I\}$$

$$\vec{\Xi}_{ijlt} = \begin{bmatrix} \vec{F}_{1ijlt}^T & \tilde{F}_{2ijlt}^T & C_{ilt}^T \\ \tilde{F}_{3ijlt}^T & \tilde{F}_{4ijlt}^T & 0 \\ \bar{E}_i^T Y_t^T & 0 & F_i^T \end{bmatrix}$$

$$\vec{F}_{1ijlt}^T = \begin{bmatrix} \vec{\Pi}_{1ijlt} & \vec{\Pi}_{2ijlt} & \vec{\alpha} C_{2i}^T \Phi_t^T Y_t^T \\ \vec{\alpha} C_{2i}^T \Phi_t^T U_{j,t} & \vec{\Pi}_{3ijlt} & \vec{\alpha} C_{2i}^T \Phi_t^T Y_t^T \\ \bar{\Phi}_t^T U_{j,t} & -\bar{\Phi}_t^T U_{j,t} & \bar{\Phi}_t^T Y_t^T \end{bmatrix}$$

$$\tilde{F}_{2ijlt}^T = \begin{bmatrix} -\tilde{\Pi}_{4ijlt} & \tilde{\Pi}_{4ijlt} & -\sqrt{\bar{\alpha}\vec{\alpha}} C_{2i}^T \Phi_t^T Y_t^T \\ -\tilde{\Pi}_{4ijlt} & \tilde{\Pi}_{4ijlt} & -\sqrt{\bar{\alpha}\vec{\alpha}} C_{2i}^T \Phi_t^T Y_t^T \\ 0 & 0 & 0 \end{bmatrix}$$

$$\tilde{F}_{3ijlt}^T = \begin{bmatrix} \bar{\alpha}\tilde{\Phi}_t^T U_{j,t} & -\bar{\alpha}\tilde{\Phi}_t^T U_{j,t} & \bar{\alpha}\tilde{\Phi}_t^T Y_t^T \end{bmatrix}$$

$$\tilde{F}_{4ijlt}^T = \begin{bmatrix} \sqrt{\bar{\alpha}\vec{\alpha}}\tilde{\Phi}_t^T U_{j,t} & -\sqrt{\bar{\alpha}\vec{\alpha}}\tilde{\Phi}_t^T U_{j,t} & \sqrt{\bar{\alpha}\vec{\alpha}}\tilde{\Phi}_t^T Y_t^T \end{bmatrix}$$

$$\vec{\Pi}_{1ijlt} = A_j^T Y_t^T + \bar{V}_{ltj} B_j^T + \vec{\alpha} C_{2i}^T \Phi_t^T U_{j,t} - C_{2j}^T U_{j,t}$$

$$\vec{\Pi}_{2ijlt} = A_i^T Y_t^T - A_j^T Y_t^T + \bar{V}_{lti} B_i^T - \bar{V}_{ltj} B_j^T - \vec{\alpha} C_{2i}^T \Phi_t^T U_{j,t} + C_{2j}^T U_{j,t}$$

$$\vec{\Pi}_{1iljt} = A_l^T Y_t^T + \bar{V}_{jtl} B_l^T + \vec{\alpha} C_{2i}^T \Phi_t^T U_{l,t} - C_{2l}^T U_{l,t}$$

$$\vec{\Pi}_{2iljt} = A_i^T Y_t^T - A_l^T Y_t^T + \bar{V}_{jti} B_i^T - \bar{V}_{jtl} B_l^T - \vec{\alpha} C_{2i}^T \Phi_t^T U_{l,t} + C_{2l}^T U_{l,t}$$

$$\tilde{\Pi}_{3ijlt} = A_i^T Y_t^T - \vec{\alpha} C_{2i}^T \Phi_t^T U_{j,t}, \quad \tilde{\Pi}_{4ijlt} = \sqrt{\bar{\alpha}\vec{\alpha}} C_{2i}^T \Phi_t^T U_{j,t}$$

$$\aleph = \begin{bmatrix} \aleph_1 & \aleph_2 \\ \aleph_3 & \aleph_4 \end{bmatrix}, \quad \Delta = \begin{bmatrix} \Delta_1 & \Delta_2 \\ \Delta_3 & \Delta_4 \end{bmatrix}$$

