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Adaptive Observer and Fault Tolerant Control for Takagi-Sugeno Descriptor Nonlinear Systems with Sensor and Actuator Faults

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Abstract: This paper concerns the problem of state, fault estimation (FE) and Fault Tolerant Control (FTC) of Takagi-Sugeno (T-S) descriptor systems affected by sensor, actuator and external disturbances simultaneously. An Adaptive Fuzzy Observer is firstly proposed to achieve a simultaneous estimation of descriptor system states, actuator and sensor faults by using the H_∞ optimization technique. A FTC is secondly proposed to stabilize the faulty descriptor system. Based on Lyapunov method, stability analysis and design conditions of the resulting closed-loop system are formulated in a set of Linear Matrices Inequalities (LMIs). The adaptive fuzzy observer and the FTC are independently designed, in order to avoid the coupling problem. Accordingly, the observer and controller gains are computed separately by solving a set of LMIs and then used to estimate the unmeasured states, sensor and actuator faults at the same time. Finally, a truck-trailer system application is given to illustrate the validity of the proposed approach.

Keywords: Adaptive fuzzy observer, T-S descriptor systems, Actuator/sensor faults estimation, FTC, LMI, Lyapunov functional.

1. INTRODUCTION

An important number of industrial applications such as electrical power lines and manufacturing processes can have an undesirable behavior because of sensor, actuator and/or process faults or even external disturbances. Generally speaking, to overcome component malfunctions and to maintain a certain level of safety, reliability and performance efficiency of a dynamic system, techniques and tools of fault detection and isolation (FDI), fault estimation (FE) and fault tolerant control (FTC) have been established (see [1–7]).

FDI strategy is used to monitor whether a fault occurs and in which component it is occurred. However, it is generally difficult in practical systems to have the exact information of the size of faults from a FDI strategy only. Accordingly, considerable attention has been devoted to FE; it provides further accurate information of the fault, such as shape, size and duration (see [8–10] and references therein).

Furthermore, FE plays an important role in FTC, which is developed to preserve overall system stability as well as acceptable performance. It possesses the ability to accommodate component failures automatically. By using the obtained fault information, an additional controller can be designed to compensate the faults. More precisely, FTC guarantees the stability of a closed-loop system even in the presence of component malfunctions. Besides maintaining stability properties, it could also keep desirable performances.

FTC approach has been firstly adapted for linear systems (see [1, 11] and references therein). However, most realistic engineering systems have nonlinear behaviors. It is well known that T-S fuzzy representation is a good way to approximate a large class of nonlinear dynamic systems [12]. T-S fuzzy models are nonlinear systems represented by a set of local linear models. By fuzzy blending of the linear system representations the overall fuzzy model of the system is achieved, which greatly facilitates observer/controller synthesis for complex nonlinear systems. One of the primary advantage is that it offers an effective and simple design strategy to represent a nonlinear system. In the literature, many important results have been reported in [13–15] and [16].

Consequently, many researchers have interested to FTC approach for T-S fuzzy systems (see [17–19]). In [20] for example, authors have extended the adaptive observer proposed in [21] to FTC of T-S fuzzy models.

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The problem of state/fault estimation for T-S fuzzy systems affected by sensor and actuator faults under external disturbances, has been investigated in [8]. In this latter, a fuzzy reduced-order observer has been designed which can estimate system states, sensor and actuator faults simultaneously. Then a FTC has been developed for standard T-S fuzzy systems.

Recently, T-S fuzzy model has been extended to deal with descriptor nonlinear systems, many scholars have been interested to T-S descriptor systems as well as FE and FTC (see for instance [22–26]). It is well known that descriptor systems resulting from natural modeling approaches, can represent a wide class of practical systems including electrical circuits, robotic systems, aircraft systems and chemical process (see for example [27–30] and references therein). It should be pointed that the stability and stabilization problems for descriptor systems are much more difficult than for regular ones because it affects the regularity and impulse-free problems [15, 31, 32].

Reference [23] is an existing work for both state and actuator faults reconstruction in which a FTC has been designed to stabilize the closed-loop T-S descriptor system in presence of actuator faults. The work in [3] deals with the problem of simultaneous sensor and actuator fault estimation for descriptor linear parameter varying systems. However the FTC approach and the stabilization analysis have not been discussed.

There are, so far as the authors know, no works dealing with adaptive observer-based FTC for T-S descriptor systems considering simultaneously actuator, sensor faults and external disturbances. Motivated by the above observations, an adaptive observer allowing to estimate both states and sensor/actuator faults is developed. Then an observer-based FTC is introduced to preserve the stability of the closed-loop faulty system. Using the H_∞ optimization technique, we show that the adaptive observer and the controller could be independently designed and their gains computed separately by solving a set of LMIs using LMI Toolbox or Yalmip of MATLAB software [33, 34].

The reminder of this paper is structured as follows: In the second section an overview of the T-S fuzzy descriptor systems is given and some preliminaries are provided. Section 3 includes the main results. An adaptive fuzzy observer is proposed to estimate system states, actuator and sensor faults simultaneously. Sufficient conditions are expressed in the form of LMI for the observer-based FTC. A simulation example is given in Section 4 to illustrate the validity of the proposed approach. Finally, Section 5 concludes this contribution.

Notations: The following notations are considered. $A \in \mathbb{R}^n$ indicates the n-dimensional Euclidean space, whereas $A \in \mathbb{R}^{n\times p}$ denotes the set of all $n \times p$ real matrices. A real symmetric positive definite matrix (respectively, negative definite matrix) is represented by $A > 0$ (respectively, $A < 0$). Notation $(*)$ signifies the transposed element in the symmetric position of a matrix and $sym(A)$ signifies $A + A^T$. $\lambda_{max}(A)$ and $\lambda_{min}(A)$ represent the maximum and minimum eigenvalues of A, respectively. $A^\dagger$ stands for the generalized inverse of A and $\forall$ denotes "for all".

2. PROBLEM FORMULATION

Consider a T-S fuzzy descriptor system composed of a set of If-Then rules. The i^{th} rule of the system is given as follows:

Plant Rule $i (i = 1, 2, .., r)$: If θ_1 is μ_{i1} and, $\cdots$, and θ_p is μ_{ip} , Then

$$\begin{cases} E\dot{x}(t) = A_i x(t) + B_i(u(t) + f_a(t)) + D_i d(t), \\ y(t) = Cx(t) + F f_s(t), \\ z(t) = C_{L_i} x(t). \end{cases} \tag{1}$$

where $\theta_j(x(t))$ are the premise variables which are supposed to be measurable, $\mu_{ij} (i = 1, \cdots, r, j = 1, \cdots, p)$ are the fuzzy sets which are characterized by the membership functions, r and p are the total number of If-Then rules and the premise variables, respectively. $x(t) \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}^m$ is the control input, $y(t) \in \mathbb{R}^p$ is the measured output, $d(t) \in \mathbb{R}^v$ is the external disturbance, $f_a(t) \in \mathbb{R}^m$ and $f_s(t) \in \mathbb{R}^w$ represent actuator and sensor fault, respectively. They can be constant or time-varying function. $z(t) \in \mathbb{R}^{p_1}$ is the controlled output. Matrix $E \in \mathbb{R}^{n\times n}$ is assumed to be singular and we suppose that $rank(E) = q \le n$. A_i, B_i, D_i, C, F and C_{L_i} are known real constant matrices of appropriate dimensions. We assume that $p \ge m + w$, (A_i, B_i) are controllable, $rank(B_i) = m$, $rank(F) = w$, $rank([C, F]) = p$.

