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Adaptive event-triggered dynamic output feedback H_∞ control for networked T-S fuzzy systems

Yameng Hu and Chong Lin

Institute of Complexity Science, Qingdao University, Qingdao, People's Republic of China

ABSTRACT

This paper investigates the design problem of fuzzy dynamic output feedback H_∞ controller for nonlinear networked systems via mismatched membership functions and adaptive event-triggered (AET) mechanism. Firstly, an AET mechanism is introduced to save communication resources, which causes the controller and the original system's premise variables to be asynchronous. Then, considering the influence of AET and mismatched membership functions, a model of fuzzy control system is established. In addition, utilizing the Lyapunov-Krasovskii(L-K) functional, sufficient conditions for the global exponential stability of the closed-loop system with H_∞ performance are derived. Besides, the controller parameters and event-triggered (ET) weight matrix are solved by a set of linear matrix inequalities (LMIs). Finally, an example is given to demonstrate the effectiveness of the proposed control method.

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Networked T-S fuzzy systems; adaptive event-triggered mechanism; dynamic output feedback H_∞ control

1. Introduction

Compared with traditional point-to-point control systems, networked control systems (NCSs) have become a research hotspot in the field of control due to their strong adaptability and low cost, and many important literatures have been published (Qiu et al., 2016; X. Zhang et al., 2016). However, the limited bandwidth makes the NCSs inevitably have problems such as network delay and blocked transmission when sharing communication information, and the system performance is greatly reduced. An ET mechanism is proposed to replace the traditional communication scheme in Tabuada (2007). You et al. (2019) and Hua et al. (2019) study the related issues of multi-agent systems through ET mechanisms. Gu et al. (2018) propose an AET mechanism to further save communication resources and apply it to the comprehensive problem of fuzzy networked systems. In K. Zhang et al. (2020), Ran et al. (2018), and Liu et al. (2020), the introduction of the ET mechanism designs dynamic output feedback controller for nonlinear networked systems. However, how to design a fuzzy dynamic output feedback controller utilizing AET mechanism is worthy of further investigation.

The well-known Takagi-Sugeno (T-S) fuzzy model (Takagi & Sugeno, 1985) is a powerful tool to approximate the nonlinear systems through linear subsystems described by IF-THEN fuzzy rules. In Guerra and Vermeiren (2004) and Kim and Kim (2002), the classical linear system theory is successfully extended to nonlinear systems. The L-K functional method is used to analyze the stability of time-varying delay systems in C. Zhang, He, Jiang, Wang, et al. (2017), C. Zhang, He, Jiang, Wu, et al. (2017), and X. Zhang et al. (2017). It is worth mentioning that this paper fully considers that after the introduction of the ET mechanism, the membership functions of the fuzzy system and the fuzzy controller may be different. Firstly, a fuzzy dynamic output feedback H_∞ controller with unmatched premise variables is designed by using AET mechanism. Then, based on L-K functional method, the stability and stabilization conditions of the closed-loop system with network delays are provided. Finally, the effectiveness of the proposed method is verified by an example.

The rest of the structure of this paper is organized as follows: Section 2 introduces the problem under consideration, AET mechanism and establishes a closed-loop system under dynamic output feedback H_∞ control. The main results of controller design, system stability and qualitative analysis are given in Section 3. An example is shown in Section 4 to describe the effectiveness of the control method. Section 5 summarizes the conclusion.

Notation: R^n denotes the n-dimensional Euclidean space; $\mathbb{N}$ denotes non-negative integer set; I is the identity matrix with appropriate dimension; T and -1 stand for

CONTACT Chong Lin linchong_2004@hotmail.com

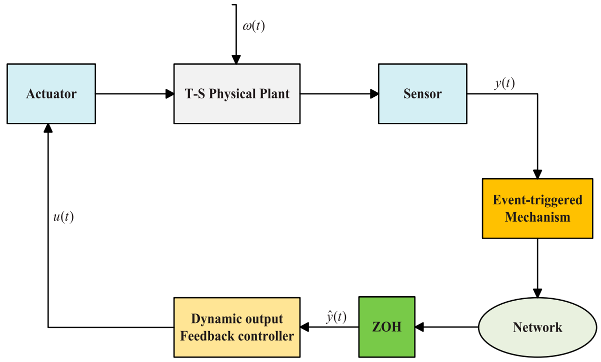

Figure 1. The structure of dynamic output feedback control for nonlinear networked system.

the matrix transpose and inverse, respectively; $*$ stands for the transposed elements of the symmetric matrix; $He(X)$ denotes the expression $X^T + X$; diag$\{\ldots\}$ stands for the the block-diagonal matrix; $\|\cdot\|$ stands for the Euclidean norm; $L_2[0,\infty)$ denotes the space of square integrable vector functions.

2. Problem formulation

2.1. System description

Consider a nonlinear networked system represented by the T-S fuzzy model, in which the entire structure of dynamic output feedback controller is shown in Figure 1. The system is described as follows:

Plant Rule i: IF $f_1(x(t))$ is M_1^i and $\ldots f_p(x(t))$ is M_p^i THEN

$$\begin{aligned} \dot{x}(t) &= A_i x(t) + B_i u(t) + B_{\omega i}\omega(t) \\ z(t) &= C_i x(t) + D_{\omega i}\omega(t) \\ y(t) &= E_i x(t) \end{aligned} \quad (1)$$

where $x(t) \in R^n, z(t) \in R^{n_1}, y(t) \in R^{n_2}, u(t) \in R^{m_1}$ and $w(t) \in R^{m_2}$ stand for the state vector, control output, measurement output, control input and the noise disturbance input which belongs to $L_2 \in [0,\infty)$, respectively. $A_i, B_i, B_{\omega i}, C_i, D_{\omega i}, E_i$ are constant matrices with appropriate dimensions. $f_j(x(t))$ denotes the premise variable, M_j^i $(i = 1,2,\ldots,r, j = 1,2,\ldots,p)$ represents the fuzzy set, r and p are the number of the IF-THEN rules and the prerequisite variables, respectively. For simplicity, $f_j(x(t))$ is represented by $f_j(x)$ and $f(x) = [f_1(x), f_2(x),\ldots,f_p(x)]^T$. By using central average defuzzifier and single-case fuzzer to generate fuzzy inference, system (1) can be rewritten as

$$\dot{x}(t) = \sum_{i=1}^{r} \varphi_i(f(x))\,[A_i x(t) + B_i u(t) + B_{\omega i}\omega(t)]$$

$$z(t) = \sum_{i=1}^{r} \varphi_i(f(x))\,[C_i x(t) + D_{\omega i}\omega(t)] \quad (2)$$

$$y(t) = \sum_{i=1}^{r} \varphi_i(f(x)) E_i x(t)$$

where $\varpi_i(f(x)) = \prod_{j=1}^{p} M_j^i(f_j(x))$ denotes the normalized membership function, $M_j^i(f_j(x))$ represents the membership of $f_j(x)$ in M_j^i, and satisfies

$$\varphi_i(f(x)) = \frac{\varpi_i(f(x))}{\sum_{i=1}^{r}\varpi_i(f(x))} \geq 0, \ (i = 1,2,\ldots,r), \quad \sum_{i=1}^{r}\varphi_i(f(x)) = 1$$

For subsequent development, the following assumptions are required.