$$\aleph_1 = \begin{bmatrix} \aleph_{11} & \aleph_{12} & -\Lambda_{13} \\ \aleph_{21} & \aleph_{22} & -\Lambda_{23} \\ -\Lambda_{31} & -\Lambda_{32} & -P_{3,t} - \Lambda_{33} \end{bmatrix}$$

$$\aleph_2 = \begin{bmatrix} -\Lambda_{14} & -\Lambda_{15} \\ -\Lambda_{24} & -\Lambda_{25} \\ -\Lambda_{34} & -\Lambda_{35} \end{bmatrix}, \aleph_3 = \begin{bmatrix} -\Lambda_{41} & -\Lambda_{42} & -\Lambda_{43} \\ -\Lambda_{51} & -\Lambda_{52} & -\Lambda_{53} \end{bmatrix},$$

$$\aleph_4 = \begin{bmatrix} -I - \Lambda_{44} & -\Lambda_{45} \\ -\Lambda_{54} & -\gamma^2 I - \Lambda_{55} \end{bmatrix},$$

$$\aleph_{11} = -P_{1,t} + G^T G - \Lambda_{11}, \quad \aleph_{12} = G^T G - \Lambda_{12},$$

$$\aleph_{21} = G^T G - \Lambda_{21}, \quad \aleph_{22} = -P_{2,t} + G^T G - \Lambda_{22},$$

$$\Delta_1 = \begin{bmatrix} \Delta_{11} & \Delta_{12} & \bar{\tau}_{lj}\Lambda_{13} \\ \Delta_{21} & \Delta_{22} & \bar{\tau}_{lj}\Lambda_{23} \\ \bar{\tau}_{lj}\Lambda_{31} & \bar{\tau}_{lj}\Lambda_{32} & \Delta_{33} \end{bmatrix}$$

$$\Delta_2 = -\bar{\tau}_{lj}\aleph_2, \quad \Delta_3 = -\bar{\tau}_{lj}\aleph_3$$

$$\Delta_4 = \begin{bmatrix} -\tau_{lj} I + \bar{\tau}_{lj}\Lambda_{44} & \bar{\tau}_{lj}\Lambda_{45} \\ \bar{\tau}_{lj}\Lambda_{54} & -\tau_{lj}\gamma^2 I + \bar{\tau}_{lj}\Lambda_{55} \end{bmatrix}$$

$$\Delta_{11} = -\tau_{lj} P_{1,t} + \tau_{lj} G^T G + \bar{\tau}_{lj}\Lambda_{11}$$

$$\Delta_{12} = \tau_{lj} G^T G + \bar{\tau}_{lj}\Lambda_{12}, \quad \Delta_{21} = \tau_{lj} G^T G + \bar{\tau}_{lj}\Lambda_{21}$$

$$\Delta_{22} = -\tau_{lj} P_{2,t} + \tau_{lj} G^T G + \bar{\tau}_{lj}\Lambda_{22}$$

$$\Delta_{33} = -\tau_{lj} P_{3,t} + \bar{\tau}_{lj}\Lambda_{33}$$

$$\tau_{lj} = \tau_l + \tau_j, \quad \bar{\tau}_{lj} = 2 - \tau_{lj}.$$

Proof: According to Schur complement lemma, (20) and (21) hold if and only if the following matrices hold:

$$\begin{bmatrix} 2\bar{P}_h & * \\ \Xi_{ijlt} + \Xi_{iljt} & 2\aleph \end{bmatrix} < 0, \quad j \le l \tag{31}$$

$$\begin{bmatrix} 2\bar{P}_h & * \\ \sqrt{\tau_l}\Xi_{ijlt} + \sqrt{\tau_j}\Xi_{iljt} & \Delta \end{bmatrix} < 0, \quad j \le l \tag{32}$$

where

$$\bar{P}_h = \mathrm{diag}\{-P_h^{-1}, -P_h^{-1}, -I\}$$

$$P_h = \mathrm{diag}\{P_{1,h}, P_{2,h}, P_{3,h}\}$$

$$\Xi_{ijlt} = \begin{bmatrix} F_{1ijlt}^T & F_{2ijlt}^T & C_{ilt}^T \\ F_{3ijlt}^T & F_{4ijlt}^T & 0 \\ \bar{E}_i^T & 0 & F_i^T \end{bmatrix}.$$

