

Research Article

Control Design for Discrete-Time Fuzzy Systems with Disturbance Inputs via Delta Operator Approach

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This paper is concerned with the problem of passive control design for discrete-time Takagi-Sugeno (T-S) fuzzy systems with time delay and disturbance input via delta operator approach. The discrete-time passive performance index is established in this paper for the control design problem. By constructing a new type of Lyapunov-Krasovskii function (LKF) in delta domain, and utilizing some fuzzy weighing matrices, a new passive performance condition is proposed for the system under consideration. Based on the condition, a state-feedback passive controller is designed to guarantee that the resulting closed-loop system is very-strictly passive. The existence conditions of the controller can be expressed by linear matrix inequalities (LMIs). Finally, a numerical example is provided to demonstrate the feasibility and effectiveness of the proposed method.

1. Introduction

It is well known that the fuzzy logic control [1–4] is one of the most effective approaches to handle complex nonlinear systems. Takagi-Sugeno (T-S) fuzzy model has been proposed in [5] and applied to formulate a complex nonlinear systems into a framework. Some affine local models can be interpolated by a set of fuzzy membership functions in this framework. By T-S fuzzy model, a set of complex nonlinear systems can be possibly described as a weighed sum of some simple linear subsystems. Recently, the problem of stability analysis and controller synthesis of nonlinear systems in T-S fuzzy model has been extensively investigated in [5–18]. Due to the effect of time delay in systems, the problems of T-S fuzzy systems with time delays have got considerable attention in recent years, and some results have been developed in [9, 19–31].

Recently, due to the fact that the passive properties can keep the system internally stable and have been frequently used to improve the stability of control systems. The passivity

control has been widely applied in various engineering areas, such as electrical circuits systems, complex networks systems, mechanical systems, and nonlinear systems. The problems of passivity analysis and passive control for systems have been widely investigated [32–38]. The passive control problem has been investigated for fuzzy systems [35, 39, 40]. Among them, the authors in [40] are concerned with the very strict passive controller design problem for T-S fuzzy systems with time-varying delay.

It is well known that the best system performances can be obtained with the shorter sampling period. In [41, 42], the authors pointed out that the excellent finite word length performance can be achieved under fast sampling via delta operator approach. The authors in [43] introduced the transformations between shift operator and delta operator transfer function models. A technique was developed in [44] to obtain an approximate delta operator system for a given continuous system. In [45], a tabular method was presented for real polynomial root distribution with respect to a circle in the complex plane, which is useful in stability of delta operator

formulated discrete-time systems with a sampling time. By using delta operator formulation, the main design features of a loop transfer recovery controller both at input and output have been overviewed in [46]. More recently, many stability analysis and controller synthesis results about delta operator approach have been proposed in [47–49]. To mention a few, the robust stabilization problem was investigated in [47] for delta operator systems with time-varying delays. The authors in [49] investigated the robust H_∞ control problem for a class of T-S fuzzy systems with time delays by using delta operator approach. However, there have been few results on the passive control for T-S fuzzy systems with time delays and disturbance inputs via delta operator approach, which motivates this study.

In this paper, the problem of passive control is investigated for discrete-time T-S fuzzy systems with time delay and disturbance input via delta operator approach. The discrete-time passive performance index is concerned in this paper for the control design problem. A novel type Lyapunov-Krasovskii functional (LKF) is constructed in delta domain to present a new passive performance condition for discrete-time T-S fuzzy systems. Based on the condition, a state-feedback passive controller is designed to guarantee that the resulting closed-loop system is very strictly passive. The controller existence condition can be obtained in terms of linear matrix inequalities (LMIs), which can be solved by the standard software. A numerical example is given to illustrate the effectiveness of the proposed approach.

At first, the T-S fuzzy model is employed to represent the nonlinear systems. By applying the LMIs techniques and LKF in δ -domain, the problem of passive control design for the discrete T-S fuzzy system with time delay and disturbance inputs is chewed. Then a new fuzzy state-feedback controller is designed which guarantees that the closed-loop fuzzy delta operator system with time delay is robustly asymptotically stable and satisfies a prescribed passive performance level. And those are some key points of contribution. It is worthwhile to note that a faster sampling method is utilized, and hence a better control effect by applying delta operator approach than shift operator approach is achieved. Finally, a numerical example is shown to indicate the feasibility and effectiveness of the proposed method.

This paper is organized as follows. The problem to be solved is formulated in Section 2. Main results, including passive analysis and passive controller design, are presented in Section 3. Section 4 provides an illustrative example to show the effectiveness and potential of the proposed design techniques. It is concluded this paper in Section 5.

Notation. The notation used throughout the paper is fairly standard. $L_2[0, \infty)$ denotes the space of square-integrable vector functions over $[0, \infty)$. The notation $X > 0$ (resp., $X \geq 0$), for $X \in \mathbb{R}^{n \times n}$, means that the matrix X is real symmetric positive definite (resp., positive semidefinite). The symbol “ $*$ ” in a matrix $A \in \mathbb{R}^{n \times n}$ stands for the transposed elements in the symmetric positions. The superscripts “ T ” and “ -1 ” denote the matrix transpose and inverse, respectively. Identity matrices of appropriate dimensions will be denoted by I .

The shorthand $\text{diag}\{M_1, M_2, \dots, M_r\}$ denotes a block diagonal matrix with diagonal blocks being the matrices M_1, M_2, \dots, M_r . If not explicitly stated, all matrices are assumed to have compatible dimensions for algebraic operations.

2. Problem Formulation

Considering the following fuzzy delta operator system with time delay, which is described by

Plant Rule i . IF $\theta_1(t_k)$ is N_{i1} , and \dots , and $\theta_j(t_k)$ is N_{ij} , and \dots , and $\theta_p(t_k)$ is N_{ip} , THEN

$$\begin{aligned} \delta x(t_k) &= A_i x(t_k) + A_{di} x(t_k - d_k) + B_i u(t_k) + B_{wi} w(t_k), \\ z(t_k) &= C_i x(t_k) + C_{di} x(t_k - d_k) + D_i u(t_k) + D_{wi} w(t_k), \\ x(t_k) &= \phi(t_k), \quad t_k = -d_M, d_M + T, \dots, 0, \quad i = 1, 2, \dots, r, \end{aligned} \quad (1)$$

where $x(t_k) \in \mathbb{R}^n$ is the state variable, $u(t_k) \in \mathbb{R}^m$ is the control input variable, $w(t_k) \in \mathbb{R}^l$ is the disturbance input variable which belongs to $L_2[0, \infty)$, $z(t_k) \in \mathbb{R}^p$ is the control output, and $\phi(t_k)$ is a continuous vector-valued initial function. Let $t_k = kT$ for the convenience in analysis. $A_i, A_{di}, B_i, B_{wi}, C_i, C_{di}, D_i$, and D_{wi} ($i = 1, 2, \dots, r$) are system matrices with appropriate dimensions. The scalar r is the number of IF-THEN rules. $\theta_j(t_k)$ and N_{ij} are the premise variable and the fuzzy set, respectively, for $j = 1, 2, \dots, p$. The parametric variable $d_k = nT$ which is the bounded time delay in the state and satisfies $0 < d_m \leq d_k \leq d_M$ with $d_m = n_m T$ and $d_M = n_M T$ (n_m and n_M are the known positive and finite integers, and T is a sampling period). $\delta x(t_k)$ is the delta operator of $x(t_k)$, which is defined by

$$\delta x(t_k) = \begin{cases} \frac{d}{dt_k} x(t_k), & T = 0, \\ \frac{x(t_k + T) - x(t_k)}{T}, & T \neq 0. \end{cases} \quad (2)$$

