ICIC Express Letters
Volume **14**, Number **3**, March **2020**

ICIC International ©2020 ISSN 1881-803X
pp. **257–264**

H_∞ FILTERING DESIGN FOR TAKAGI-SUGENO FUZZY MODEL WITH IMMEASURABLE PREMISE VARIABLES BY APPLYING A SWITCHING METHOD

Yuankun Xie, Juanjuan Liu and Likui Wang

School of Mathematics and Information Science
Nanchang Hangkong University
No. 696, Fenghe South Avenue, Nanchang 330063, P. R. China
wlk0228@163.com

Received September 2019; accepted December 2019

Abstract. *This brief paper studies the problem of H_∞ fuzzy filtering design with immeasurable premise variables for T-S (Takagi-Sugeno) model. First, a switching method is proposed to deal with the time derivatives of the membership functions. Then, a switching filtering is designed and a membership function dependent Lyapunov function is applied to deriving some LMIs. In the end, two numerical examples are given to show the effectiveness of the proposed approach.*
Keywords: H_∞ filtering design, Linear matrix inequality, Robust control

1. Introduction.

In recent years, as the development of artificial intelligence, there are lots of results about nonlinear system [1, 2] and fuzzy systems [3-16] especially for T-S fuzzy model [17-31] (see [32] and the references therein) among which, filtering design is a hot topic. Up to now, there are lots of results about filtering design; for example, the problem of H_∞ fuzzy filtering with quadratic D stability is derived in terms of LMIs in [33]. For some cases, the premise variable is measurable as stated in [34] which shows the premise variables are not dependent on the states estimated by fuzzy observer; however, in some practical cases, the premise variables depend on the immeasurable states such as [35-38]. Note, all the above results are based on quadratic Lyapunov function whcih requires the positive definite Lyapunov matrix to satisfy all local models, but this requirement can not be always satisfied. Recently, in order to reduce the conservativeness, the membership function dependent Lyapunov function is proposed in [39] and extended to filtering design in [40] but the results are only local.

Based on the above discussion, the problem of H_∞ filtering design for continuous-time T-S fuzzy systems with unknown premise variables is further investigated in this paper and summarized as follows. First, a switching method is applied to dealing with the time derivatives of membership functions and a membership function dependent Lyapunov function which has the diagonal form is designed. Then, an algorithm is designed to get the switching filtering gains such that the fuzzy system is globally asymptotically stable with better H_∞ performance. In the end, two examples are provided to verify the results given in this paper.

2. Problem Statement and Preliminaries.

Considering the following T-S fuzzy model where the ith rule is described as follows:

R^i:

$$\text{if } \xi_1(t) \text{ is } M_{1i} \text{ and } \dots \text{ and } \xi_p(t) \text{ is } M_{pi}$$

DOI: 10.24507/icicel.14.03.257

then:

$$\begin{aligned} \dot{x}(t) &= A_i x(t) + B_i w(t) \\ z(t) &= L_i x(t) \\ y(t) &= C_i x(t) + D_i x(t) \end{aligned} \tag{1}$$

where $x(t) \in R^n$ is the state variable, $w(t) \in R^m$ is the noise signal that is assumed to be the signal in $L_2[0, \infty)$, $z(t) \in R^{q_1}$ is the signal to be estimated, $y(t) \in R^{q_2}$ is measurement output. The matrices A_i, B_i, C_i, D_i and L_i for $i = 1, \dots, r$ are of appropriate dimensions. $\xi_1(t), \dots \xi_p(t)$ are premise variables. $\xi(t) = [\xi_1(t), \dots, \xi_p(t)]$ and $\xi(t)$ is assumed to be a function of $x(t)$. For brevity, the notation with respect to time t is simplified, for instance, we will use x instead of $x(t)$.