Assumptions 2.1 (Peng et al., 2017): The sampler maintains a constant sampling period h. The zero-order-hold (ZOH) is used to hold the sampled measurement output signal until a new sampled measurement output appears.

Assumptions 2.2 (Peng et al., 2017): The sum of all delays in the communication network is τ_k, which represents the communication delay at the transmission time $t_k h$, and $\tau_m \leq \tau_k \leq \tau_M$, where τ_m and τ_M denote the minimum and maximum values of the transmission delay, respectively.

2.2. Event-triggered mechanism

As seen in Figure 1, considering the bandwidth limitation of the communication network, an ET device is introduced between the sensor and the controller to determine whether the sampling output is transmitted instantaneously, in order to save communication resources. Inspired by W. Li et al. (2020), define the error between the latest released data $y(t_k h)$ and the current sampling data $y(t_k h + ch)$ as follows:

$$e_y(t) = y(t_k h + ch) - y(t_k h) \quad (3)$$

Then the next transmission instant through the AET mechanism can be expressed as

$$\begin{aligned} t_{k+1}h = t_k h + \min_{n\in\mathbb{N}}\{ch \mid\, & e_y^T(t)\Psi e_y(t) \\ & \geq \alpha(t) y^T(t_k h)\Psi y(t_k h) \\ & + \beta(t) y^T(t_k h + ch)\Psi y(t_k h + ch)\} \end{aligned} \quad (4)$$

where h is the sampling period, $y(t_k h)$ and $y(t_k h + ch)$ denote the latest released signal and the current sampled signal, respectively; $\Psi > 0$ is the weight matrix to be designed; $\alpha(t)$ and $\beta(t)$ are two independent ET thresholds, which are two adaptive functions and satisfy the following constrains

$$\dot{\alpha}(t) = \frac{1}{\alpha(t)}\left[\frac{1}{\alpha(t)} - \mu_1\right]\Big[e_y^T(t)\Psi e_y(t) - \kappa_1 y^T(t_kh+ch)\Psi y(t_kh+ch) + \kappa_1 y^T(t_kh)\Psi y(t_kh)\Big] \tag{5}$$

$$\dot{\beta}(t) = \frac{1}{\beta(t)}\left[\frac{1}{\beta(t)} - \mu_2\right]\Big[e_y^T(t)\Psi e_y(t) - \kappa_2 y^T(t_kh+ch)\Psi y(t_kh+ch) + \kappa_2 y^T(t_kh)\Psi y(t_kh)\Big] \tag{6}$$

where $\dot{\alpha}(t)$ and $\dot{\beta}(t)$ are adaptive law, $\mu_1, \mu_2, \kappa_1, \kappa_2$ are given constants greater than zero, (5) and (6) are given to ensure that $\alpha(t)$ and $\beta(t)$ satisfy the following formula :

$$\frac{1}{\mu_1} \le \alpha(t) \le \kappa_2, \quad \frac{1}{\mu_2} \le \beta(t) \le \kappa_1 \tag{7}$$

Remark 2.1: It is worth noting that through using AET mechanism, which can further improve transmission efficiency and save communication resources compared with Ran et al. (2018) and K. Zhang et al. (2020). And ET thresholds $\alpha(t)$ and $\beta(t)$ are no longer a constant that is related to error $e_y(t)$, the latest released data $y(t_kh)$ and the current sampling data $y(t_kh+ch)$.

Remark 2.2: When $\beta(t) = 0$ and $\kappa_1 = 0$, the AET mechanism (4) will degenerate to the form in Gu et al. (2018) and Ning et al. (2018), as follows

$$t_{k+1}h = t_kh + \min_{n\in\mathbb{N}}\{ch \mid e_y^T(t)\Psi e_y(t) \ge \alpha(t)y^T(t_kh)\Psi y(t_kh)\} \tag{8}$$

where $\dot{\alpha}(t) = 1/\alpha(t)[1/\alpha(t) - \mu][e_y^T(t)\Psi e_y(t)]$. In addition, if $\beta(t) = 0, \kappa_1 = 0$ and $\alpha(t)$ is a constant, then adaptive law $\dot{\alpha}(t) = 0$ and AET mechanism (4) will reduce to the traditional ET mechanism (Hu & Yue, 2012).

$$t_{k+1}h = t_kh + \min_{n\in\mathbb{N}}\{ch \mid e_y^T(t)\Psi e_y(t) \ge \bar{\alpha}(t)y^T(t_kh)\Psi y(t_kh)\} \tag{9}$$

where $\bar{\alpha}(t) \in (0, 1)$ is a predefined constant. In other words, AET (4) in this paper contains more possibilities.

2.3. Networked dynamic output feedback controller design with asynchronous premise variables

Suppose $\lambda_k = \min\{l \mid t_kh + \tau_k + lh \ge t_{k+1}h + \tau_{k+1}\}$. Define the following subintervals on the time interval $[t_kh + \tau_k, t_{k+1}h + \tau_{k+1})$:

$$\begin{aligned} \Gamma_1 &= [t_kh + \tau_k, t_kh + \tau_k + h) \\ \Gamma_2 &= [t_kh + \tau_k + h, t_kh + \tau_k + 2h) \\ &\vdots \\ \Gamma_{\lambda_k} &= [t_kh + \tau_k + (\lambda_k - 1)h, t_{k+1}h + \tau_{k+1}) \end{aligned} \tag{10}$$

Define

$$\tau(t) = \begin{cases} t - t_kh, & t \in \Gamma_1 \\ t - t_kh - h, & t \in \Gamma_2 \\ \vdots \\ t - t_kh - (\lambda_k - 1)h, & t \in \Gamma_{\lambda_k} \end{cases} \tag{11}$$

and

$$e_y(t) = \begin{cases} 0, & t \in \Gamma_1 \\ y(t_kh + h) - y(t_kh), & t \in \Gamma_2 \\ \vdots \\ y(t - kh + (\lambda_k - 1)h) - y(t_kh), & t \in \Gamma_{\lambda_k} \end{cases} \tag{12}$$

Then, according to (10)–(12), the actual input $\hat{y}(t)$ of the dynamic output feedback controller can be given by

$$\hat{y}(t) = y(t_kh) = y(t - \tau(t)) - e_y(t), \quad t \in [t_kh + \tau_k, t_{k+1}h + \tau_{k+1}), \quad k = 1, 2, 3 \ldots \tag{13}$$

where $\tau_1 = \bar{\tau}_m \le \tau(t) \le h + \bar{\tau}_M = \tau_2$, $\bar{\tau}_m = \min\{\tau_k\}$, $\bar{\tau}_M = \max\{\tau_k\}$, $k = 1, 2, \ldots$

There is an AET mechanism between the sensor and the controller, which makes the premise variables of the controller and the system model asynchronous, so the IF-THEN rules of the controller are designed as

Control Rule j: IF $g_1(x_c(t))$ is N_1^j and $\ldots g_q(x_c(t))$ is N_q^j THEN

$$\begin{aligned} \dot{x}_c(t) &= A_{cj}x_c(t) + B_{cj}\hat{y}(t) \\ u(t) &= C_{cj}x_c(t) \end{aligned} \tag{14}$$

where $N_d^j (j = 1, 2, \ldots, r, d = 1, 2, \ldots, q)$ represents the fuzzy set. $x_c(t) \in R^n$ is the state vector of the controller, $\hat{y}(t)$ denotes measured output through the event-triggered communication network, A_{cj}, B_{cj}, C_{cj} are the controller matrices to be designed.

