Advances in Fuzzy Sets and Systems
Volume 9, Number 2, 2011, Pages 111-122
Published Online: September 2011
Available online at http://pphmj.com/journals/afss.htm
Published by Pushpa Publishing House, Allahabad, INDIA

DESIGN METHOD OF OBSERVER-BASED OUTPUT FEEDBACK CONTROLLER FOR UNCERTAIN T-S FUZZY DISCRETE SYSTEMS WITH TIME-DELAY

Han-Liang Huang

Department of Mathematics and Information Science
Zhangzhou Normal University
Zhangzhou 363000, P. R. China
e-mail: hl_huang1980.student@sina.com

Abstract

In this paper, we consider the stability analysis of uncertain discrete systems with time-delay when the states are unmeasurable. Takagi-Sugeno (T-S) fuzzy model is used to describe this kind of systems. Based on Lyapunov functional approach, a new design method of observer-based output feedback controller is proposed. A numerical example is given to illustrate the effectiveness of our method.

1. Introduction

In the past few decades, a number of research activities have been concentrated on the topic of stability analysis of nonlinear time-delay systems with parameter uncertainties. This kind of systems can be found in many real life systems such as electric systems, rolling mill systems, different types of societal systems and so on. Takagi-Sugeno (T-S) fuzzy model [10] can be used to describe this kind of systems.

2010 Mathematics Subject Classification: 93C42.

Keywords and phrases: observer, time-delay, T-S fuzzy discrete systems, uncertainty, stability analysis.

This work is supported by the National Natural Science Foundation of China (10971186), the Natural Science Foundation of Fujian Province, China (2011J05013), the Science Research Foundation of Zhangzhou Normal University, China (SJ1005).

Received July 8, 2011

For continuous-time systems, Cao et al. [1, 5, 8, 9, 17, 19] considered the robust H_∞ control; and Huang et al. [6, 13, 14, 16, 20] proposed some design methods of fuzzy controller for the discrete-time systems. When the states are measurable, Antai et al. [3] designed a stabilizing state-feedback controller for uncertain time-delay systems, Li and Xia [7] studied the H_2 controller design for uncertain discrete-time delay piecewise systems, and stabilizability of linear quadratic state-feedback control problem has been researched in [12]. Under the unmeasurable states environment, stability and stabilization conditions for uncertain fuzzy systems with time-delay are also considered via output feedback controller in [11, 15, 16]. In a previous paper [4], we proposed an observer-based output feedback controller design method for a class of uncertain T-S fuzzy systems with time-delay, this method fixed an error in [11], and now we pay attention to stability analysis of the discrete-time systems when the states are unmeasurable in this paper.

Notation. For a symmetric matrix *X*, the notation $X > 0$ means that the matrix *X* is positive definite. *I* is an identity matrix of appropriate dimension. X^T denotes the transpose of matrix *X*. For any nonsingular matrix *X*, X^{-1} denotes the inverse of matrix *X*. R^n denotes the *n*-dimensional Euclidean space. $R^{m\times n}$ is the set of all $m \times n$ matrices. $*$ denotes the transposed element in the symmetric position of a matrix.

2. System Description

Consider the following parameter uncertain discrete system with time-delay described by Takagi-Sugeno fuzzy model:

Plant rule *i*. If $z_1(t)$ is λ_{i1} and $z_2(t)$ is λ_{i2} and $\cdots$ and $z_g(t)$ is λ_{ig}, then

$$\begin{cases} x(t+1) = \tilde{A}_{i1}x(t) + \tilde{A}_{i2}x(t-d) + \tilde{B}_i u(t), \\ y(t) = C_{i1}x(t) + C_{i2}x(t-d), \\ x(t) = \varphi(t), \quad t \in [-d, 0], \end{cases} \tag{1}$$

