Robust passive control for discrete-time T-S fuzzy systems with delays*

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Abstract: This article deals with the robust stability analysis and passivity of uncertain discrete-time Takagi-Sugeno (T-S) fuzzy systems with time delays. The T-S fuzzy model with parametric uncertainties can approximate nonlinear uncertain systems at any precision. A sufficient condition on the existence of robust passive controller is established based on the Lyapunov stability theory. With the help of linear matrix inequality (LMI) method, robust passive controllers are designed so that the closed-loop system is robust stable and strictly passive. Furthermore, a convex optimization problem with LMI constraints is formulated to design robust passive controllers with the maximum dissipation rate. A numerical example illustrates the validity of the proposed method.

Keywords: discrete-time T-S fuzzy systems, time delays, robust control, passive performance, linear matrix inequality.

1. Introduction

Since produced by Zadeh[1], fuzzy logic control has been developed into a significant and useful branch of automation and control theory. Takagi-Sugeno fuzzy controllers have been successfully applied to the stabilization control design of nonlinear systems[2–3]. Takagi-Sugeno (T-S) fuzzy systems which are described by a set of IF-THEN rules can provide an effective representation of complex nonlinear systems in terms of fuzzy sets. IF-THEN rules can locally represent linear input-output relations of nonlinear systems[4]. There has been an increasing interest in fuzzy control in recent years, and there have been a lot of useful results on fuzzy systems, mainly on topics related to stability and systematic design of fuzzy systems[4–9].

Moreover, control problems on fuzzy systems with uncertainty have attracted many researchers in devoting their time and efforts to solve the robust stabilization problems concerned with uncertain fuzzy systems. Since uncertainties often lead to system instability, the issue of robust fuzzy controller design for uncertain fuzzy systems is regarded as an important topic. There are many important results on it[10–14].

Since the notion of a dissipative dynamical system was introduced by Willems[15,16], dissipative systems have been of particular interest in system, circuit, network and control engineering and theory. In the classical Ref. [15] and Ref. [16], not only the fundamental notion of dissipativeness was introduced, but also its applications to the stability of linear systems with certain nonlinear feedback were discussed. On the other hand, passive theory plays an important role in dissipation theory. There are many important results having been done[17–18].

In this article, passive control of uncertain discrete-time T-S fuzzy systems with time delays is investigated. By analyzing Lyapunov stability, a sufficient condition on the existence of robust passive controller is derived. The problem of designing robust passive controller is turned into a feasible problem of a set of linear matrix inequalities.

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Throughout this article, \( R^n \) denotes the \( n \)-dimensional Euclidean space, and \( R^{n \times m} \) represents the set of all \( n \times m \) dimensional real matrices. The notation \( X > 0 (< 0) \) means that the matrix \( X \) is a symmetric positive-definite (negative-definite) matrix. \( X^T \) represents the transposition of the matrix \( X \). The matrix \( I \) stands for an identity matrix with appropriate dimensions. \( L_2(0, \infty) \) denotes all integrable functions on \([0, \infty)\). \( (A)_s \) represents \( A + A_s \). The symbol * is used to denote a symmetric structure in a matrix, that is

\[
\begin{bmatrix} L & N \\ * & R \end{bmatrix} = \begin{bmatrix} L & N \\ N^T & R \end{bmatrix}
\]

2. Problem formulation

Consider the uncertain time-delay T-S fuzzy system in which the ith rule is formulated in the following form.

Plant Rule i:

If \( \theta_1(k) \) is \( N_{i1}, \ldots, \) and \( \theta_p(k) \) is \( N_{ip} \), then

\[
\begin{aligned}
  x(k+1) &= \hat{A}_i x(k) + \hat{A}_{di} x(k-\tau) + \hat{B}_i u(k) + \hat{D}_i w(k) \\
  z(k) &= C_i x(k) + C_{di} x(k-\tau) + B_{i1} u(k) + D_{i1} w(k) \\
  x(k) &= 0, \quad k = -\tau, -\tau + 1, \ldots, 0; \quad i = 1, 2, \ldots, r
\end{aligned}
\]