By using central average defuzzifier and single-case fuzzer to generate fuzzy inference, system (12) can be rewritten as

$$\dot{x}_c(t) = \sum_{j=1}^{r} \psi_j\left(g\left(x_c\right)\right)\left[A_{cj}x_c(t) + B_{cj}\hat{y}(t)\right]$$
$$u(t) = \sum_{j=1}^{r} \psi_j\left(g\left(x_c\right)\right)C_{cj}x_c(t), \quad j = 1,2,\ldots,r \tag{15}$$

where

$$\psi_j(g(x_c)) = \frac{\vartheta_j(g(x_c))}{\sum_{j=1}^{r}\vartheta_j(g(x_c))} \geq 0, \quad \sum_{j=1}^{r}\psi_j(g(x_c)) = 1$$

Remark 2.3: It is worth mentioning that the membership functions of the controller are different from the original system, in other words, $\varphi_i(f(x))$ are not necessarily the same as $\psi_j(g(x_c))$. In addition, unlike (Ning et al., 2018), asynchronous constraints are embodied in the mismatched premise variables in this paper. If $\varphi_i(f(x)) = \psi_j(g(x_c))$, the method presented in this paper can be reduced to the case in Z. Zhang et al. (2015), the controller and the system use membership functions of the same structure, then by using the PDC method, the parameters of the fuzzy controller can be obtained.

For simplicity, denote $\varphi_i(f(x)) \triangleq \varphi_i(x), \psi_j(g(x_c)) \triangleq \psi_j(x_c)$. From (2), (13) and (15), the closed-loop fuzzy system is constructed as follows:

$$\dot{\xi}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r}\varphi_i(x)\psi_j\left(x_c\right)\left[\bar{A}_{ij}\xi(t) + \bar{B}_{1ij}\xi(t-\tau(t)) + \bar{B}_{2ij}e_y(t) + \bar{B}_{\omega ij}\omega(t)\right]$$
$$z(t) = \sum_{i=1}^{r}\sum_{j=1}^{r}\varphi_i(x)\psi_j\left(x_c\right)\left[\bar{C}_i\xi(t) + \bar{D}_{\omega i}\omega(t)\right] \tag{16}$$

where

$$\xi(t) = [x^T(t) \quad x_c^T(t)]^T, \quad \bar{A}_{ij} = \begin{bmatrix} A_i & B_iC_{cj} \\ 0 & A_{cj} \end{bmatrix},$$
$$\bar{B}_{1ij} = \begin{bmatrix} 0 & 0 \\ B_{cj}E_i & 0 \end{bmatrix},$$
$$\bar{B}_{2ij} = \begin{bmatrix} 0 \\ -B_{cj} \end{bmatrix}, \quad \bar{B}_{\omega ij} = \begin{bmatrix} B_{\omega i} \\ 0 \end{bmatrix},$$
$$\bar{C}_i = [C_i \quad 0], \quad \bar{D}_{\omega i} = D_{\omega i}.$$

The goal of this paper is to design a dynamic feedback output controller for a fuzzy networked system based on an AET mechanism, such that:

(1) Under the condition $\omega = 0$, the closed-loop system (16) is exponentially stable;

(2) Under zero initial condition, the closed-loop system satisfies $\|z(t)\|_2 \leq \gamma\|\omega(t)\|_2$ for any nonzero $\omega(t) \in L_2[0,\infty)$, where $\gamma > 0$ is H_∞ performance target.

In order to obtain the main results, a useful lemma is first given.

Lemma 2.1 (Puangmalai et al., 2020): *For any positive definite matrix W, any differentiable function $x : [a,b] \to \mathbb{R}^n$. the following inequality holds:*

$$-\int_a^b \dot{x}^T(s)Wx(s)\,ds \leq -\frac{1}{6(b-a)}\eta^T(t)\begin{bmatrix} 22W & 10W & -32W \\ * & 16W & -26W \\ * & * & 58W \end{bmatrix}\eta(t)$$

where $\eta(t) = [x^T(b) \quad x^T(a) \quad \frac{1}{b-a}\int_a^b x^T(s)\,ds]^T$

3. Main results

3.1. H_∞ performance analysis

In this section, sufficient conditions for the asymptotic stability of the closed-loop system (16) with H_∞ performance are proposed.

Theorem 3.1: *For given positive scalars τ_1, τ_2, μ_1, μ_2, κ_1, κ_2 and γ, the membership functions satisfying $\psi_j(x_c) - \rho_j\varphi_j(x_c) \geq 0 (0 < \rho_j < 1)$, the closed-loop system (16) is exponentially stable and meets the H_∞ performance target if there exist matrices $P > 0$, $Q_1 > 0$, $Q_2 > 0$, $R_1 > 0$, $R_2 > 0, \Psi > 0$, A_{cj}, B_{cj}, C_{cj} and $\Lambda_i = \Lambda_i^T$ with suitable dimensions such that the following matrix inequities hold with $i,j = 1,2,\ldots,r$*

$$\Phi_{ij} - \Lambda_i < 0 \tag{17}$$
$$\rho_i\Phi_{ii} - \rho_i\Lambda_i + \Lambda_i < 0 \tag{18}$$
$$\rho_j\Phi_{ij} + \rho_i\Phi_{ji} - \rho_i\Lambda_j - \rho_j\Lambda_i + \Lambda_i + \Lambda_j < 0, \quad i < j \tag{19}$$

where

$$\Phi_{ij} = \begin{bmatrix} \Pi_{ij}^{11} & \Pi_{ij}^{12} \\ * & \Pi_{ij}^{22} \end{bmatrix},$$

$$\Pi_{ij}^{11} = \begin{bmatrix} \Xi_{11} & \Xi_{12} & \Xi_{13} & 0 & \Xi_{15} \\ * & \Xi_{22} & \Xi_{23} & 0 & \Xi_{25} \\ * & * & \Xi_{33} & \Xi_{34} & 0 \\ * & * & * & \Xi_{44} & 0 \\ * & * & * & * & \Xi_{55} \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \end{bmatrix}$$

$$\begin{matrix} 0 & 0 & \Xi_{18} & \Xi_{19} \\ \Xi_{26} & 0 & 0 & 0 \\ \Xi_{36} & \Xi_{37} & \Xi_{38} & 0 \\ 0 & \Xi_{47} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \Xi_{66} & 0 & 0 & 0 \\ * & \Xi_{77} & 0 & 0 \\ * & * & \Xi_{88} & 0 \\ * & * & * & -\gamma^2 I \end{bmatrix},$$

$$\Xi_{11} = He(P\bar{A}_{ij}) + Q_1 - 11R_1/3,$$

$$\Xi_{22} = -Q_1 + Q_2 - 8R_1/3 - 11R_2/3,$$

$$\Xi_{33} = -19R_2/3 + (2 + \mu_1\delta_1 + \mu_2\delta_2)H^T E_i^T \Psi E_i H,$$