where $i = 1, 2, \ldots, n$, n is the number of rules; $z_1(t), z_2(t), \ldots, z_g(t)$ are the premise variables; λ_{ij} $(i = 1, 2, \ldots, n,\ j = 1, 2, \ldots, g)$ is the fuzzy set; $x(t) \in R^q$ is the state vector; $u(t) \in R^m$ is the input vector; $y(t) \in R^l$ is the output vector; $d > 0$ is the upper bound of time-delay; $\varphi(t)$ is the initial condition of system (1); $\tilde{A}_{i1} \triangleq A_{i1} + \Delta A_{i1}(t)$, $\tilde{A}_{i2} \triangleq A_{i2} + \Delta A_{i2}(t)$ and $\tilde{B}_i \triangleq B_i + \Delta B_i(t)$; A_{i1}, A_{i2}, B_i, C_{i1} and C_{i2} $(i = 1, 2, ..., n)$ are constant matrices of appropriate dimensions; $\Delta A_{i1}(t)$, $\Delta A_{i2}(t)$, $\Delta B_i(t)$ $(i = 1, 2, ..., n)$ are real valued unknown matrices representing time-varying parameter uncertainties of (1) and satisfy the following assumption:

Assumption 1.

$$[\Delta A_{i1}(t), \Delta A_{i2}(t), \Delta B_i(t)] = U_i F_i(t)[E_{i1}, E_{i2}, E_i], \tag{2}$$

where U_i, E_{i1}, E_{i2} and E_i $(i = 1, 2, ..., n)$ are known real constant matrices of appropriate dimensions. $F_i(t)$ $(i = 1, 2, ..., n)$ is an unknown real time-varying matrix with Lebesgue measurable elements satisfying

$$F_i(t)^T F_i(t) \le I, \quad i = 1, 2, ..., n. \tag{3}$$

Let $\mu_i(z(t))$ be the normalized membership function of the inferred fuzzy set $\rho_i(z(t))$, i.e.,

$$\mu_i(z(t)) = \frac{\rho_i(z(t))}{\sum_{i=1}^{n} \rho_i(z(t))},$$

where

$$z(t) = [z_1(t), z_2(t), ..., z_g(t)], \quad \rho_i(z(t)) = \prod_{j=1}^{g} \lambda_{ij}(z_j(t)).$$

$\lambda_{ij}(z_j(t))$ is the grade of membership of $z_j(t)$ in λ_{ij}. It is assumed that

$$\rho_i(z(t)) \ge 0, \quad i = 1, 2, ..., n, \quad \sum_{i=1}^{n} \rho_i(z(t)) > 0, \quad \forall t \ge 0.$$

Then, it can be seen that

$$\mu_i(z(t)) \ge 0, \quad i = 1, 2, ..., n, \quad \sum_{i=1}^{n} \mu_i(z(t)) = 1, \quad \forall t \ge 0.$$

By using the center-average defuzzifier, product inference and singleton fuzzifier, the T-S fuzzy model (1) can be expressed by the following model:

$$\begin{cases} x(t+1) = \sum_{i=1}^{n} \mu_i \{\tilde{A}_{i1}x(t) + \tilde{A}_{i2}x(t-d) + \tilde{B}_i u(t)\}, \\ y(t) = \sum_{i=1}^{n} \mu_i \{C_{i1}x(t) + C_{i2}x(t-d)\}, \end{cases} \tag{4}$$

where $\mu_i \triangleq \mu_i(z(t))$.

Similar to the continuous system in [4], we design the fuzzy state observer as follows:

R^i: If $z_1(t)$ is λ_{i1} and $z_2(t)$ is λ_{i2} and $\cdots$ and $z_g(t)$ is λ_{ig}, then

$$\begin{cases} \hat{x}(t+1) = A_{i1}\hat{x}(t) + A_{i2}\hat{x}(t-d) + B_i u(t) + G_i(y(t) - \hat{y}(t)), \\ \hat{y}(t) = C_{i1}\hat{x}(t) + C_{i2}\hat{x}(t-d), \quad i = 1, 2, \ldots, n, \end{cases} \tag{5}$$

where $G_i \in R^{q\times l}$ is the observer gain to be determined. Then the overall fuzzy observer is given by

$$\begin{cases} \hat{x}(t+1) = \sum_{i=1}^{n} \mu_i \{A_{i1}\hat{x}(t) + A_{i2}\hat{x}(t-d) + B_i u(t) + G_i(y(t) - \hat{y}(t))\}, \\ \hat{y}(t) = \sum_{i=1}^{n} \mu_i \{C_{i1}\hat{x}(t) + C_{i2}\hat{x}(t-d)\}. \end{cases} \tag{6}$$

Based on fuzzy observer, we can design the overall output feedback controller:

$$u(t) = \sum_{i=1}^{n} \mu_i K_i \hat{x}(t), \tag{7}$$

where $K_i \in R^{m\times q}$ is the controller gain to be determined.