where \( N_{ij} \) is a fuzzy set, \( x(k) \in R^n \) is the state, \( z(k) \in R^p \) is the output, \( u(k) \in R^m \) is the control, \( w(k) \in R^q \) is the disturbance input which is energy-bounded. \( r \) is the number of rules of the T-S fuzzy model. \( \theta_1(k), \theta_2(k), \ldots, \theta_p(k) \) are the premise variables, let \( \theta(k) = (\theta_1(k), \theta_2(k), \ldots, \theta_p(k)) \). It is assumed that the premise variables do not depend on the input \( u(k) \) and the disturbance \( w(k) \), and \( \tau \) is the time delay. \( \hat{A}_i, \hat{A}_{di}, \hat{B}_i, \) and \( \hat{D}_i \) are uncertain system matrices with appropriate dimensions which can be described as follows

\[
\begin{aligned}
  \hat{A}_i &= A_i + \Delta A_i, \quad \hat{A}_{di} = A_{di} + \Delta A_{di}, \\
  \hat{B}_i &= B_i + \Delta B_i, \quad \hat{D}_i = D_i + \Delta D_i
\end{aligned}
\]

where \( A_i, A_{di}, B_i, D_i, C_i, C_{di}, B_{i1} \) and \( D_{i1} \) are constant real matrices with appropriate dimensions, and uncertain matrices satisfy

\[
\begin{bmatrix} \Delta A_i & \Delta A_{di} & \Delta B_i & \Delta D_i \end{bmatrix} = MF \begin{bmatrix} N_{i1} & N_{i2} & N_{i3} & N_{i4} \end{bmatrix}
\]

where \( M \) and \( N_{ik} (k = 1, 2, 3, 4) \) are known constant real matrices with compatible dimensions which represent the structure of uncertainties, and \( F \in R^{q \times h} \) is unknown nonlinear time-varying matrix function satisfying

\[
F^T F \leq I
\]

It is assumed that the elements of \( F \) are Lebesgue measurable. This type of uncertainty is an effective representation of some nonlinear uncertainties.

Then the state equation and the output are defined as follows

\[
\begin{aligned}
  x(k+1) &= \sum_{i=1}^r h_i(\theta(k)) (\hat{A}_i x(k) + \hat{A}_{di} x(k-\tau) + \hat{B}_i u(k) + \hat{D}_i w(k)) \\
  z(k) &= \sum_{i=1}^r h_i(\theta(k)) (C_i x(k) + C_{di} x(k-\tau) + B_{i1} u(k) + D_{i1} w(k)) \\
  x(k) &= \phi(k), \quad k = -\tau, -\tau + 1, \ldots, 0; \quad i = 1, 2, \ldots, r
\end{aligned}
\]

where

\[
\begin{aligned}
  h_i(\theta(k)) &= \frac{\mu_i(\theta(k))}{\sum_{i=1}^r \mu_i(\theta(k))}, \quad \mu_i(\theta(k)) = \prod_{j=1}^p N_{ij}(\theta_j(k))
\end{aligned}
\]

where \( N_{ij}(\theta_j(k)) \) is the degree of the membership of \( \theta_j(k) \) in \( N_{ij} \). In this article, it is assumed that

\[
\mu_i(\theta(k)) \geq 0, \quad \sum_{i=1}^r \mu_i(\theta(k)) > 0, \quad i = 1, 2, \ldots, r
\]

for \( k = 1, 2, \ldots, \) it is clear that

\[
\mu_i(\theta(k)) \geq 0, \quad \sum_{i=1}^r h_i(\theta(k)) = 1, \quad i = 1, 2, \ldots, r
\]