Premultiplying and postmultiplying (31) and (32) by $\mathrm{diag}\{Y_t, Y_t, I, I, I, I\}$ and its transpose, one has that

$$\begin{bmatrix} 2\tilde{P}_{th} & * \\ \tilde{\Xi}_{ijlt} + \tilde{\Xi}_{iljt} & 2\aleph \end{bmatrix} < 0, \quad j \le l \tag{33}$$

$$\begin{bmatrix} 2\tilde{P}_{th} & * \\ \sqrt{\tau_l}\tilde{\Xi}_{ijlt} + \sqrt{\tau_j}\tilde{\Xi}_{iljt} & \Delta \end{bmatrix} < 0, \quad j \le l \tag{34}$$

where

$$\tilde{P}_{th} = \mathrm{diag}\{-Y_t P_h^{-1} Y_t^T, -Y_t P_h^{-1} Y_t^T, -I\}$$

$$\tilde{\Xi}_{ijlt} = \begin{bmatrix} \tilde{F}_{1ijlt}^T & \tilde{F}_{2ijlt}^T & C_{ilt}^T \\ \tilde{F}_{3ijlt}^T & \tilde{F}_{4ijlt}^T & 0 \\ \bar{E}_i^T Y_t^T & 0 & F_i^T \end{bmatrix}$$

$$\tilde{F}_{1ijlt}^T = \begin{bmatrix} \tilde{\Pi}_{1ijlt} & \tilde{\Pi}_{2ijlt} & \vec{\alpha} C_{2i}^T \Phi_t^T Y_t^T \\ \vec{\alpha} C_{2i}^T \Phi_t^T U_{j,t} & \tilde{\Pi}_{3ijlt} & \vec{\alpha} C_{2i}^T \Phi_t^T Y_t^T \\ \bar{\Phi}_t^T U_{j,t} & -\bar{\Phi}_t^T U_{j,t} & \bar{\Phi}_t^T Y_t^T \end{bmatrix}$$

$$\tilde{\Pi}_{1ijlt} = A_j^T Y_t^T + K_{l,t}^T B_j^T Y_t^T + \vec{\alpha} C_{2i}^T \Phi_t^T U_{j,t} - C_{2j}^T U_{j,t}$$

$$\tilde{\Pi}_{2ijlt} = A_i^T Y_t^T - A_j^T Y_t^T + K_{l,t}^T (B_i - B_j)^T Y_t^T - \vec{\alpha} C_{2i}^T \Phi_t^T U_{j,t} + C_{2j}^T U_{j,t}$$

$$\tilde{\Pi}_{1iljt} = A_l^T Y_t^T + K_{j,t}^T B_l^T Y_t^T + \vec{\alpha} C_{2i}^T \Phi_t^T U_{l,t} - C_{2l}^T U_{l,t}$$

$$\tilde{\Pi}_{2iljt} = A_i^T Y_t^T - A_l^T Y_t^T + K_{j,t}^T (B_i - B_l)^T Y_t^T - \vec{\alpha} C_{2i}^T \Phi_t^T U_{l,t} + C_{2l}^T U_{l,t}.$$

Note that the SVD for $B_i \in \mathbb{R}^{n_x \times n_u}$ with the full rank matrix is $B_i = U_i \begin{bmatrix} S_i \\ 0 \end{bmatrix} V_i^T$, in which $U_i^T U_i = I$ and $V_i^T V_i = I$. By Lemma 1, for $Y_t^T = U_i \begin{bmatrix} D_{it} & 0 \\ 0 & E_{it} \end{bmatrix} U_i^T$, one can obtain that $\bar{Y}_{ti}^T B_i^T = B_i^T Y_t^T$ with $\bar{Y}_{ti}^T = V_i^T S_i^{-1} D_{it} S_i V_i^T$, $\bar{Y}_{tj}^T B_j^T = B_j^T Y_t^T$ with $\bar{Y}_{tj}^T = V_j^T S_j^{-1} D_{jt} S_j V_j^T$, $\bar{Y}_{tl}^T B_l^T = B_l^T Y_t^T$ with $\bar{Y}_{tl}^T = V_l^T S_l^{-1} D_{lt} S_l V_l^T$.