The T-S fuzzy model (1) is inferred as follows:

$$\begin{aligned} \dot{x}(t) &= \sum_{i=1}^{r} h_i(\xi)\{A_i x(t) + B_i w(t)\} \\ z(t) &= \sum_{i=1}^{r} h_i(\xi) L_i x(t) \\ y(t) &= \sum_{i=1}^{r} h_i(\xi)\{C_i x(t) + D_i w(t)\} \end{aligned} \tag{2}$$

When the premise variable is the state of the system, the fuzzy system (1) becomes

$$\begin{aligned} \dot{x}(t) &= A_h x(t) + B_h w(t) \\ z(t) &= L_h x(t) \\ y(t) &= C_h x(t) + D_h w(t) \end{aligned} \tag{3}$$

where

$$\begin{aligned} A_h &= \sum_{i=1}^{r} h_i(x) A_i, \quad B_h = \sum_{i=1}^{r} h_i(x) B_i, \quad C_h = \sum_{i=1}^{r} h_i(x) C_i, \\ D_h &= \sum_{i=1}^{r} h_i(x) D_i, \quad L_h = \sum_{i=1}^{r} h_i(x) L_i. \end{aligned}$$

The design of an H_∞ filter for system (3) is discussed in the paper. Because the premise variable is the estimation of the state, a fuzzy filter is designed as

$$\begin{aligned} \dot{\hat{x}}(t) &= \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(\hat{x})\, h_j(\hat{x}) \left\{ \hat{A}_{ij}\hat{x}(t) + \hat{B}_j y(t) \right\} \\ \hat{z}(t) &= \sum_{i=1}^{r} h_i(\hat{x})\, \hat{C}_i \hat{x}(t) \end{aligned} \tag{4}$$

where $\hat{x}(t)$ is the estimation of $x(t)$

$$\hat{A}_{hh} = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(\hat{x})\, h_j(\hat{x})\, \hat{A}_{ij}, \quad \hat{B}_h = \sum_{j=1}^{r} h_j(\hat{x})\, \hat{B}_j, \quad \hat{C}_h = \sum_{i=1}^{r} h_i(\hat{x})\, \hat{C}_i.$$

The matrices $\hat{A}_{ij}$, $\hat{B}_j$, and $\hat{C}_i$ with appropriate dimensions are to be determined.

Defining the augmented state vector $x_{cl} = \begin{bmatrix} x^T(t) & (x(t) - \hat{x}(t))^T \end{bmatrix}^T$ and $z_{cl} = z(t) - \hat{z}(t)$, we can obtain the following filtering error system:

$$\begin{aligned} \dot{x}_{cl} &= A_{cl} x_{cl}(t) + B_{cl} w(t) \\ z_{cl} &= C_{cl} x_{cl}(t) \end{aligned} \tag{5}$$

where

$$A_{cl} = \begin{bmatrix} A_h & 0 \\ A_h - \hat{B}_h C_h - \hat{A}_{hh} & \hat{A}_{hh} \end{bmatrix}, \quad B_{cl} = \begin{bmatrix} B_h \\ B_h - \hat{B}_h D_h \end{bmatrix}, \quad C_{cl} = \begin{bmatrix} L_h - \hat{C}_h & \hat{C}_h \end{bmatrix}.$$

3. **Main Results.**

3.1. **The time derivative of membership functions.**

For a membership function dependent matrix such as $X_h = \sum_{i=1}^{r} h_i X_i$ where X_i are positive and constant matrix, the time derivative of X_h is $\dot{X}_h = \sum_{i=1}^{r} \dot{h}_i X_i$. $\dot{X}_h$ has to be dealt with as long as the used Lyapunov function is dependent on the membership function. In the past, there are mainly two methods to deal with $\dot{h}_i$, the first is to bound it such as $\left|\dot{h}_i\right| \le \kappa$ with κ given. This is a popular method, however, it has shortcomings (more details can be found in [32]). The other method is to transform the inequality $\left|\dot{h}_i\right| \le \kappa$ into LMIs with κ searched. For this method, the scope of the system states must be known, so the results are only local. In the following, we can use a switching method to ensure $\dot{X}_h$ is negative. Note, $\dot{X}_h$ can be expressed as

$$\dot{X}_h = \sum_{i=1}^{r} \dot{h}_i X_i = \sum_{k=1}^{r-1} \dot{h}_k \left(X_k - X_r\right), \tag{6}$$

where Z_i are to be designed, if the signal (positive or negative) of $\dot{h}_i$ is known, $X_k - X_r$ can be changed to satisfy $\dot{h}_k \left(X_k - X_r\right) \le 0$ as follows:

$$\begin{cases} \text{if } \dot{h}_k \le 0, \text{ then } X_k - X_r \ge 0, \\ \text{if } \dot{h}_k > 0, \text{ then } X_k - X_r < 0. \end{cases} \tag{7}$$