Let

\[
\begin{aligned}
  \hat{A} &= \sum_{i=1}^r h_i(\theta(k)) A_i, \quad \hat{A}_{di} = \sum_{i=1}^r h_i(\theta(k)) A_{di} \\
  \hat{B} &= \sum_{i=1}^r h_i(\theta(k)) B_i, \quad \hat{D} = \sum_{i=1}^r h_i(\theta(k)) D_i \\
  \hat{N}_1 &= \sum_{i=1}^r h_i(\theta(k)) N_{i1}, \quad \hat{N}_2 = \sum_{i=1}^r h_i(\theta(k)) N_{i2}
\end{aligned}
\]
\[ \bar{N}_3 = \sum_{i=1}^{r} h_i(\theta(k))N_{i3}, \quad \bar{N}_4 = \sum_{i=1}^{r} h_i(\theta(k))N_{i4} \]

\[ C = \sum_{i=1}^{r} h_i(\theta(k))C_i, \quad \bar{C}_d = \sum_{i=1}^{r} h_i(\theta(k))C_{di} \]

\[ \bar{B}_1 = \sum_{i=1}^{r} h_i(\theta(k))B_{i1}, \quad \bar{D}_1 = \sum_{i=1}^{r} h_i(\theta(k))D_{i1} \]

\[ h_i = h_i(\theta(k)), \quad h_j = h_j(\theta(k)) \]

Next, a fuzzy model of a state feedback controller for the T-S fuzzy model is formulated as follows.

**Controller Rule:**

If \( \theta_1(k) \) is \( N_{i1}, \ldots, \) and \( \theta_p(k) \) is \( N_{ip}, \) then

\[ u(k) = K_i x(k), \quad i = 1, 2, \ldots, r \tag{4} \]

Hence, the overall fuzzy control law is represented as

\[ u(k) = \sum_{i=1}^{r} h_i(\theta(k))K_i x(k) \tag{5} \]

where \( K_i \in \mathbb{R}^{m \times n} (i = 1, 2, \ldots, r) \) are constant control gains to be determined.

Let

\[ \bar{K} = \sum_{i=1}^{r} h_i K_i \]

With the control law (5), the overall closed-loop system can be written as

\[
\begin{align*}
    x(k+1) &= [(\bar{A} + \bar{B}\bar{K}) + MF(\bar{N}_1 + \bar{N}_3\bar{K})]x(k) + (\bar{A}_d + MF\bar{N}_2)x(k-\tau) + (\bar{D} + MF\bar{N}_4)w(k) \\
    z(k) &= (\bar{C} + \bar{B}_1\bar{K})x(k) + \bar{C}_d x(k-\tau) + \bar{D}_1 w(k) \\
    x(k) &= 0, \quad k = -\tau, -\tau + 1, \ldots, 0, \quad i = 1, 2, \ldots, r 
\end{align*}
\]

\[ x(k+1) = [\tilde{A} + \tilde{B}\tilde{K}]x(k) + \tilde{A}_d x(k-\tau) + \tilde{D}_1 w(k) \tag{6} \]

**Definition 1** The dynamic system (3) with \( u(k) = 0 \) is strictly robust passive and its dissipation rate is \( \varepsilon \), if for a given scalar \( \varepsilon > 0 \), all \( M > 0 \), all energy-bounded \( w(k) \) and all uncertainties, under the following condition is satisfied under zero initial state condition

\[ \sum_{k=0}^{M} (w(k)^T z_k - \varepsilon w(k)^T w_k) \geq 0 \tag{7} \]

**Problem 1** Considering the T-S fuzzy system (3), design state feedback control law (5) such that

1. When \( w(k) = 0 \), the closed-loop system (6) is robust stable;
2. The closed-loop system (6) is strictly passive, its dissipation rate is \( \varepsilon \).

**3. Main results**

**Lemma 1**[19] Give \( Y, H \) and \( E \) with appropriate dimensions and \( Y \) is symmetric, then

\[ Y + HFE + E^TF^TH^T < 0 \]

holds for any \( F \) satisfying \( F^TF \leq I \), if and only if there exists a scalar \( \delta > 0 \) such that

\[ Y + \delta HH^T + \delta^{-1}E^TE < 0 \]

**Theorem 1** Consider system (6), under zero initial state condition, if there exist matrices \( K_i (1 \leq i \leq r) \), and symmetric positive definite matrices \( P \) and \( Q \), satisfying the following matrix inequalities

\[
\begin{bmatrix}
    \tilde{A}^* \tilde{P} \tilde{A}^* - P + Q & \tilde{A}^* \tilde{P} \tilde{A}_d^* \\
    \tilde{A}_d^* \tilde{P} \tilde{A}_d - Q & \tilde{A}_d^* \tilde{P} \tilde{D}^* - (\tilde{C} + \tilde{B}_1\tilde{K})^T
\end{bmatrix} < 0 \tag{8}
\]