$$\Xi_{38} = -(1 + \mu_2\delta_2)H^T E_i^T \Psi,$$

$$\Xi_{88} = (1 + \mu_2\delta_2 - \mu_1 - \mu_2)\Psi,$$

$$\Xi_{12} = P\bar{B}_{2ij}, \qquad \Xi_{13} = P\bar{B}_{1ij},$$
$$\Xi_{15} = 16R_1/3,$$
$$\Xi_{25} = 13R_1/3, \qquad \Xi_{19} = P\bar{B}_{\omega ij},$$
$$\Xi_{23} = -5R_2/3,$$
$$\Xi_{36} = 13R_2/3, \qquad \Xi_{26} = 16R_2/3,$$
$$\Xi_{34} = -5R_2/3,$$
$$\Xi_{47} = 13R_2/3, \qquad \Xi_{37} = 16R_2/3,$$
$$\Xi_{44} = -Q_2 - 8R_2/3,$$
$$\Xi_{77} = -29R_2/3, \qquad \Xi_{55} = -29R_1/3,$$
$$\Xi_{66} = -29R_2/3,$$

$$\Pi_{ij}^{12} = [\tau_1 F_{ij}^1 \quad (\tau_2 - \tau_1)F_{ij}^1 \quad F_{ij}^2],$$

$$\Pi_{ij}^{22} = \mathrm{diag}\{-PR_1^{-1}P, -PR_2^{-1}P, I\},$$

$$F_{ij}^1 = [P\bar{A}_{ij} \quad 0 \quad P\bar{B}_{1ij} \quad 0 \quad 0 \quad 0 \quad 0 \quad P\bar{B}_{2ij} \quad P\bar{B}_{\omega ij}],$$

$$F_{ij}^2 = [\bar{C}_i \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad \bar{D}_i].$$

Proof: Consider the following Lyapunov-Krasovskii functional

$$V(t) = V_1(t) + V_2(t)$$

where

$$\begin{aligned} V_1(t) &= \xi^T(t)P\xi(t) + \int_{t-\tau_1}^{t} \xi^T(s)Q_1\xi(s)\,\mathrm{d}s \\ &\quad + \int_{t-\tau_2}^{t-\tau_1} \xi^T(s)Q_2\xi(s)\,\mathrm{d}s \\ &\quad + \tau_1 \int_{-\tau_1}^{0}\int_{t+\theta}^{t} \dot{\xi}^T(s)R_1\dot{\xi}(s)\,\mathrm{d}s\,\mathrm{d}\theta \\ &\quad + (\tau_2 - \tau_1)\int_{-\tau_2}^{-\tau_1}\int_{t+\theta}^{t} \dot{\xi}^T(s)R_2\dot{\xi}(s)\,\mathrm{d}s\,\mathrm{d}\theta \end{aligned}$$

$$V_2(t) = \frac{1}{2}\alpha^2(t) + \frac{1}{2}\beta^2(t)$$

Then, seeking the time derivative of $V(t)$ with respect to t gets

$$\begin{aligned} \dot{V}_1(t) &= 2\xi^T(t)P\dot{\xi}(t) + \xi^T(t)Q_1\xi(t) \\ &\quad - \xi^T(t-\tau_1)Q_1\xi(t-\tau_1) + \xi^T(t-\tau_1)Q_2\xi(t-\tau_1) \\ &\quad - \xi^T(t-\tau_2)Q_2\xi(t-\tau_2) + \tau_1^2\dot{\xi}^T(t)R_1\dot{\xi}(t) \\ &\quad + (\tau_2-\tau_1)^2\dot{\xi}^T(t)R_2\dot{\xi}(t) + \alpha(t)\dot{\alpha}(t) \\ &\quad + \beta(t)\dot{\beta}(t) - \tau_1\int_{t-\tau_1}^{t} \dot{\xi}^T(s)R_1\dot{\xi}(s)\,\mathrm{d}s \\ &\quad - (\tau_2-\tau_1)\int_{t-\tau_2}^{t-\tau_1} \dot{\xi}^T(s)R_2\dot{\xi}(s)\,\mathrm{d}s \end{aligned} \tag{20}$$

$$\begin{aligned} \dot{V}_2(t) &= \alpha(t)\dot{\alpha}(t) + \beta(t)\dot{\beta}(t) \le y^T(t_k h)(1+\mu_2\delta_2)\Psi y(t_k h) \\ &\quad + y^T(t_k h + ch)(1+\mu_1\delta_1)\Psi y(t_k h + ch) \\ &\quad - e_y^T(t)(\mu_1+\mu_2)\Psi e_y(t) \\ &= \Upsilon_4^T \begin{bmatrix} (2+\mu_1\delta_1+\mu_2\delta_2)\Psi & -(1+\mu_2\delta_2)\Psi \\ * & (1+\mu_2\delta_2-\mu_1-\mu_2)\Psi \end{bmatrix} \Upsilon_4 \end{aligned} \tag{21}$$

By use of Lemma 2.1, we obtain

$$-\int_{t-\tau_1}^{t} \dot{\xi}^T(s)R_1\dot{\xi}(s)\,\mathrm{d}s \le -\Upsilon_1^T\hat{R}_1\Upsilon_1 \tag{22}$$

$$\begin{aligned} &-\int_{t-\tau_2}^{t-\tau_1} \dot{\xi}^T(s)R_2\dot{\xi}(s)\,\mathrm{d}s \\ &\le -\int_{t-\tau(t)}^{t-\tau_1} \dot{\xi}^T(s)R_2\dot{\xi}(s)\,\mathrm{d}s - \int_{t-\tau_2}^{t-\tau(t)} \dot{\xi}^T(s)R_2\dot{\xi}(s)\,\mathrm{d}s \\ &\le -\Upsilon_2^T\hat{R}_2\Upsilon_2 - \Upsilon_3^T\hat{R}_2\Upsilon_3 \end{aligned} \tag{23}$$

where

$$\upsilon_1 = \frac{1}{\tau_1}\int_{t-\tau_1}^{t} \xi(s)\,\mathrm{d}s, \quad \upsilon_2 = \frac{1}{\tau(t)-\tau_1}\int_{t-\tau(t)}^{t-\tau_1} \xi(s)\,\mathrm{d}s,$$

$$\upsilon_3 = \frac{1}{\tau_2-\tau(t)}\int_{t-\tau_2}^{t-\tau(t)} \xi(s)\,\mathrm{d}s$$

$$\Upsilon_1 = \begin{bmatrix} \xi(t) \\ \xi(t-\tau_1) \\ \upsilon_1 \end{bmatrix}, \quad \Upsilon_2 = \begin{bmatrix} \xi(t-\tau_1) \\ \xi(t-\tau(t)) \\ \upsilon_2 \end{bmatrix},$$

$$\Upsilon_3 = \begin{bmatrix} \xi(t-\tau(t)) \\ \xi(t-\tau_2) \\ \upsilon_3 \end{bmatrix}, \quad \Upsilon_4 = \begin{bmatrix} \xi(t-\tau(t)) \\ e_y(t) \end{bmatrix},$$

$$\hat{R}_1 = \begin{bmatrix} 11R_1/3 & 5R_1/3 & -16R_1/3 \\ * & 8R_1/3 & -13R_1/3 \\ * & * & 29R_1/3 \end{bmatrix},$$

$$\hat{R}_2 = \begin{bmatrix} 11R_2/3 & 5R_2/3 & -16R_2/3 \\ * & 8R_2/3 & -13R_2/3 \\ * & * & 29R_2/3 \end{bmatrix}.$$