In addition, for positive-define matrices P_h, we have $P_{1,h}^{-1} > 0, P_{2,h}^{-1} > 0, P_{3,h}^{-1} > 0$. If there exist a nonsingular matrix Y_t, the following inequality holds:

$$(P_{1,h} - Y_t) P_{1,h}^{-1} (P_{1,h} - Y_t)^T \geq 0$$

which yields

$$-Y_t P_{1,h}^{-1} Y_t^T \leq P_{1,h} - \mathcal{H}_e\{Y_t\}.$$

Similarly

$$-Y_t P_{2,h}^{-1} Y_t^T \leq P_{2,h} - \mathcal{H}_e\{Y_t\}$$

$$-Y_t P_{3,h}^{-1} Y_t^T \leq P_{3,h} - \mathcal{H}_e\{Y_t\}.$$

Subsequently, replace $B_i^T Y_t^T, B_j^T Y_t^T, B_l^T Y_t^T, -Y_t P_{1,h}^{-1} Y_t^T, -Y_t P_{2,h}^{-1} Y_t^T, -Y_t P_{3,h}^{-1} Y_t^T$ with $\bar{Y}_{ti}^T B_i^T, \bar{Y}_{tj}^T B_j^T, \bar{Y}_{tl}^T B_l^T, P_{1,h} - \mathcal{H}_e\{Y_t\}, P_{2,h} - \mathcal{H}_e\{Y_t\}, P_{3,h} - \mathcal{H}_e\{Y_t\}$ in (31) and (32), respectively. Define $U_{j,t} = L_{j,t}^T Y_t^T, U_{l,t} = L_{l,t}^T Y_t^T, \bar{V}_{lti} = K_{l,t}^T \bar{Y}_{ti}^T, \bar{V}_{ltj} = K_{l,t}^T \bar{Y}_{tj}^T, \bar{V}_{jti} = K_{j,t}^T \bar{Y}_{ti}^T, \bar{V}_{jtl} = K_{j,t}^T \bar{Y}_{tl}^T$, and then (29) and (30) can be exactly derived. So far, the proof of Theorem 2 is completed. ∎

IV. Simulation Results

In this section, a numerical example is carried out to illustrate the validity of the observer-based security fuzzy controller design approach under WTOD protocol transmission scheme. The parameters in (1) with two fuzzy rules are given as

$$A_1 = \begin{bmatrix} 0.7306 & 0.4893 \\ 0.5239 & 0.0867 \end{bmatrix}, \quad A_2 = \begin{bmatrix} 0.9632 & 0.0883 \\ 0.5639 & 0.0037 \end{bmatrix}$$

$$B_1 = \begin{bmatrix} 0.3129 \\ 0.4133 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0.1205 \\ 0.1389 \end{bmatrix}$$

$$C_{11} = \begin{bmatrix} -0.5789 & -0.0850 \end{bmatrix}, \ C_{12} = \begin{bmatrix} -0.6062 & -0.0630 \end{bmatrix}$$

$$C_{21} = \begin{bmatrix} -0.1187 & 0 \\ 0 & -0.0830 \end{bmatrix}, C_{22} = \begin{bmatrix} -0.1587 & 0 \\ 0 & -0.0650 \end{bmatrix}$$

$$D_1 = -1.8188, \quad D_2 = -1.8425$$

$$E_1 = \begin{bmatrix} 0.0005 \\ 0.0124 \end{bmatrix}, \quad E_2 = \begin{bmatrix} 0.0011 \\ 0.0031 \end{bmatrix}$$

$$F_1 = -0.0102, \quad F_2 = -0.0059$$

TABLE I
MFs With Lower and Upper Bounds of the Plant

Lower bounds	Upper bounds
$\underline{M}_1^1(x_1(k)) = 1 - e^{-\frac{x_1^2(k)}{1.5}}$	$\overline{M}_1^1(x_1(k)) = 0.25e^{-\frac{x_1^2(k)}{0.3}}$
$\underline{M}_2^1(x_1(k)) = 1 - 0.25e^{-\frac{x_1^2(k)}{0.3}}$	$\overline{M}_2^1(x_1(k)) = e^{-\frac{x_1^2(k)}{1.5}}$
$\underline{M}_1^2(x_1(k)) = 0.4e^{-\frac{x_1^2(k)}{0.2}}$	$\overline{M}_1^2(x_1(k)) = e^{-\frac{x_1^2(k)}{2.5}}$
$\underline{M}_2^2(x_1(k)) = 1 - e^{-\frac{x_1^2(k)}{2.5}}$	$\overline{M}_2^2(x_1(k)) = 1 - 0.4e^{-\frac{x_1^2(k)}{0.2}}$