There are 2^{r-1} possible cases in (7). Let H_l, $l = 1, 2, \ldots, 2^{r-1}$ be the set that contains the possible permutations of $\dot{h}_k$ and C_l be the set that contains the constraints of X_i, Y_i and Z_i, (7) can be presented as

$$\text{if } H_l, \text{ then } C_l. \tag{8}$$

3.2. **Filtering design.**

Theorem 3.1. *Supposed the switching times are finite, the filter (4) is stable with H_∞ disturbance attenuation γ_p for system (3) if (9), (10) hold with $P_{1i}^p > 0$, $P_2^p > 0$*

$$\Theta_{kii} < 0, \quad i \in \{1, \ldots, r\} \tag{9}$$

$$\frac{2}{r-1}\Theta_{kii} + \Theta_{kij} + \Theta_{kji} < 0, \quad (i, j) \in \{1, \ldots, r\}^2, \quad i \ne j \tag{10}$$

where

$$\Theta_{ij} = \begin{bmatrix} \Phi_{11} & * & * & * \\ \Phi_{21} & \left(\phi_{ij}^p\right)^T + \phi_{ij}^p & * & * \\ B_k^T P_{1j}^p & B_k^T P_2^p - D_k^T \left(\psi_j^p\right)^T & -\gamma_p^2 I & 0 \\ L_k - \hat{C}_j^p & \hat{C}_j^p & 0 & -I \end{bmatrix},$$

$$\Phi_{11} = P_{1j}^p A_k + A_k^T P_{1j}^p,$$

$$\Phi_{21} = P_2^p A_k - \psi_j^p C_k - \phi_{ij}^p,$$

$$\phi_{ij}^p = P_2^p \hat{A}_{ij}^p, \quad \psi_j^p = P_2^p \hat{B}_j^p.$$

The switching filter gain matrices in (4) are given by

$$\hat{A}_{ij}^p = \left(P_2^p\right)^{-1} \phi_{ij}^p, \quad \hat{B}_i^p = \left(P_2^p\right)^{-1} \psi_i^p, \quad \hat{C}_i^p, \quad i, j = 1, \ldots, r.$$

Proof: In order to ensure

$$\dot{V}(x_{cl}) + z_{cl}^T z_{cl} - \gamma_p^2 w^T(t)w(t) < 0, \tag{11}$$

applying the Lyapunov function

$$V(x_{cl}) = x_{cl}^T P_{\hat{x}}^{\sigma(t)} x_{cl}, \quad P_{\hat{x}}^{\sigma(t)} = \begin{bmatrix} P_{1\hat{x}}^{\sigma(t)} & 0 \\ 0 & P_2^{\sigma(t)} \end{bmatrix},$$

and suppose the pth filter is activated, we have

$$\begin{bmatrix} A_{cl}^T P_{\hat{x}}^p + P_{\hat{x}}^p A_{cl} + \frac{dP_{\hat{x}}^p}{dt} + C_{cl}^T C_{cl} & P_{\hat{x}}^p B_{cl} \\ B_{cl}^T P_{\hat{x}}^p & -\gamma_p^2 I \end{bmatrix} < 0. \tag{12}$$

