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Robust fault estimation design for discrete-time nonlinear systems via a modified fuzzy fault estimation observer☆

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ABSTRACT

The paper provides relaxed designs of fault estimation observer for nonlinear dynamical plants in the Takagi–Sugeno form. Compared with previous theoretical achievements, a modified version of fuzzy fault estimation observer is implemented with the aid of the so-called maximum-priority-based switching law. Given each activated switching status, the appropriate group of designed matrices can be provided so as to explore certain key properties of the considered plants by means of introducing a set of matrix-valued variables. Owing to the reason that more abundant information of the considered plants can be updated in due course and effectively exploited for each time instant, the conservatism of the obtained result is less than previous theoretical achievements and thus the main defect of those existing methods can be overcome to some extent in practice. Finally, comparative simulation studies on the classical nonlinear truck-trailer model are given to certify the benefits of the theoretic achievement which is obtained in our study.

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1. Introduction

Since the recent two decades, there have been much enthusiasm in fuzzy-logic-based controller designs owing to the reason that fuzzy models could be employed as universal approximators in reported references [2–6]. Among those theoretic achievements, Takagi-Sugeno (T-S) fuzzy models [1] are constituted by a bank of IF-THEN-based fuzzy rules and they are proved to be capable of describing plenty of nonlinear plants. Consequently, many theoretic achievements about fuzzy state/output feedback control designs by using T-S fuzzy models have been reported in previous literature [7–10]. Likewise, T-S fuzzy models also have been used to deal with fuzzy filters [11–13], fuzzy tracking controls [14], adaptive sliding mode controls [15], etc. However, a large quantity of previous theoretic achievements are based upon the common Lyapunov function that may result in conservative results [16]. On the other hand, much effort has been devoted for obtaining some efficient ways to reduce its conservatism [17,18]. Lately, profit from the powerful analysis tool of homogenous polynomial solutions [19], less conservative results have been developed for stabilization of discrete-time T-S fuzzy control systems by proposing proper homogenous polynomially parameter-dependent(HPPD) Lyapunov functions [20–24]. But, although the distribution of real-time normalized fuzzy weighting functions often varies between any two adjacent time instants, no information is utilized and all the previous results must play up to any possible distribution. As a trade-off, a lot of conservatism is added. In a word, it is rather remarkable that there may be a large amount of room that can be improved if the distribution of real-time normalized fuzzy weighting functions could be considered by some way.

On another frontier of study, fault detection and isolation (FDI) and fault tolerant control (FTC) have gotten much enthusiasm because a significant number of practical problems may fall under component malfunctions which may lead to serious performance degradation or even instability of the original system [25–28]. By way of one chief branch, the issue of nonlinear fault detection/estimation was mightily investigated and some featured methods were given in [29–33], respectively. Particularly, concerning the special case that external noises/disturbances are part of certain finite-frequency range [34], the issue of fault estimation pertain to some finite-frequency range has been investigated by authors in [35–37]. Considering one important fact that related results for the entire-frequency domain remain in effect for any case when the

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finite-frequency range of external noises/disturbances isn't determinate, it becomes an interesting topic for studying the issue of less conservative fuzzy fault estimation conditions for the so-called entire-frequency domain. For instance, with the aid of the efficient piecewise Lyapunov functions [38], a relaxed result is produced in [40]. More importantly, The authors in [41] provided a novel integral quadratic Lyapunov functional (IQLF) stability analysis approach such that the system transformation and weighting matrix are not required, which is a significant breakthrough in Markovian jump stochastic system. There is few theoretical achievements on fuzzy fault estimation based on the HPPD method, say nothing of giving improved HPPD methods, which results in that the conservatism of those existing theoretical achievements is still too considerable to be entirely implemented in practice and this belongs to one of the main defect of them. In other words, the main defect of those existing theoretical achievements hasn't been avoided, some embedded study deserves to proceed, which impels the authors to develop the following work.