Then the defuzzified model of system (1) is inferred as follows:

$$\begin{aligned} \delta x(t_k) &= \sum_{i=1}^r h_i(\theta(t_k)) [A_i x(t_k) + A_{di} x(t_k - d_k) \\ &\quad + B_i u(t_k) + B_{wi} w(t_k)], \\ z(t_k) &= \sum_{i=1}^r h_i(\theta(t_k)) [C_i x(t_k) + C_{di} x(t_k - d_k) \\ &\quad + D_i u(t_k) + D_{wi} w(t_k)], \end{aligned} \quad (3)$$

where $h_i(\theta(t_k)) = \mu_i(\theta(t_k)) / \sum_{i=1}^r \mu_i(\theta(t_k))$, $\mu_i(\theta(t_k)) = \prod_{j=1}^p N_{ij}(\theta_j(t_k))$, and $N_{ij}(\theta_j(t_k))$ is the degree of the membership of $\theta_j(t_k)$ in fuzzy set N_{ij} . It can be assumed that $\mu_i(\theta(t_k)) \geq 0$ (for $i = 1, 2, \dots, r$) and $\sum_{i=1}^r \mu_i(\theta(t_k)) \geq 0$ (for all t_k). Therefore, $h_i(\theta(t_k)) \geq 0$ (for $i = 1, 2, \dots, r$) and

$\sum_{i=1}^r h_i(\theta(t_k)) = 1$. Based on the parallel distributed compensation (PDC), similar to the fuzzy model, the following overall fuzzy control law can be constructed as

$$u(t_k) = \sum_{s=1}^r h_s(\theta(t_k)) K_s x(t_k), \quad (4)$$

where K_s ($s = 1, 2, \dots, r$) is the local control gain such that closed-loop fuzzy system (3) is asymptotically stable. Then substituting (4) into system (3), the closed-loop fuzzy system can be expressed as

$$\begin{aligned} \delta x(t_k) = & \sum_{i=1}^r \sum_{s=1}^r h_i h_s [(A_i + B_i K_s) x(t_k) \\ & + A_{di} x(t_k - d_k) + B_{wi} w(t_k)], \end{aligned} \quad (5)$$

$$\begin{aligned} z(t_k) = & \sum_{i=1}^r \sum_{s=1}^r h_i h_s [(C_i + D_i K_s) x(t_k) \\ & + C_{di} x(t_k - d_k) + D_{wi} w(t_k)], \end{aligned}$$

where $\sum_{i=1}^r h_i = \sum_{i=1}^r h_i(\theta(t_k))$. For the convenience, system (5) can be rewritten as

$$\begin{aligned} \delta x(t_k) = & A(t_k) x(t_k) + A_d(t_k) x(t_k - d_k) \\ & + B_w(t_k) w(t_k), \\ z(t_k) = & C(t_k) x(t_k) + C_d(t_k) x(t_k - d_k) \\ & + D_w(t_k) w(t_k), \end{aligned} \quad (6)$$

where

$$\begin{aligned} A(t_k) = & \sum_{i=1}^r \sum_{s=1}^r h_i h_s (A_i + B_i K_s), \\ A_d(t_k) = & \sum_{i=1}^r h_i A_{di}, \quad B_w(t_k) = \sum_{i=1}^r h_i B_{wi}, \\ C(t_k) = & \sum_{i=1}^r \sum_{s=1}^r h_i h_s (C_i + D_i K_s), \\ C_d(t_k) = & \sum_{i=1}^r h_i C_{di}, \quad D_w(t_k) = \sum_{i=1}^r h_i D_{wi}. \end{aligned} \quad (7)$$

In the next section, the following definitions and lemmas are introduced for developing the main results.

Definition 1 (see [47]). The conditions for the asymptotic stability of a delta operator system hold:

- (a) $V(x(t_k)) \geq 0$, with equality if and only if $x(t_k) = 0$,
- (b) $\delta V(x(t_k)) = [V(x(t_k + T)) - V(x(t_k))]/T < 0$,

where $V(x(t_k))$ is a Lyapunov function in δ -domain. For Lyapunov function both in s -domain and z -domain, the

condition (a) $V(x(t_k)) \geq 0$ in Definition 1 is given. On the other hand for the condition (b), when $T \rightarrow 0$, there exists

$$\begin{aligned} \lim_{T \rightarrow 0} \delta V(x(t_k)) &= \lim_{T \rightarrow 0} \frac{V(x(t_k + T)) - V(x(t_k))}{T} \\ &= \frac{dV(x(t_k))}{dt_k} < 0, \end{aligned} \quad (8)$$

and when $T = 1$, there exists

$$\begin{aligned} \delta V(x(t_k)) &= \frac{[V(x(t_k + 1)) - V(x(t_k))]}{1} \\ &= V(x(t_k + 1)) - V(x(t_k)) < 0. \end{aligned} \quad (9)$$

Obviously, the Lyapunov function in δ -domain can be reduced to the traditional Lyapunov function in s -domain or z -domain when the sampling period T tends to 0 or is 1.

Definition 2 (see [50]). (i) System (5) is said to be passive if there exists constant ρ such that

$$2 \sum_{t_k=0}^{\infty} z^T(t_k) w(t_k) \geq \rho. \quad (10)$$

(ii) System (5) is said to be strictly passive if there exist constants $\zeta > 0$ and ρ such that

$$2 \sum_{t_k=0}^{\infty} z^T(t_k) w(t_k) \geq \rho + \zeta \sum_{t_k=0}^{\infty} w^T(t_k) w(t_k). \quad (11)$$

(iii) System (5) is said to be output strictly passive if there exist constants $\varepsilon > 0$ and ρ such that

$$2 \sum_{t_k=0}^{\infty} z^T(t_k) w(t_k) \geq \rho + \varepsilon \sum_{t_k=0}^{\infty} z^T(t_k) z(t_k). \quad (12)$$

(iv) System (5) is said to be very strictly passive if there exist constants $\varepsilon > 0$, $\zeta > 0$, and ρ such that

$$\begin{aligned} 2 \sum_{t_k=0}^{\infty} z^T(t_k) w(t_k) &\geq \rho + \varepsilon \sum_{t_k=0}^{\infty} z^T(t_k) z(t_k) \\ &+ \zeta \sum_{t_k=0}^{\infty} w^T(t_k) w(t_k). \end{aligned} \quad (13)$$

Lemma 3 (see [47]). For any of the time functions $x(t_k)$ and $y(t_k)$,

$$\begin{aligned} \delta(x(t_k) y(t_k)) &= \delta(x(t_k)) y(t_k) + x(t_k) \delta(y(t_k)) \\ &+ T \delta(x(t_k)) \delta(y(t_k)), \end{aligned} \quad (14)$$

where T is a sampling period.