Define,

$$\zeta^T(t) = \big[\xi^T(t) \quad \xi^T(t-\tau_1) \quad \xi^T(t-\tau(t)) \quad \xi^T(t-\tau_2) \quad \upsilon_1^T \quad \upsilon_2^T \quad \upsilon_3^T \quad e_y^T(t) \quad \omega^T(t)\big].$$

Combining (20) to (23), one has

$$\dot{V}(t) + z^T(t)z(t) - \gamma^2\omega^T(t)\omega(t) \le \sum_{i=1}^{r}\sum_{j=1}^{r}\varphi_i(x)\psi_j(x_c)\zeta^T(t)\Phi_{ij}\zeta(t).$$

Introduce a relaxation matrix $\Lambda_i = \Lambda_i^T$ and consider $\sum_{i=1}^{r}\sum_{j=1}^{r}\varphi_i(x)[\varphi_j(x_c) - \psi_j(x_c)]\Lambda_i = 0$, then we can have

$$\begin{aligned}
\sum_{i=1}^{r}\sum_{j=1}^{r}\varphi_i(x)\psi_j(x_c)\Phi_{ij} &= \sum_{i=1}^{r}\varphi_i(x)\varphi_i(x_c)(\rho_i\Phi_{ii} - \rho_i\Lambda_i + \Lambda_i) \\
&\quad + \sum_{i=1}^{r}\sum_{j=1}^{r}\varphi_i(x)(\psi_j(x_c) - \rho_j\varphi_j(x_c))(\Phi_{ij} - \Lambda_i) \\
&\quad + \sum_{i=1}^{r-1}\sum_{j=i+1}^{r}\varphi_i(x)\varphi_j(x_c)(\rho_j\Phi_{ij} \\
&\quad + \rho_i\Phi_{ji} - \rho_j\Lambda_i - \rho_i\Lambda_j + \Lambda_i + \Lambda_j)
\end{aligned}$$

Under $\psi_j(x_c) - \rho_j\varphi_j(x_c) \ge 0$ for any j, according to the conditions (17)–(19), it yields that

$$\dot{V}(t) + z^T(t)z(t) - \gamma^2\omega^T(t)\omega(t) < 0 \tag{24}$$

When the initial condition is zero, integrating the left and right sides of (22) from 0 to ∞ gives

$$\int_0^\infty \|z(t)\|^2\,\mathrm{d}t \le \gamma^2\int_0^\infty \|\omega(t)\|^2\,\mathrm{d}t \tag{25}$$

Therefore, the closed-loop system (16) is asymptotically stable with the H_∞ performance index. In addition, it can be seen from (17)–(19) that $\dot{V}(t) < 0$ is satisfied when $\omega = 0$. This completes the proof. ■

Remark 3.1: Theorem 3.1 is obtained by the combination of Wirtinger inequality and relaxation matrix. Different from some existing works (H. Li et al., 2014; Z. Zhang et al., 2015), this paper fully considers the effects of network-induced delay and AET, the membership functions of the system (2) and the controller (15) are asynchronous and make use of the membership function information with designing the controller.

3.2. Fuzzy H_∞ controller design

On the basis of Theorem 3.1, the following Theorem 3.2 is given to obtain the ET weight matrix and fuzzy controller parameters by matrix decomposition.

Theorem 3.2: *For given positive scalars τ_1, τ_2, μ_1, μ_2, κ_1, κ_2, γ and σ, the membership functions satisfying $\psi_j(x_c) - \rho_j\varphi_j(x_c) \ge 0 (0 < \rho_j < 1)$, the closed-loop system (16) is exponentially stable and meets the H_∞ performance target if there exist matrices $P > 0$, $Q_1 > 0$, $Q_2 > 0$, $R_1 > 0$, $R_2 > 0$, $\tilde{\Psi} > 0$, $\tilde{A}_{cj}$, $\tilde{B}_{cj}$, $\tilde{C}_{cj}$ and $\tilde{\Lambda}_i = \tilde{\Lambda}_i^T$ with suitable dimensions such that the following matrix inequities hold with $i, j = 1, 2, \ldots, r$*

$$\tilde{\Phi}_{ij} - \tilde{\Lambda}_i < 0 \tag{26}$$

$$\rho_i\tilde{\Phi}_{ii} - \rho_i\tilde{\Lambda}_i + \tilde{\Lambda}_i < 0 \tag{27}$$

$$\rho_j\tilde{\Phi}_{ij} + \rho_i\tilde{\Phi}_{ji} - \rho_j\tilde{\Lambda}_i - \rho_i\tilde{\Lambda}_j + \tilde{\Lambda}_i + \tilde{\Lambda}_j < 0, \quad i < j \tag{28}$$

where

$$\tilde{\Phi}_{ij} = \begin{bmatrix} \tilde{\Pi}_{ij}^{11} & \tilde{\Pi}_{ij}^{12} \\ * & \tilde{\Pi}_{ij}^{22} \end{bmatrix}, \quad \tilde{\Pi}_{ij}^{11} = \begin{bmatrix} \tilde{\Omega}_{11} & \tilde{\Omega}_{12} & \tilde{\Omega}_{13} \\ * & \tilde{\Omega}_{22} & \tilde{\Omega}_{23} \\ * & * & \tilde{\Omega}_{33} \end{bmatrix},$$

$$\tilde{\Omega}_{11} = \begin{bmatrix} \tilde{\Xi}_{11} & \tilde{\Xi}_{12} & -5R_{11}/3 & -5R_{12}/3 & 0 & 0 \\ * & \tilde{\Xi}_{22} & -5R_{12}^{\mathrm{T}}/3 & -5R_{13}/3 & \tilde{B}_{cj}E_i & 0 \\ * & * & \tilde{\Xi}_{33} & \tilde{\Xi}_{34} & -5R_{21}/3 & -5R_{22}/3 \\ * & * & * & \tilde{\Xi}_{44} & -5R_{22}^T/3 & -5R_{23}/3 \\ * & * & * & * & \tilde{\Xi}_{55} & -19R_{22}/3 \\ * & * & * & * & * & \tilde{\Xi}_{66} \end{bmatrix},$$

$$\tilde{\Omega}_{12} = \begin{bmatrix} 0 & 0 & 16R_{11}/3 & 16R_{12}/3 & 0 \\ 0 & 0 & 16R_{12}^T/3 & 16R_{13}/3 & 0 \\ 0 & 0 & 13R_{11}/3 & 13R_{12}/3 & 16R_{21}/3 \\ 0 & 0 & 13R_{12}^T/3 & 13R_{13}/3 & 16R_{22}^T/3 \\ -5R_{21}/3 & -5R_{22}/3 & 0 & 0 & 13R_{21}/3 \\ -5R_{22}^T/3 & -5R_{23}/3 & 0 & 0 & 13R_{22}^T/3 \end{bmatrix},$$

