Resilient Reliable Dynamic-output-feedback Control for Takagi-Sugeno Fuzzy Time-Delayed Systems with Time-Varying Actuator Fault

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Abstract—This article investigates the reliable dynamic-output-feedback problem for a class of Takagi-Sugeno (T-S) fuzzy model subject to time-varying delay and actuator fault. The main intention is to design a fault-detection mixed H_∞ and passivity based dynamic-output-feedback controller that guarantees the resulting closed-loop system to be asymptotically stable by using adaptive fault estimation algorithm subject to admissible time-varying actuator faults. More precisely, the asymptotic stability of the concerned system is obtained by constructing an appropriate Lyapunov-Krasovskii functional and novel sufficient stabilization conditions in terms of linear matrix inequalities are established with a prescribed disturbance attenuation level. Finally, the simulation studies are incorporated to exhibit the power of prescribed control design.

Keywords: T-S Fuzzy systems, Time-varying actuator failure, Fault estimation, Dynamic-output-feedback.

1. Introduction

In recent years, fuzzy dynamical systems in the texture of Takagi-Sugeno (T-S) model have rapid growth due to its attractive features [1]- [5]. Moreover many real-world systems exhibit nonlinear characteristics which bring severe difficulties during the process of stabilization. T-S fuzzy model based approach provides an efficient way to analyse and synthesize nonlinear systems [6]- [8]. On the other hand, T-S fuzzy model with time-delay cause nonlinear retarded systems. Therefore the issue of time-delay has been taken into account in T-S fuzzy model by many researchers. By constructing a novel augmented Lyapunov-Krasovskii(L-K) functional, Kwon et al. in [9] designed stability conditions for T-S fuzzy systems with time-varying delay. In [10] the problem of delay-dependent stability is discussed for T-S fuzzy systems with time-varying delay.

Obviously, many engineering systems in the real world cannot work perfectly at all times under all situations. In order to acquire higher safety and reliability criterion, the possible faults which may affect the system performance have be able to detected and

identified as early as possible. To estimate such faults, observer-based fault detection, isolation and fault tolerant control using T-S fuzzy model have gained considerable interest [11]. Youssef et.al [13] designed a Proportional Integral observer for estimating the actuator and sensor faults with unmeasurable premise variables based on T-S fuzzy model. A novel fault estimation and fault tolerant control has been proposed in [14] for T-S fuzzy sytems with time-varying state delay against actuator faults. In particular, some practical systems may have time varying faults. The fault detection technique is employed to handle these kinds of time-varying faults. With the aid of Kalman-Yakubovic-Popov lemma in a local linear model, fault detection filter system and the dynamics of filtering error generator are constructed in [15] for T-S fuzzy discrete systems. The fault detection problem for continuous-time T-S fuzzy systems in finite frequency domain against sensor faults is studied in [16]. The problem of fault detection, isolation and estimation of nonlinear systems using T-S fuzzy model is proposed in [17], wherein the minimization problem

is formulated by bounded real lemma and Polya's theorem is used to reduce the conservatism.

In many real-world systems, state-feedback control approach will fail to guarantee the stabilizability when complete knowledge of the system is not known. In such cases, observer-based dynamic output feedback control is need to be designed so that the unmeasurable states can be estimated from the dynamical process. Moreover, the observer-based dynamic feedback control plays a positive role in system performance and stabilizing the unstable systems. Therefore, this control using T-S fuzzy model approach for dynamical systems has attracted remarkable attention in the control theory ([18]- [19]). By employing the reciprocally converse approach, in [20] an investigation is made on dynamic-output-feedback control for T-S fuzzy system with time-varying input delay and output constraints. The robust dynamic output feedback control problem for a class of discrete-time nonlinear systems is investigated in [21], by employing T-S fuzzy model. External noises are common barrier for the process of stabilization of dynamical systems, which should be controlled or removed by using some performance. The local H_∞ control problem is designed in [22] for the continuous-time T-S systems where the derived LMIs are solved by means of Convex Optimization Technique. A novel robust H_∞ dynamic sliding mode control is proposed in [24] for a class of uncertain stochastic nonlinear systems, wherein a new set of conditions guaranteeing the stochastic stability are derived in terms of LMIs. The problem of mixed H_∞ and passivity performance analysis and design is discussed in [23] for discrete time-delay neural networks represented by T-S fuzzy model. Yet, to the authors best knowledge, the fault estimation control together with the dynamic-output-feedback and mixed H_∞ and passivity performance has not been studied for T-S fuzzy systems. Motivated by this thought, this investigation deals on the stabilization of the T-S fuzzy time-delayed system with the incorporation of fault-tolerant dynamic-output-feedback control via adaptive fault estimation algorithm.

2.Problem formulation and preliminaries

In this section our focus is to construct the closed-loop system by using dynamic-output-feedback control.