Because of C_p and applying the Schur Complement to the above inequality, we get

$$\begin{bmatrix} A_{cl}^T P_{\hat{x}}^p + P_{\hat{x}}^p A_{cl} & P_{\hat{x}}^p B_{cl} & C_{cl}^T \\ B_{cl}^T P_{\hat{x}}^p & -\gamma_p^2 I & 0 \\ C_{cl} & 0 & -I \end{bmatrix} < 0 \tag{13}$$

then, substituting A_{cl}, B_{cl} and C_{cl} into (13) we have

$$\begin{bmatrix} A_h^T P_{\hat{x}}^p + P_{\hat{x}}^p A_{ch} & * & * & * \\ \left\{ \begin{array}{c} P_2^p A_h \\ -P_2^p \hat{B}_h C_h \\ -P_2^p \hat{A}_{hh} \end{array} \right\} & \left\{ \begin{array}{c} \hat{A}_{hh}^T P_2^p \\ +P_2^p \hat{A}_{hh} \end{array} \right\} & * & * \\ B_h^T P_{1\hat{x}}^p & \left\{ \begin{array}{c} B_h^T P_2^p \\ -D_h^T \hat{B}_h^T P_2^p \end{array} \right\} & -\gamma_p^2 I & * \\ L_h - \hat{C}_h & \hat{C}_h & 0 & -I \end{bmatrix} < 0. \tag{14}$$

(14) is ensured by (9) and (10). □

The following algorithm can be used to get filtering gains.

Algorithm 3.1. *For different $p \in S$, solving the LMIs in C_p and (9)-(10) to find the corresponding minimal performance γ_p, the final performance is $\gamma = \max\{\gamma_1, \gamma_2, \ldots, \gamma_{2^{r-1}}\}$ and the corresponding feedback gains and observer gains are $\left\{\hat{A}_{ij}^p, \hat{B}_i^p, \hat{C}_i^p\right\}$.*

4. Examples.

Example 4.1. *Consider the following continuous-time T-S fuzzy system in* [35]

$$\begin{aligned} \dot{x}(t) &= \sum_{k=1}^{2} h_i(x_1) \left\{ A_i x(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} w(t) \right\} \\ z(t) &= \begin{bmatrix} 1 & 0 \end{bmatrix} x(t) \\ y(t) &= \begin{bmatrix} 0 & 1 \end{bmatrix} x(t) + w(t) \end{aligned}$$

where

$$A_1 = \begin{bmatrix} -0.1 & 50 \\ -1 & -10 \end{bmatrix}, \quad A_2 = \begin{bmatrix} -4.6 & 50 \\ -1 & -10 \end{bmatrix},$$
$$h_1(x_1) = 1 - \frac{x_1^2}{9}, \quad h_2(x_1) = \frac{x_1^2}{9}.$$

For this system x_2 is known and x_1 need be estimated by the observer. Let

$$h_1(x_1) = w_0^1 = 1 - \frac{x_1^2}{9}, \quad h_2(x_1) = 1 - h_1(x_1),$$

applying the method in [35] *and* [40] *we get* $\gamma = 0.55$ *and* $\gamma = 0.52$ *respectively, while the system is still stable even with* $\gamma = 0.3$ *obtained by applying Algorithm 3.1 in this paper. For* C_1 $(P^1_{11} \geq P^1_{12})$*, the corresponding filtering gains are*

$$\hat{A}^1_{11} = \begin{bmatrix} -2.1602 & 39.3801 \\ -0.5486 & -8.8816 \end{bmatrix}, \quad \hat{A}^1_{12} = \begin{bmatrix} -6.0395 & 91.4773 \\ -0.2711 & -25.2491 \end{bmatrix},$$
$$\hat{A}^1_{21} = \begin{bmatrix} 10.2433 & 1.8522 \\ -3.6835 & 5.5285 \end{bmatrix}, \quad \hat{A}^1_{22} = \begin{bmatrix} -4.2851 & 59.3443 \\ -1.0200 & -13.1189 \end{bmatrix},$$
$$\hat{B}^1_1 = \begin{bmatrix} 2.5248 \\ 0.4603 \end{bmatrix}, \quad \hat{B}^1_2 = \begin{bmatrix} -2.1911 \\ 1.4472 \end{bmatrix},$$
$$\hat{C}^1_1 = \begin{bmatrix} 0.91120 & 0.0509 \end{bmatrix}, \quad \hat{C}^1_2 = \begin{bmatrix} 0.8405 & 0.0132 \end{bmatrix},$$