$$\tilde{\Omega}_{13} = \begin{bmatrix} 0 & 0 & 0 & 0 & \tilde{\Xi}_{116} \\ 0 & 0 & 0 & -\tilde{B}_{cj} & 0 \\ 16R_{22}/3 & 0 & 0 & 0 & 0 \\ 16R_{23}/3 & 0 & 0 & 0 & 0 \\ 13R_{22}/3 & 16R_{21}/3 & 16R_{22}/3 & \tilde{\Xi}_{515} & 0 \\ 13R_{23}/3 & 16R_{22}^T/3 & 16R_{23}/3 & 0 & 0 \end{bmatrix},$$

$$\tilde{\Omega}_{22} = \begin{bmatrix} \tilde{\Xi}_{77} & \tilde{\Xi}_{78} & 0 & 0 & 0 \\ * & \tilde{\Xi}_{88} & 0 & 0 & 0 \\ * & * & \tilde{\Xi}_{99} & \tilde{\Xi}_{910} & 0 \\ * & * & * & \tilde{\Xi}_{1010} & 0 \\ * & * & * & * & \tilde{\Xi}_{1111} \end{bmatrix},$$

$$\tilde{\Omega}_{23} = \begin{bmatrix} 0 & 13R_{21}/3 & 13R_{22}/3 & 0 & 0 \\ 0 & 13R_{22}^T/3 & 13R_{23}/3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \tilde{\Xi}_{1112} & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\tilde{\Omega}_{33} = \begin{bmatrix} \tilde{\Xi}_{1212} & 0 & 0 & 0 & 0 \\ * & \tilde{\Xi}_{1313} & \tilde{\Xi}_{1314} & 0 & 0 \\ * & * & \tilde{\Xi}_{1414} & 0 & 0 \\ * & * & * & \tilde{\Xi}_{1515} & 0 \\ * & * & * & * & -\gamma^2 \end{bmatrix},$$

$$\tilde{\Pi}_{ij}^{22} = \begin{bmatrix} \tilde{\Theta}_{ij}^{11} & \sigma^2 R_{12} & 0 & 0 & 0 \\ * & \tilde{\Theta}_{ij}^{22} & 0 & 0 & 0 \\ * & * & \tilde{\Theta}_{ij}^{33} & \sigma^2 R_{22} & 0 \\ * & * & * & \tilde{\Theta}_{ij}^{44} & 0 \\ * & * & * & * & -I \end{bmatrix},$$

$$\tilde{\Xi}_{11} = He(P_{11}A_i) + Q_{11} - 11R_{11}/3,$$

$$\tilde{\Xi}_{12} = \tilde{C}_{cj} + Q_{12} - 11R_{12}/3,$$

$$\tilde{\Xi}_{13} = He(\tilde{A}_{cj}) + Q_{13} - 11R_{13}/3,$$

$$\tilde{\Xi}_{33} = -Q_{11} + Q_{21} - 8R_{11}/3 - 11R_{21}/3,$$

$$\tilde{\Xi}_{34} = -Q_{12} + Q_{22} - 8R_{12}/3 - 11R_{22}/3,$$

$$\tilde{\Xi}_{44} = -Q_{13} + Q_{23} - 8R_{13}/3 - 11R_{23}/3,$$

$$\tilde{\Xi}_{55} = -19R_{21}/3 + (2 + \mu_1\delta_1 + \mu_2\delta_2)E_i^T\tilde{\Psi}E_i,$$

$$\tilde{\Xi}_{515} = -(1 + \mu_2\delta_2)E_i^T\tilde{\Psi},$$

$$\tilde{\Xi}_{66} = -19R_{23}/3,$$

$$\tilde{\Xi}_{77} = -Q_{21} - 8R_{21}/3,$$

$$\tilde{\Xi}_{88} = -Q_{23} - 8R_{23}/3,$$

$$\tilde{\Xi}_{99} = -29R_{11}/3,$$

$$\tilde{\Xi}_{910} = -29R_{12}/3,$$

$$\tilde{\Xi}_{1010} = -29R_{13}/3,$$

$$\tilde{\Xi}_{1111} = -29R_{21}/3,$$

$$\tilde{\Xi}_{1112} = -29R_{22}/3,$$

$$\tilde{\Xi}_{1212} = -29R_{23}/3,$$

$$\tilde{\Xi}_{1313} = -29R_{21}/3,$$

$$\tilde{\Xi}_{1314} = -29R_{22}/3,$$

$$\tilde{\Xi}_{1414} = -29R_{23}/3,$$

$$\tilde{\Xi}_{1515} = (1 + \mu_2\delta_2 - \mu_1 - \mu_2)\Psi,$$

$$\tilde{\Xi}_{116} = P_{11}B_{\omega i},$$

$$\tilde{\Theta}_{ij}^{11} = -2\sigma^2 P_{11} + \sigma^2 R_{11},$$

$$\tilde{\Theta}_{ij}^{22} = -2\sigma P_{12} + \sigma^2 R_{13},$$

$$\tilde{\Theta}_{ij}^{33} = -2\sigma P_{11} + \sigma^2 R_{21},$$

$$\tilde{\Theta}_{ij}^{44} = -2\sigma P_{11} + \sigma^2 R_{23},$$

$$\tilde{\Pi}_{ij}^{12} = [\tau_1(\tilde{F}_{ij}^{11})^T \quad \tau_1(\tilde{F}_{ij}^{12})^T \quad (\tau_2 - \tau_1)(\tilde{F}_{ij}^{11})^T \quad (\tau_2 - \tau_1)(\tilde{F}_{ij}^{12})^T \quad (\tilde{F}_{ij}^{2})^T],$$

$$\tilde{F}_{ij}^{11} = [P_{11}A_i \quad \tilde{C}_{cj} \quad 0 \quad 0 \quad 0 \quad \underbrace{0\cdots 0}_{9} \quad 0 \quad P_{11}B_{\omega i}],$$

$$\tilde{F}_{ij}^{12} = [0 \quad \tilde{A}_{cj} \quad 0 \quad 0 \quad \tilde{B}_{cj}E_i \quad \underbrace{0\cdots 0}_{9} \quad -\tilde{B}_{cj} \quad 0],$$

$$\tilde{F}_{ij}^{2} = [C_i \quad \underbrace{0\cdots 0}_{14} \quad D_{\omega i}].$$

In this case, dynamic output feedback controller parameters in (15) are solved by

$$A_{cj} = P_{12}^{-1}\tilde{A}_{cj}, \quad B_{cj} = P_{12}^{-1}\tilde{B}_{cj}, \quad C_{cj} = (B_i^T B_i)^{-1}B_i^T P_{11}^{-1}\tilde{C}_{cj}. \tag{29}$$