Consider the following T-S fuzzy model with time-varying delay:

System rule p: If $g_1(x(t))$ is $\mathcal{M}_1^p$ and $g_2(x(t))$ is $\mathcal{M}_2^p$ and ... and $g_p(x(t))$ is $\mathcal{M}_h^p$ then

$$\begin{aligned}\dot{x}(t) &= A_p x(t) + A_{d_p} x(t - \tau(t)) + B_p u(t) + D_p \omega(t) \\ &\quad + B_{a_p} f(t), \\ y(t) &= C x(t),\end{aligned}\quad (1)$$

where $p \in \{1, 2, \dots, l\}$, l is the number of T-S fuzzy system rules, $g_q(x(t))$ are premises variables and $\mathcal{M}_q^p$ are fuzzy sets. Let $x(t) = [x_1^T \ x_2^T \ \dots \ x_n^T]^T$ be state vector, $y(t)$ is the output signal, $\tau(t)$ denotes time-varying delay with $\tau_1 \leq \tau(t) \leq \tau_2 < \infty$ for some $\tau_1 \geq 0$ and $\tau_2 > 0$, $u(t)$ and $\omega(t)$ stands for control input and time-varying actuator fault respectively, $f(t)$ denotes noise term and $A_p, A_{d_p}, B_p, B_{a_p}, C, D_p$ are system parameters of appropriate dimensions. Then the over all T-S fuzzy model based on (1) can be written in the form,

$$\begin{aligned}\dot{x}(t) &= \sum_{p=1}^l \varphi_p(g(t)) \{A_p x(t) + A_{d_p} x(t - \tau(t)) + B_p u(t) \\ &\quad + D_p \omega(t) + B_{a_p} f(t)\}, \\ y(t) &= C x(t),\end{aligned}\quad (2)$$

where $\varphi_p(g_p(x(t))) = \frac{\varpi_p(g_p(x(t)))}{\sum_{p=1}^l \varpi_p(g_p(x(t)))}$, $\varpi_p(g_p(x(t))) = \prod_{q=1}^h \mathcal{M}_q^p(g_q(x(t)))$, $g(t) = [g_1^T(x(t)) \ g_2^T(x(t)) \ \dots \ g_h^T(x(t))]^T$ and $\mathcal{M}_q^p(g_q(x(t)))$ represents membership degree of $g_p(x(t))$ in $\mathcal{M}_q^p$. Let $A(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) A_p$, $A_d(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) A_{d_p}$, $B(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) B_p$, $B_a(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) B_{a_p}$ and $D(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) D_p$. Then the system (2) can be rewritten in the following form:

$$\begin{aligned}\dot{x}(t) &= A(\varphi) x(t) + A_d(\varphi) x(t - \tau(t)) + B(\varphi) u(t) \\ &\quad + D(\varphi) \omega(t) + B_a(\varphi) f(t), \\ y(t) &= C x(t).\end{aligned}\quad (5)$$

Taking the effects of actuator fault into account and by implementing adaptive algorithm, the fuzzy observer is constructed in the following form to estimate the faults:

Observer rule p: If $g_1(x_O(t))$ is $\mathcal{M}_1^p$ and $g_2(x_O(t))$ is $\mathcal{M}_2^p$ and ... and $g_p(x_O(t))$ is $\mathcal{M}_h^p$ then,

$$\dot{x}_O(t) = A_p x_O(t) + A_{d_p} x_O(t - \tau(t)) + B_p u(t) + B_{a_p} f_O(t) + L_p [y_O(t) - y(t)], \quad (6)$$

$$y_O(t) = C x_O(t), \quad (7)$$

$$\dot{f}_O(t) = -P_4^{-1} F_p [\dot{e}_y(t) + e_y(t)], \quad (8)$$

where $x_O(t)$ denotes observer state, $f_O(t)$ is estimated fault and L_p represents observer gain to be determined. After the process of de-fuzzification as discussed above the observer system becomes,

$$\dot{x}_O(t) = A(\varphi) x_O(t) + A_d(\varphi) x_O(t - \tau(t)) + B(\varphi) u(t) + B_a(\varphi) f_O(t) + L(\varphi) [y_O(t) - y(t)], \quad (9)$$

$$y_O(t) = C x_O(t), \quad (10)$$

$$\dot{f}_O(t) = -P_4^{-1} F(\varphi) [\dot{e}_y(t) + e_y(t)], \quad (11)$$

where L_p and F_p are the unknown gains, P_4^{-1} represents learning rate, $L(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) L_p$, $F(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) F_p$, and $e_y(t) = y_O(t) - y(t)$. Let $e(t) = x_O(t) - x(t)$, then the error system can be expressed in the following form:

$$\dot{e}(t) = [A(\varphi) + L(\varphi)C]e(t) + A_d(\varphi)e(t - \tau(t)) - D(\varphi)\omega(t) + B_a(\varphi)e_f(t) \quad (12)$$

$$e_y(t) = Ce(t), \quad (13)$$

where $e_f(t) = f_O(t) - f(t)$.

In order to design a controller in a more effective and unbreakable way, a resilient reliable dynamic-output-feedback fuzzy controller is designed in the following form,

Controller rule p: If $g_1(x_c(t))$ is $\mathcal{M}_1^p$ and $g_2(x_c(t))$ is $\mathcal{M}_2^p$ and ... and $g_p(x_c(t))$ is $\mathcal{M}_h^p$ then,

$$\dot{x}_c(t) = A_{c_p} x_c(t) + B_{c_p} y(t), \quad (14)$$

$$u(t) = (K_p + \delta K(t)) x_c(t) - B^+(\varphi) B_a(\varphi) f_O(t), \quad (15)$$

where A_c , B_c , K_q are controller gains, $B^+(\varphi) = B^T(\varphi)B(\varphi)$ and $\delta K(t)$ represents the gain fluctuation which is described in the form $\delta K(t) = M_K \mathcal{F}(t) N_K$

where M_K , N_K are known suitable dimensional matrices with $\mathcal{F}^T(t)\mathcal{F}(t) \leq I$ is Lebesgue measurable. Moreover, by the de-fuzzification process the following equations can be obtained,

$$\dot{x}_c(t) = A_c(\varphi) x_c(t) + B_c(\varphi) y(t), \quad (16)$$

$$u(t) = (K(\varphi) + \delta K(t)) x_c(t) - B^+(\varphi) B_a(\varphi) f_O(t), \quad (17)$$