By fuzzy blending, the overall fuzzy system is given as follows:

$$\begin{aligned} E\dot{x}(t) = \sum_{i=1}^{r} & h_i(\theta(x(t))) \\ & \times [A_i x(t) + B_i(u(t) + f_a(t)) + D_i d(t)], \end{aligned} \tag{2}$$

$$y(t) = Cx(t) + F f_s(t), \tag{3}$$

$$z(t) = \sum_{i=1}^{r} h_i(\theta(x(t)))[C_{L_i} x(t)], \tag{4}$$

in which

$$\begin{aligned} \theta(x(t)) &= [\theta_1(x(t)), ..., \theta_p(x(t))], \\ h_i(\theta(x(t))) &= \frac{\nu_i(\theta(x(t)))}{\sum_{i=1}^{r} \nu_i(\theta(x(t)))}, \nu_i(\theta(x(t))) \\ &= \prod_{j=1}^{p} \mu_{ij}(\theta_i(x(t))), \end{aligned}$$

where $\mu_{ij}(\theta_i(x(t))$ is the membership degree of $\theta_i(x(t))$ in μ_{ij}. It is evident that $0 \le h_i(\theta(x(t))) \le 1$ and $\sum_{i=1}^{r} h_i(\theta(x(t))) = 1$.

In the following, for briefness we get h_i to stand for $h_i(\theta(x(t)))$.

Before giving the main results, the following three assumptions and two lemmas are needed.

Assumption 1 [35]**:** System (E, A_i, C) is observable,

$$rank \begin{bmatrix} E \\ C \end{bmatrix} = n, \tag{5}$$

and

$$rank \begin{bmatrix} sE - A_i \\ C \end{bmatrix} = n, \forall s \in \mathbb{C}, Re(s) \geq 0, \forall i = [1, \cdots, r]. \tag{6}$$

Assumption 2 [36, 37] **:**

$$rank \begin{bmatrix} \bar{E} \\ \bar{C} \end{bmatrix} = rank \begin{bmatrix} E & 0 \\ C & F \end{bmatrix} = n + w. \tag{7}$$

Assumption 3 [20]**:** Actuator fault $f_a(t)$ and sensor fault $f_s(t)$ satisfy $\|f_a(t)\| \leq \alpha_a$ and $\|f_s(t)\| \leq \alpha_s$, respectively. The derivative of $f_a(t)$ and $f_s(t)$ with respect to time are norm bounded i.e. $\|\dot{f}_a(t)\| \leq f_{a_{max}}$ and $0 \leq \alpha_a$, $f_{a_{max}} < \infty$ and $\|\dot{f}_s(t)\| \leq f_{s_{max}}$ and $0 \leq \alpha_s$, $f_{s_{max}} < \infty$.

Lemma 1 [38]**:** For a symmetric positive definite matrix R and a scalar $\mu \in \mathbb{R}^+$ we have the following inequality

$$2u^{\mathsf{T}}v \leq \frac{1}{\mu}u^{\mathsf{T}}Ru + \mu v^{\mathsf{T}}R^{-1}v\ ,\ u, v \in \mathbb{R}^n. \tag{8}$$

Lemma 2 [15, 20]**:** Given a negative definite matrix $\Upsilon < 0$. Consider a matrix Y of appropriate dimension such that $Y^T \Upsilon Y < 0$, then $\exists\, \lambda > 0$ such that

$$Y^T \Upsilon Y \leq -\lambda(Y + Y^T) - \lambda^2 \Upsilon^{-1}. \tag{9}$$

Remark 1: Assumption 2 implies that there exists a full-row rank matrix

$$\begin{bmatrix} T & H \end{bmatrix} = \begin{bmatrix} \bar{E} \\ \bar{C} \end{bmatrix}^{\dagger} \tag{10}$$

such that

$$\begin{bmatrix} T & H \end{bmatrix} \begin{bmatrix} \bar{E} \\ \bar{C} \end{bmatrix} = I_{n+w}. \tag{11}$$

It also guarantees the impulse observability of the triple matrix $(\bar{E}, \bar{A}_i, \bar{C}), \forall i \in [1, \cdots, r]$. It should be noted that the designed observer (13) require necessary conditions introduced in Assumptions 1 and 2. Similar assumptions can be also found in [35] and [29] and the references therein.

3. MAIN RESULTS

3.1. Augmented system

Using the descriptor approach and by taking sensor fault f_s as an auxiliary state, an augmented system can be constructed. The faulty system given by (2- 4) can be rewritten as follows:

$$\begin{cases} \bar{E}\dot{\bar{x}}(t) = \sum_{i=1}^{r} h_i[\bar{A}_i\bar{x}(t) + B_i(u(t) + f_a(t)) + D_i d(t)], \\ y(t) = \bar{C}\bar{x}(t), \\ z(t) = \sum_{i=1}^{r} h_i[C_{L_i}x(t)]. \end{cases} \tag{12}$$

where

$$\bar{x}(t) = \begin{bmatrix} x(t) \\ f_s(t) \end{bmatrix},\ \bar{E} = \begin{bmatrix} E & 0_{n\times w} \end{bmatrix},\ \bar{A}_i = \begin{bmatrix} A_i & 0_{n\times w} \end{bmatrix},$$
$$\bar{C} = \begin{bmatrix} C & F \end{bmatrix}.$$

3.2. Design of adaptive fuzzy observer

In this part, an adaptive fuzzy observer is proposed to a simultaneous estimation of descriptor system states, actuator and sensor faults for system (12).

$$\begin{cases} \dot{w}(t) = \sum_{i=1}^{r} h_i[T\bar{A}_i\hat{\bar{x}}(t) + TB_i(u(t) + \hat{f}_a(t)) \\ \qquad + L_i(y(t) - \hat{y}(t))], \\ \hat{\bar{x}}(t) = w(t) + Hy(t), \\ e_y(t) = y(t) - \hat{y}(t), \\ \hat{y}(t) = \bar{C}\hat{\bar{x}}(t), \\ \dot{\hat{f}}_a(t) = \Gamma \sum_{i=1}^{r} h_i N_i(\dot{e}_y(t) + \sigma e_y(t)), \end{cases} \tag{13}$$

where $w(t) \in \mathbb{R}^{n+w}$ and $\hat{\bar{x}}(t) \in \mathbb{R}^{n+w}$ are the observer state and the estimation of state vector, respectively. $\hat{y}(t) \in \mathbb{R}^p$ is the estimation of the output vector. $e_y(t) \in \mathbb{R}^p$ is the output estimation error and $\hat{f}_a(t) \in \mathbb{R}^m$ is the estimated of the actuator fault $f_a(t)$, and T, H, L_i and N_i are gain matrices with appropriate dimensions to be solved. $\sigma \in \mathbb{R}$ is a positive scalar. $\Gamma \in \mathbb{R}^{m\times m}$ is the learning rate which is chosen to be symmetric, positive definite matrix and set to balance the convergence speeds of the states and actuator fault. Under assumption 2, there exist nonsingular matrices $T \in \mathbf{R}^{n+w\times n}$ and $H \in \mathbf{R}^{n+w\times p}$ such that

$$T\bar{E} + H\bar{C} = I_{n+w}. \tag{14}$$

State and fault estimation errors are given as follows:

$$e_x(t) = \bar{x}(t) - \hat{\bar{x}}(t),\ \ e_f(t) = f_a(t) - \hat{f}_a(t).$$

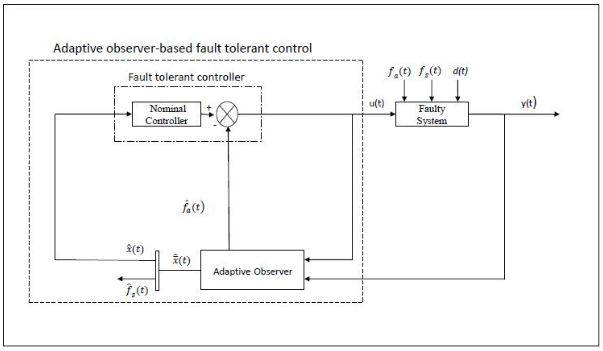

Fig. 1. Adaptive fuzzy observer-based fault tolerant control scheme.