Define the observation error as follows:

$$e(t) = x(t) - \hat{x}(t). \tag{8}$$

Combining (4), (6), (7) and (8), we can obtain the global model:

$$\begin{cases} x(t+1) = \sum_{i=1}^{n}\sum_{j=1}^{n}\mu_i\mu_j\{(\tilde{A}_{i1} + \tilde{B}_i K_j)x(t) + \tilde{A}_{i2}x(t-d) - \tilde{B}_i K_j e(t)\}, \\ e(t+1) = \sum_{i=1}^{n}\sum_{j=1}^{n}\mu_i\mu_j\{R_{ij}x(t) + \Delta A_{i2}(t)x(t-d) + S_{ij}e(t) + T_{ij}e(t-d)\}, \end{cases} \tag{9}$$

where $R_{ij} = \Delta A_{i1}(t) + \Delta B_i(t)K_j$, $S_{ij} = A_{i1} - G_i C_{j1} - \Delta B_i(t)K_j$, $T_{ij} = A_{i2} - G_i C_{j2}$.

3. Main Result

Two important lemmas should be introduced because they are the key to prove the main theorem.

Lemma 1 [2]**.** *For any two matrices* $X \in R^{m\times n}$, $Y \in R^{m\times n}$, *we have*

$$X^T Y + Y^T X \le X^T SX + Y^T S^{-1} Y,$$

where $S \in R^{m\times m}$ *and* $S > 0$.

Lemma 2 [18]**.** *Y*, *U and E are the matrices of appropriate dimensions, and* $Y = Y^T$, *then for any matrix F satisfying* $F^T F \le I$, *we have the following equivalent condition*:

$$Y + UFE + E^T F^T U^T < 0$$

if and only if there exists a constant $\varepsilon > 0$ *satisfying*

$$Y + \varepsilon UU^T + \varepsilon^{-1}E^T E < 0.$$

When the states are unmeasurable, based on the Lyapunov functional approach, the delay-independent stabilization result of T-S fuzzy discrete system (9) is summarized in the following theorem:

Theorem 1. *For the prescribed scalars* $\varepsilon_{ij} > 0$ *and* $\eta_{ij} > 0$ $(1 \le i \le j \le n)$, *if there exist matrices* $X > 0$, $\tilde{P}_2 > 0$, $P_3 > 0$, $P_4 > 0$, Y_i *and* N_i $(i, j = 1, 2, ..., n)$ *satisfying the following LMIs*:

$$\begin{bmatrix} \Omega_{11}^{ii} & * \\ \Omega_{21}^{ii} & \Omega_{22}^{ii} \end{bmatrix} < 0, \quad 1 \le i \le n, \tag{10}$$

$$\begin{bmatrix} \Omega_{11}^{ij} + \Omega_{11}^{ji} & * & * \\ \Omega_{21}^{ij} & \Omega_{22}^{ij} & * \\ \Omega_{21}^{ji} & 0 & \Omega_{22}^{ji} \end{bmatrix} < 0, \quad 1 \le i < j \le n, \tag{11}$$

$$\Psi_{ii} < 0, \quad 1 \le i \le n, \tag{12}$$

$$\Psi_{ij} + \Psi_{ji} < 0, \quad 1 \le i < j \le n, \tag{13}$$

then the closed-loop fuzzy system (9) *is asymptotically stable. Moreover, the controller gains are given by*