The main goal of the study is to overcome this main defect of previous fuzzy fault estimation(FE) observers and make the obtained theoretical achievement more practical. A modified fuzzy FE observer is developed with the aid of the so-called maximum-priority-based switching law. Given any activated switching status, its appropriate group of designed matrices can be provided so as to explore certain key properties of the underlying systems by means of introducing a set of matrix-valued variables. Owing to the reason that more abundant information of the considered plants can be updated in due course and effectively exploited for each time instant, the conservatism of the obtained result is less than previous theoretical achievements and thus the main of those existing methods can be overcome to some extent in practice. Finally, comparative simulation studies on the classical nonlinear truck-trailer model are given to certify the benefits of the theoretic achievement which is obtained in our study (Fig. 1).

2. Problem formulation and preliminaries

Like that applied in [40], the whole T–S fuzzy system that represent a class of discrete-time nonlinear models with process/actuator faults can be written as:

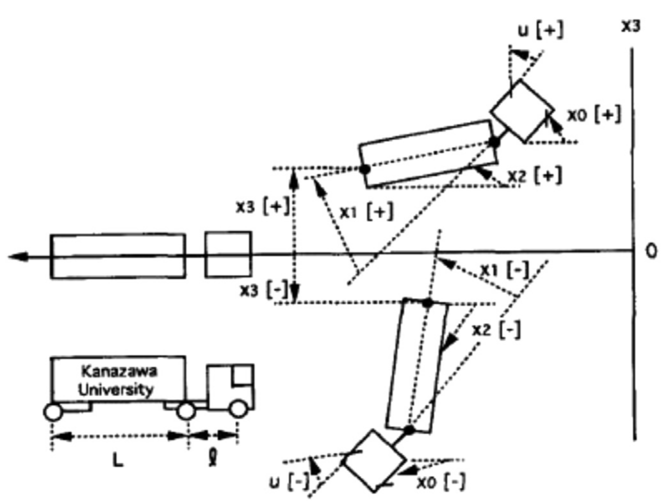

Fig. 1. Truck-trailer model and its coordinate system [39].

$$\begin{cases} x(t+1) = \sum_{j=1}^{r} h_j(z(t))\left(A_j x(t) + B_j u(t) + E_j f(t) + D_{1j} w(t)\right) \\ y(t) = \sum_{j=1}^{r} h_j(z(t))\left(C_j x(t) + D_{2j} w(t)\right), \end{cases} \tag{1}$$

where $x(t) \in \mathbb{R}^{n_1}$ is system state vector, $u(t) \in \mathbb{R}^{n_2}$ stands for control input vector, $y(t) \in \mathbb{R}^{n_3}$ stands for measurable output vector, $f(t) \in \mathbb{R}^{n_4}$ stands for process/actuator fault vector, $w(t) \in \mathbb{R}^{n_3}$ stands for disturbance and model uncertainties that can be assumed to belong to $l_2[0, \infty)$. In the customary manner, the number of measurable output channels is bigger than or equal to the number of input ones, $n_3 \ge n_4$. $z(t)$ stands for the fuzzy premise variable, $h_j(z(t))$ is the i-th current-time normalized fuzzy weighting function. $A_j \in \mathbb{R}^{n_1 \times n_1}$, $B_j \in \mathbb{R}^{n_1 \times n_2}$, $E_j \in \mathbb{R}^{n_1 \times n_4}$, $D_{1i} \in \mathbb{R}^{n_1 \times n_5}$, $C_j \in \mathbb{R}^{n_3 \times n_1}$, $D_{2i} \in \mathbb{R}^{n_3 \times n_5}$ are constant real matrices. It is assumed that as follows: E_j and C_j belong to full rank matrices, rank $(E_j) = n_4$, rank $(C_j) = n_3$, and (A_j, C_j) must be observable.