By taking into account (12), (13) and by using relation (14), estimation error dynamics $e_x(t)$ and output estimation error $e_y(t)$ are given by:

$$\begin{aligned} \dot{e}_x(t) = \sum_{i=1}^{r} h_i [(T\bar{A}_i - L_i\bar{C})e_x(t) + TB_ie_f(t) \\ + TD_id(t)], \end{aligned} \tag{15}$$

$$e_y(t) = \bar{C}e_x(t). \tag{16}$$

Matrices T and H can be found simultaneously from (10).

In contrast to the constant fault giving in [21] and [38]. In this work, time-varying faults are considered (i.e. $\dot{f}(t) \neq 0$). Consequently, the dynamic of fault estimation error is given by the following expression:

$$\dot{e}_f(t) = \dot{f}_a(t) - \dot{\hat{f}}_a(t), \tag{17}$$

Then

$$\dot{e}_f(t) = \dot{f}_a(t) - \Gamma \sum_{i=1}^{r} h_i N_i (\dot{e}_y(t) + \sigma e_y(t)). \tag{18}$$

By taking into consideration (15) and (16), one can obtain

$$\begin{aligned} \dot{e}_f(t) =& \dot{f}_a(t) - \Gamma \sum_{i=1}^{r}\sum_{j=1}^{r} h_i h_j N_i \bar{C}\Big(\big[(T\bar{A}_j - L_j\bar{C})e_x(t) \\ & + TB_je_f(t) + TD_jd(t)\big] + \sigma e_x(t) \Big). \end{aligned} \tag{19}$$

3.3. Stability and stabilization analysis

3.3.1 Stability analysis of the adaptive fuzzy observer

Theorem 1: Consider system (12) under assumptions $1-3$. Given a real positive scalar $\gamma_1 > 0$, two scalar tuning parameters σ and $\mu > 0$, and definite positive matrices M_1, M_2 and M_3, the adaptive fuzzy observer can ensure the asymptotic stability of the error dynamics under H_∞ performance level γ_1, that is

$$\begin{aligned} &\int_0^\infty (e_x^T(s)M_1e_x(s) + e_f^T(s)M_2e_f(s))\,\mathrm{d}s \\ &\leq \gamma_1^2 \int_0^\infty d^T(s)M_3d(s)\,\mathrm{d}s, \end{aligned} \tag{20}$$

if there exist symmetric positive definite matrix P_1 and positive definite matrices N_i and M such that $\forall i \in [1,\cdots,r]$ the following conditions hold:

$$(TB_i)^T P_1 = N_i\bar{C}, \quad i = 1,2,\cdots,r, \tag{21}$$

$$\phi_{ij} + \phi_{ji} < 0, \quad i,j = 1,2,\cdots,r, i \leq j, \tag{22}$$

where

$$\phi_{ij} = \begin{bmatrix} \varphi_i^{11} & \varphi_{ij}^{12} & \varphi_i^{13} \\ * & \varphi_{ij}^{22} & \varphi_{ij}^{23} \\ * & * & -\rho_1 M_3 \end{bmatrix}, \tag{23}$$

in which

$$\begin{aligned} \varphi_i^{11} &= sym(P_1T\bar{A}_i - Y_i\bar{C}) + M_1, \\ \varphi_{ij}^{12} &= -\frac{1}{\sigma}(\bar{A}_j^T T^T P_1 TB_i - \bar{C}^T Y_j^T TB_i), \\ \varphi_i^{13} &= P_1TD_i, \\ \varphi_{ij}^{22} &= \frac{M}{\sigma\mu} - \frac{1}{\sigma} sym((TB_i)^T P_1 (TB_j)) + M_2, \\ \varphi_{ij}^{23} &= -\frac{1}{\sigma}(TB_i)^T P_1 TD_j, \end{aligned}$$

The observer gains can then be computed from $L_i = P_1^{-1}Y_i$.

Proof: Taking the following Lyapunov function:

$$V_1(t) = e_x^T(t)P_1e_x(t) + \frac{1}{\sigma}e_f^T(t)\Gamma^{-1}e_f(t).$$

The time derivative of $V_1(t)$ can be shown to be

$$\begin{aligned} \dot{V}_1(t) =& \dot{e}_x^T(t)P_1e_x(t) + e_x^T(t)P_1\dot{e}_x(t) \\ & + \frac{2}{\sigma}e_f^T(t)\Gamma^{-1}\dot{e}_f(t). \end{aligned} \tag{24}$$

Considering Lemma 1 we have

$$\begin{aligned} \frac{2}{\sigma}e_f^T(t)\Gamma^{-1}\dot{f}_a(t) \leqslant& \frac{1}{\sigma\mu}e_f^T(t)Me_f(t) \\ & + \frac{\mu}{\sigma}\dot{f}_a^T(t)\Gamma^{-1}M^{-1}\Gamma^{-1}\dot{f}_a(t), \end{aligned} \tag{25}$$

$$\frac{2}{\sigma}e_f^T(t)\Gamma^{-1}\dot{f}_a(t) \leqslant \frac{1}{\sigma\mu}e_f^T(t)Me_f(t) + \delta, \tag{26}$$

where

$$\delta = \frac{\mu}{\sigma} f_{a_{max}}^2 \lambda_{max}(\Gamma^{-1}M^{-1}\Gamma^{-1}). \tag{27}$$

By substituting (15), (19) into equation (24) and by considering (26), one can obtain

$$\dot{V}_1(t) \leq \sum_{i=1}^{r}\sum_{j=1}^{r} h_i h_j \{ e_x^T(t)[P_1(T\bar{A}_i - L_i\bar{C})$$

$$
\begin{aligned}
&+(T\bar{A}_i - L_i\bar{C})^T P_1]e_x(t) + 2e_x^T(t)P_1TB_ie_f(t)\\
&+2e_x^T(t)P_1TD_id(t) - 2e_f^T(t)N_i\bar{C}e_x(t)\\
&-\frac{2}{\sigma}e_f^T(t)N_i\bar{C}(T\bar{A}_j - L_j\bar{C})e_x(t)\\
&-\frac{1}{\sigma}e_f^T(t)sym(N_i\bar{C}TB_j)e_f(t)\\
&+\frac{1}{\sigma\mu}e_f^T(t)Me_f(t)\\
&-\frac{2}{\sigma}e_f^T(t)N_i\bar{C}TD_jd(t) + \delta\}. \qquad (28)
\end{aligned}
$$

Taking into account equation (21), one can obtain

$$
\begin{aligned}
\dot{V}_1(t) \le &\sum_{i=1}^{r}\sum_{j=1}^{r} h_ih_j\{e_x^T(t)sym(P_1(T\bar{A}_i - L_i\bar{C}))e_x(t)\\
&+2e_x^T(t)P_1TD_id(t) + \frac{1}{\sigma\mu}e_f^T(t)Me_f(t)\\
&-\frac{2}{\sigma}e_f^T(t)(TB_i)^T P_1(T\bar{A}_j - L_j\bar{C})e_x(t)\\
&-\frac{1}{\sigma}e_f^T(t)sym((TB_i)^T P_1TB_j)e_f(t)\\
&-\frac{2}{\sigma}e_f^T(t)(TB_i)^T P_1TD_jd(t) + \delta\}. \qquad (29)
\end{aligned}
$$

Let

$$
\begin{aligned}
J_1(t) = &\dot{V}_1(t) + e_x^T(t)M_1e_x(t) + e_f^T(t)M_2e_f(t)\\
&-\gamma_1^2 d^T(t)M_3d(t), \qquad (30)\\
J_1(t) \le &\sum_{i=1}^{r}\sum_{j=1}^{r} h_ih_j\{e_x^T(t)(sym(P_1(T\bar{A}_i - L_i\bar{C}))\\
&+M_1)e_x(t) + 2e_x^T(t)P_1TD_id(t)\\
&+\frac{1}{\sigma\mu}e_f^T(t)Me_f(t)\\
&-\frac{2}{\sigma}e_f^T(t)(TB_i)^T P_1(T\bar{A}_j - L_j\bar{C})e_x(t)\\
&-\frac{1}{\sigma}e_f^T(t)sym((TB_i)^T P_1TB_j)e_f(t)\\
&-\frac{2}{\sigma}e_f^T(t)(TB_i)^T P_1TD_jd(t) + e_f^T(t)M_2e_f(t)\\
&-\gamma_1^2 d^T(t)M_3d(t) + \delta\}. \qquad (31)
\end{aligned}
$$

Let $\xi(t) = \begin{bmatrix} e_x^T & e_f^T(t) & d^T(t) \end{bmatrix}^T$, then we obtain

$$
J_1(t) \le \sum_{i=1}^{r}\sum_{j=1}^{r} h_ih_j\{\xi^T(t)\phi_{ij}\xi(t) + \delta\}. \qquad (32)
$$

If condition (22) holds we can obtain

$$
J_1(t) \le -\zeta\|\xi(t)\|^2 + \delta, \qquad (33)
$$

where $\zeta = \lambda_{min}(-\phi_{ij})$.