where $A_c(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) A_{c_p}$, $B_c(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) B_{c_p}$ and $K(\varphi) = \sum_{q=1}^l \varphi_q(g(t)) K_q$. By substituting (17) into (5), the closed-loop is obtained in the following form,

$$\dot{x}(t) = A(\varphi) x(t) + A_d(\varphi) x(t - \tau(t)) + B(\varphi) (K(\varphi) + \delta K(t)) x_c(t) + D(\varphi) \omega(t) - B_a(\varphi) e_f(t), \quad (18)$$

$$y(t) = C x(t). \quad (19)$$

By defining the augmented vector $\eta(t)$ as $[x^T(t) \ e^T(t) \ x_c^T(t) \ e_f^T(t)]^T$ and combining the equations (11) - (19) the augmented form of T-S fuzzy system can be written as,

$$\dot{\eta}(t) = A\eta(t) + A_d\eta(t - \tau(t)) + D\omega(t) + B_a\dot{f}(t), \quad (20)$$

$$A = \begin{bmatrix} A(\varphi) & 0 & A_{13} & -B_a(\varphi) \\ 0 & (A(\varphi) + L(\varphi)C) & 0 & B_a(\varphi) \\ B_c(\varphi)C & 0 & A_c(\varphi) & 0 \\ 0 & A_{42} & 0 & A_{44} \end{bmatrix},$$

$$A_{13} = B(\varphi)(K(\varphi) + \delta K(t)), A_{42} = -P_4^{-1} F(\varphi)C [A(\varphi) + L(\varphi)C + 1], A_{44} = -P_4^{-1} F(\varphi)CB_a(\varphi),$$

$$A_d = \begin{bmatrix} A_d(\varphi) & 0 & 0 & 0 \\ 0 & A_a(\varphi) & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -P_4^{-1} F(\varphi)CA_d(\varphi) & 0 & 0 \end{bmatrix},$$

$$D = \begin{bmatrix} D(\varphi) \\ -D(\varphi) \\ 0 \end{bmatrix} \text{ and } B_a = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -1 \end{bmatrix}.$$

In order to derive the required theoretical result, consider the following assumptions, definition and lemmas:

Assumption 1. $\dot{f}(t)$ is norm bounded. i.e. $\|\dot{f}(t)\| \leq f_{max}$ where $0 \leq f_{max} < \infty$.

Assumption 2. $\text{Rank}(CB_{a_p}) = r$, where r is the rank of B_{a_p} .

Assumption 3. Invariant zeros of (A_p, B_{a_p}, C) lie in open left plane.

2.1. Lemma [12] Let the Assumption 2 and Assumption 3 hold then there exist a positive definite matrix P_2 such that the following condition holds, $F(\varphi)C = B_a^T(\varphi)P_2$.

2.2. Lemma [21] Let matrices X , Y and $Z(t)$ be real matrices with appropriate dimensions and $Z(t)$ satisfying $Z^T(t)Z(t) \leq I$ is lebeque measurable, then for any scalar $\epsilon > 0$, the following inequality holds, $XZ(t)Y + Y^T Z(t)X^T \leq \epsilon XX^T + \epsilon^{-1}Y^T Y$.

2.3. Definition [23] For given positive scalar γ and $\theta \in [0, 1]$, the constructed T-S fuzzy system (19) achieves asymptotic stability with the performance mixed H_∞ and passivity iff $\gamma\theta^{-1}y^T(t)y(t) - 2(1 - \theta)y^T(t)\omega(t) - \gamma\omega^T(t)\omega(t) \leq 0$ where, $\theta = \begin{cases} 1 & \text{if } H_\infty \\ 0 & \text{if Passivity.} \end{cases}$

3. Main results

This section deals with the stability analysis of the prescribed system by employing L-K functional and adaptive algorithm. In order to do this, it is sufficient to prove that the system (5) is asymptotically stable with the prescribed performance index. To be precise, the following theorem presents the sufficient conditions guaranteeing the asymptotic stability of the system (5) without considering the gain fluctuations. From these conditions, the dynamic-output feedback controller is obtained in Theorem (2) by considering gain fluctuations.

3.1. Theorem Let the Assumptions 1-3 hold. For given positive scalars γ and θ , the system (5) is robustly asymptotically stable with mixed H_∞ and passivity performance if there exist positive definite matrices $P_1, P_2, P_3, P_4, Q_{11}, Q_{11}, Q_{12}, Q_{13}, Q_{14}, Q_{21}, Q_{22}, Q_{23}, Q_{24}, Q_{31}, Q_{32}, Q_{33}, Q_{34}, M_1$ such that the following LMI