TABLE II
MFs With Lower and Upper Bounds of the Controller

Lower bounds	Upper bounds
$\underline{W}_1^1(\hat{x}_1(k)) = e^{-\frac{\hat{x}_1^2(k)}{0.5}}$	$\overline{W}_1^1(\hat{x}_1(k)) = \underline{W}_1^1(\hat{x}_1(k))$
$\underline{W}_2^1(\hat{x}_1(k)) = e^{-\frac{\hat{x}_1^2(k)}{0.5}}$	$\overline{W}_2^1(\hat{x}_1(k)) = \underline{W}_2^1(\hat{x}_1(k))$
$\underline{W}_1^2(\hat{x}_1(k)) = e^{-\frac{\hat{x}_1^2(k)}{0.35}}$	$\overline{W}_1^2(\hat{x}_1(k)) = \underline{W}_1^2(\hat{x}_1(k))$
$\underline{W}_2^2(\hat{x}_1(k)) = e^{-\frac{\hat{x}_1^2(k)}{0.35}}$	$\overline{W}_2^2(\hat{x}_1(k)) = \underline{W}_2^2(\hat{x}_1(k))$

and $x(k) = [x_1^T(k) \quad x_2^T(k)]^T$ stands for the system state with the initial condition $x(0) = [0.2 \quad -0.1]^T, \hat{x}(0) = [0 \quad 0]^T$. The parameter of the disturbance input is given as $\omega(k) = 2e^{-2k}$.

Moreover, by choosing the premise variable as $x_1(k)$, the MFs with lower and upper bounds of the plant and those of the controller are given in Tables I and II, respectively.

In order to determine $\epsilon_i(x(k))$ and $\kappa_l(\hat{x}(k))$, the nonlinear weighting functions are given as follows:

$$\underline{a}_i(x(k)) = \sin^2(x_1(k)), \ \bar{a}_i(x(k)) = 1 - \underline{a}_i(x(k))$$

$$\underline{b}_l(\hat{x}(k)) = \cos^2(\hat{x}_1(k)), \ \bar{b}_l(\hat{x}(k)) = 1 - \underline{b}_l(\hat{x}(k)).$$

Suppose the sensors can be divided into two groups (i.e., $N = 2$) and let $W_1 = 0.1, W_2 = 0.3$. Under WTOD protocol, only one sensor group can be granted the privilege to transmit signal through the communication network at time instant k, that is $\varphi(k) \in \mathbb{L} \triangleq \{1, 2\}$. Then, it is easy to obtain the updating matrices for $y(k)$, which can be given as $\Phi_t = \text{diag}\{1, 0\}$ when $\varphi(k) = 1$.

The probability $\bar{\alpha}$ of the deception attacks is given as 0.2. It is assumed that the energy signal in deception attacks $v(k) = 0.1\sin(k)x_i(k)$ $(i = 1, 2)$ with $G = \text{diag}\{0.1, 0.1\}$, and the disturbance attenuation level γ is set to be 0.35.

Then, by solving the LMIs conditions in Theorem 2, the observer and controller gain matrices are listed as follows:

$$K_{11} = \begin{bmatrix} -0.3240 & -0.0173 \end{bmatrix}, K_{12} = \begin{bmatrix} -0.3957 & -0.0586 \end{bmatrix}$$

$$K_{21} = \begin{bmatrix} -0.4372 & -0.0832 \end{bmatrix}, K_{22} = \begin{bmatrix} -0.2641 & -0.0473 \end{bmatrix}$$

$$L_{11} = \begin{bmatrix} -2.8830 & -0.0019 \\ -1.5378 & 0.0023 \end{bmatrix}, L_{12} = \begin{bmatrix} 0.0008 & -1.0784 \\ 0.0011 & 0.0359 \end{bmatrix}$$

$$L_{21} = \begin{bmatrix} -2.8903 & 0.0019 \\ -1.4346 & 0.0010 \end{bmatrix}, L_{22} = \begin{bmatrix} -0.0012 & 0.2382 \\ 0.0023 & -0.3211 \end{bmatrix}.$$