It follows that

$$
\begin{aligned}
&\dot{V}_1(t) + e_x^T(t)M_1e_x(t) + e_f^T(t)M_2e_f(t)\\
&\quad -\gamma_1^2 d^T(t)M_3d(t) \le 0,\\
&\text{for } \zeta\|\xi(t)\|^2 > \delta, \qquad (34)
\end{aligned}
$$

when $d(t) = 0$, (34) means $\dot{V}_1(t) \le 0$ for $\zeta\|\xi(t)\|^2 > \delta$ and under the Lyapunov stability theory, $\xi(t)$ will converge to a small set $\Psi = \{\xi(t)/\|\xi(t)\|^2 \le \frac{\delta}{\zeta}\}$; thus $\xi(t)$ is uniformly bounded in the case of $d(t) = 0$.

When $d(t) \ne 0$, integrating both sides of (34) with respect to t over time period $[0\ \infty]$ yields

$$
\begin{aligned}
&\int_0^\infty \dot{V}_1(s)\mathrm{d}s + \int_0^\infty e_x^T(s)M_1e_x(s)\mathrm{d}s\\
&\quad + \int_0^\infty e_f^T(s)M_2e_f(s)\mathrm{d}s - \gamma_1^2\int_0^\infty d^T(s)M_3d(s)\mathrm{d}s\\
&\le 0, \text{ for } \zeta\|\xi(t)\|^2 > \delta. \qquad (35)
\end{aligned}
$$

As $V_1(\infty) \ge 0$, and with zero initial condition $V_1(0) = 0$, one obtains

$$
\begin{aligned}
&\int_0^\infty e_x^T(s)M_1e_x(s)\mathrm{d}s + \int_0^\infty e_f^T(s)M_2e_f(s)\mathrm{d}s\\
&\le \gamma_1^2\int_0^\infty d^T(s)M_3d(s)\mathrm{d}s, \text{ for } \zeta\|\xi(t)\|^2 > \delta. \qquad (36)
\end{aligned}
$$

Therefore, $J_1 < 0$ for $\zeta\|\xi(t)\|^2 > \delta$.

By posing $Y_i = P_1L_i$ and $\rho_1 = \gamma_1^2$ we obtain (23). □

Remark 2: By making a transformation into the following optimization problem, inequality (21) in Theorem 1 can be easily solved thanks to LMI Toolbox.

Minimize $\eta > 0$ subject to

$$
\begin{bmatrix} \eta I_q & (TB_i)^T P_1 - N_i\bar{C}\\ * & \eta I_{n+w} \end{bmatrix} > 0, \quad i = 1, 2, \cdots, r. \qquad (37)
$$

3.3.2 Design of observer-based FTC

In this part, an observer-based FTC is proposed to compensate the effects of actuator faults and to stabilize the closed-loop faulty descriptor system.

The observer-based FTC can be given as follows:

$$
u(t) = -\sum_{i=1}^{r} h_iK_i\hat{x}(t) - \hat{f}_a(t). \qquad (38)
$$

The closed-loop of the T-S Descriptor System becomes

$$
\begin{aligned}
E\dot{x}(t) = &\sum_{i=1}^{r}\sum_{j=1}^{r} h_ih_j[(A_i - B_iK_j)x(t) + B_iK_je_x(t)\\
&+B_ie_f(t) + D_id(t)], \qquad (39)\\
z(t) = &\sum_{i=1}^{r} h_i(\theta(x(t)))[C_{L_i}x(t)]. \qquad (40)
\end{aligned}
$$

Theorem 2: Given the H_∞ performance level γ_2, and positive definite matrices M_{44}, $M_5 = diag(M_{11}, M_{22}, M_{33})$, systems (39)-(40) are robustly asymptotically stable under H_∞ performance level γ_2, that is

$$\int_0^\infty z^T(s)M_4 z(s)\mathrm{d}s \le \gamma_2^2 \int_0^\infty \eta^T(s)M_5\eta(s)\mathrm{d}s \tag{41}$$

with $\eta(t) = \begin{bmatrix} e_x^T(t) & e_f^T(t) & d^T(t) \end{bmatrix}^T$ if there exist positive definite matrices X and W_i $(i = 1,\cdots,r)$ such that the following conditions hold:

$$EX = X^T E^T \ge 0, \tag{42}$$

$$\Xi_{ij} + \Xi_{ji} < 0,\ \ i,j = 1,2,\cdots,r,\ \ i \le j, \tag{43}$$

where

$$\Xi_{ij} = \begin{bmatrix} \psi_{ij}^{11} & B_iW_j & B_i & D_i & X^TC_{L_i}^T \\ * & \psi^{22} & 0 & 0 & 0 \\ * & * & -\rho_2M_{22} & 0 & 0 \\ * & * & * & -\rho_2M_{33} & 0 \\ * & * & * & * & -M_{44} \end{bmatrix}, \tag{44}$$

in which

$$\psi_{ij}^{11} = sym(A_iX - B_iW_j),$$
$$\psi^{22} = -\rho_2\lambda(XM_{11} + M_{11}X) + \rho_2\lambda M_{11},$$

with $\rho_2 = \gamma_2^2$.

In this case, the gains of the controller are given by $K_i = W_iX^{-1}$.

Proof: Considering the Lyapunov function as follows: $V_2(t) = x^T(t)E^TP_2x(t)$.

The time derivative of $V_2(t)$ can then be written as

$$\dot V_2(t) = \dot x^T(t)E^TP_2x(t) + x^T(t)E^TP_2\dot x(t). \tag{45}$$

Define

$$E^TP_2 = P_2^TE \ge 0. \tag{46}$$

By considering (39) and (46) we obtain

$$\begin{aligned}\dot V_2(t) = \sum_{i=1}^r\sum_{j=1}^r h_ih_j\{&x^T(t)sym(P_2^T(A_i - B_iK_j))x(t) \\ &+ 2x^T(t)P_2^TB_iK_je_x(t) + 2x^T(t)P_2^TB_ie_f(t) \\ &+ 2x^T(t)P_2^TD_id(t)\}.\end{aligned} \tag{47}$$

Let

$$J_2(t) = \dot V_2(t) + z^T(t)M_4z(t) - \gamma_2^2\eta^T(t)M_5\eta(t). \tag{48}$$

It proceeds that

$$\dot V_2(t) + z^T(t)M_4z(t) - \gamma_2^2\eta^T(t)M_5\eta(t) < 0, \tag{49}$$

when $\eta(t) = 0$, (49) means $\dot V_2(t) \le 0$, then closed-loop systems (39)-(40) are robustly asymptotically stable in the case of $\eta(t) = 0$.

When $\eta(t) \ne 0$, integrating both sides of (49) with respect to t over time period $[0\ \infty]$ yields

$$\begin{aligned}&\int_0^\infty \dot V_2(s)\mathrm{d}s + \int_0^\infty z^T(s)M_4z(s)\mathrm{d}s \\ &\quad - \gamma_2^2\int_0^\infty \eta^T(s)M_5\eta(s)\mathrm{d}s \le 0.\end{aligned} \tag{50}$$

As $V_2(\infty) \ge 0$, and with zero initial condition $V_2(0) = 0$, one obtains

$$\int_0^\infty z^T(s)M_4z(s)\,\mathrm{d}s \le \gamma_2^2\int_0^\infty \eta^T(s)M_5\eta(s)\,\mathrm{d}s. \tag{51}$$

Therefore, $J_2 < 0$.