$$[\Xi]_{18 \times 18} = [\Xi_{ij}] \leq 0, \quad (21)$$

$$F(\varphi)C = B_a^T(\varphi)P_2, \quad (22)$$

where $\Xi_{i,j} = \Xi_{j,i}, \forall i, j \in \{1, 2, \dots, 18\}$, $\Xi_{1,1} = A^T(\varphi)P_1 + P_1A(\varphi) + Q_{11} + Q_{21} + Q_{31}$, $\Xi_{1,3} = C^T B_c^T(\varphi)P_3 + P_1B(\varphi)K(\varphi)$, $\Xi_{1,4} = -P_1B_a(\varphi)$, $\Xi_{1,5} = P_1D(\varphi) - (1 - \theta)C^T$, $\Xi_{1,6} = P_1A_d(\varphi)$, $\Xi_{1,18} = \theta C^T$, $\Xi_{2,2} = A^T(\varphi)P_2 + P_2A(\varphi) + C^T L^T(\varphi)P_2 + P_2L(\varphi)C + Q_{12} + Q_{22} + Q_{32}$, $\Xi_{2,4} = -A(\varphi)P_2B_a(\varphi) - C^T L^T(\varphi)P_2B_a(\varphi)$, $\Xi_{2,5} = -P_2D(\varphi)$, $\Xi_{2,6} = P_2A_d(\varphi)$, $\Xi_{3,3} = A_c^T(\varphi)P_3 + P_3A_c(\varphi) + Q_{13} + Q_{23} + Q_{33} + M_1$, $\Xi_{4,4} = -2B_a^T(\varphi)P_2B_a(\varphi) + Q_{14} + Q_{24} + Q_{34} + M$, $\Xi_{4,5} = B_a^T(\varphi)P_2D(\varphi)$, $\Xi_{4,6} = -B_a^T(\varphi)P_2A_d(\varphi)$, $\Xi_{5,5} = -\gamma I$, $\Xi_{6,6} = -(1 - \mu)Q_{11}$, $\Xi_{7,7} = -(1 - \mu)Q_{12}$, $\Xi_{8,8} = -(1 - \mu)Q_{13}$, $\Xi_{9,9} = -(1 - \mu)Q_{14}$, $\Xi_{10,10} = -Q_{21}$, $\Xi_{11,11} = -Q_{22}$, $\Xi_{12,12} = -Q_{23}$, $\Xi_{13,13} = -Q_{24}$, $\Xi_{14,14} = -Q_{31}$, $\Xi_{15,15} = -Q_{32}$, $\Xi_{16,16} = -Q_{33}$, $\Xi_{17,17} = -Q_{34}$, $\Xi_{18,18} = -\gamma\theta$ and remaining terms are zeros. Moreover the error state of the fault are uniformly bounded.

Proof:

In order to prove the stability of the considered system (5), consider the following time-varying L-K functional,

$$V(t) = \sum_{i=1}^n V_p(t), \quad \text{where} \quad (23)$$

$$V_1(t) = \eta^T(t)P\eta(t),$$

$$V_2(t) = \int_{t-\tau(t)}^t \eta^T(s)Q_1\eta(s)ds,$$

$$V_3(t) = \int_{t-\tau_1}^t \eta^T(s)Q_2\eta(s)ds,$$

$$V_4(t) = \int_{t-\tau_2}^t \eta^T(s)Q_3\eta(s)ds,$$

$P = \text{diag}\{P_1, P_2, P_3, P_4\}$, $Q_p = \text{diag}\{Q_{i1}, Q_{i2}, Q_{i3}, Q_{i4}\} \forall i \in \{1, 2, 3\}$. By taking derivatives of $V_p(t)$'s along the trajectories of augmented system (20) we get,

$$\dot{V}_1(t) = \dot{\eta}^T(t)P\eta(t) + \eta^T(t)P\dot{\eta}(t), \quad (24)$$

$$\dot{V}_2(t) = \eta^T(t)Q_1\eta(t) - (1 - \mu)\eta^T(t - \tau(t))Q_1 \times \eta(t - \tau(t)), \quad (25)$$

$$\dot{V}_3(t) = \eta^T(t)Q_2\eta(t) - \eta^T(t - \tau_1)Q_2\eta(t - \tau_1), \quad (26)$$

$$\dot{V}_4(t) = \eta^T(t)Q_3\eta(t) - \eta^T(t - \tau_2)Q_3\eta(t - \tau_2). \quad (27)$$

Substitute the augmented system (20) into (24), we obtain

$$\begin{aligned} \dot{V}_1(t) = & 2\eta^T(t)P[A\eta(t) + A_d\eta(t - \tau(t)) + D\omega(t) + B_a \\ & \times \dot{f}(t)] \\ = & 2x^T(t)P_1A(\varphi)x(t) + 2x^T(t)P_1B(\varphi)(K(\varphi) + \delta K(t)) \\ & \times x_c(t) - 2x^T(t)P_1B_a(\varphi)e_f(t) - 2x^T(t)P_1A_d(\varphi) \\ & \times x(t - \tau(t)) + 2x^T(t)P_1D\omega(t) + 2e^T(t)P_2[A(\varphi) \\ & + L(\varphi)C]e(t) + 2e^T(t)P_2B_a(\varphi)e_f(t) + 2e^T(t)P_2 \\ & \times A_d(\varphi)e(t - \tau(t)) - 2e^T(t)P_2D(\varphi)\omega(t) + 2x_c^T(t) \\ & \times P_3B_c(\varphi)Cx(t) + 2x_c^T(t)P_3A_c(\varphi)x_c(t) - 2e_f^T(t) \\ & \times F(\varphi)C[A(\varphi) + L(\varphi)C + 1]e(t) - 2e_f^T(t)F(\varphi)C \\ & \times B_a(\varphi)e_f(t) - 2e_f^T(t)F(\varphi)CA_d(\varphi)e(t - \tau(t)) \\ & + 2e_f^T(t)F(\varphi)CD(\varphi)\omega(t) - e_f^T(t)P_3\dot{f}(t). \end{aligned} \quad (28)$$