$$K_i = Y_i X^{-1}, \tag{14}$$

where

$$\Omega_{11}^{ij} = \begin{bmatrix} -X + \tilde{P}_2 & * & * & * \\ 0 & -\tilde{P}_2 & * & * \\ A_{i1}X + B_i Y_j & A_{i2}X & -\frac{1}{3}X + \varepsilon_{ij}U_i U_i^T & * \\ 0 & 0 & \varepsilon_{ij}P_3 U_i U_i^T & -\frac{1}{4}P_3 \end{bmatrix},$$

$$\Omega_{21}^{ij} = \begin{bmatrix} E_{i1}X + E_i Y_j & E_{i2}X & 0 & 0 \\ 0 & 0 & 0 & U_i^T P_3 \end{bmatrix}, \quad \Omega_{22}^{ij} = \begin{bmatrix} -\varepsilon_{ij}I & * \\ 0 & -\varepsilon_{ij}^{-1}I \end{bmatrix},$$

$$\Psi_{ij} = \begin{bmatrix} \Lambda_{ij} & * & * & * \\ 0 & -P_4 & * & * \\ B_i K_j & 0 & -\frac{1}{3}X + \eta_{ij}U_i U_i^T & * \\ A_{i1} - G_i C_{j1} & A_{i2} - G_i C_{j2} & -\eta_{ij}U_i U_i^T & -\frac{1}{4}P_3^{-1} + \eta_{ij}U_i U_i^T \end{bmatrix},$$

$$\Lambda_{ij} = -P_3 + P_4 + \eta_{ij}^{-1}K_j^T E_i^T E_i K_j.$$

Proof. Choose the Lyapunov function as

$$V(t) = x^T(t)P_1 x(t) + \sum_{w=1}^{d} x^T(t-w)P_2 x(t-w)$$

$$+ e^T(t)P_3 e(t) + \sum_{w=1}^{d} e^T(t-w)P_4 e(t-w), \tag{15}$$

where $P_k > 0$ $(k = 1, 2, 3, 4)$. Let

$$V_1(x(t)) = x^T(t)P_1x(t) + \sum_{w=1}^{d} x^T(t-w)P_2x(t-w),$$

$$V_2(e(t)) = e^T(t)P_3e(t) + \sum_{w=1}^{d} e^T(t-w)P_4e(t-w),$$

$$H_{ij} = A_{i1} + \Delta A_{i1}(t) + (B_i + \Delta B_i(t))K_j.$$

Then we have

$$\begin{aligned}
\Delta V_1(x(t)) &= V_1(x(t+1)) - V_1(x(t)) \\
&= x^T(t+1)P_1x(t+1) - x^T(t)P_1x(t) + x^T(t)P_2x(t) - x^T(t-d)P_2x(t-d) \\
&= \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} \mu_i\mu_j\mu_k\mu_l \\
&\quad \cdot \left\{ x^T(t)\left[\left(\frac{H_{ij}+H_{ji}}{2}\right)^T P_1\left(\frac{H_{kl}+H_{lk}}{2}\right) - P_1 + P_2\right]x(t)\right. \\
&\quad + x^T(t-d)\left[\left(\frac{\tilde{A}_{i2}+\tilde{A}_{j2}}{2}\right)^T P_1\left(\frac{\tilde{A}_{k2}+\tilde{A}_{l2}}{2}\right) - P_2\right]x(t-d) \\
&\quad + e^T(t)\left[\left(\frac{\tilde{B}_iK_j+\tilde{B}_jK_i}{2}\right)^T P_1\left(\frac{\tilde{B}_kK_l+\tilde{B}_lK_k}{2}\right)\right]e(t) \\
&\quad + 2x^T(t)\left[\left(\frac{H_{ij}+H_{ji}}{2}\right)^T P_1\left(\frac{\tilde{A}_{k2}+\tilde{A}_{l2}}{2}\right)\right]x(t-d) \\
&\quad - 2x^T(t)\left[\left(\frac{H_{ij}+H_{ji}}{2}\right)^T P_1\left(\frac{\tilde{B}_kK_l+\tilde{B}_lK_k}{2}\right)\right]e(t) \\
&\quad \left. - 2x^T(t-d)\left[\left(\frac{\tilde{A}_{i2}+\tilde{A}_{j2}}{2}\right)^T P_1\left(\frac{\tilde{B}_kK_l+\tilde{B}_lK_k}{2}\right)\right]e(t)\right\},
\end{aligned}$$