By replacing (47) and (40) into (48), one can obtain

$$\begin{aligned}J_2(t) = \sum_{i=1}^r\sum_{j=1}^r h_ih_j\{&x^T(t)sym(P_2^T(A_i - B_iK_j))x(t) \\ &+ 2x^T(t)P_2^TB_iK_je_x(t) + 2x^T(t)P_2^TB_ie_f(t) \\ &+ 2x^T(t)P_2^TD_id(t) + x^T(t)C_{L_i}^TM_4C_{L_i}x(t) \\ &- \gamma_2^2\eta^T(t)M_5\eta(t)\},\end{aligned} \tag{52}$$

then,

$$\begin{aligned}&J_2(t) \\ &= \sum_{i=1}^r\sum_{j=1}^r h_ih_j\left\{\begin{bmatrix} x(t) \\ \eta(t)\end{bmatrix}^T\begin{bmatrix}\Theta_{ij}^{11} & \Theta_{ij}^{12} \\ * & -\gamma_2^2M_5\end{bmatrix}\begin{bmatrix} x(t) \\ \eta(t)\end{bmatrix}\right\},\end{aligned}$$

where

$$\eta(t) = \begin{bmatrix} e_x(t) \\ e_f(t) \\ d(t)\end{bmatrix},$$
$$\Theta_{ij}^{11} = \theta_{ij} + C_{L_i}^TM_4C_{L_i},\ \theta_{ij} = sym(P_2^T(A_i - B_iK_j)),$$
$$\Theta_{ij}^{12} = \begin{bmatrix} P_2^TB_iK_j & P_2^TB_i & P_2^TD_i \end{bmatrix},$$
$$M_5 = \begin{bmatrix} M_{11} & 0 & 0 \\ * & M_{22} & 0 \\ * & * & M_{33}\end{bmatrix}.$$

By applying the Schur complement,

$$\sum_{i=1}^r\sum_{j=1}^r h_ih_j\begin{bmatrix}\Theta_{ij}^{11} & \Theta_{ij}^{12} \\ * & -\gamma_2^2M_5\end{bmatrix} < 0 \tag{53}$$

can be written as

$$\begin{aligned}&\sum_{i=1}^r\sum_{j=1}^r h_ih_j\begin{bmatrix}\theta_{ij} & P_2^TB_iK_j & P_2^TB_i & P_2^TD_i & C_{L_i}^T \\ * & -\gamma_2^2M_{11} & 0 & 0 & 0 \\ * & * & -\gamma_2^2M_{22} & 0 & 0 \\ * & * & * & -\gamma_2^2M_{33} & 0 \\ * & * & * & * & -M_4^{-1}\end{bmatrix} \\ &< 0.\end{aligned} \tag{54}$$

Consider the following symmetric matrix:

$$\mathbb{X} = diag(P_2^{-T}, P_2^{-T}, I, I, I).$$

We can transform inequality (54) by pre and post multiplying it by $\mathbb{X}$, we obtain:

$$\sum_{i=1}^{r}\sum_{j=1}^{r} h_i h_j \begin{bmatrix} \vartheta_{ij} & B_iK_jP_2^{-1} & B_i & D_i & P_2^{-T}C_{Li}^T \\ * & \vartheta^{22} & 0 & 0 & 0 \\ * & * & -\gamma_2^2 M_{22} & 0 & 0 \\ * & * & * & -\gamma_2^2 M_{33} & 0 \\ * & * & * & * & -M_4^{-1} \end{bmatrix} < 0, \tag{55}$$

where $\vartheta_{ij}^{11} = sym((A_i - B_iK_j)P_2^{-1})$ and $\vartheta_{ij}^{22} = -\gamma_2^2 P_2^{-T} M_{11} P_2^{-1}$.

Considering Lemma 2, the following inequality can be obtained

$$\begin{aligned} &-\gamma_2^2 P_2^{-T} M_{11} P_2^{-1} \\ &\leq -\lambda\gamma_2^2(P_2^{-T}M_{11} + M_{11}P_2^{-1}) + \lambda^2\gamma_2^2 M_{11}. \end{aligned} \tag{56}$$

By posing $X = P_2^{-1}$, $W_i = K_iP_2^{-1}$, $M_{44} = M_4^{-1}$ and $\rho_2 = \gamma_2^2$ we obtain inequality (44). □

Remark 3: From augmented estimation vector $\hat{\bar{x}}(t)$, we can deduce easily the estimation of states and sensor faults as follows: $\hat{x}(t) = \begin{bmatrix} I_n & 0_w \end{bmatrix}\hat{\bar{x}}(t)$ and $\hat{f}_s(t) = \begin{bmatrix} 0_n & I_w \end{bmatrix}\hat{\bar{x}}(t)$. The actuator faults can be regulated by the adaptive observer proposed in (13).

Algorithm 1: The design of the proposed adaptive observer and the fault tolerant controller can be summarized as follows.

- Compute the matrices T and H by solving equation (10).
- Compute the gains of the adaptive observer by solving the optimization problem given by (37) and the LMI constraints given by (22).
- Compute the gains of the FTC by solving the LMI constraints given by (42) and (43).
- Implement the observer (13) to estimate both states and sensor/actuator faults, then the FTC (38) to achieve the objectives of the FTC.

4. NUMERICAL EXAMPLE

In this part we consider a truck-trailer system to show the effectiveness of our results.

Considering the following dynamic model of the truck-trailer system [23, 38]

$$\begin{aligned} \dot{x}_1(t) &= -\frac{v\bar{t}}{Lt_0}x_1(t) + \frac{v\bar{t}}{lt_0}u(t), \\ \dot{x}_2(t) &= \frac{v\bar{t}}{Lt_0}x_1(t), \\ \dot{x}_3(t) &= \frac{v\bar{t}}{t_0}sin[x_2(t) + \frac{v\bar{t}}{2L}x_1(t)], \end{aligned} \tag{57}$$

The model parameters are $l = 2.8$, $L = 5.5$, $v = -1$, $\bar{t} = 2$ and $t_0 = 0.5$.

To have the T-S descriptor representation, the following state variable is introduced:

$$x_4(t) = x_2(t) - \frac{v\bar{t}}{Lt_0}x_1(t). \tag{58}$$

The following fuzzy rules can be employed:

Rule 1: If $\theta(t) = x_2(t) + \frac{v\bar{t}}{Lt_0}x_1(t)$ is about 0, Then

$$\begin{cases} E\dot{x}(t) = A_1x(t) + B_1u(t) + Dd(t), \\ y(t) = Cx(t). \end{cases}$$

Rule 2: If $\theta(t) = x_2(t) + \frac{v\bar{t}}{Lt_0}x_1(t)$ is about π or $-\pi$, Then

$$\begin{cases} E\dot{x}(t) = A_2x(t) + B_2u(t) + Dd(t), \\ y(t) = Cx(t), \end{cases}$$

where

$$E = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad A_1 = \begin{bmatrix} -\frac{v\bar{t}}{Lt_0} & 0 & 0 & 0 \\ \frac{v\bar{t}}{Lt_0} & 0 & 0 & 0 \\ -\frac{v^2\bar{t}^2}{2Lt_0} & \frac{v\bar{t}}{t_0} & 0 & 0 \\ -\frac{v\bar{t}}{Lt_0} & 1 & 0 & -1 \end{bmatrix},$$

$$B_1 = \begin{bmatrix} \frac{v\bar{t}}{lt_0} \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad A_2 = \begin{bmatrix} -\frac{v\bar{t}}{Lt_0} & 0 & 0 & 0 \\ \frac{v\bar{t}}{Lt_0} & 0 & 0 & 0 \\ -\frac{\varphi v^2\bar{t}^2}{2Lt_0} & \frac{\varphi v\bar{t}}{t_0} & 0 & 0 \\ -\frac{v\bar{t}}{Lt_0} & 1 & 0 & -1 \end{bmatrix},$$

$$B_2 = \begin{bmatrix} \frac{v\bar{t}}{lt_0} \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad D = \begin{bmatrix} 0 \\ 0 \\ \frac{v\bar{t}}{t_0} \\ 0 \end{bmatrix}, \quad C = I_4, \quad F = \begin{bmatrix} 2 \\ 1 \\ 1 \\ 1 \end{bmatrix},$$

$$C_{L_1} = \begin{bmatrix} 2 & 1 & 0 & 1 \end{bmatrix}, \quad C_{L_2} = \begin{bmatrix} 0 & -1 & -1 & 1 \end{bmatrix}.$$

We set $\varphi = \frac{10t_0}{\pi}$ and $d(t) = 0.2sin(\theta(t)) - \theta(t)$.