Proof: Assumption (17)–(19) holds, then the positive definite symmetric matrix P, Q_1, Q_2, R_1, R_2 is defined as

$$P = \begin{bmatrix} P_{11} & 0 \\ 0 & P_{12} \end{bmatrix}, \quad Q_1 = \begin{bmatrix} Q_{11} & Q_{12} \\ * & Q_{13} \end{bmatrix},$$
$$Q_2 = \begin{bmatrix} Q_{21} & Q_{22} \\ * & Q_{23} \end{bmatrix}, \tag{30}$$
$$R_1 = \begin{bmatrix} R_{11} & R_{12} \\ * & R_{13} \end{bmatrix}, \quad R_2 = \begin{bmatrix} R_{21} & R_{22} \\ * & R_{23} \end{bmatrix},$$

and define

$$\tilde{A}_{cj} = P_{12}A_{cj}, \quad \tilde{B}_{cj} = P_{12}B_{cj}, \quad \tilde{C}_{cj} = P_{11}B_iC_{cj}. \tag{31}$$

Obviously, there are non-linear terms $-PR_1^{-1}P$ and $-PR_2^{-1}P$ in (26), therefore, the feasible solution of the matrix inequality cannot be directly obtained through MATLAB LMI Toolbox. Inspired by B. Zhang et al. (2007), the inequality $-PR^{-1}P \leq -2\sigma P + \sigma^2 R$ is used to linearize the nonlinear terms. Substituting (30), (31) into (17)–(19), we get (26)–(28). This completes the proof. ■

Then, the parameters of the dynamic output feedback controller, the ET weight matrix, and the performance target can be obtained by the following algorithm.

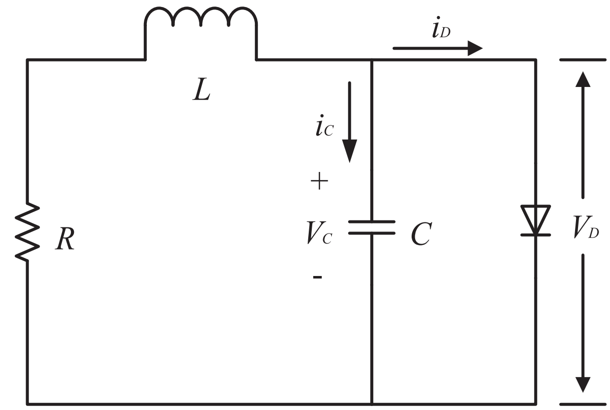

Figure 2. Tunnel diode circuit.

Algorithm 3.1: The solution of Theorem 3.2 is converted to the optimization problem as follows

$$\min \quad \gamma$$
$$\text{s.t.} \quad (26), (27) \text{ and } (28), \text{ hold for } i, j = 1, 2, \ldots, r. \tag{32}$$

Remark 3.2: Notice that the major differences between the present paper and Ran et al. (2018) are as follows: (1) A more general adaptive event-triggered mechanism is adopted, which saves communication resources; (2) By constructing a slightly different L-K functional and using the improved Wirtinger inequality, the results and the performance target have been improved, which will be illustrated by subsequent examples.

4. Simulation example

Consider a tunnel diode circuit system as shown in Figure 2, which is modelled as follows:

$$i_D(t) = 0.002v_D(t) + 0.01v_D^3(t).$$

Letting $x_1(t) = v_c(t)$ and $x_2(t) = i_L(t)$, the circuit system can be expressed by the following differential state equation

$$C\dot{x}_1(t) = -0.002x_1(t) - 0.01x_1^3(t) + x_2(t),$$
$$L\dot{x}_2(t) = -x_1(t) - Rx_2(t) + \omega(t),$$
$$z(t) = x_1(t) + \omega(t),$$
$$y(t) = x_1(t),$$

where $y(t)$ is the measurement output, $z(t)$ is the controlled output, $\omega(t)$ is the disturbance input. Given $L = 1\,\text{H}, C = 20\,\text{mF}, R = 10\,\Omega$, the above can be rewritten as

$$\dot{x}_1(t) = -0.1x_1(t) - \left(0.5x_1^2(t)\right) \cdot x_1(t) + 50x_2(t),$$
$$\dot{x}_2(t) = -x_1(t) - 10x_2(t) + \omega(t),$$
$$z(t) = x_1(t) + \omega(t),$$
$$y(t) = x_1(t).$$

Under the assumption $|x_1(t)| < 3$, the circuit system can be modeled by the following T-S fuzzy systems

$$\dot{x}(t) = \sum_{i=1}^{2} \varphi_i(x(t)) \left[A_i x(t) + B_i u(t) + B_{\omega i}\omega(t)\right]$$
$$z(t) = \sum_{i=1}^{2} \varphi_i(x(t)) \left[C_i x(t) + D_{\omega i}\omega(t)\right]$$
$$y(t) = \sum_{i=1}^{2} \varphi_i(x(t)) E_i x(t)$$

where

$$A_1 = \begin{bmatrix} -0.1 & 50 \\ -1 & -10 \end{bmatrix}, \quad A_2 = \begin{bmatrix} -4.6 & 50 \\ -1 & -10 \end{bmatrix},$$
$$B_1 = B_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix},$$
$$B_{\omega 1} = B_{\omega 2} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad C_1 = C_2 = [1 \quad 0],$$
$$D_1 = D_2 = 1, \quad E_1 = E_2 = [1 \quad 0].$$

Define the membership functions of the system as

$$\varphi_1(x(t)) = \left(1 - \frac{1}{1 + e^{-3(x(t)+0.5\pi)}}\right) \times \left(\frac{1}{1 + e^{-3(x(t)+0.5\pi)}}\right),$$
$$\varphi_2(x(t)) = 1 - \varphi_1(x(t)).$$

The controller's membership functions are chosen as

$$\psi_1(x_c(t)) = 0.79\, e^{\frac{-(x_c(t))^2}{3\times 1.5}}, \quad \psi_2(x_c(t)) = 1 - \psi_1(x_c(t)).$$

Letting $\tau_1 = 0.03$ s, $\tau_1 = 0.24$ s, $\rho_1 = 0.65$, $\rho_2 = 0.50$, $\alpha(t) = \beta(t) = 0.2$ and $\varepsilon = 0.2$ (ET threshold in Ran et al., 2018), the minimum value of γ is given in Table 1 under different methods. It is easy to see from Table 1 that the smaller γ are obtained by using improved Wirtinger inequality or Theorem 3.2.

Setting sampling periodic $h = 0.05$ s, $\tau_1 = 0.03$ s, $\tau_1 = 0.24$ s, $\mu_1 = \mu_2 = 5$, $\kappa_1 = \kappa_2 = 0.2$ and $\sigma = 2$, $\rho_1 = 0.65$, $\rho_2 = 0.50$ which ensure that $\psi_j(x_c) - \rho_j\varphi_j(x_c) \geq 0$. By solving (31), the minimum value of $\gamma = 1.9807$ and the weight matrix $\Psi = 0.035$ are obtained. In addition, the parameters of the controller are given by

$$A_{c1} = \begin{bmatrix} -3.6003 & -0.0025 \\ -0.0048 & -3.6003 \end{bmatrix},$$

Table 1. The minimum value of γ is compared under different methods.