From Eq. (9), it is obtained

\[
\Delta V(x(k), k) = V(x(k+1), k+1) - V(x(k), k) = x^T(k)(\tilde{A}^* \tilde{P} \tilde{A}^* - P + Q)x(k) + 2x^T(k)\tilde{A}^* \tilde{P} \tilde{D}^* w(k) + w^T(k)\tilde{D}^* \tilde{P} \tilde{D}^* w(k) + x^T(k-\tau)(\tilde{A}_d^* \tilde{P} \tilde{A}_d - Q)x(k-\tau) + 2x^T(k-\tau)\tilde{A}_d^* \tilde{P} \tilde{D}^* w(k) + 2x^T(k)\tilde{A}^* \tilde{P} \tilde{A}_d x(k-\tau) \tag{10}
\]
where
\[
\bar{A}^* = (\bar{A} + \bar{B}\bar{K}) + MF(\bar{N}_1 + \bar{N}_2\bar{K}),
\]
\[
\bar{A}_d^* = \bar{A}_d + MF\bar{N}_2, \; \bar{D}^* = \bar{D} + MF\bar{N}_4.
\]
From Eq. (10), it is gotten
\[
\Delta V(x(k), k) = \begin{bmatrix} x(k) \\ x(k - \tau) \\ w(k) \end{bmatrix}^T.
\]
\[
\begin{bmatrix}
\bar{A}^*P\bar{A}^* - P + Q & \bar{A}^*P\bar{A}_d^* & \bar{A}^*P\bar{D}^* \\
\bar{A}_d^*P\bar{A}_d - Q & \bar{A}_d^*P\bar{D}^* & \bar{D}^*P\bar{D}^* \\
* & * & *
\end{bmatrix}
\begin{bmatrix}
x(k) \\
x(k - \tau) \\
w(k)
\end{bmatrix}
\]
\begin{equation}
(11)
\end{equation}

When \(w(k) = 0\), it is easy to obtain from Eq. (7) and Eq. (11) that
\[
\Delta V(x(k), k) < 0
\]

\[
J_r = \sum_{k=0}^{M} \begin{bmatrix} x(k) \\ x(k - \tau) \\ w(k) \end{bmatrix}^T
\begin{bmatrix}
\bar{A}^*P\bar{A}^* - P + Q & \bar{A}^*P\bar{A}_d^* & \bar{A}^*P\bar{D}^* - (\bar{C} + \bar{B}_1\bar{K})^T \\
\bar{A}_d^*P\bar{A}_d - Q & \bar{A}_d^*P\bar{D}^* - \bar{C}_d^T & \bar{D}^*P\bar{D}^* - (\bar{D}_1)_s + 2\varepsilon I \\
* & * & *
\end{bmatrix}
\begin{bmatrix}
x(k) \\
x(k - \tau) \\
w(k)
\end{bmatrix} \leq 0
\]

then Eq. (7) holds for all \(T > 0\), namely, the closed-loop system (6) is strictly robust passive.

Based on the well-known Schur complement formula and Theorem 1, the design problem of robust passive controller is turned into the feasible problem of linear matrix inequalities.

**Theorem 2** Under zero initial state condition, the closed-loop system (6) is stable and strictly robust passive if there exist matrices \(Y_i(1 \leq i \leq r)\) and \(Y_j(1 \leq i < j \leq r)\), symmetric positive definite matrices \(W\) and \(X\), and some scalars \(\delta_i > 0, 1 \leq i \leq r, \alpha_{ij} > 0, \gamma_{ij} > 0, 1 \leq i < j \leq r\), satisfying the following linear matrix inequalities
\[
\begin{bmatrix}
-X & -(C_1X + B_{11}Y_i)^T & (A_1X + B_{12}Y_i)^T & 0 & (N_{11}X + N_{12}Y_i)^T & X \\
* & -W & -(C_2W)^T & (A_2W)^T & 0 & (N_{22}W)^T & 0 \\
* & * & -(D_{11})_s + 2\varepsilon I & D_{11}^T & 0 & N_{12}^T & 0 \\
* & * & * & -X & \delta_i M & 0 & 0 \\
* & * & * & * & -\delta_i I & 0 & 0 \\
* & * & * & * & * & -\delta_i I & 0 \\
* & * & * & * & * & * & -W
\end{bmatrix} < 0, 1 \leq i \leq r
\]
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In this case, the robust passive control law of system (1) is given as follows

$$u(k) = \sum_{i=1}^{r} h_{i}(\theta(k)) Y_{i} X^{-1} x(k)$$  \hspace{1cm} (15)$$