The membership functions for Rules 1 and 2 are as follows:

$$\begin{aligned} h_1(\theta(t)) = &\left(\frac{1}{1+\exp(-3(\theta(t)+0.5\pi))}\right) \\ &\times \left(1 - \frac{1}{1+\exp(-3(\theta(t)-0.5\pi))}\right), \\ h_2(\theta(t)) = &1 - h_1(\theta(t)). \end{aligned}$$

By solving (10), T and H can be given as follows

$$T = \begin{bmatrix} 0.8333 & 0.1667 & 0.1667 & 0 \\ 0.1667 & 0.5833 & 0.0833 & 0 \\ 0.1667 & 0.0833 & 0.5833 & 0 \\ 0.3333 & 0.1667 & 0.1667 & 0 \\ -0.3333 & -0.1667 & -0.1667 & 0 \end{bmatrix},$$

$$H = \begin{bmatrix} 0.1667 & -0.1667 & -0.1667 & 0 \\ -0.1667 & 0.4167 & -0.0833 & 0 \\ -0.1667 & -0.0833 & 0.4167 & 0 \\ -0.3333 & -0.1667 & -0.1667 & 1 \\ 0.3333 & 0.1667 & 0.1667 & 0 \end{bmatrix}.$$

By choosing the tuning parameter values as follows: $\sigma = 2$, $\mu = 0.5$, $\eta = 10^{-4}$ and $\rho_1 = 1$ to satisfy Theorem 1 and Remark 1 then $\lambda = 2$, $\rho_2 = 1$ and $M_{11} = eye(4)$ to satisfy Theorem 2.

Using MATLAB LMI Toolbox, the optimization problem of theorem 1 and 2 can be easily solved.

The gains of the Adaptive Fuzzy Observer:

$$L_1 = \begin{bmatrix} 5.4503 & -5.3322 & -4.4967 & -0.3343 \\ 1.5950 & -2.3439 & -0.6450 & -0.0142 \\ 4.2856 & -16.3160 & 6.5687 & 0.4703 \\ 2.3915 & -5.0311 & -0.7733 & 0.9286 \\ -2.5356 & 4.8958 & 0.7645 & 0.2876 \end{bmatrix},$$

$$L_2 = \begin{bmatrix} 5.9981 & -6.0296 & -5.5375 & -0.9673 \\ 1.7971 & -2.5434 & -1.1143 & -0.2667 \\ 3.9047 & -15.5800 & 6.7274 & 1.3254 \\ 2.6698 & -4.9917 & -1.2290 & 0.8808 \\ -2.5629 & 5.3867 & 0.9408 & -0.0410 \end{bmatrix},$$

and controller gains:

$$K_1 = \begin{bmatrix} -2.7152 & 5.2551 & -0.5846 & -0.1428 \end{bmatrix},$$
$$K_2 = \begin{bmatrix} -2.6972 & 5.7485 & -0.5806 & -0.1003 \end{bmatrix}.$$

Let us consider in the first time the sensor fault $f_{s_1}(t)$ as a square-wave signal between 10s and 25s, and the actuator fault as

$$f_{a_1}(t) = \begin{cases} 0, & t < 5, \\ 5(1-\exp(-0.5(t-5))), & 5 \le t \le 30. \end{cases} \tag{59}$$

Consider now the sensor fault $f_{s_2}(t)$ as a square-wave signal between 10 s and 25 s, and the actuator fault as

$$f_{a_2}(t) = \begin{cases} 0, & t \le 5, \\ 5+0.5sin(0.2\pi(t-5)), & 5 < t \le 17, \\ 5.5, & 17 < t \le 30. \end{cases} \tag{60}$$

The simulation initial states in the first case are set as $x_0 = \begin{bmatrix} -0.1 & -0.1 & -0.2 \end{bmatrix}^T$ and $w_0 = \begin{bmatrix} 0.1 & 0.1 & 0.1 & 0.2 & 0 \end{bmatrix}^T$. And in the second case, they are set as $x_0 = \begin{bmatrix} -0.1 & -0.1 & -0.2 \end{bmatrix}^T$ and $w_0 = \begin{bmatrix} 0.2 & 0.1 & 0.2 & 0.1 & 0 \end{bmatrix}^T$. By choosing $\Gamma = 2.5$ in the simulation example, for the two types of actuator faults, the derivative of $f_{a_1}(t)$ and $f_{a_2}(t)$ over time are norm bounded by $f_{a_{1max}} = 2.5$ and $f_{a_{2max}} = 0.31$, respectively. $\delta_1 = \frac{\mu}{\sigma} f^2_{a_{1max}} \lambda_{max}(\Gamma^{-1}M^{-1}\Gamma^{-1}) = 8.6.10^{-3}$ and $\delta_2 = \frac{\mu}{\sigma} f^2_{a_{2max}} \lambda_{max}(\Gamma^{-1}M^{-1}\Gamma^{-1}) = 1.35.10^{-4}$ reduce the radius of the ball in which the estimation errors converge.

It should be noted that when selecting the learning rate $\Gamma = 2.5$, based on the proposed adaptive fault estimation algorithm, the fault-tolerant controller can rapidly recover the performance of the system in the presence of sensor/actuator faults and external disturbances simultaneously. The learning rate should be minutely selected, otherwise, increasing or decreasing this value will lead to an unsatisfactory accuracy and rapidity of estimation. The evolutions of system states, sensor and actuator faults as well as their estimated are depicted in Figs. 2-7 in the two cases. It is quite clear to remark that the adaptive observer designed in this work leads to a good estimation of system states, actuator and sensor faults. Based on the simulation

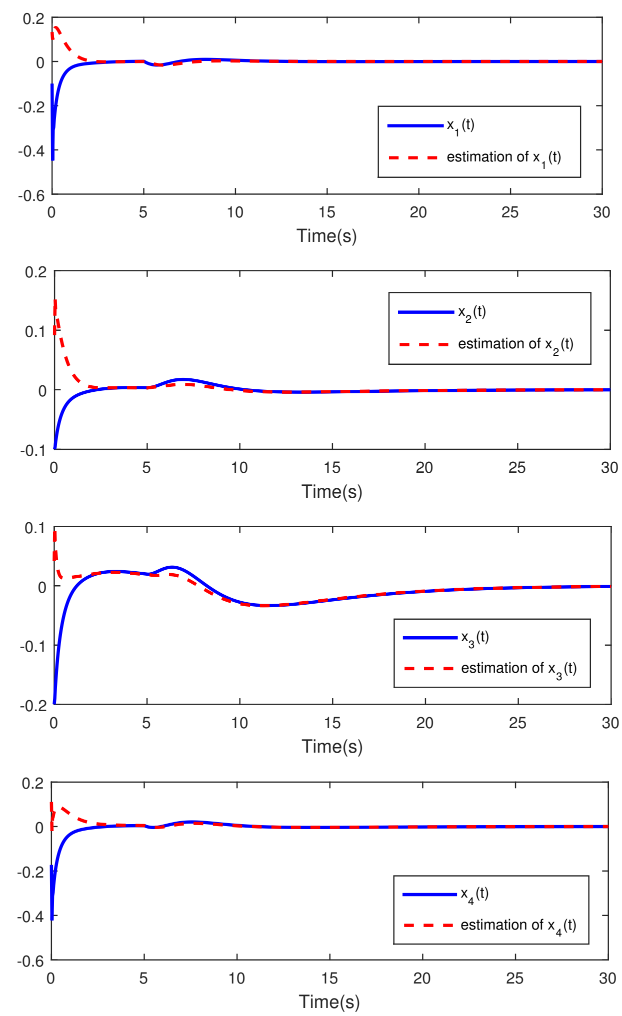

Fig. 2. System states and their estimations under FTC law.