and for C_1 $(P^1_{11} < P^1_{12})$*, the corresponding filtering gains are*

$$\hat{A}^2_{11} = \begin{bmatrix} -1.8296 & 44.1183 \\ -0.6445 & -9.9638 \end{bmatrix}, \quad \hat{A}^2_{12} = \begin{bmatrix} 143.7778 & 49.2255 \\ -33.7229 & -11.2661 \end{bmatrix},$$
$$\hat{A}^2_{21} = \begin{bmatrix} -139.8379 & 50.1011 \\ 29.8910 & -9.8174 \end{bmatrix}, \quad \hat{A}^2_{22} = \begin{bmatrix} -4.3711 & 65.9286 \\ -1.0049 & -14.6547 \end{bmatrix},$$
$$\hat{B}^2_1 = \begin{bmatrix} 1.9029 \\ 0.5948 \end{bmatrix}, \quad \hat{B}^2_2 = \begin{bmatrix} -3.4971 \\ 1.7423 \end{bmatrix},$$
$$\hat{C}^2_1 = \begin{bmatrix} 0.8781 & -0.0251 \end{bmatrix}, \quad \hat{C}^2_2 = \begin{bmatrix} 0.7955 & 0.0404 \end{bmatrix}.$$

The fuzzy system (5) is asymptotically stable with the above switching filtering.

Example 4.2. *Consider the following continuous-time T-S fuzzy model in* [38]

$$x(t) = \sum_{i=1}^{2} h_i(\xi)(A_i x(t) + B_i w(t))$$
$$z(t) = \sum_{i=1}^{2} h_i(\xi) L_i x(t)$$
$$y(t) = \sum_{i=1}^{2} h_i(\xi)(C_i x(t) + D_i w(t))$$

where

$$A_1 = \begin{bmatrix} -3 & 0.6 \\ 0.2 & -2 \end{bmatrix}, \quad A_2 = \begin{bmatrix} -1 & 0.4 \\ -0.2 & -1 \end{bmatrix},$$
$$B_1 = \begin{bmatrix} 0 \\ 0.3 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ 0.2 \end{bmatrix},$$
$$L_1 = \begin{bmatrix} 0.3 & 0.5 \end{bmatrix}, \quad L_2 = \begin{bmatrix} 0.3 & 0.2 \end{bmatrix},$$
$$C_1 = \begin{bmatrix} 1.5 & 0.5 \end{bmatrix}, \quad C_2 = \begin{bmatrix} 1 & 0.1 \end{bmatrix},$$
$$D_1 = D_2 = 0.1.$$

For this fuzzy system, applying the method in [35] *we get* $\gamma = 0.0924$*, while the system is still stable even with* $\gamma = 0.03$ *obtained by applying Algorithm 3.1 in this paper. For* C_1 $(P^1_{11} \geq P^1_{12})$*, the corresponding filtering gains are*

$$\hat{A}^1_{11} = \begin{bmatrix} -0.2851 & 1.6690 \\ -2.5319 & -3.2971 \end{bmatrix}, \quad \hat{A}^1_{12} = \begin{bmatrix} 277.7163 & -172.6369 \\ -211.3659 & 746.0213 \end{bmatrix},$$
$$\hat{A}^1_{21} = \begin{bmatrix} -276.9262 & 173.6134 \\ 208.0111 & -745.7539 \end{bmatrix}, \quad \hat{A}^1_{22} = \begin{bmatrix} -0.6465 & 0.7524 \\ -0.4370 & -2.4035 \end{bmatrix},$$

$$\hat{B}_1^1 = \begin{bmatrix} -2.0570 \\ 1.8870 \end{bmatrix}, \quad \hat{B}_2^1 = \begin{bmatrix} -0.8290 \\ 0.4990 \end{bmatrix},$$
$$\hat{C}_1^1 = \begin{bmatrix} 0.0971 & 0.1980 \end{bmatrix}, \quad \hat{C}_2^1 = \begin{bmatrix} 0.1694 & 0.1028 \end{bmatrix},$$