**Proof** Applying Schur complement formula, it is gotten from Eq. (8)

$$\begin{bmatrix}
-P + Q & 0 & -(\bar{C} + \bar{B}_{1}\bar{K})^T \\
* & -Q & -\bar{C}_{d}^T \\
* & * & (\bar{D}_{1})_{s} + 2\varepsilon I
\end{bmatrix} < 0 \hspace{1cm} (16)$$

then from Eq. (16), it is obtained

$$\sum_{i=1}^{r} h_{i}^2 \Delta_{i} + \sum_{i=1}^{r} \sum_{i<j} h_{i} h_{j} \Delta_{ij} < 0$$

where

$$\Delta_{i} = \begin{bmatrix}
-P + Q & 0 & -(C_{i} + B_{i1}K_{i})^T \\
* & -Q & -C_{d i}^T \\
* & * & (D_{i1})_{s} + 2\varepsilon I
\end{bmatrix}$$

$$\Delta_{ij} = \begin{bmatrix}
-2(P - Q) & 0 & -(C_{i} + C_{j} + B_{i1}K_{j} + B_{j1}K_{i})^T \\
* & -2Q & -C_{d i}^T - C_{d j}^T \\
* & * & -(D_{i1})_{s} - (D_{j1})_{s} + 4\varepsilon I
\end{bmatrix}$$

$$\bar{A}_{ij} = (\bar{A}_{i} + B_{i}K_{j}) + MF(N_{i1} + N_{j3}K_{j})$$

$$\bar{A}_{di} = A_{di} + MFN_{i 2}, \ 2\bar{D}_{i} = D_{i} + MFN_{i 4}$$

Let

$$A_{i} = \begin{bmatrix}
-P + Q & 0 & -(C_{i} + B_{i1}K_{i})^T \\
* & -Q & -C_{d i}^T \\
* & * & -(D_{i1})_{s} + 2\varepsilon I
\end{bmatrix}$$

then

$$\Delta_{i} = A_{i} + \begin{bmatrix}
0 \\
0 \\
F \begin{bmatrix} N_{i 1} + N_{i 3}K_{i} & N_{i 2} & N_{i 4} & 0 \end{bmatrix}
\end{bmatrix}$$

$$\begin{bmatrix} N_{i 1} + N_{i 3}K_{i} & N_{i 2} & N_{i 4} & 0 \end{bmatrix}^T P^T \begin{bmatrix} 0 \\
0 \\
M \end{bmatrix} \hspace{1cm} (17)$$

By applying Lemma 1

$$\Delta_{i} < 0$$

holds if and only if there exists constant $\delta_{i} > 0 (1 \leq i \leq r)$, satisfying the following inequality

$$A_{i} + \delta_{i} I \begin{bmatrix} 0 \\
0 \\
M \end{bmatrix} > \begin{bmatrix} 0 \\
0 \\
M \end{bmatrix} \hspace{1cm} (18)$$

According to Schur complement formula, Eq. (18) can be rewritten as
Let

\[ X = P^{-1}, \quad W = Q^{-1}, \quad Y_i = K_i X \]

premultiplying and postmultiplying on both sides of Eq. (19) by

\[ \text{diag}(X \quad W \quad I \quad I \quad \delta I \quad I) \]

Applying Schur complement formula, Eq. (19) equals Eq. (13).

Also

\[ \Delta_{ij} < 0 \]

equals Eq. (14).