Methods	ε	0.2
(Ran et al., 2018)	γ	3.9219
Improved Wirtinger inequality	γ	1.9813
Theorem 3.2	γ	1.9807

Note: $\varepsilon = 0.2$ is embodied in Theorem 3.2 as $\alpha(t) = 0.2$ and $\beta(t) = 0.2$.

$$A_{c2} = \begin{bmatrix} -3.6926 & -0.0001 \\ -0.0006 & -3.6926 \end{bmatrix},$$

$$B_{c1} = 10^{-2} \times \begin{bmatrix} -0.0164 \\ 0.0433 \end{bmatrix},$$

$$B_{c2} = 10^{-2} \times \begin{bmatrix} -0.0050 \\ 0.0241 \end{bmatrix},$$

$$C_{c1} = [0.0009 \quad -0.0146], \quad C_{c2} = [0.0011 \quad -0.0052].$$

5. Conclusion

This paper has investigated the problem of dynamic output feedback H_∞ controller design for networked T-S fuzzy system under AET mechanism. The membership function of the designed controller and the original system is asynchronous. Based on L-K functional method, the stability and stabilization conditions of the control system are obtained. Finally, an example is used to verify the feasibility of the design method. Future research includes extending the method to static output feedback control.

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References

Gu, Z., Yue, D., & Tian, E. (2018). On designing of an adaptive event-triggered communication scheme for nonlinear networked interconnected control systems. *Information Sciences*, *422*, 257–270. https://doi.org/10.1016/j.ins.2017.09.005

Guerra, T. M., & Vermeiren, L. (2004). LMI-based relaxed non-quadratic stabilization conditions for nonlinear systems in the Takagi-Sugeno's form. *Automatica*, *40*(5), 823–829. https://doi.org/10.1016/j.automatica.2003.12.014

Hua, C., Li, K., & Guan, X. (2019). Semi-global/global output consensus for nonlinear multiagent systems with time delays. *Automatica*, *103*, 480–489. https://doi.org/10.1016/j.automatica.2019.02.022

Hu, S., & Yue, D. (2012). Event-based H_∞ filtering for networked system with communication delay. *Signal Processing*, *92*(9), 2029–2039. https://doi.org/10.1016/j.sigpro.2012.01.012

Kim, E., & Kim, S. (2002). Stability analysis and synthesis for an affine fuzzy control system via LMI and ILMI: A continuous case. *IEEE Transactions on Fuzzy Systems*, *10*(3), 391–400. https://doi.org/10.1109/TFUZZ.2002.1006442

Li, H., Pan, Y., Yu, Z., Zhao, X., & Yang, X. (2014). Fuzzy output-feedback control for non-linear systems with input time-varying delay. *IET Control Theory & Applications*, *8*(9), 738–745. https://doi.org/10.1049/iet-cta.2013.0501

Li, W., Xie, Z., Zhao, J., Chu, S., Wong, P., & Gao, J. (2020). Improved AET robust control for networked T-S fuzzy systems with asynchronous constraints. *IEEE Transactions on Cybernetics*, 1–14. https://doi.org/10.1109/TCYB.2020.2989404.

Liu, D., Yang, G., & Er, M. (2020). Event-triggered control for T-S fuzzy systems under asynchronous network communications. *IEEE Transactions on Fuzzy Systems*, *28*(2), 390–399. https://doi.org/10.1109/TFUZZ.2019.2906857.

Ning, Z., Yu, J., Pan, Y., & Li, H. (2018). Adaptive event-triggered fault detection for fuzzy stochastic systems with missing measurements. *IEEE Transactions on Fuzzy Systems*, *26*(4), 2201–2212. https://doi.org/10.1109/TFUZZ.2017.2780799.

Peng, C., Yang, M. J., Zhang, J., Fei, M., & Hu, S. (2017, December 15). Network-based H_∞ control for T-S fuzzy systems with an adaptive event-triggered communication scheme. *Fuzzy Sets and Systems*, *329*, 61–76. https://doi.org/10.1016/j.fss.2016.12.011

Puangmalai, J., Tongkum, J., & Rojsiraphisal, T. (2020). Finite-time stability criteria of linear system with non-differentiable time-varying delay via new integral inequality. *Mathematics and Computers in Simulation*, *171*, 170–186. https://doi.org/10.1016/j.matcom.2019.06.013

Qiu, J., Gao, H., & Ding, S. (2016). Recent advances on fuzzy-model-based nonlinear networked control systems: A survey. *IEEE Transactions on Industrial Electronics*, *63*(2), 1207–1217. https://doi.org/10.1109/TIE.2015.2504351

Ran, G., Lu, Z., Xu, F., & Lu, J. (2018). Event-triggered dynamic output feedback control for networked T-S fuzzy systems with asynchronous premise variables. *IEEE Access*, *6*, 78740–78750. https://doi.org/10.1109/ACCESS.2018.2885212.

Tabuada, P. (2007). Event-triggered real-time scheduling of stabilizing control tasks. *IEEE Transactions on Automatic Control*, *52*(9), 1680–1685. https://doi.org/10.1109/TAC.2007.904277

Takagi, T., & Sugeno, M. (1985). Fuzzy identification of systems and its applications to modeling and control. *IEEE Transactions on Systems, Man, and Cybernetics*, *SMC-15*(1), 116–132. https://doi.org/10.1109/TSMC.1985.6313399

You, X., Hua, C., & Guan, X. (2019). Self-triggered leader-following consensus for high-order nonlinear multiagent systems via dynamic output feedback control. *IEEE Transactions on Cybernetics*, *49*(6), 2002–2010. https://doi.org/10.1109/TCYB.2018.2813423

Zhang, X., Han, Q., Seuret, A., & Gouaisbaut, F. (2017). An improved reciprocally convex inequality and an augmented Lyapunov-Krasovskii functional for stability of linear systems with time-varying delay. *Automatica*, *84*, 221–226. https://doi.org/10.1016/j.automatica.2017.04.048

Zhang, X., Han, Q., & Yu, X. (2016). Survey on recent advances in networked control systems. *IEEE Transactions on Industrial*

Informatics, *12*(5), 1740–1752. https://doi.org/10.1109/TII.2015.2506545

Zhang, C., He, Y., Jiang, L., Wang, Q., & Wu, M. (2017). Stability analysis of discrete-time neural networks with time-varying delay via an extended reciprocally convex matrix inequality. *IEEE Transactions on Cybernetics*, *47*(10), 3040–3049. https://doi.org/10.1109/TCYB.2017.2665683

Zhang, C., He, Y., Jiang, L., Wu, M., & Wang, Q. (2017). An extended reciprocally convex matrix inequality for stability analysis of systems with time-varying delay. *Automatica*, *85*, 481–485. https://doi.org/10.1016/j.automatica.2017.07.056

Zhang, Z., Lin, C., Chen, B., Chen, J., & Zhou, S. (2015). H_∞ control for fuzzy time-delay systems via dynamic output feedback. In 10th Asian control conference (ASCC) (pp. 1–6), Control Conference IEEE. https://doi.org/10.1109/ASCC.2015.7244422.

Zhang, B., Xu, S., Zong, G., & Zou, Y. (2007). Delay-dependent stabilization for stochastic fuzzy systems with time delays. *Fuzzy Sets and Systems*, *158*(20), 2238–2250. https://doi.org/10.1016/j.fss.2007.05.011

Zhang, K., Zhao, T., & Dian, S. (2020). Dynamic output feedback control for nonlinear networked control systems with a two-terminal event-triggered mechanism. *Nonlinear Dynamics*, *100*(1). https://doi.org/10.1007/s11071-020-05635-1.