and for C_1 $(P_{11}^1 < P_{12}^1)$*, the corresponding filtering gains are*

$$\hat{A}_{11}^2 = \begin{bmatrix} -1.0428 & 1.7256 \\ -3.1752 & -5.2158 \end{bmatrix}, \quad \hat{A}_{12}^2 = \begin{bmatrix} 821.9 & -317.7 \\ -433.9 & 2481.9 \end{bmatrix},$$
$$\hat{A}_{21}^2 = \begin{bmatrix} -820.7 & 318.6 \\ 429.7 & -2479.4 \end{bmatrix}, \quad \hat{A}_{22}^2 = \begin{bmatrix} -1.2608 & 0.8147 \\ -0.6786 & -4.3338 \end{bmatrix},$$
$$\hat{B}_1^2 = \begin{bmatrix} -1.9005 \\ 2.3631 \end{bmatrix}, \quad \hat{B}_2^2 = \begin{bmatrix} -0.7411 \\ 0.7956 \end{bmatrix},$$
$$\hat{C}_1^2 = \begin{bmatrix} 0.1500 & 0.2500 \end{bmatrix}, \quad \hat{C}_2^2 = \begin{bmatrix} 0.1500 & 0.1000 \end{bmatrix}.$$

The fuzzy system (5) is asymptotically stable with the above switching filtering.

5. **Conclusions.** In this paper, we have studied the H_∞ fuzzy filtering design with immeasurable variables for the Takagi-Sugeno fuzzy systems. A switching method is proposed to deal with the time derivatives of the membership functions and the filtering gains can be obtained by an algorithm presented as LMIs. Two examples have been given to show the effectiveness of the proposed approach. The method can be used to deal with other control problems like observer design and positive fuzzy system.

REFERENCES

[1] H. Y. Li, Y. Wang, D. Yao and R. Lu, A sliding mode approach to stabilization of nonlinear Markovian jump singularly perturbed systems, *Automatica*, vol.97, pp.404-413, 2018.

[2] H. Y. Li, S. Zhao, W. He and R. Lu, Adaptive finite-time tracking control of full states constrained nonlinear systems with dead-zone, *Automatica*, vol.100, pp.99-107, 2019.

[3] J. W. Wang, Dynamic boundary fuzzy control design of semilinear parabolic PDE systems with spatially noncollocated discrete observation, *IEEE Trans. Cybernetics*, vol.49, no.8, pp.3041-3051, 2019.

[4] J. W. Wang, S. H. Tsai, H. X. Li and H. K. Lam, Spatially piecewise fuzzy control design for sampled-data exponential stabilization of semilinear parabolic PDE systems, *IEEE Trans. Fuzzy Systems*, vol.26, no.5, pp.2967-2980, 2018.

[5] X. Su, F. Xia, Y. D. Song, M. V. Basin and L. Zhao, $\mathcal{L}_2$-$\mathcal{L}_\infty$ output feedback controller design for fuzzy systems over switching parameters, *IEEE Trans. Fuzzy Systems*, vol.26, no.6, pp.3755-3769, 2018.

[6] X. Su, H. Zhou and Y. D. Song, An optimal divisioning technique to stabilization synthesis of T-S fuzzy delayed systems, *IEEE Trans. Cybernetics*, vol.47, no.5, pp.1147-1156, 2017.

[7] Y. M. Li and S. C. Tong, Adaptive fuzzy output-feedback stabilization control for a class of switched non-strict-feedback nonlinear systems, *IEEE Trans. Cybernetics*, vol.47, no.4, pp.1007-1016, 2017.

[8] Y. M. Li, S. C. Tong and T. S. Li, Composite adaptive fuzzy output feedback control design for uncertain nonlinear strict-feedback systems with input saturation, *IEEE Trans. Cybernetics*, vol.45, no.10, pp.2299-2308, 2015.

[9] X. P. Xie, D. Yue and C. Peng, Observer, design of discrete-time fuzzy systems based on an alterable weights method, *IEEE Trans. Cybernetics*, DOI: 10.1109/TCYB.2018.2878419, 2018.