Lemma 4 (see [51]). For any of the two positive integers r and r_0 , satisfying $1 \leq r_0 \leq r$ holds:

$$\left[\sum_{i=r_0}^r x(i) \right]^T M \left[\sum_{i=r_0}^r x(i) \right] \leq (r - r_0 + 1) \sum_{i=r_0}^r x^T(i) M x(i), \quad (15)$$

where M is a constant positive semidefinite symmetric matrix.

Lemma 5 (see [52]). *For the given constant matrices G, H and a symmetric constant matrix χ of appropriate dimensions, the following inequality holds:*

$$\chi + GF(t_k)H + H^T F^T(t_k)G^T \leq 0, \quad (16)$$

where $F(t_k)$ satisfies $F^T(t_k)F(t_k) \leq I$, if and only if for $\xi > 0$ the following inequality holds:

$$\chi + \xi^{-1}H^T H + \xi GG^T \leq 0. \quad (17)$$

Lemma 6. *If there exist scalars $\varepsilon > 0, \zeta > 0$, and a differential function $V(x(t_k)) \geq 0$ such that*

$$\begin{aligned} \delta V(x(t_k)) + \varepsilon z^T(t_k)z(t_k) + \zeta w^T(t_k)w(t_k) \\ - 2z^T(t_k)w(t_k) \leq 0, \end{aligned} \quad (18)$$

then system (5) is very strictly passive.

Proof. It follows from (18) that

$$\begin{aligned} 2 \sum_{t_k=0}^{\infty} z^T(t_k)w(t_k) &\geq -V(x(0)) + \varepsilon \sum_{t_k=0}^{\infty} z^T(t_k)z(t_k) \\ &\quad + \zeta \sum_{t_k=0}^{\infty} w^T(t_k)w(t_k) \\ &= \rho + \varepsilon \sum_{t_k=0}^{\infty} z^T(t_k)z(t_k) \\ &\quad + \zeta \sum_{t_k=0}^{\infty} w^T(t_k)w(t_k), \end{aligned} \quad (19)$$

where $\rho = -V(x(0))$. Then, it can be seen that (13) is equivalent to (18) for very strict passive definition. \square

Remark 7. Based on Definition 2, the main objective of this paper is just to prove that T-S fuzzy system (5) is very strictly passive via delta operator approach, which can also satisfy other three indexes. The very strictly passive control for system (5) is shown in the next section.

3. Main Results

This section focuses on designing a sufficient condition for the solvability of the proposed passive control problem and a developed LMI approach for designing the passive controller for fuzzy system (5). Firstly, the passivity analysis criterion is derived for the system (5) in the following theorem.

Theorem 8. *Considering fuzzy delta operator system (5), for a given sampling period $T > 0$, constants d_m, d_M ($0 < d_m \leq d_M$), and matrix K_s ($s = 1, 2, \dots, r$), system (5) is very strictly passive if there exist scalars $\varepsilon > 0, \zeta > 0$ and symmetric matrices $P > 0, R_1 > 0, R_2 > 0, Q_\kappa > 0, S_{1\kappa} > 0$, and $S_{2\kappa} > 0$ ($\kappa = 1, 2, \dots, r$) with appropriate dimensions, such that the following LMIs hold for $\kappa, \lambda, \mu, \nu, i, s = 1, 2, \dots, r$:*

$$\begin{aligned} \Theta_{\kappa\lambda\mu\nu ii} &< 0, \\ \Theta_{\kappa\lambda\mu\nu is} + \Theta_{\kappa\lambda\mu\nu si} &< 0, \quad s \neq i, \end{aligned} \quad (20)$$

where

$$\begin{aligned} \Theta_{\kappa\lambda\mu\nu is} &= \begin{bmatrix} \Omega_{1\kappa\lambda\mu\nu is} & \Omega_{2is}^T \\ * & -\varepsilon I \end{bmatrix}, \quad \Omega_{2is} = \begin{bmatrix} 0 & C_i + D_i K_s & C_{di} & 0 & 0 & D_{wi} \end{bmatrix}, \\ \Omega_{1\kappa\lambda\mu\nu is} &= \begin{bmatrix} \Xi_1 & P(A_i + B_i K_s) & P A_{di} & 0 & 0 & P B_{wi} \\ * & \Xi_{2\kappa is} & P A_{di} & \frac{1}{d_m} R_1 & \frac{1}{d_M} R_2 & \Xi_{3is} \\ * & * & -Q_\lambda & 0 & 0 & -C_{di} \\ * & * & * & -S_{1\mu} - \frac{1}{d_m} R_1 & 0 & 0 \\ * & * & * & * & -S_{2\nu} - \frac{1}{d_M} R_2 & 0 \\ * & * & * & * & * & \zeta I - D_{wi} - D_{wi}^T \end{bmatrix}, \end{aligned} \quad (21)$$

$$\Xi_1 = (T-2)P + d_m R_1 + d_M R_2, \quad \Xi_{3is} = P B_{wi} - (C_i + D_i K_s)^T,$$

$$\Xi_{2\kappa is} = P(A_i + B_i K_s) + (A_i + B_i K_s)^T P + (d_M - d_m + T + 1)Q_\kappa + S_{1\kappa} + S_{2\kappa} - \frac{1}{d_m} R_1 - \frac{1}{d_M} R_2.$$

Proof. Firstly, in order to simplify the calculation, relevant fuzzy weighing matrices which directly include the membership functions are defined as follows:

$$\begin{aligned}\check{Q}(t_k) &= \sum_{\kappa=1}^r h_{\kappa}(\theta(t_k)) Q_{\kappa}, & \check{S}_1(t_k) &= \sum_{\kappa=1}^r h_{\kappa}(\theta(t_k)) S_{1\kappa}, \\ \check{S}_2(t_k) &= \sum_{\kappa=1}^r h_{\kappa}(\theta(t_k)) S_{2\kappa}.\end{aligned}\quad (22)$$

Choose a LKF $V(x(t_k))$ for system (5) as follows:

$$\begin{aligned}V(x(t_k)) &= V_1(x(t_k)) + V_2(x(t_k)) + V_3(x(t_k)) \\ &\quad + V_4(x(t_k)) + V_5(x(t_k)),\end{aligned}\quad (23)$$

where

$$\begin{aligned}V_1(x(t_k)) &= x^T(t_k) P x(t_k), \\ V_2(x(t_k)) &= T \sum_{i=1}^n x^T(t_k - iT) \check{Q}(t_k - iT) x(t_k - iT), \\ V_3(x(t_k)) &= T \sum_{i=1}^{n_m} x^T(t_k - iT) \check{S}_1(t_k - iT) x(t_k - iT) \\ &\quad + T \sum_{i=1}^{n_M} x^T(t_k - iT) \check{S}_2(t_k - iT) x(t_k - iT), \\ V_4(x(t_k)) &= T^2 \sum_{i=n_m}^{n_M} \sum_{s=1}^i x^T(t_k - sT) \check{Q}(t_k - sT) x(t_k - sT), \\ V_5(x(t_k)) &= \sum_{i=1}^{n_m} \sum_{s=1}^i e^T(t_k - sT) R_1 e(t_k - sT) \\ &\quad + \sum_{i=1}^{n_M} \sum_{s=1}^i e^T(t_k - sT) R_2 e(t_k - sT),\end{aligned}\quad (24)$$

and symmetric matrices $P > 0, R_1 > 0, R_2 > 0, Q_{\kappa} > 0, S_{1\kappa} > 0, S_{2\kappa} > 0$ (for $\kappa = 1, 2, \dots, r$), and $e(s) = x(s) - x(s+T)$ from which it can be concluded that there exist $e(t_k - iT) = x(t_k - iT) - x(t_k - (i-1)T)$ and $\delta x(t_k) = -e(t_k)/T$.