From equation (22) the above equation becomes,

$$\begin{aligned} \dot{V}_1(t) = & 2x^T(t)P_1A(\varphi)x(t) + 2x^T(t)P_1B(\varphi)(K(\varphi) + \delta K(t)) \\ & \times x_c(t) - 2x^T(t)P_1B_a(\varphi)e_f(t) - 2x^T(t)P_1A_d(\varphi) \\ & \times x(t - \tau(t)) + 2x^T(t)P_1D\omega(t) + 2e^T(t)P_2[A(\varphi) \\ & + L(\varphi)C]e(t) + 2e^T(t)P_2A_d(\varphi)e(t - \tau(t)) - 2e^T(t) \\ & \times P_2D(\varphi)\omega(t) + 2x_c^T(t)P_3B_c(\varphi)Cx(t) + 2x_c^T(t)P_3 \\ & \times A_c(\varphi)x_c(t) - 2e_f^T(t)B_a^T(\varphi)P_2[A(\varphi) + L(\varphi)C]e(t) \\ & - 2e_f^T(t)B_a^T(\varphi)P_2B_a(\varphi)e_f(t) - 2e_f^T(t)B_a^T(\varphi)P_2 \\ & \times A_d(\varphi)e(t - \tau(t)) + 2e_f^T(t)B_a^T(\varphi)P_2D(\varphi)\omega(t) \\ & - e_f^T(t)P_3\dot{f}(t). \end{aligned} \quad (29)$$

For any positive definite matrix M and based on Assumption 1, we can rewrite the last term of the above equation as follows

$$\begin{aligned} -2e_f^T(t)P_3\dot{f}(t) & \leq e_f^T(t)Me_f(t) + \dot{f}^T(t)P_4M_1^{-1}P_4\dot{f}(t) \\ & \leq e_f^T(t)Me_f(t) + f_{max}^2\lambda_M, \end{aligned} \quad (30)$$

where λ_M denotes maximum eigen value of $P_4M_1^{-1}P_4$. From the equations (23)-(30) we have,

$$\begin{aligned} \dot{V}(t) + \gamma\theta^{-1}y^T(t)y(t) - 2(1 - \theta)y^T(t)\omega(t) - \\ \gamma\omega^T(t)\omega(t) & \leq \Theta^T(t)[\Phi]_{17 \times 17}\Theta(t) + f_{max}^2\lambda_M \\ & \leq \Theta^T(t)[\Phi]_{17 \times 17}\Theta(t) + \Lambda, \end{aligned} \quad (31)$$

where $\Theta(t) = [\eta^T(t) \quad \omega^T(t) \quad \eta^T(t - \tau(t)) \quad \eta^T(t - \tau_1) \quad \eta^T(t - \tau_2)]^T$, $\Phi_{i,j} = \Phi_{j,i}$, $\forall i, j \in \{1, 2, \dots, 17\}$, $\Phi_{1,1} =$

$A^T(\varphi)P_1 + P_1A(\varphi) + Q_{11} + Q_{21} + Q_{31} + \gamma\theta^{-1}C^TC$, $\Phi_{1,3} = C^TB_c^T(\varphi)P_3 + P_1B(\varphi)[K(\varphi) + \delta K(t)]$, $\Phi_{1,4} = -P_1B_a(\varphi)$, $\Phi_{1,5} = P_1D(\varphi) - (1 - \theta)C^T$, $\Phi_{1,6} = P_1A_d(\varphi)$, $\Phi_{2,2} = A^T(\varphi)P_2 + P_2A(\varphi) + C^TL^T(\varphi)P_2 + P_2L(\varphi)C + Q_{12} + Q_{22} + Q_{32}$, $\Phi_{2,4} = -A(\varphi)P_2B_a(\varphi) - C^TL^T(\varphi)P_2B_a(\varphi)$, $\Phi_{2,5} = -P_2D(\varphi)$, $\Phi_{2,6} = P_2A_d(\varphi)$, $\Phi_{3,3} = A_c^T(\varphi)P_3 + P_3A_c(\varphi) + Q_{13} + Q_{23} + Q_{33}$, $\Phi_{4,4} = -2B_a^T(\varphi)P_2B_a(\varphi) + Q_{14} + Q_{24} + Q_{34} + M$, $\Phi_{4,5} = B_a^T(\varphi)P_2D(\varphi)$, $\Phi_{4,6} = -B_a^T(\varphi)P_2A_d(\varphi)$, $\Phi_{5,5} = -\gamma I$, $\Phi_{6,6} = -(1 - \mu)Q_{11}$, $\Phi_{7,7} = -(1 - \mu)Q_{12}$, $\Phi_{8,8} = -(1 - \mu)Q_{13}$, $\Phi_{9,9} = -(1 - \mu)Q_{14}$, $\Phi_{10,10} = -Q_{21}$, $\Phi_{11,11} = -Q_{22}$, $\Phi_{12,12} = -Q_{23}$, $\Phi_{13,13} = -Q_{24}$, $\Phi_{14,14} = -Q_{31}$, $\Phi_{15,15} = -Q_{32}$, $\Phi_{16,16} = -Q_{33}$, $\Phi_{17,17} = -Q_{34}$, $\Lambda = f_{max}^2\lambda_MP_4$ and remaining terms are zeros. By applying schur complement for the term C^TC , we can obtain the LMI which is given in (21), then we have $[\Phi]_{17 \times 17} \leq 0$ i.e. the eigen values of $[\Phi]_{17 \times 17}$ are negative, let the maximum among them is $-\Omega$ then

$$\begin{aligned} \dot{V}(t) + \gamma\theta^{-1}y^T(t)y(t) - 2(1 - \theta)y^T(t)\omega(t) - \gamma\omega^T(t)\omega(t) \\ \leq -\Omega\|\Theta(t)\|^2 + \Lambda. \end{aligned}$$

From the above equation, it is clear that that $\dot{V}(t) + \gamma\theta^{-1}y^T(t)y(t) - 2(1 - \theta)y^T(t)\omega(t) - \gamma\omega^T(t)\omega(t) \leq 0$ if and only if $\Lambda \leq \Omega\|\Theta(t)\|^2$ which implies that the error states of the fault are uniformly bounded. Under the zero initial conditions, we have $V(0) = 0$ and $V(\infty) > 0$ which implies that $\gamma\theta^{-1}y^T(t)y(t) - 2(1 - \theta)y^T(t)\omega(t) - \gamma\omega^T(t)\omega(t) \leq 0$, then from the **2.3. Definition** the above said inequality achieves mixed H_∞ and passivity performance. By taking the noise term as zero we can show the asymptotic stability of the given system by using Lyapunov's stability theorem.