$$\Delta V_2(e(t)) = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n}\mu_i\mu_j\mu_k\mu_l\left\{x^T(t)\left[\left(\frac{R_{ij}+R_{ji}}{2}\right)^T P_3\left(\frac{R_{kl}+R_{lk}}{2}\right)\right]x(t)\right.$$

$$+ x^T(t-d)\left[\left(\frac{\Delta A_{i2}(t)+\Delta A_{j2}(t)}{2}\right)^T P_3\left(\frac{\Delta A_{k2}(t)+\Delta A_{k2}(t)}{2}\right)\right]x(t-d)$$

$$+ e^T(t)\left[\left(\frac{S_{ij}+S_{ji}}{2}\right)^T P_3\left(\frac{S_{kl}+S_{lk}}{2}\right)-P_3+P_4\right]e(t)$$

$$+ e^T(t-d)\left[\left(\frac{T_{ij}+T_{ji}}{2}\right)^T P_3\left(\frac{T_{kl}+T_{lk}}{2}\right)-P_4\right]e(t-d)$$

$$+ 2x^T(t)\left[\left(\frac{R_{ij}+R_{ji}}{2}\right)^T P_3\left(\frac{\Delta A_{k2}(t)+\Delta A_{k2}(t)}{2}\right)\right]x(t-d)$$

$$+ 2x^T(t)\left[\left(\frac{R_{ij}+R_{ji}}{2}\right)^T P_3\left(\frac{S_{kl}+S_{lk}}{2}\right)\right]e(t)$$

$$+ 2x^T(t)\left[\left(\frac{R_{ij}+R_{ji}}{2}\right)^T P_3\left(\frac{T_{kl}+T_{lk}}{2}\right)\right]e(t-d)$$

$$+ 2x^T(t-d)\left[\left(\frac{\Delta A_{i2}(t)+\Delta A_{j2}(t)}{2}\right)^T P_3\left(\frac{S_{kl}+S_{lk}}{2}\right)\right]e(t)$$

$$+ 2x^T(t-d)\left[\left(\frac{\Delta A_{i2}(t)+\Delta A_{j2}(t)}{2}\right)^T P_3\left(\frac{T_{kl}+T_{lk}}{2}\right)\right]e(t-d)$$

$$\left.+ 2e^T(t)\left[\left(\frac{S_{ij}+S_{ji}}{2}\right)^T P_3\left(\frac{T_{kl}+T_{lk}}{2}\right)\right]e(t-d)\right\}.$$

By Lemma 1, we obtain that

$$\Delta V(t) \le \sum_{i=1}^{n}\mu_i^2\{x^T(t)[H_{ii}^T(3P_1)(H_{ii})+R_{ii}^T(4P_3)R_{ii}-P_1+P_2]x(t)$$

$$+ x^T(t-d)[\tilde{A}_{i2}^T(3P_1)\tilde{A}_{i2}+\Delta A_{i2}^T(t)(4P_3)\Delta A_{i2}(t)-P_2]x(t-d)\}$$