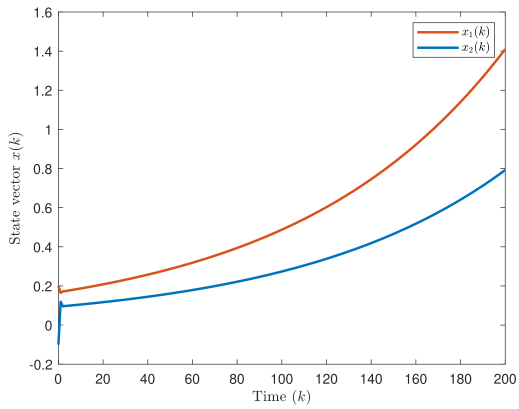

Fig. 2. State responses of the open-loop system.

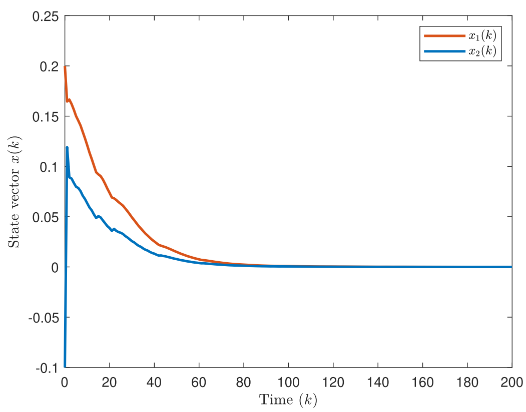

Fig. 3. State responses of the closed-loop system.

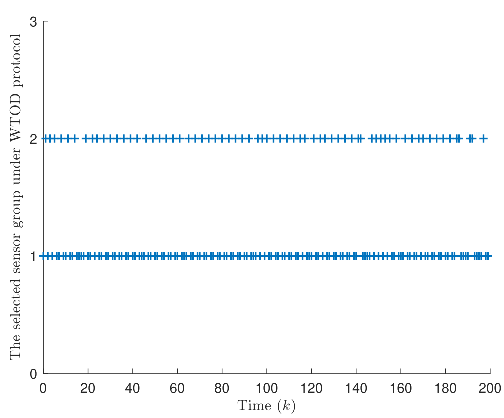

Fig. 4. Distribution of signal transmission under WTOD protocol.

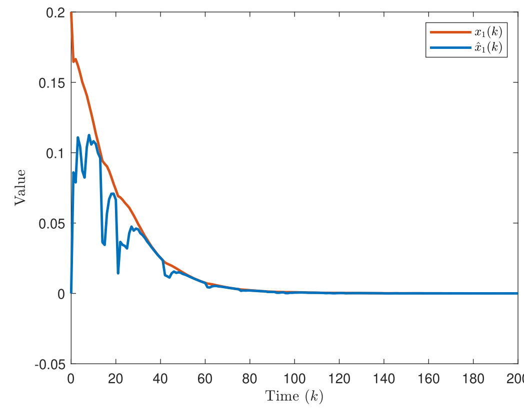

Fig. 5. State of the $x_1(k)$ and $\hat{x}_1(k)$.

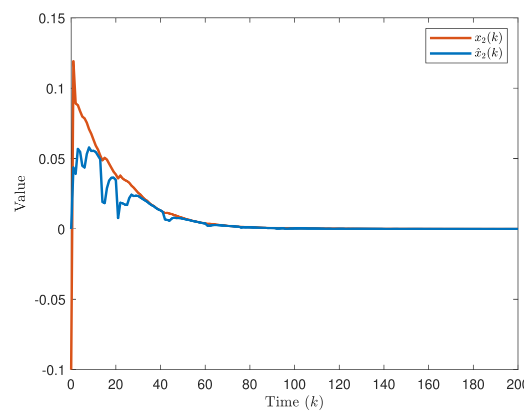

Fig. 6. State of the $x_2(k)$ and $\hat{x}_2(k)$.