3.2. Remark We cannot solve and find the unknown of the equation (22) by using LMI toolbox in Matlab. So we have to transform this equality into following LMI as the transformation of optimization problem

$$\begin{pmatrix} \rho I_n & B_a(\varphi)^T X_2 - F(\varphi)C \\ * & \rho I_n \end{pmatrix} > 0.$$

3.3. Theorem Let the Assumptions 1-3 hold. For given positive scalars γ , ρ , θ the system (5) is robust asymptotically stable with mixed H_∞ and passivity performance if there exist matrices W_1 , W_2 , W_3 , W_4 , positive definite matrices X_1 , X_2 , X_3 , P_4 , Q_{11} , $\hat{Q}_{11}$, Q_{12} , $\hat{Q}_{13}$, Q_{14} , $\hat{Q}_{21}$, Q_{22} , $\hat{Q}_{23}$, Q_{24} , $\hat{Q}_{31}$, Q_{32} , $\hat{Q}_{33}$, Q_{34} , M and positive

scalar ϵ such that the following LMIs are feasible,

$$[\phi_{i,j}^{pp}] < 0, \quad p = q \quad (32)$$

$$[\phi_{i,j}^{pq}] + [\phi_{i,j}^{qp}] < 0, \quad p < q \quad (33)$$

$$\begin{pmatrix} \rho I_n & B_{a_p}^T X_2 - F(\varphi)C \\ * & \rho I_n \end{pmatrix} > 0, \quad (34)$$

where $i, j \in \{1, 2, \dots, 20\}$, $\phi_{i,j}^{pq} = \phi_{j,i}^{qp}$, $\forall p, q \in \{1, 2, \dots, l\}$, $\phi_{1,1}^{pq} = X_1 A_p^T + A_p X_1 + \hat{Q}_{11} + \hat{Q}_{21} + \hat{Q}_{31}$, $\phi_{1,3}^{pq} = C^T W_{1q}^T + B_p W_{1q}$, $\phi_{1,4}^{pq} = -B_{a_p}$, $\phi_{1,5}^{pq} = D_p$, $\phi_{1,6}^{pq} = A_{d_p}$, $\phi_{1,18}^{pq} = X_1 C^T$, $\phi_{1,19}^{pq} = \epsilon B_p M_K$, $\phi_{2,2}^{pq} = A_p^T X_2 + X_2 A_p + C^T W_{2p}^T + W_{2p} C + Q_{12} + Q_{22} + Q_{32}$, $\phi_{2,4}^{pq} = -A_p X_2 B_{a_p} - C^T W_{2p}^T B_{a_p}$, $\phi_{2,5}^{pq} = -X_2 D_p$, $\phi_{2,6}^{pq} = X_2 A_{d_p}$, $\phi_{3,3}^{pq} = W_{3p}^T + W_{3p} + \hat{Q}_{13} + \hat{Q}_{23} + \hat{Q}_{33}$, $\phi_{3,20}^{pq} = X_3 N_K^T$, $\phi_{4,4}^{pq} = -2B_{a_p}^T X_2 B_{a_p} + Q_{14} + Q_{24} + Q_{34} + M$, $\phi_{4,5}^{pq} = B_{a_p}^T X_2 D_p$, $\phi_{4,6}^{pq} = -B_{a_p}^T X_2 A_{d_p}$, $\phi_{5,5}^{pq} = -\gamma I$, $\phi_{6,6}^{pq} = -(1 - \mu)\hat{Q}_{11}$, $\phi_{7,7}^{pq} = -(1 - \mu)Q_{12}$, $\phi_{8,8}^{pq} = -(1 - \mu)\hat{Q}_{13}$, $\phi_{9,9}^{pq} = -(1 - \mu)Q_{14}$, $\phi_{10,10}^{pq} = -\hat{Q}_{21}$, $\phi_{11,11}^{pq} = -Q_{22}$, $\phi_{12,12}^{pq} = -\hat{Q}_{23}$, $\phi_{13,13}^{pq} = -Q_{24}$, $\phi_{14,14}^{pq} = -\hat{Q}_{31}$, $\phi_{15,15}^{pq} = -Q_{32}$, $\phi_{16,16}^{pq} = -\hat{Q}_{33}$, $\phi_{17,17}^{pq} = -Q_{34}$, $\phi_{18,18}^{pq} = -I$, $\phi_{19,19}^{pq} = -\epsilon I$, $\phi_{20,20}^{pq} = -\epsilon I$ and remaining terms are zero. Further $K_q = W_{1q} X_3^{-1}$, $L_p = X_2^{-1} W_{2p}$, $A_{ci} = W_{3p} X_3^{-1}$ and $B_{c_p} = W_{4p} \mathcal{U} S X_{11}^{-1} S^{-1} \mathcal{U}^{-1}$. Furthermore, the error states of the fault are uniformly bounded.