$$
\begin{aligned}
&+\sum_{i=1}^{n-1}\sum_{j>i}^{n}\mu_i\mu_j\Big\{x^T(t)\Big[(H_{ij}+H_{ji})^T\Big(\frac{3}{2}P_1\Big)(H_{ij}+H_{ji})-2P_1+2P_2\\
&+(R_{ij}+R_{ji})^T(2P_3)(R_{ij}+R_{ji})\Big]x(t)\\
&+x^T(t-d)\Big[(\tilde{A}_{i2}+\tilde{A}_{j2})^T\Big(\frac{3}{2}P_1\Big)(\tilde{A}_{i2}+\tilde{A}_{j2})-2P_2\\
&+(\Delta A_{i2}(t)+\Delta A_{j2}(t))^T(2P_3)(\Delta A_{i2}(t)+\Delta A_{j2}(t))\Big]x(t-d)\Big\}\\
&+\sum_{i=1}^{n}\mu_i^2\{e^T(t)[K_i^T\tilde{B}_i^T(3P_1)\tilde{B}_iK_i+S_{ii}^T(4P_3)S_{ii}-P_3+P_4]e(t)\\
&+e^T(t-d)[T_{ii}^T(4P_3)T_{ii}-P_4]e(t-d)\}\\
&+\sum_{i=1}^{n-1}\sum_{j>i}^{n}\mu_i\mu_j\Big\{e^T(t)\Big[(\tilde{B}_iK_j+\tilde{B}_jK_i)^T\Big(\frac{3}{2}P_1\Big)(\tilde{B}_iK_j+\tilde{B}_jK_i)-2P_3+2P_4\\
&+(S_{ij}+S_{ji})^T(2P_3)(S_{ij}+S_{ji})\Big]e(t)\\
&+e^T(t-d)[(T_{ij}+T_{ji})^T(2P_3)(T_{ij}+T_{ji})-2P_4]e(t-d)\Big\}.
\end{aligned}
\tag{16}
$$

If $(16) < 0$ while $\tilde{x}(t) \neq 0$ and $\tilde{e}(t) \neq 0$, then the discrete system (9) is asymptotically stable. Similar to the method proposed in [4], suppose each sum in (16) is negative definite, we can complete the proof of Theorem 1 by using Lemma 1, Lemma 2 and Schur complement.

Remark 1. With the following steps:

Step 1. Solving LMIs (10) and (11), we can obtain X, Y_i and P_3;

Step 2. By equation (14), we can have K_i;

Step 3. Put the above results into equations (12) and (13), then calculate P_4 and G_i by solving the LMIs (12) and (13);

we can easily have the controller gains K_i and the observer gains G_i $(i = 1, 2, ..., n)$.

4. A Numerical Example

In this section, an example is used to illustrate the proposed method.

Example. Assuming an uncertain T-S fuzzy discrete system with time-delay (4) has the following parameters:

$$A_{11} = \begin{bmatrix} -0.13 & -0.39 \\ 1 & 0 \end{bmatrix}, \quad A_{12} = \begin{bmatrix} -0.57 & -0.83 \\ 0 & 0 \end{bmatrix}, \quad B_1 = B_2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix},$$

$$A_{21} = \begin{bmatrix} -1.24 & -7.62 \\ 1 & 0 \end{bmatrix}, \quad A_{22} = \begin{bmatrix} -1.33 & -8.72 \\ 0 & 0 \end{bmatrix}, \quad C_{11} = C_{21} = \begin{bmatrix} 0 & 0.8 \end{bmatrix},$$

$$C_{12} = C_{22} = \begin{bmatrix} 0.4 & 0 \end{bmatrix}, \quad U_1 = U_2 = \begin{bmatrix} 0.1 & 0.08 \\ 0.02 & 0 \end{bmatrix}, \quad E_{11} = E_{21} = \begin{bmatrix} 0.1 & 0 \\ 0 & 0 \end{bmatrix},$$

$$E_{12} = E_{22} = \begin{bmatrix} 0.4 & 0 \\ 0.3 & 0 \end{bmatrix}, \quad E_1 = E_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

Let $\varepsilon_{11} = 12.16$, $\varepsilon_{22} = 6.55$ and $\varepsilon_{12} = 8.73$, solving LMIs (10) and (11), by Step 2 in Remark 1, we have

$$K_1 = \begin{bmatrix} -13.8391 & -29.1143 \end{bmatrix}, \quad K_2 = \begin{bmatrix} -11.2369 & -25.3347 \end{bmatrix}.$$

Then put them into (12) and (13), let $\eta_{ij} = \varepsilon_{ij}$, finally, we can obtain

$$G_1 = \begin{bmatrix} 2.3781 \\ 5.2596 \end{bmatrix}, \quad G_2 = \begin{bmatrix} 2.1024 \\ 4.9815 \end{bmatrix}$$

by Step 3 in Remark 1.

5. Conclusion

In this paper, under the unmeasurable states environment, we proposed a new method to design an observer-based output feedback controller for a class of uncertain T-S fuzzy discrete systems with time-delay. The effectiveness of this method can be verified by the given numerical example.