Applying Lemma 3 to $V_1(x(t_k))$ and along the trajectory of the system (5), it can be obtained that

$$\begin{aligned}\delta V_1(x(t_k)) &= \delta^T(x(t_k)) P x(t_k) + x^T(t_k) P \delta(x(t_k)) \\ &\quad + T \delta^T(x(t_k)) P \delta(x(t_k)) \\ &= x^T(t_k) [PA(t_k) + A^T(t_k) P] x(t_k) \\ &\quad + 2x^T(t_k) P A_d(t_k) x(t_k - d_k)\end{aligned}$$

$$\begin{aligned}&+ 2x^T(t_k) P B_w(t_k) w(t_k) \\ &+ T \delta^T(x(t_k)) P \delta(x(t_k)).\end{aligned}\quad (25)$$

Similarly, applying the delta operator to $V_2(x(t_k)), V_3(x(t_k)),$ and $V_4(x(t_k)),$ it can be obtained as follows:

$$\begin{aligned}\delta V_2(x(t_k)) &= \frac{1}{T} \left[T \sum_{i=1}^n x^T(t_k - iT + T) \check{Q}(t_k - iT + T) \right. \\ &\quad \times x(t_k - iT + T) \\ &\quad \left. - T \sum_{i=1}^n x^T(t_k - iT) \check{Q}(t_k - iT) x(t_k - iT) \right] \\ &\leq x^T(t_k) \check{Q}(t_k) x(t_k) \\ &\quad - x^T(t_k - d_k) \check{Q}(t_k - d_k) x(t_k - d_k) \\ &\quad + T \sum_{i=n_m}^{n_M} x^T(t_k - iT) \check{Q}(t_k - iT) x(t_k - iT), \\ \delta V_3(x(t_k)) &= x^T(t_k) (\check{S}_1(t_k) + \check{S}_2(t_k)) x(t_k) \\ &\quad - x^T(t_k - d_m) \check{S}_1(t_k - d_m) x(t_k - d_m) \\ &\quad - x^T(t_k - d_M) \check{S}_2(t_k - d_M) x(t_k - d_M), \\ \delta V_4(x(t_k)) &= T \left[\sum_{s=1}^i (x^T(t_k - sT + T) \check{Q}(t_k - sT + T) \right. \\ &\quad \times x(t_k - sT + T)) \\ &\quad \left. - \sum_{s=1}^i (x^T(t_k - sT) \check{Q}(t_k - sT) \right. \\ &\quad \left. \times x(t_k - sT)) \right] \\ &= (d_M - d_m + T) x^T(t_k) \check{Q}(t_k) x(t_k) \\ &\quad - T \sum_{i=n_m}^{n_M} x^T(t_k - iT) \check{Q}(t_k - iT) x(t_k - iT).\end{aligned}\quad (26)$$

Applying Lemma 4 to $V_5(x(t_k))$ and along the trajectory of system (5), it can be obtained that

$$\begin{aligned}\delta V_5(x(t_k)) &= \frac{1}{T} \left[\sum_{i=1}^{n_m} \sum_{s=1}^i e^T(t_k - sT + T) R_1 e(t_k - sT + T) \right. \\ &\quad \left. - \sum_{i=1}^{n_m} \sum_{s=1}^i e^T(t_k - sT) R_1 e(t_k - sT) \right. \\ &\quad \left. + \sum_{i=1}^{n_M} \sum_{s=1}^i e^T(t_k - sT + T) \right.\end{aligned}$$

$$\begin{aligned}
& \times R_2 e(t_k - sT + T) \\
& - \sum_{i=1}^{n_M} e^T(t_k - sT) R_2 e(t_k - sT) \Big] \\
= & \frac{1}{T} \left[\sum_{i=1}^{n_m} e^T(t_k) R_1 e(t_k) \right. \\
& - \sum_{i=1}^{n_m} e^T(t_k - iT) R_1 e(t_k - iT) \\
& + \sum_{i=1}^{n_M} e^T(t_k) R_2 e(t_k) \\
& \left. - \sum_{i=1}^{n_M} e^T(t_k - iT) R_2 e(t_k - iT) \right] \\
\leq & e^T(t_k) \left(\frac{n_m}{T} R_1 + \frac{n_M}{T} R_2 \right) e(t_k) \\
& - \frac{1}{n_m T} \left[\sum_{i=1}^{n_m} e(t_k - iT) \right]^T R_1 \\
& \times \left[\sum_{i=1}^{n_m} e(t_k - iT) \right] - \frac{1}{n_M T} \left[\sum_{i=1}^{n_M} e(t_k - iT) \right]^T \\
& \times R_2 \left[\sum_{i=1}^{n_M} e(t_k - iT) \right] \\
= & \delta^T(x(t_k)) (d_m R_1 + d_M R_2) \delta(x(t_k)) \\
& - \frac{1}{d_m} [x(t_k) - x(t_k - d_m)]^T \\
& \times R_1 [x(t_k) - x(t_k - d_m)] \\
& - \frac{1}{d_M} [x(t_k) - x(t_k - d_M)]^T \\
& \times R_2 [x(t_k) - x(t_k - d_M)]. \tag{27}
\end{aligned}$$

For the real matrix $P > 0$, the following equation is tenable:

$$\begin{aligned}
0 = & -2\delta^T(x(t_k)) P [\delta(x(t_k)) - A(t_k) x(t_k) \\
& - A_d(t_k) x(t_k - d_k) - B_w(t_k) w(t_k)] \\
= & -2\delta^T(x(t_k)) P \delta(x(t_k)) + 2\delta^T(x(t_k)) P A(t_k) x(t_k) \\
& + 2\delta^T(x(t_k)) P A_d(t_k) x(t_k - d_k) \\
& + 2\delta^T(x(t_k)) P B_w(t_k) w(t_k). \tag{28}
\end{aligned}$$

Generally, considering the passive performance index in Definition 2, which is described as the passivity analysis, performance of system (5) can be established as follows:

$$\begin{aligned}
J = & \varepsilon^{-1} z^T(t_k) z(t_k) + \zeta w^T(t_k) w(t_k) \\
& - 2z^T(t_k) w(t_k) + \delta V(t_k). \tag{29}
\end{aligned}$$