[10] X. P. Xie, D. Yue, H. G. Zhang and C. Peng, Control synthesis of discrete-time T-S fuzzy systems: Reducing the conservatism whilst alleviating the computational burden, *IEEE Trans. Cybernetics*, vol.47, no.9, pp.2480-2491, 2017.

[11] Y. J. Liu, M. Z. Gong, S. C. Tong, C. L. P. Chen and D. J. Li, Adaptive fuzzy output feedback control for a class of nonlinear systems with full state constraints, *IEEE Trans. Fuzzy Systems*, vol.26, no.5, pp.2607-2617, 2018.

[12] Y. J. Liu, S. C. Tong, D. J. Li and Y. Gao, Fuzzy adaptive control with state observer for a class of nonlinear discrete-time systems with input constraint, *IEEE Trans. Fuzzy Systems*, vol.24, no.5, pp.1147-1158, 2016.

[13] C. C. Hua, G. P. Liu, L. Li and X. P. Guan, Adaptive fuzzy prescribed performance control for nonlinear switched time-delay systems with unmodeled dynamics, *IEEE Trans. Fuzzy Systems*, vol.26, no.4, pp.1934-1945, 2018.

[14] C. C. Hua, K. Li and X. P. Guan, Event-based dynamic output feedback adaptive fuzzy control for stochastic nonlinear systems, *IEEE Trans. Fuzzy Systems*, vol.26, no.5, pp.3004-3015, 2018.

[15] H. Ma, Q. Zhou, L. Bai and H. Liang, Observer-based adaptive fuzzy fault-tolerant control for stochastic nonstrict-feedback nonlinear systems with input quantization, *IEEE Trans. Systems, Man and Cybernetics: Systems*, vol.49, no.2, pp.287-298, 2019.

[16] H. Y. Li, J. H. Wang, L. G. Wu, H. K. Lam and Y. B. Gao, Optimal guaranteed cost sliding-mode control of interval type-2 fuzzy time-delay systems, *IEEE Trans. Fuzzy Systems*, vol.26, no.1, pp.246-257, 2018.

[17] J. B. Qiu, G. Feng and H. J. Gao, Static-output-feedback H_∞ control of continuous-time T-S fuzzy affine systems via piecewise lyapunov functions, *IEEE Trans. Fuzzy Systems*, vol.21, no.2, pp.245-260, 2013.

[18] Z. P. Wang and H. N. Wu, On fuzzy sampled-data control of chaotic systems via a time-dependent Lyapunov functional approach, *IEEE Trans. Cybernetics*, vol.45, no.4, pp.819-829, 2015.

[19] S. F. Derakhshan, A. Fatehi and M. G. Sharabiany, Nonmonotonic observer-based fuzzy controller designs for discrete time T-S fuzzy systems via LMI, *IEEE Trans. Cybernetics*, vol.44, no.12, pp.2557-2567, 2014.

[20] K. Tanaka, T. Hori and H. O. Wang, A multiple Lyapunov function approach to stabilization of fuzzy control systems, *IEEE Trans. Fuzzy Systems*, vol.11, no.4, pp.582-589, 2003.

[21] E. S. Tognetti, R. C. L. F. Oliveira and P. L. D. Peres, Selective H_2 and H_∞ stabilization of Takagi-Sugeno fuzzy systems, *IEEE Trans. Fuzzy Systems*, vol.19, no.5, pp.890-900, 2011.

[22] B. Chen, X. P. Liu, S. C. Tong and C. Lin, Observer-based stabilization of T-S fuzzy systems with input delay, *IEEE Trans. Fuzzy Systems*, vol.16, no.3, pp.652-663, 2008.

[23] S. K. Nguang and P. Shi, H_∞ fuzzy output feedback control design for nonlinear systems: An LMI approach, *IEEE Trans. Fuzzy Systems*, vol.11, no.3, pp.331-340, 2003.