References

[1] Y. Y. Cao and P. M. Frank, Robust H_∞ disturbance attenuation for a class of uncertain discrete-time fuzzy systems, IEEE Trans. Fuzzy Systems 8 (2000), 406-415.

[2] T. M. Guerra and L. Vermeiren, LMI-based relaxed nonquadratic stabilization conditions for nonlinear systems in the Takagi-Sugeno's form, Automatica 40 (2004), 823-829.

[3] H. Antai, C. Guoding, Y. Maying and Y. Li, Stabilizing fuzzy controller design for uncertain time-delay systems, Proceedings of the 3rd World Congress on Intelligent Control and Automation, Vol. 3, 2000, pp. 1540-1543.

[4] H. L. Huang, Observer-based output feedback control for uncertain T-S fuzzy systems with time-delay, Pioneer J. Math. Math. Sci. 1 (2011), 163-179.

[5] H. L. Huang and F. G. Shi, Delay-dependent stability analysis and robust H_∞ control for uncertain fuzzy systems with time-delay, J. Math. Sci.: Adv. Appl. 1 (2008), 131-152.

[6] H. L. Huang and F. G. Shi, State time-delay feedback robust H_∞ control for uncertain fuzzy discrete systems with time-delay, Adv. Fuzzy Sets and Systems 4 (2009), 189-202.

[7] J. R. Li and Z. L. Xia, Generalized H_2 controller design for uncertain discrete-time-delay piecewise systems, Fuzzy Systems Math. 20 (2006), 298-304.

[8] C. Lin, Q. G. Wang and T. H. Lee, Delay-dependent LMI conditions for stability and stabilization of T-S fuzzy systems with bounded time-delay, Fuzzy Sets and Systems 157 (2006), 1229-1247.

[9] X. Liu and H. Zhang, Delay-dependent robust stability of uncertain fuzzy large-scale systems with time-varying delays, Automatica 44 (2008), 193-198.

[10] T. Takagi and M. Sugeno, Fuzzy identification of systems and its applications to modeling and control, IEEE Trans. Systems, Man and Cybernetics 15 (1985), 116-132.

[11] S. Tong and H. Li, Observer-based robust fuzzy control of nonlinear systems with parametric uncertainties, Fuzzy Sets and Systems 131 (2002), 165-184.

[12] R. J. Wang, W. W. Lin and W. J. Wang, Stabilizability of linear quardratic state feedback for uncertain fuzzy time-delay systems, IEEE Trans. Systems, Man and Cybernetics (Part B) 34 (2004), 1288-1292.

[13] W. J. Wang and C. H. Sun, Relaxed stability and stabilization conditions for a T-S fuzzy discrete system, Fuzzy Sets and Systems 156 (2005), 208-225.

[14] W. J. Wang, G. H. Wu and D. C. Yang, Variable structure control design for uncertain discrete-time systems, IEEE Trans. Automat. Control 39 (1994), 99-102.

[15] L. Xie, Output feedback H_∞ control of systems with parameter uncertainty, Internat. J. Control 63 (1996), 741-750.

[16] S. Xu and J. Lam, Robust H_∞ control for uncertain discrete-time-delay fuzzy systems via output feedback controllers, IEEE Trans. Fuzzy Systems 13 (2005), 82-93.

[17] J. Yoneyama, Robust guaranteed cost control of uncertain fuzzy systems under time-varying sampling, Appl. Soft Computing 11 (2011), 249-255.

[18] L. Yu, Robust Control - An LMI Method, Tsinghua University Press, 2002.

[19] B. Zhang, J. Lam, S. Xu and Z. Shu, Robust stabilization of uncertain T-S fuzzy time-delay systems with exponential estimates, Fuzzy Sets and Systems 160(12) (2009), 1720-1737.

[20] Y. Zhang, S. Xu, Y. Zou and J. Lu, Delay-dependent robust stabilization for uncertain discrete-time fuzzy Markovian jump systems with mode-dependent time delays, Fuzzy Sets and Systems 164 (2011), 66-81.