By adding (28) into $\delta V(t_k)$ and applying (7), it can be found that

$$\begin{aligned}
J = & \varepsilon^{-1} z^T(t_k) z(t_k) + \zeta w^T(t_k) w(t_k) - 2z^T(t_k) w(t_k) \\
& + \delta V(t_k) \\
\leq & \eta^T(t_k) \sum_{\kappa=1}^r \sum_{\lambda=1}^r \sum_{\mu=1}^r \sum_{\nu=1}^r \sum_{i=1}^r \sum_{s=1}^r h_\kappa h_\lambda h_\mu h_\nu h_i h_s \eta^T(t_k) \\
& \times [\Omega_{1\kappa\lambda\mu\nu is} + \varepsilon^{-1} \Omega_{2is}^T \Omega_{2is}] \eta(t_k), \tag{30}
\end{aligned}$$

where $h_\kappa = h_\kappa(\theta(t_k))$, $h_\lambda = h_\lambda(\theta(t_k - d_k))$, $h_\mu = h_\mu(\theta(t_k - d_m))$, $h_\nu = h_\nu(\theta(t_k - d_M))$, $h_i = h_i(\theta(t_k))$, $h_s = h_s(\theta(t_k))$, and

$$\eta^T(t_k) = [\delta^T(x(t_k)) \quad x^T(t_k) \quad x^T(t_k - d_k) \quad x^T(t_k - d_m) \quad x^T(t_k - d_M) \quad w^T(t_k)]. \tag{31}$$

On the other hand, it can be seen from Theorem 8 that

$$\begin{aligned}
& \sum_{\kappa=1}^r \sum_{\lambda=1}^r \sum_{\mu=1}^r \sum_{\nu=1}^r \sum_{i=1}^r \sum_{s=1}^r h_\kappa h_\lambda h_\mu h_\nu h_i h_s \Theta_{\kappa\lambda\mu\nu is} \\
= & \sum_{\kappa=1}^r \sum_{\lambda=1}^r \sum_{\mu=1}^r \sum_{\nu=1}^r h_\kappa h_\lambda h_\mu h_\nu \\
& \times \left[\sum_{i=1}^r h_i^2 \Theta_{\kappa\lambda\mu\nu ii} \right]
\end{aligned}$$

$$+ \sum_{i=1}^{r-1} \sum_{s=i+1}^r h_i h_s (\Theta_{\kappa\lambda\mu\nu is} + \Theta_{\kappa\lambda\mu\nu si}) < 0. \tag{32}$$

Applying Schur complement, it can be obtained that

$$\begin{aligned}
J = & \varepsilon^{-1} z^T(t_k) z(t_k) + \zeta w^T(t_k) w(t_k) \\
& - 2z^T(t_k) w(t_k) + \delta V(t_k) < 0. \tag{33}
\end{aligned}$$

It can be seen that the LMIs conditions in Theorem 8 satisfy the very strictly passive performance index for the fuzzy delta operator system (5). The proof is completed. \square

Based on the conditions in Theorem 8, the state-feedback control gain matrices K_s ($s = 1, 2, \dots, r$) will be designed in the following theorem.

Theorem 9. *Considering fuzzy delta operator system (5), for a given sampling period $T > 0$ and constants d_m, d_M ($0 <$*

$d_m \leq d_M$), system (5) is very strictly passive if there exist scalars $\varepsilon > 0, \zeta > 0$ and symmetric matrices $\bar{P} > 0, \bar{R}_1 > 0, \bar{R}_2 > 0, \bar{Q}_\kappa > 0, \bar{S}_{1\kappa} > 0$, and $\bar{S}_{2\kappa} > 0$ ($\kappa = 1, 2, \dots, r$) with appropriate dimensions, such that the following LMIs hold for $\kappa, \lambda, \mu, \nu, i, s = 1, 2, \dots, r$:

$$\begin{aligned} \bar{\Theta}_{\kappa\lambda\mu\nu ii} &< 0, \\ \bar{\Theta}_{\kappa\lambda\mu\nu is} + \bar{\Theta}_{\kappa\lambda\mu\nu si} &< 0, \quad s \neq i, \end{aligned} \quad (34)$$

where

$$\begin{aligned} \bar{\Theta}_{\kappa\lambda\mu\nu is} &= \begin{bmatrix} \bar{\Omega}_{1\kappa\lambda\mu\nu is} & \bar{\Omega}_{2is}^T \\ * & -\varepsilon I \end{bmatrix}, \quad \bar{\Omega}_{2\lambda\mu\nu is} = [0 \quad \bar{C}_i \bar{P} + D_i \bar{K}_s \quad C_{di} \bar{P} \quad 0 \quad 0 \quad D_{wi}], \\ \bar{\Omega}_{1\kappa\lambda\mu\nu is} &= \begin{bmatrix} \bar{\Xi}_1 & A_i \bar{P} + B_i \bar{K}_s & A_{di} \bar{P} & 0 & 0 & B_{wi} \\ * & \bar{\Xi}_{2\kappa is} & A_{di} \bar{P} & \frac{1}{d_m} \bar{R}_1 & \frac{1}{d_M} \bar{R}_2 & \bar{\Xi}_{3is} \\ * & * & -\bar{Q}_\lambda & 0 & 0 & -\bar{P} C_{di}^T \\ * & * & * & -\bar{S}_{1\mu} - \frac{1}{d_m} \bar{R}_1 & 0 & 0 \\ * & * & * & * & -\bar{S}_{2\nu} - \frac{1}{d_M} \bar{R}_2 & 0 \\ * & * & * & * & * & \zeta I - D_{wi} - D_{wi}^T \end{bmatrix}, \quad (35) \\ \bar{\Xi}_1 &= (T - 2) \bar{P} + d_m \bar{R}_1 + d_M \bar{R}_2, \quad \bar{\Xi}_{3is} = B_{wi} - \bar{P} C_i^T - \bar{K}_s^T D_i^T, \end{aligned}$$

$$\bar{\Xi}_{2\kappa is} = A_i \bar{P} + \bar{P} A_i^T + B_i \bar{K}_s + \bar{K}_s^T B_i^T + (d_M - d_m + T + 1) \bar{Q}_\kappa + \bar{S}_{1\kappa} + \bar{S}_{2\kappa} - \frac{1}{d_m} \bar{R}_1 - \frac{1}{d_M} \bar{R}_2.$$

The fuzzy state-feedback controller can be obtained:

$$u(t_k) = \bar{K}_s \bar{P}^{-1} x(t_k). \quad (36)$$

Proof. Premultiplying and postmultiplying (34) by diagonal matrix

$$\text{diag} \{ \bar{P}^{-1}, \bar{P}^{-1}, \bar{P}^{-1}, \bar{P}^{-1}, \bar{P}^{-1}, I, I \} \quad (37)$$

and letting

$$\begin{aligned} P &= \bar{P}^{-1}, \quad K_s = \bar{K}_s \bar{P}^{-1}, \quad R_1 = \bar{P}^{-1} \bar{R}_1 \bar{P}^{-1}, \\ R_2 &= \bar{P}^{-1} \bar{R}_2 \bar{P}^{-1}, \\ Q_i &= \bar{P}^{-1} \bar{Q}_i \bar{P}^{-1}, \quad S_{li} = \bar{P}^{-1} \bar{S}_{li} \bar{P}^{-1}, \\ S_{2i} &= \bar{P}^{-1} \bar{S}_{2i} \bar{P}^{-1}, \end{aligned} \quad (38)$$

for $i = 1, 2, \dots, r$, it can be found that the conditions (20) hold, which means that system (5) is very strictly passive. The proof is completed. \square

Remark 10. In this paper, the modeling uncertainties are not taken into account in system (1). It should be pointed out that the robust passive controller design condition can be presented for uncertain discrete-time T-S fuzzy systems with time delay and disturbance input via delta operator approach.