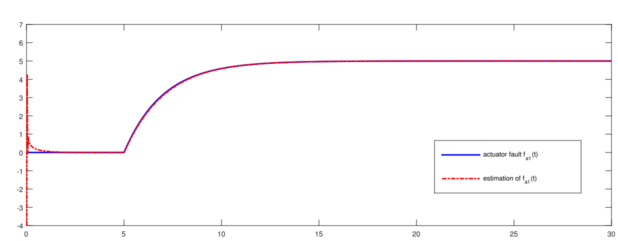

Fig. 3. Actuator fault f_{a_1}(t) and its estimated $\hat{f}_{a_1}$(t) under FTC law.

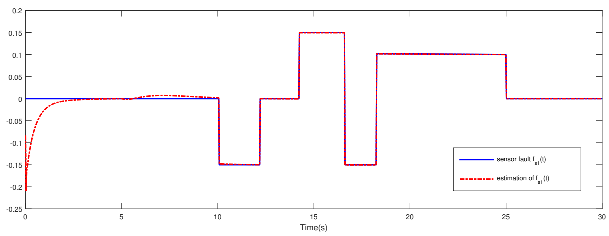

Fig. 4. Sensor fault $f_{s_1}(t)$ and its estimated $\hat{f}_{s_1}(t)$ under FTC law.

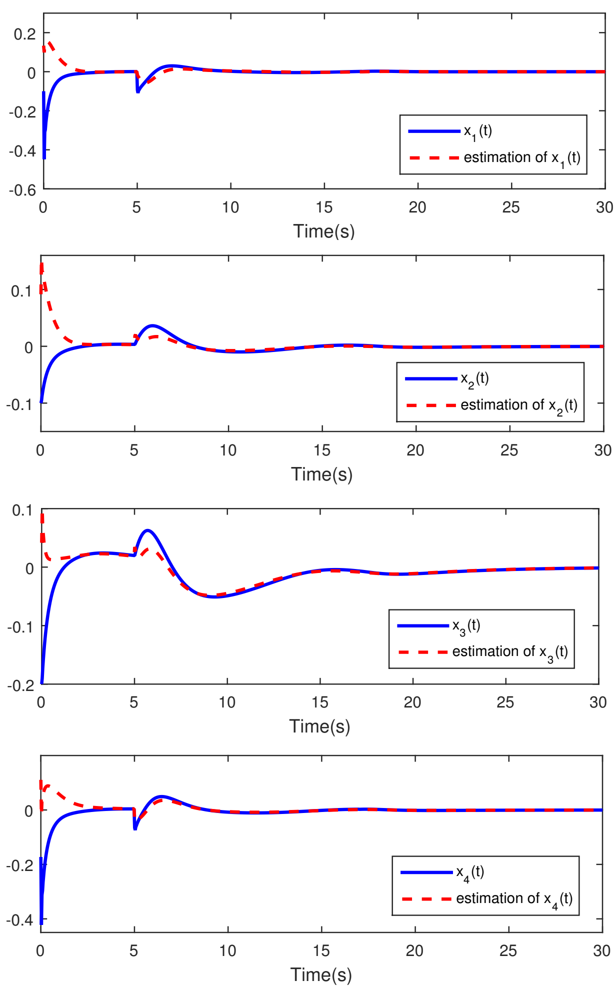

Fig. 5. System states and their estimations under FTC law.

results, we can conclude that the adaptive fuzzy observer-based FTC used in this paper can rapidly recover the performance and the stability of the closed-loop descriptor system despite the presence of actuator, sensor faults and external disturbances.

5. CONCLUSION

In this paper, we have proposed a strategy of fault estimation and fault tolerant control for T-S descriptor sys-

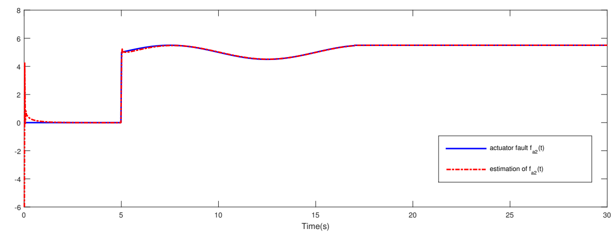

Fig. 6. Actuator fault $f_{a_2}(t)$ and its estimated $\hat{f}_{a_2}(t)$ under FTC law.

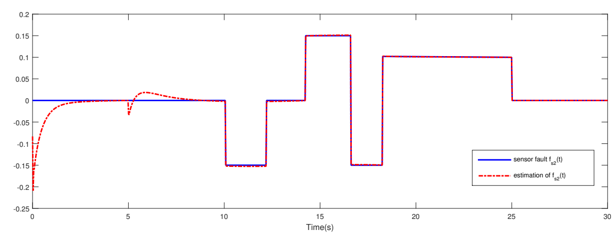

Fig. 7. Sensor fault $f_{s_2}(t)$ and its estimated $\hat{f}_{s_2}(t)$ under FTC law.

tems. This kind of systems may be affected by actuator, sensor faults and external disturbances. By considering the sensor faults as an auxiliary state vector, the original descriptor system has been transformed into another one. Using the H_∞ optimization technique, an Adaptive Fuzzy Observer has been firstly proposed to achieve a simultaneous estimation of descriptor system states, actuator and sensor faults. Secondly, we have introduced an observer-based FTC to stabilize the closed-loop faulty descriptor system. Considering the H_∞ performance index, it is important to mention that the coupling issue resulting from the observer and the controller design can be avoided by introducing them independently. Thus, sufficient conditions are presented in terms of LMIs. The effectiveness of the proposed method has been proven by simulation on a truck-trailer system.

REFERENCES

[1] S. de Oca, V. Puig, M. Witczak, and Ł. Dziekan, "Fault-tolerant control strategy for actuator faults using LPV techniques: Application to a two degree of freedom helicopter," *International Journal of Applied Mathematics and Computer Science*, vol. 22, no. 1, pp. 161-171, 2012.

[2] X. Li and F. Zhu, "Simultaneous time-varying actuator and sensor fault reconstruction based on PI observer for LPV systems," *International Journal of Adaptive Control and Signal Processing*, vol. 29, no. 9, 1086-1098, 2015. [click]

[3] X. Li and F. Zhu, "Simultaneous actuator and sensor fault estimation for descriptor LPV system based on H_∞ reduced-order observer," *Optimal Control Applications and Methods*, vol. 37, no. 6, pp. 1122-1138, 2016.

[4] Q. Shen, B. Jiang, and P. Shi, "Active fault-tolerant control against actuator fault and performance analysis of the effect of time delay due to fault diagnosis," *International Journal of Control, Automation and Systems*, vol. 15, no. 2, pp. 537-546, 2017. [click]

[5] J. Yang, F. Zhu, X. Wang, and X. Bu, "Robust sliding-mode observer-based sensor fault estimation, actuator fault detection and isolation for uncertain nonlinear systems," *International Journal of Control, Automation and Systems*, vol. 13, no. 5, pp. 1037-1046, 2015. [click]

[6] J. Zhang, A. K. Swain, and S. K. Nguang, *Robust Observer-Based Fault Diagnosis for Nonlinear Systems Using MATLAB*, Advances in Industrial Control, 2016.

[7] S. H. S. Ziyabari and M. A. Shoorehdeli, "Robust fault diagnosis scheme in a class of nonlinear system based on UIO and fuzzy residual," *International Journal of Control, Automation and Systems*, pp. 1-10, 2017.