**Remark 1** The solutions in Theorem 2 parameterize the set of robust passive controllers. The maximum of dissipation rate \( \varepsilon \) can be obtained by solving the following convex optimization problem

\[
\min_{X, Y_i, W, \delta_i, \alpha_{ij}, \gamma_{ij}, \varepsilon} \varepsilon \\
\text{s.t. LMI}s \ (13) \sim (14)
\]

### 4. Numerical example

To illustrate the proposed results, consider a control system, the system matrices and other matrices are given as follows

\[
A_1 = \begin{bmatrix} 0.5 & 0.1 & 0 \\ 0.1 & 0.4 & 0.2 \\ 0.1 & 0.1 & 0.5 \end{bmatrix}, \quad A_2 = \begin{bmatrix} -0.2 & 0 & 0.1 \\ 0 & -0.6 & 0.2 \\ 0.1 & 0 & -0.1 \end{bmatrix}
\]

\[
B_1 = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.2 \\ -0.2 & 0.1 \end{bmatrix}, \quad B_{d1} = \begin{bmatrix} 0.02 & 0 & 0.01 \\ 0 & 0.01 & -0.06 \\ 0.02 & -0.08 & 0.05 \end{bmatrix}
\]

\[
D_1 = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.2 \\ 0.1 & 0.1 \end{bmatrix}, \quad C_1 = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.2 & 0.1 \end{bmatrix}
\]

\[
B_{11} = \begin{bmatrix} 0.1 & 0.1 \\ 0.1 & 0.5 \end{bmatrix}, \quad D_{11} = \begin{bmatrix} 1 & 0 \\ 0 & 0.5 \end{bmatrix}
\]

\[
C_{d1} = \begin{bmatrix} 0.05 & 0 & 0 \\ 0 & 0.01 & 0 \end{bmatrix}, \quad A_{d2} = \begin{bmatrix} 0.01 & 0 \\ 0 & 0.02 \end{bmatrix}
\]

\[
B_2 = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.2 \end{bmatrix}, \quad D_2 = \begin{bmatrix} 0.3 & 0 \\ 0 & 0.3 \end{bmatrix}
\]

\[
C_2 = \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.1 & 0 \end{bmatrix}, \quad B_{21} = \begin{bmatrix} 0.1 & 0.1 \\ 0 & 0.1 \end{bmatrix}
\]

\[
D_{21} = \begin{bmatrix} 0.5 & 0 \\ 0 & 1.5 \end{bmatrix}, \quad C_{d2} = \begin{bmatrix} 0.02 & 0 & 0.01 \\ 0 & 0.01 & 0 \end{bmatrix}
\]

\[
M = \begin{bmatrix} 0 & 0 & 0.03 \end{bmatrix}^T, \quad N_{11} = N_{21} = \begin{bmatrix} 0.8 & 0.4 & 0.5 \end{bmatrix}
\]

\[
N_{12} = N_{22} = \begin{bmatrix} 0.02 & 0.01 & 0 \end{bmatrix}, \quad N_{13} = N_{23} = \begin{bmatrix} 0.8 & 0.5 \end{bmatrix}, \quad N_{14} = N_{24} = \begin{bmatrix} 0.01 & 0.01 \end{bmatrix}
\]

By the LMI toolbox in MATLAB and Theorem 2, the following state feedback gains matrices are obtained

\[
K_1 = \begin{bmatrix} -0.5375 & -0.2511 & -0.1329 \\ -0.7128 & -0.3825 & -0.7721 \end{bmatrix}
\]

\[
K_2 = \begin{bmatrix} -0.6388 & -0.4351 & -0.2359 \\ -0.5223 & -0.0755 & -0.5921 \end{bmatrix}
\]

### 5. Conclusions

This article studies the passive analysis and control synthesis of uncertain discrete-time T-S fuzzy systems
with time delays by LMI approach together with Lyapunov function method. The sufficient conditions on the existence of robust passive controller are given. It is shown that the passive controller can be obtained by LMI techniques after a suitable transformation, that transforms the existential nonlinear matrix inequalities condition into a solvable LMIs condition. A set of LMIs have been presented guaranteeing that a closed-loop system is stable with the passive performance. Furthermore, the problem of designing passive controller with maximum dissipation rate is turned into a convex optimization problem with LMI constraints. All these results established are independent of delay time.

References

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