In order to present the stability and stabilization condition for discrete-time T-S fuzzy systems with time delay via delta operator approach, it is assumed that the disturbance input $w(t_k) = 0$ in fuzzy delta operator system (3), which can be described as

$$\begin{aligned} \delta x(t_k) &= \sum_{i=1}^r h_i(\theta(t_k)) \\ &\quad \times [A_i x(t_k) + A_{di} x(t_k - d_k) + B_i u(t_k)], \\ z(t_k) &= \sum_{i=1}^r h_i(\theta(t_k)) \\ &\quad \times [C_i x(t_k) + C_{di} x(t_k - d_k) + D_i u(t_k)]. \end{aligned} \quad (39)$$

Similar to the proof of Theorems 8 and 9, the following two corollaries can be obtained.

Corollary 11. For a given sampling period $T > 0$ and constants d_m and d_M ($0 < d_m \leq d_M$), system (39) ($u(t_k) = 0$) is asymptotically stable if there exist symmetric matrices $P > 0$, $R_1 > 0$, $R_2 > 0$, $Q_\kappa > 0$, $S_{1\kappa} > 0$, and $S_{2\kappa} > 0$ ($\kappa = 1, 2, \dots, r$)

with appropriate dimensions, such that the following LMIs hold for $\kappa, \lambda, \mu, \nu, i = 1, 2, \dots, r$:

$$\check{\Theta}_{\kappa\lambda\mu\nu i} < 0, \quad (40)$$

where

$$\check{\Theta}_{\kappa\lambda\mu\nu i} = \begin{bmatrix} \Xi_1 & PA_i & PA_{di} & 0 & 0 \\ * & \check{\Xi}_{2\kappa i} & PA_{di} & \frac{1}{d_m}R_1 & \frac{1}{d_M}R_2 \\ * & * & -Q_\lambda & 0 & 0 \\ * & * & * & -S_{1\mu} - \frac{1}{d_m}R_1 & 0 \\ * & * & * & * & -S_{2\nu} - \frac{1}{d_M}R_2 \end{bmatrix}, \quad (41)$$

$$\Xi_1 = (T - 2)P + d_m R_1 + d_M R_2,$$

$$\check{\Xi}_{2\kappa i} = PA_i + A_i^T P + (d_M - d_m + T + 1)Q_\kappa + S_{1\kappa} + S_{2\kappa} - \frac{1}{d_m}R_1 - \frac{1}{d_M}R_2.$$

Corollary 12. System (39) with the controller in (4) is asymptotically stable for a given sampling period $T > 0$ and constants d_m and d_M ($0 < d_m \leq d_M$), if there exist symmetric matrices $\bar{P} > 0$, $\bar{R}_1 > 0$, $\bar{R}_2 > 0$, $\bar{Q}_\kappa > 0$, $\bar{S}_{1\kappa} > 0$, and $\bar{S}_{2\kappa} > 0$ ($\kappa = 1, 2, \dots, r$) with appropriate dimensions, such that the following LMIs hold for $\kappa, \lambda, \mu, \nu, i, s = 1, 2, \dots, r$:

$$\bar{\Theta}_{\kappa\lambda\mu\nu i i} < 0, \quad (42)$$

$$\bar{\Theta}_{\kappa\lambda\mu\nu i s} + \bar{\Theta}_{\kappa\lambda\mu\nu s i} < 0, \quad s \neq i,$$

where

$$\bar{\Theta}_{\kappa\lambda\mu\nu i s} = \begin{bmatrix} \bar{\Xi}_1 & A_i \bar{P} + B_i \bar{K}_s & A_{di} \bar{P} & 0 & 0 \\ * & \bar{\Xi}_{2\kappa i s} & A_{di} \bar{P} & \frac{1}{d_m} \bar{R}_1 & \frac{1}{d_M} \bar{R}_2 \\ * & * & -\bar{Q}_\lambda & 0 & 0 \\ * & * & * & -\bar{S}_{1\mu} - \frac{1}{d_m} \bar{R}_1 & 0 \\ * & * & * & * & -\bar{S}_{2\nu} - \frac{1}{d_M} \bar{R}_2 \end{bmatrix}, \quad (43)$$

$$\bar{\Xi}_{1\kappa} = (T - 2)\bar{P} + d_m \bar{R}_1 + d_M \bar{R}_2,$$

$$\bar{\Xi}_{2\kappa i s} = A_i \bar{P} + \bar{P} A_i^T + B_i \bar{K}_s + \bar{K}_s^T B_i^T + (d_M - d_m + T + 1)\bar{Q}_\kappa + \bar{S}_{1\kappa} + \bar{S}_{2\kappa} - \frac{1}{d_m} \bar{R}_1 - \frac{1}{d_M} \bar{R}_2.$$

Then, the controller (4) can be designed as

$$u(t_k) = \bar{K}_s \bar{P}^{-1} x(t_k). \quad (44)$$

4. Numerical Example

In this section, one example is presented to demonstrate the effectiveness of the proposed method.

Example 1. Consider the following fuzzy system with time-varying delay and input disturbance:

Plant Rule 1. IF $\theta(t_k)$ is 0, THEN

$$\begin{aligned} \delta x(t_k) &= A_1 x(t_k) + A_{d1} x(t_k - d_k) + B_1 u(t_k) \\ &\quad + B_{w1} w(t_k), \end{aligned}$$

TABLE 1: The feasibility of the system with $T = 0.001$.

	d_m	d_M	K_1	K_2
$T = 0.001$	0.01	7.44	[-0.2229 -13.6801]	[-1.7743 -4.5044]

$$\begin{aligned}
 z(t_k) &= C_1 x(t_k) + C_{d1} x(t_k - d_k) + D_1 u(t_k) \\
 &\quad + D_{w1} w(t_k).
 \end{aligned} \tag{45}$$

Plant Rule 2. IF $\theta(t_k)$ is $\pm(\pi/2)$ ($|\theta(t_k)| < \pi/2$), THEN

$$\begin{aligned}
 \delta x(t_k) &= A_2 x(t_k) + A_{d2} x(t_k - d_k) + B_2 u(t_k) \\
 &\quad + B_{w2} w(t_k),
 \end{aligned} \tag{46}$$

$$\begin{aligned}
 z(t_k) &= C_2 x(t_k) + C_{d2} x(t_k - d_k) + D_2 u(t_k) \\
 &\quad + D_{w2} w(t_k).
 \end{aligned}$$