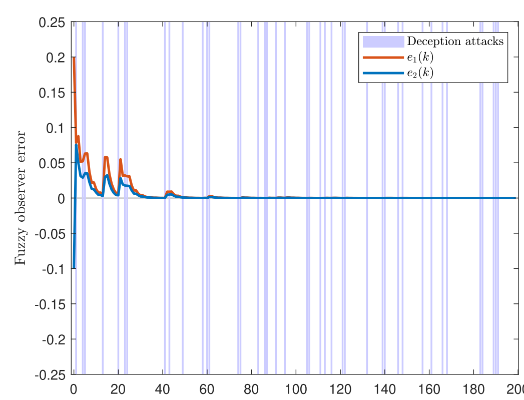

Fig. 7. Error responses between system states and observer estimates subject to deception attacks.

Taking account of WTOD protocol and deception attacks, Fig. 2 depicts the state responses of the open-loop system, from which it can be seen that the open-loop system is unstable without considering the proposed observed-based controller. In this case, by applying the observer-based controller with abovementioned gain matrices, the state responses of $x_1(k)$ and $x_2(k)$ are depicted in Fig. 3. In contrast to Fig. 2, the effectiveness of the observer-based controller developed in this article is validated.

The distribution of signal transmission is presented in Fig. 4 according to the principle of WTOD protocol mechanism. Figs. 5 and 6 plot the unmeasurable system states and their estimates, respectively. According to Figs. 3, 5, and 6, it is clear that the proposed observer-based controller can effectively stabilize the augmented closed-loop IT2 T-S fuzzy system, and the unmeasurable states can also be estimated by the designed observer efficiently.

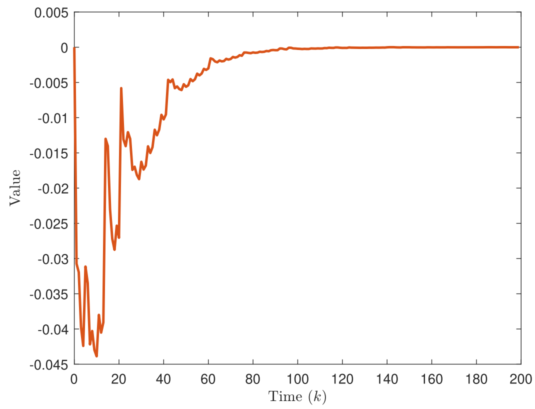

Fig. 8. Response of $u(k)$.

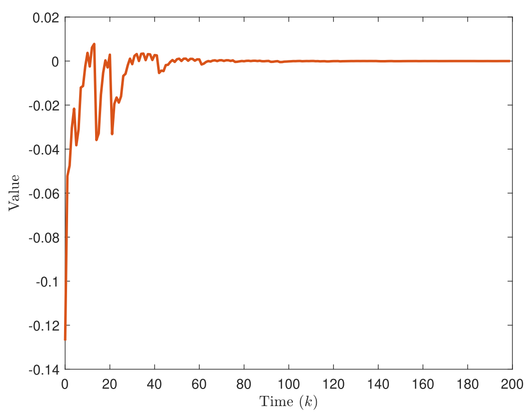

Fig. 9. Response of $z(k)$.

The occurrence of stochastic deception attacks with the probability $\bar{\alpha} = 0.2$ and the estimation error are depicted in Fig. 7. It can be seen that in the process of simulation, the estimation error is small at the time when no deception attack occurs, and the estimation error is relatively large under deception attacks. However, as simulation time goes by, under the effect of the observer-based controller we design, the estimation error gradually stabilizes and tends to zero, this powerfully confirms the validity of the controller and its security capability against attacks.

In addition, the responses of the control input $u(k)$ and the control output $z(k)$ are displayed in Figs. 8 and 9, respectively.

V. Conclusion

In this article, we have investigated the observer-based security control problem for nonlinear networked system with the effects of WTOD protocol and deception attacks based on IT2 T-S fuzzy model. The observer is designed under immeasurable premise variables, and then the controller with the imperfect matching MFs is designed according to the estimated states. The sufficient conditions for the stochastic stability with predefined control performance of the augmented closed-loop IT2 T-S fuzzy system are analyzed and guaranteed. Moreover, the observer and controller gains are derived by solving a set of LMIs, respectively. Finally, a numerical example has been carried out to demonstrate the effectiveness of the proposed observer-based fuzzy controller design method. In our future work, more effort will be devoted to optimizing observer and controller MFs to achieve a superior system performance. Besides, the MFs optimization problem based on machine learning will be a challenging research to be investigated.

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