Proof:

Inspect and replace the following forms into (21):

$$\begin{aligned} A(\varphi) &= \sum_{p=1}^l \varphi_p(g(t)) A_p, \quad A_d(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) A_{d_p}, \\ B(\varphi) &= \sum_{p=1}^l \varphi_p(g(t)) B_p, \quad B_a(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) B_{a_p}, \\ D(\varphi) &= \sum_{p=1}^l \varphi_p(g(t)) D_p, \quad C = \sum_{p=1}^l \varphi_p(g(t)) C, \quad A_c(\varphi) = \sum_{p=1}^l \varphi_p(g(t)) A_{c_p}, \\ B_c(\varphi) &= \sum_{p=1}^l \varphi_p(g(t)) B_{c_p}, \quad K(\varphi) = \sum_{q=1}^l \varphi_q(g(t)) K_q, \quad K_q = K_q + \delta K(t). \end{aligned}$$

Then (21) can be wrutten as,

$$[\Xi_{i,j}] = \sum_{p=1}^l \sum_{q=1}^l \varphi_p(g(t)) \varphi_q(g(t)) \mathcal{Z}^{pq}, \quad (35)$$

where $\mathcal{Z}^{pq} = [\mathcal{Z}_{i,j}^{pq}]$, $\mathcal{Z}_{i,j}^{pq} = \mathcal{Z}_{j,i}^{qp}$, $\forall i, j \in \{1, 2, \dots, 18\}$, $\mathcal{Z}_{1,1}^{pq} = A_p^T P_1 + P_1 A_p + Q_{11} + Q_{21} + Q_{31}$, $\mathcal{Z}_{1,3}^{pq} = C^T B_{c_p}^T P_3 + P_1 B_p (K_q + \delta K(t))$, $\mathcal{Z}_{1,4}^{pq} = -P_1 B_{a_p}$, $\mathcal{Z}_{1,5}^{pq} =$

$$\begin{aligned} P_1 D_p - (1 - \theta) C^T, \mathcal{Z}_{1,6}^{pq} &= P_1 A_{d_p}, \mathcal{Z}_{1,18}^{pq} = \theta C^T, \mathcal{Z}_{2,2}^{pq} = A_p^T P_2 + P_2 A_p + C^T L_p^T P_2 + P_2 L_p C + Q_{12} + Q_{22} + Q_{32}, \\ \mathcal{Z}_{2,4}^{pq} &= -A_p P_2 B_{a_p} - C^T L_p^T P_2 B_{a_p}, \mathcal{Z}_{2,5}^{pq} = -P_2 D_p, \\ \mathcal{Z}_{2,6}^{pq} &= P_2 A_{d_p}, \mathcal{Z}_{3,3}^{pq} = A_{c_p}^T P_3 + P_3 A_{c_p} + Q_{13} + Q_{23} + Q_{33}, \\ \mathcal{Z}_{4,4}^{pq} &= -2B_{a_p}^T P_2 B_{a_p} + Q_{14} + Q_{24} + Q_{34} + M, \\ \mathcal{Z}_{4,5}^{pq} &= B_{a_p}^T P_2 D_p, \mathcal{Z}_{4,6}^{pq} = -B_{a_p}^T P_2 A_{d_p}, \mathcal{Z}_{5,5}^{pq} = -\gamma I, \\ \mathcal{Z}_{6,6}^{pq} &= -(1 - \mu) Q_{11}, \mathcal{Z}_{7,7}^{pq} = -(1 - \mu) Q_{12}, \\ \mathcal{Z}_{8,8}^{pq} &= -(1 - \mu) Q_{13}, \mathcal{Z}_{9,9}^{pq} = -(1 - \mu) Q_{14}, \\ \mathcal{Z}_{10,10}^{pq} &= -Q_{21}, \mathcal{Z}_{11,11}^{pq} = -Q_{22}, \mathcal{Z}_{12,12}^{pq} = -Q_{23}, \\ \mathcal{Z}_{13,13}^{pq} &= -Q_{24}, \mathcal{Z}_{14,14}^{pq} = -Q_{31}, \mathcal{Z}_{15,15}^{pq} = -Q_{32}, \\ \mathcal{Z}_{16,16}^{pq} &= -Q_{33}, \mathcal{Z}_{17,17}^{pq} = -Q_{34}, \mathcal{Z}_{18,18}^{pq} = -\gamma \theta \end{aligned}$$

and the remaining terms are zeros. Define $\delta K(t) = M_K \mathcal{F}(t) N_K$, $X_1 = P_1^{-1}$, $X_2 = P_2$, $X_3 = P_3^{-1}$, $\hat{Q}_{11} = X_1 Q_{11} X_1$, $\hat{Q}_{21} = X_1 Q_{21} X_1$, $\hat{Q}_{31} = X_1 Q_{31} X_1$, $\hat{Q}_{13} = X_3 Q_{13} X_3$, $\hat{Q}_{23} = X_3 Q_{23} X_3$, $\hat{Q}_{33} = X_3 Q_{33} X_3$, $W_{1q} = X_1 K_q$, $W_{2p} = X_2 L_p$, $W_{3p} = X_3 A_{c_p}$ and according to the Lemma 2 in [4], for $X_3 = \mathcal{V} X \mathcal{V}^T$ there exists $\bar{X}_3 = \mathcal{U} S X_{11} S^{-1} \mathcal{U}^{-1}$ such that $C X_3 = \bar{X}_3 C$ where $X = \text{diag}\{X_{11}, X_{22}, \dots, X_{nn}\}$, $\bar{X}_3^{-1} = \mathcal{U} S X_{11}^{-1} S^{-1} \mathcal{U}^{-1}$ and $W_{4p} = X_3 B_{c_p}$. Make the pre and post multiplication for (35) with $\mathcal{M} = \text{diag}\{X_1, I, X_3, I, I, X_1, I, X_3, I, X_1, I, X_3, I, X_1, I, X_3, I, I\}$ and by applying the 2.2. Lemma for the terms involving $\delta K(t)$ then it is easy to obtain the LMI terms in (33). By the 3.2. Remark, we can rewrite the equality (22) as in (34). Then the proof is obvious from the first theorem.