The system matrix parameters in (45) and (46) are given as follows:

$$\begin{aligned}
 A_1 &= \begin{bmatrix} -2.000 & -0.060 \\ 0.070 & 0.100 \end{bmatrix}, & A_2 &= \begin{bmatrix} -1.800 & 0.080 \\ -0.050 & 0.100 \end{bmatrix}, \\
 B_1 &= \begin{bmatrix} 0.080 \\ 0.050 \end{bmatrix}, & B_2 &= \begin{bmatrix} 0.080 \\ 0.090 \end{bmatrix}, \\
 A_{d1} &= \begin{bmatrix} -0.020 & -0.010 \\ 0.010 & 0.020 \end{bmatrix}, & A_{d2} &= \begin{bmatrix} -1.800 & 0.080 \\ -0.050 & 0.100 \end{bmatrix}, \\
 B_{w1} &= [0.010 \quad -0.100]^T, \\
 B_{w2} &= [-0.010 \quad -0.100]^T, & C_1 &= [-0.010 \quad 0.010], \\
 C_2 &= [0.120 \quad -0.100], & D_1 &= 0.010, \\
 C_{d1} &= [0.080 \quad 0.010], & C_{d2} &= [-0.010 \quad -0.050], \\
 D_2 &= 0.020, & D_{w1} &= 0.010, & D_{w2} &= 0.020.
 \end{aligned} \tag{47}$$

Two membership functions are chosen for Plant Rules 1 and 2 as follows:

$$\begin{aligned}
 h_1(\theta(t_k)) &= \begin{cases} 1 - \frac{2}{\pi} \theta(t_k), & 0 \leq \theta(t_k) \leq \frac{\pi}{2}, \\ 1 + \frac{2}{\pi} \theta(t_k), & -\frac{\pi}{2} \leq \theta(t_k) < 0, \end{cases} \\
 h_2(\theta(t_k)) &= 1 - h_1(\theta(t_k)).
 \end{aligned} \tag{48}$$

And Figure 1 shows the membership functions.

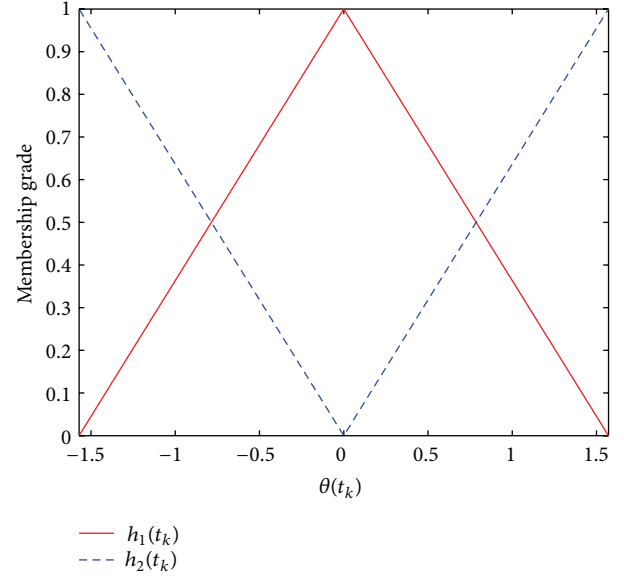
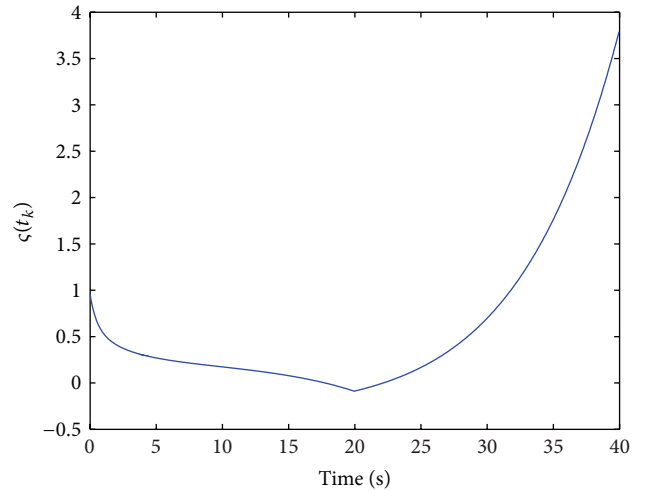


FIGURE 1: Membership functions of two rules.


 FIGURE 2: Response of $\zeta(t_k)$ of the open-loop system.

Define the value range of time delay $d_k = nT$, and choosing the lower bound $d_m = 0.01$, the sampling period T may be assumed as $T = 0.001$ and it can be found from Theorem 9 that the maximum upper bound of time delay d_k and the control gain matrices are listed in Table 1.

Assume that time delay $d_k = nT = 40T$ and the disturbance input $w(t_k) = -1/(2 + t_k)$. It can be calculated

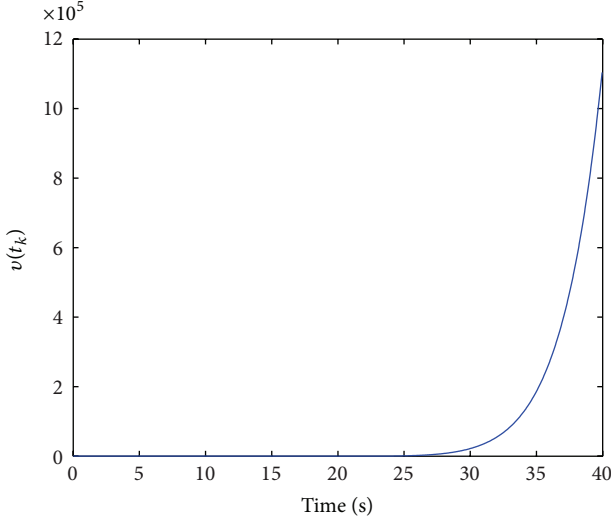
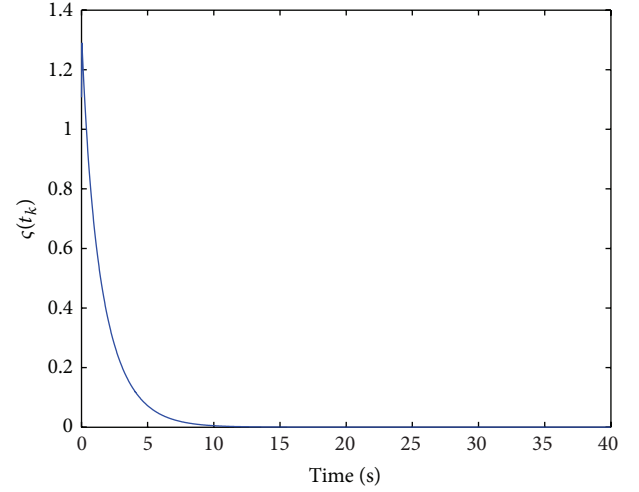
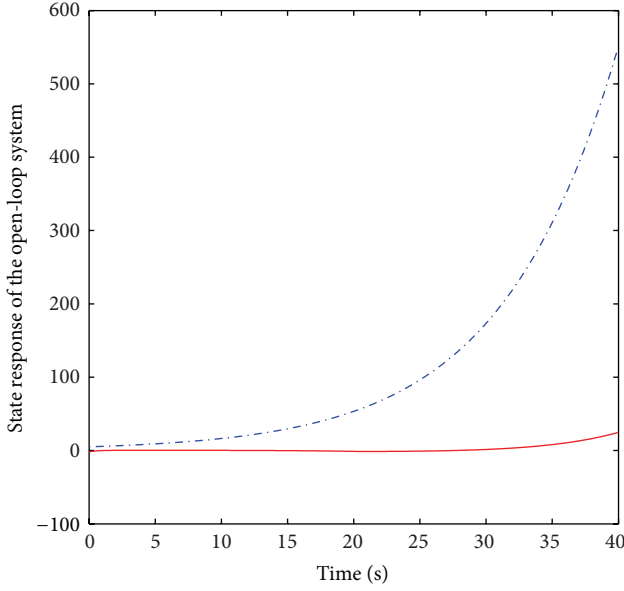
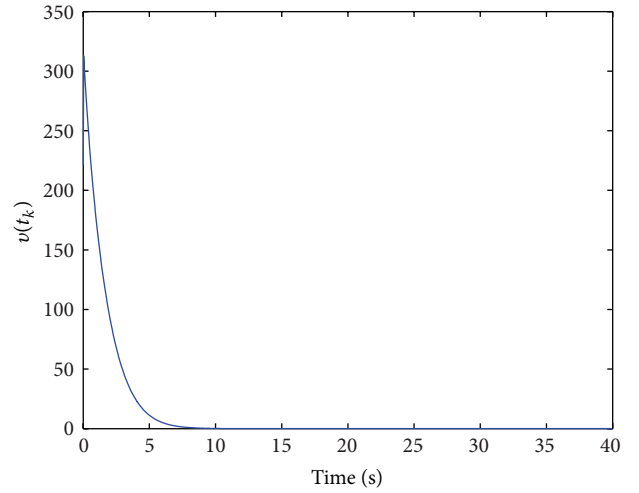
FIGURE 3: Response of $v(t_k)$ of the open-loop system.FIGURE 5: Response of $\zeta(t_k)$ of the closed-loop system.