With the purpose of estimating $f(t)$, the so-called full-order FE observers are often utilized in previous references, e.g., [40]:

$$\begin{cases} \hat{x}(t+1) = A_{z(t)}\hat{x}(t) + B_{z(t)}u(t) + E_{z(t)}\hat{f}(t) + L(h)(y(t) - \hat{y}(t)), \\ \hat{y}(t) = C_{z(t)}\hat{x}(t), \\ \hat{f}(t+1) = \hat{f}(t) + F(h)(y(t) - \hat{y}(t)), \end{cases} \tag{2}$$

where $A_{z(t)} = \sum_{j=1}^{r} h_j(z(t))A_j$, $B_{z(t)} = \sum_{j=1}^{r} h_j(z(t))B_j$, $E_{z(t)} = \sum_{j=1}^{r} h_j(z(t))E_j$, and, $C_{z(t)} = \sum_{j=1}^{r} h_j(z(t))C_i$. Particularly, $L(h) = \sum_{j=1}^{r} h_j(z(t))L_j \in \mathbb{R}^{n_1 \times n_3}$ and $F(h) = \sum_{j=1}^{r} h_j(z(t))F_j \in \mathbb{R}^{n_4 \times n_3}$ are two set of FE observer matrices that are dependent on $h_j(z(t))$. As a result, one can define two error signals as $e_x(t) = \hat{x}(t) - x(t)$ and $e_f(t) = \hat{f}(k) - f(k)$ [40].

Then, a group of existing definitions, which are borrowed from those given in [19–21] and their cited references, are placed here.

As the set Δ_r can be defined as $\Delta_r = \left\{ \alpha \in \mathbb{R}^r;\ \sum_{i=1}^{r} \alpha_i = 1;\ \alpha \ge 0 \right\}$, we can define $\alpha_1^{k_1}\alpha_2^{k_2}\cdots\alpha_r^{k_r}$, $\alpha \in \Delta_r$, $k_i \in \mathbb{Z}_+$, $i = 1, 2, \ldots, r$ as the monomials with $k = k_1 k_2 \cdots k_r$. $P_k \in \mathbb{R}^{n \times n}$, $\forall\ k \in \mathcal{K}(g)$, $g \in \mathbb{Z}_+$ mean matrix-valued coefficients. What deserves to be mentioned is that $\mathcal{K}(n)$ means the set of r-tuples which is composed of all possible combinations of nonnegative integers $k_j, j \in \{1, \ldots, r\}$, satisfying $\sum_{j=1}^{r} k_j = n$.

Given two r-tuples, i.e., k and k', the authors write $k \ge k'$ if the following proposition holds in true: $k_j \ge k'_j$, $\forall\ j \in \{1, 2, \ldots, r\}$. These related operations of summation, $k + k'$, and subtraction, $k - k'$ (whenever $k \ge k'$), can be both written as componentwise. On the other hand, two special definitions for the r-tuple $\chi_i \in \mathcal{K}(1)$ and the coefficient $\pi(k)$, $\forall\ k \in \mathcal{K}(g)$ are written as those given in [21]:

$$\chi_i = \underbrace{0}_{1-\text{th element}} \cdots 0 \underbrace{1}_{i-\text{th element}} 0 \cdots \underbrace{0}_{r-\text{th element}},$$
$$\pi(k) = (k_1!) \times (k_2!) \times \cdots \times (k_r!). \tag{3}$$

With the purpose of saving space, a bank of shortenings are used like those given in [21].

$$\begin{cases} h_i = h_j(z(t)),\ h_j^{+} = h_j(z(t+1)),\ h = (h_1, \ldots, h_r)^T,\ k = k_1 k_2 \cdots k_r, \\ h^{+} = (h_1^{+}, \ldots, h_r^{+})^T,\ h^{+k} = h_1^{+k_1} h_2^{+k_2} \cdots h_r^{+k_r},\ h^{k} = h_1^{k_1} h_2^{k_2} \cdots h_r^{k_r}. \end{cases}$$

Some illustrative examples are placed here for explaining the above notations. Consider a set of homogeneous polynomials while one has $g = 3$ and $r = 4$ variables, we have $\chi_1 = 1000$, $\chi_2 = 0100$, $\chi_3 = 0001$, $\pi(2010) = (2!) \times (0!) \times (1!) \times (0!) = 2$, $\mathcal{K}(g) = \{3000, 0300, 0030, 0003, 2100, 2010, 2001, 1200, 0210, 0201, 1020, 0120, 0021, 1002, 0102, 0012, 1110, 1101, 1011, 0111\}$,

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