4. Simulation Verifications

In this section, a numerical example is presented to show the effectiveness of the proposed nonfragile fault-tolerance control.

Example : Let us consider the T-S fuzzy system (2) with two fuzzy rules and the system parameters as follows:

$$\begin{aligned} A_1 &= \begin{bmatrix} -10 & 10 & -1 \\ -0.8 & -1 & 0.1 \\ 0.2 & 0 & -8/3 \end{bmatrix}, \quad A_2 = \begin{bmatrix} -7 & 10 & -1 \\ -0.8 & -1 & 0.1 \\ 0.1 & 0 & -8/3 \end{bmatrix}, \\ B_1 &= \begin{bmatrix} 0.66 \\ 0.9 \\ 1 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0.69 \\ 0.9 \\ 1 \end{bmatrix}, \\ A_{d_1} &= 0.01 A_1, \quad A_{d_2} = 0.01 A_2, \quad C = [0 \ 1 \ 0], \\ D_1 &= \begin{bmatrix} 0 \\ 0.1 \\ 0.1 \end{bmatrix}, \quad D_2 = \begin{bmatrix} 0 \\ 0.1 \\ 0 \end{bmatrix}, \quad M_K = [0.1 \ 0.01 \ 0.2], \end{aligned}$$

$$N_K = 0.05I_3.$$

The corresponding membership functions are selected as $\varphi_1(g(t)) = \frac{1}{1+e^{x_1-0.5}}$ and $\varphi_2(g(t)) = 1 - \varphi_1(g(t))$. The other vectors participated in the numerical simulation are taken as, $\tau_1 = 0$, $\tau_2 = 0.4$, $\mu = 0.1$, $\rho = 0.18$, $\gamma = 0.09$, $\theta = 0.8$, $\mathcal{F}(t) = \sin t I_3$, $\tau(t) = 0.3 + 0.1 \sin t$, $\omega = 0.5 \sin 7t$ and $P_4 = 0.015$.

For the purpose of stabilization of the perturbed T-S fuzzy system (2), we design the time varying fault-tolerant nonfragile controller as constructed in (17) with the above given parameters. Then, by solving the LMIs obtained in 3.3. **Theorem**, the following controller and observer gain matrices are obtained as

$$K_1 = [0.0242 \quad -0.0406 \quad 0.7476], L_1 = \begin{bmatrix} -11.5193 \\ -9.3788 \\ -11.7501 \end{bmatrix},$$

$$A_{c_1} = \begin{bmatrix} -1.9751 & -0.0973 & -0.0459 \\ 0.0962 & -1.9753 & 0.1469 \\ 0.0539 & -0.1491 & -2.0318 \end{bmatrix}, B_{c_1} = \begin{bmatrix} -0.0220 \\ 0.0369 \\ -0.6802 \end{bmatrix},$$

$$K_2 = [-0.2780 \quad 0.2834 \quad -2.8035], L_2 = \begin{bmatrix} -7.2572 \\ -8.8008 \\ -8.6846 \end{bmatrix},$$

$$A_{c_2} = \begin{bmatrix} -1.9980 & -0.1435 & -0.0611 \\ 0.1888 & -1.9988 & 0.8379 \\ -0.3882 & -0.3808 & -4.2251 \end{bmatrix}, B_{c_2} = \begin{bmatrix} 0.2482 \\ -0.2530 \\ 2.5029 \end{bmatrix}$$

$$F_1 = F_2 = [2.9400].$$

Fig. 1: State response for closed-loop system

For the fault $f(t) = 1.5(0.4 \cos(5t) + 0.3 \sin(20t))$

Fig. 2: State response for open-loop system

Fig. 3: Estimation of estimated fault with actual fault

with the initial condition $[x_1(0) \ x_2(0) \ x_3(0)]^T = [-1 \ 0.8 \ 0.3]^T$ and the obtained gain values, the state response of the closed-loop and open-loop system are displayed in the Fig. 1 and Fig. 2 respectively. In particular, from Fig. 1 it is obvious that the system attains stability with in 2-5 seconds even in the presence of time-varying actuator fault. It is noticed from the Fig. 3 the estimated fault tracks the original fault with maximum estimation error 0.8650, which shows the effectiveness of prescribed fault-tolerance controller. The membership function is illustrated in Fig. 4. The output response with and without fault is displayed in Fig. 5.

Suppose, the fault is taken as $f(t) = \sin 10(t+1) - 3e^{-10*(t+2)^2+1}$, then from the Fig. 6 the estimation of fault with its estimated fault also have more accuracy. By observing the simulation studies, it is obvious that

Fig. 4: Membership function

Fig. 6: Estimation of estimated fault with actual fault

Fig. 5: Output response for with fault and without fault

the dynamic-output-feedback controller can promptly reclaim performance and stability of the considered closed-loop even in the existence of disturbance and time-varying fault with precious estimation of the actuator faults.

5. Conclusion

In this paper, the problem of resilient reliable dynamic-output-feedback H_∞ control for the class of T-S fuzzy model with time varying fault and delay is investigated. Especially, the time-varying fault is dealt by using adaptive fault algorithm. In conjunction of L-K functional technique, S-procedure and Schur's lemma, a set of necessary and sufficient conditions has been obtained for asymptomatic stability of T-S fuzzy delayed system in the presence of time-varying actuator fault. Finally a numerical example is given to demonstrate the

effectiveness of the proposed controller.

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