[8] J, Han, H. Zhangn, Y. Wang, and X. Liu, "Robust state/fault estimation and fault tolerant control for T-S fuzzy systems with sensor and actuator faults," *Journal of the Franklin Institute*, vol. 353, pp. 615-641, 2016.

[9] M. Liu, X. Cao, and P. Shi, "Fuzzy-model-based fault-tolerant design for nonlinear stochastic systems against simultaneous sensor and actuator faults," *IEEE Transactions on Fuzzy Systems*, vol. 21, no. 5, pp. 789-799, 2013. [click]

[10] K. Zhang, B. Jiang, V. Cocquempot, and H. Zhang, "A framework of robust fault estimation observer design for continuous-time/discrete-time systems," *Optimal Control Applications and Methods*, vol. 34, no. 4, pp. 442-457, 2013. [click]

[11] X.-J. Li and G.-H. Yang, "Robust adaptive fault-tolerant control for uncertain linear systems with actuator failures," *IET control theory & applications*, vol. 6, no. 10, pp. 1544-1551, 2012. [click]

[12] M. Sami and R. J. Patton, "Active fault tolerant control for nonlinear systems with simultaneous actuator and sensor faults," *International Journal of Control, Automation and Systems*, vol. 11, no. 6, pp. 1149-1161, 2013.

[13] X.-H. Chang, Z.-M. Li, and J. H. Park, "Fuzzy generalized H_2 filtering for nonlinear discrete-time systems with measurement quantization," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2017.

[14] X.-H. Chang, J. H. Park, and P. Shi, "Fuzzy resilient energy-to-peak filtering for continuous-time nonlinear systems," *IEEE Transactions on Fuzzy Systems*, 2016.

[15] H. Gassara, A. El Hajjaji, M. Kchaou, and M. Chaabane, "Observer based (Q, V, R)-α-dissipative control for TS fuzzy descriptor systems with time delay," *Journal of the Franklin Institute*, vol. 351, no. 1, pp. 187-206, 2014.

[16] D. Ichalal, B. Marx, J. Ragot, S. Mammar, and D. Maquin, "Sensor fault tolerant control of nonlinear Takagi-Sugeno systems, application to vehicle lateral dynamics," *International Journal of Robust and Nonlinear Control*, vol. 26, no. 7, pp. 1376-1394, 2016. [click]

[17] H. Li, F. You, F. Wang, and S. Guan, "Robust fast adaptive fault estimation and tolerant control for TS fuzzy systems with interval time-varying delay," *International Journal of Systems Science*, vol. 48, no. 8, pp. 1708-1730, 2017. [click]

[18] X. Li, D. Lu, G. Zeng, J. Liu, and W. Zhang, "Integrated fault estimation and non-fragile fault tolerant control design for uncertain Takagi-Sugeno fuzzy systems with actuator fault and sensor fault," *IET Control Theory & Applications*, 2017.

[19] F. You and M. Li, "Fault tolerant control for TS fuzzy systems with simultaneous actuator and sensor faults," *Proc. of Control And Decision Conference (CCDC), 2017 29th Chinese*, pp. 7354-7359, IEEE, 2017.

[20] H. Gassara, A. El Hajjaji, and M. Chaabane, "Adaptive fault tolerant control design for Takagi-Sugeno fuzzy systems with interval time-varying delay," *Optimal Control Applications And Methods*, vol. 35, pp. 609-625, 2014. [click]

[21] K. Zhang, B. Jiang, and V.t Cocquempot, "Adaptive observer-based fast fault estimation," *International Journal of Control*, vol. 6, no. 3, pp. 320-326, 2008.

[22] Z. Gao and S. X. Ding, "Actuator fault robust estimation and fault-tolerant control for a class of nonlinear descriptor systems," *Automatica*, vol. 43, no. 5, pp. 912-920, 2007.

[23] Q. Jia, W. Chen, Y. Zhang, and H. Li, "Fault reconstruction and fault-tolerant control via learning observers in Takagi-Sugeno fuzzy descriptor systems with time delays," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 6, pp. 3885-3895, 2015.

[24] D. Kharrat, H. Gassara, M. Chaabane, and A. El-Hajjaji, "Fault tolerant control based on adaptive observer for Takagi-Sugeno fuzzy descriptor systems," *Proc. of 16th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA)*, pp. 273-278, IEEE, 2015.

[25] D. Kharrat, H. Gassara, A. El Hajjaji, and M. Chaabane, "Adaptive fuzzy observer-based fault-tolerant control for Takagi-Sugeno descriptor nonlinear systems with time delay," *Circuits, Systems, and Signal Processing*, pp. 1-20, 2017.

[26] T. Taniguchi, K. Tanaka, and H. O. Wang, "Fuzzy descriptor systems and nonlinear model following control," *IEEE Transactions on Fuzzy Systems*, vol. 8, no. 4, pp. 442-452, 2000. [click]

[27] Q.-X. Jia, Y.-C. Zhang, W. Chen, and H.-Y. Li, "Fault reconstruction in descriptor linear parameter-varying systems via polytopic unknown-input proportional-integral observers," *Optimal Control Applications and Methods*, vol. 36, no. 6, pp. 873-888, 2015.

[28] Y. Ma and Y. Yan, "Observer-based H_∞ guaranteed cost control for uncertain singular time-delay systems with input saturation," *International Journal of Control, Automation and Systems*, vol. 14, no. 5, pp. 1254-1261, 2016. [click]

[29] B. Marx, D. Koenig, and J. Ragot, "Design of observers for Takagi-Sugeno descriptor systems with unknown inputs and application to fault diagnosis," *IET Control Theory and Applications*, vol. 1, no. 5, pp. 1487-1495, 2007. [click]

[30] K. Tanaka, H. Ohtake, and H. O. Wang, "A descriptor system approach to fuzzy control system design via fuzzy lyapunov functions," *IEEE Transactions on Fuzzy Systems*, vol. 15, pp. 333-341, 2007. [click]

[31] C. Lin, Q.-G. Wang, and T. H. Lee, "Stability and stabilization of a class of fuzzy time-delay descriptor systems," *IEEE Transactions on Fuzzy Systems*, vol. 14, no. 4, pp. 542-551, 2006.

[32] S. Xu, P. Van Dooren, R. Stefan, and J. Lam, "Robust stability and stabilization for singular systems with state delay and parameter uncertainty," *IEEE Transactions on Automatic Control*, vol. 47, no. 7, pp. 1122-1128, 2002. [click]

[33] H. H. Choi, "LMI-based nonlinear fuzzy observer-controller design for uncertain MIMO nonlinear systems," *IEEE Transactions on Fuzzy Systems*, vol. 15, no. 5, pp. 956-971, 2007. [click]

[34] B. Erkus and Y. J. Lee, "Linear matrix inequalities and matlab LMI toolbox," *University of Southern California Group Meeting Report*, Los Angeles, California, 2004.

[35] D. Koenig, "Observer design for unknown input nonlinear descriptor systems via convex optimization," *IEEE Transactions on Automatic Control*, vol. 51, pp. 1047-1052, 2006.

[36] M. Alma and M. Darouach, "Adaptive observers design for a class of linear descriptor systems," *Automatica*, vol. 50, no. 2, pp. 578 - 583, 2014.

[37] M. Darouach and M. Boutayeb, "Design of observers for descriptor systems," *IEEE Transactions on Automatic Control*, vol. 40, no. 7, pp. 1323-1327, 1995.

[38] K. Zhang, B. Jiang, and P. Shi, "A new approach to observer-based fault-tolerant controller design for Takagi-Sugeno fuzzy systems with state delay," *Circuits Syst Signal Process*, vol. 28, pp. 679-697, 2009. [click]

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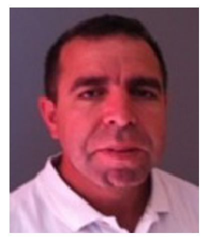

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