FIGURE 4: State response of the open-loop system.

FIGURE 6: Response of $v(t_k)$ of the closed-loop system.

that $\sum_{t_k=0}^{\infty} w^T(t_k)w(t_k) = 0.5 < \infty$, which means that $w(t_k) \in L_2[0, \infty)$. Let

$$v(t_k) = 2 \sum_{t_k=0}^{\infty} z^T(t_k) w(t_k) - \varepsilon \sum_{t_k=0}^{\infty} z^T(t_k) z(t_k) - \zeta \sum_{t_k=0}^{\infty} w^T(t_k) w(t_k), \quad (49)$$

$$\zeta(t_k) = 2 \sum_{t_k=0}^{\infty} z^T(t_k) w(t_k).$$

In Figure 2, it can be observed that $\zeta(t_k)$ decreases finally as the time t_k increases, which means that there may not exist a scalar ρ such that $\zeta(t_k) \geq \rho$ hold for all $t_k \geq 0$ for $T = 0.001$. Furthermore, Figure 3 shows that there may not exist a scalar ρ such that $v(t_k) \geq \rho$, which means that the open-loop system is not passive in the sense of Definition 2, and it is not very strictly passive. Figure 4 illustrates that the open-loop system is not stable for $T = 0.001$.

Under the control gain matrices in Table 1, Figure 5 plots the responses of $\zeta(t_k)$ for the closed-loop system for $T = 0.001$. It can be seen that there may exist a scalar ρ such that $\zeta(t_k) \geq \rho$ holds for all $t_k \geq 0$. It can be seen from Figure 6 that there may exist a scalar ρ such that $v(t_k) \geq \rho$. Then, it is clear that the closed-loop system is very strictly passive under the control gain matrices in Table 1. In addition, Figure 7 shows that the closed-loop system is stable. Furthermore, Figure 8 depicts the control input responses. These simulation results have demonstrated the effectiveness of the proposed method.

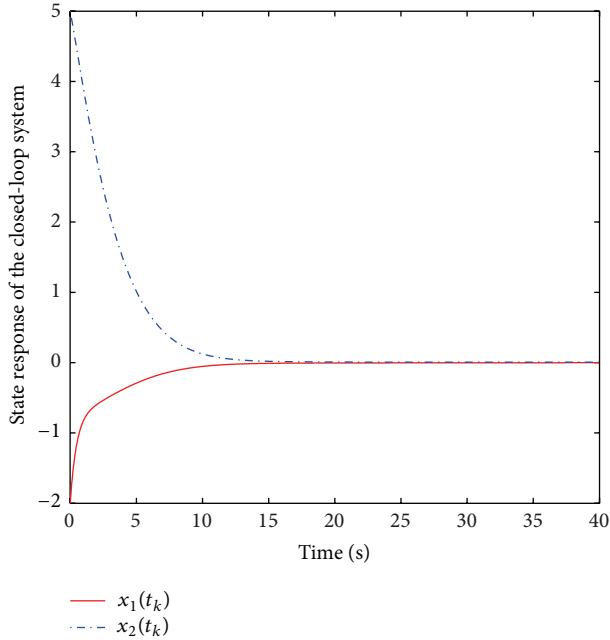


FIGURE 7: State response of the open-loop system.

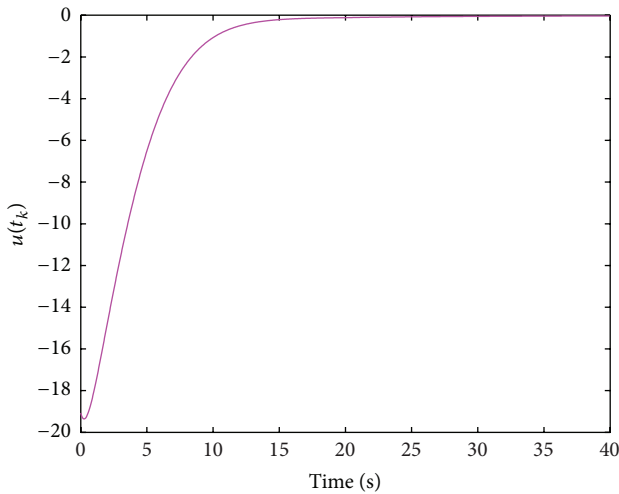


FIGURE 8: Control signal response of the closed-loop system.

5. Conclusions

In this paper, the problems of passivity analysis and passive control have been investigated for fuzzy delta operator systems with time delay and disturbance input. By applying some new LKF in δ -domain and utilizing some fuzzy weighing matrices, the state-feedback controller has been designed to guarantee that the resulting closed-loop system is very strictly passive. The existence conditions for the controller have been expressed as LMIs. Finally, a numerical example has been included to illustrate the effectiveness of the proposed results. In future work, based on T-S fuzzy control method, the problems of control and monitoring in the data-driven framework [53, 54] could be further studied.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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