[24] K. Y. Lian and J. J. Liou, Output tracking control for fuzzy systems via output feedback design, *IEEE Trans. Fuzzy Systems*, vol.14, no.5, pp.628-639, 2006.

[25] T. M. Guerra, A. Kruszewski, L. Vermeiren and H. Tirmant, Conditions of output stabilization for nonlinear models in the Takagi-Sugeno's form, *Fuzzy Sets Syst.*, vol.157, no.9, pp.1248-1259, 2006.

[26] H. N. Wu and H. X. Li, H_∞ fuzzy observer-based control for a class of nonlinear distributed parameter systems with control contraints, *IEEE Trans. Fuzzy Systems*, vol.16, no.2, pp.502-516, 2008.

[27] J. X. Dong, Y. Y. Wang and G. H. Yang, Control synthesis of continuous-time T-S fuzzy systems with local nonlinear models, *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol.39, no.5, pp.1245-1258, 2009.

[28] B. Jiang, H. R. Karimi, Y. Kao and C. Gao, Adaptive control of nonlinear semi-Markovian jump T-S fuzzy systems with immeasurable premise variables via sliding mode observer, *IEEE Trans. Cybernetics*, vol.50, no.2, pp.810-820, DOI: 10.1109/TCYB.2018.2874166, 2020.

[29] M. Chadli and H. R. Karimi, Robust observer design for unknown inputs Takagi-Sugeno models, *IEEE Trans. Fuzzy Systems*, vol.21, no.1, pp.158-164, 2013.

[30] Y. Wei, J. Qiu and H. R. Karimi, Reliable output feedback control of discrete-time fuzzy affine systems with actuator faults, *IEEE Trans. Circuits and Systems I: Regular Papers*, vol.64, no.1, pp.170-181, 2017.

[31] P. Selvaraj, B. Kaviarasan, R. Sakthivel and H. R. Karimi, Fault-tolerant SMC for Takagi-Sugeno fuzzy systems with time-varying delay and actuator saturation, *IET Control Theory & Applications*, vol.11, no.8, pp.1112-1123, 2017.

[32] H. K. Lam, A review on stability analysis of continuous-time fuzzy-model-based control systems: From membership-function-independent to membership-function-dependent analysis, *Engineering Applications of Artificial Intelligence*, vol.67, pp.390-408, 2018.

[33] S. K. Nguang and W. Assawinchaichote, H_∞ filtering for fuzzy dynamical systems with D stability constraints, *IEEE Trans. Circuits System I: Fundamental Theory and Applications*, vol.50, no.11, pp.1503-1508, 2003.

[34] K. Tanaka and H. O. Wang, *Fuzzy Control Systems Design and Analysis: A Linear Matrix Inequality Approach*, John Wiley and Sons, New York, USA, 2001.

[35] J. Yoneyama, H_∞ filtering for fuzzy systems with unmeasurable premise variables: An uncertain system approach, *Fuzzy Sets Syst.* vol.160, pp.1738-1748, 2009.

[36] M. H. Asemani and V. J. Majd, A robust H_∞ observer-based controller design for uncertain T-S fuzzy systems with unknown premise variables via LMI, *Fuzzy Sets Syst.*, vol.212, pp.21-40, 2013.

[37] D. Ichalal, B. Marx, J. Ragot and D. Maquin, State estimation of Takagi-Sugeno systems with unmeasurable premise variables, *IET Control Theory Appl.*, vol.4, pp.897-908, 2010.
[38] J. Yoneyama, Output feedback control for fuzzy systems with unmeasurable premise variables, *Proc. of IEEE Conference on Fuzzy Systems*, Korea, pp.802-807, 2009.
[39] J. T. Pan, T. M. Guerra, S. M. Fei and A. Jaadari, Non-quadratic stabilization of continuous T-S fuzzy models: LMI solution for a local approach, *IEEE Trans. Fuzzy Systems*, vol.20, no.3, pp.594-602, 2012.
[40] L. K. Wang and J. J. Liu, Local stability analysis for continuous-time Takagi-Sugeno fuzzy systems with time delay, *Neurocomputing*, vol.273, no.1, pp.152-158, 2018.