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Fuzzy unknown input observer-based robust fault estimation design for discrete-time fuzzy systems ☆

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ABSTRACT

This paper investigates the problem of fuzzy unknown input observer (FUIO)-based fault estimation for discrete-time Takagi–Sugeno fuzzy systems. Firstly, an augmented system description is given. Then a FUIO is proposed to achieve fault estimation, which is robust against the effect of the external disturbance. Furthermore, a less conservative FUIO design method is proposed by using a finite-frequency range technique instead of an entire-frequency method. The gain matrices of the FUIO are obtained by solving linear matrix inequalities. Finally, simulation results of a discrete-time nonlinear system are presented to illustrate the effectiveness of the proposed strategy.

1. Introduction

The issue of fault diagnosis has been an active field of research in both theoretical and practical areas because of the increasing demand of reliability and maintainability of automatic control systems. During the past three decades, fault diagnosis of dynamic systems has attracted considerable attention and fruitful results can be found in several excellent books [1–3]. On the other hand, fuzzy control theory has been developed over the past few decades. Takagi–Sugeno (T–S) fuzzy models have proven to be capable of approximating any smooth nonlinear systems to any specified accuracy within any compact set. T–S fuzzy models can be used to express complex nonlinear systems as a set of local linear subsystems interpolated by membership functions. Therefore, in the past few decades, analysis and design of the T–S fuzzy systems have been studied extensively, and many significant results have been obtained [4–12].

In practical situations, there almost are unknown inputs in control systems, which leads to system performance degradation, such as process noises and external disturbances. How to effectively deal with unknown inputs of practical systems has been an interesting and attractive topic. During the past three decades, special attention has been focused on the design of unknown input observer (UIO) [13–16]. An UIO can realize the state estimation for dynamic systems subject to unknown inputs and one of the most significant features resorts to the unknown input decoupling principle, so the design of UIO for uncertain control systems subject to external disturbances has been extensively studied in both theory and application such as crane set-up, lateral vehicle dynamics, and chemical process [17–19]. An UIO has also provided a useful method to achieve fault diagnosis with robustness against unknown inputs, in which the residual is designed to be insensitive to unknown inputs. For UIO-based fault detection and isolation, many contributions have been proposed in the literature [20–23] and applied to machine infinite bus systems, ship models, etc. Different from fault detection and isolation [24], fault estimation is used to online determine fault's size and magnitude, aimed at providing accurate fault information to active fault-tolerant control. In [25], an approach for robust fault estimation and reconstruction for a class of nonlinear systems with uncertainties was proposed based on a sliding mode observer and simulations of a single-link flexible joint robot system are used to verify the effectiveness. For a class of nonlinear systems, an exact observer design for nonlinear locally detectable systems with unknown inputs was proposed based on higher-order sliding-mode observers and a satellite model is taken as a simulation model [26]. In [27], an UIO-based fault estimation strategy is proposed by using a coordinate transformation, but the derivative of the output is required. In practice, it is not an easy task to obtain signal derivatives because of the presence of noises. Therefore, how to realize UIO-based robust fault estimation for control systems with

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unknown inputs is challenging and motivates our study in this paper.

Model uncertainties and external disturbances acting on the system have to be handled in the observer design in order to provide accurate estimation. This paper aims at designing a fuzzy unknown input observer (FUIO) for fault estimation which is strictly robust against such external disturbances. In this paper, we propose a FUIO design method to estimate accurately the fault for discrete-time T–S fuzzy systems in the presence of disturbances. The advantages and novelties of this paper are as follows: First, a FUIO is proposed for discrete-time T–S fuzzy systems to achieve fault estimation, which is unaffected by the effect of external disturbances. Second, by using the finite-frequency-based design technique [28], sufficient conditions of FUIO are proposed to calculate the gain matrices of FUIO, which is less conservative than an entire-frequency spectrum design.

This paper is structured as follows. Section 2 gives the system description and preliminaries. Section 3 is devoted to the proposed FUIO-based fault estimation method to estimate the occurred faults for discrete T–S fuzzy systems. In Section 4, simulation results of a discrete-time nonlinear truck–trailer system are presented to illustrate the effectiveness of the proposed FUIO-based fault estimation design. Finally, Section 5 concludes this paper.

2. System description

T–S fuzzy models are described by fuzzy IF–THEN rules, each of which represents local linear input–output relationship of nonlinear systems. The ith rule of the fuzzy linear model for a nonlinear discrete-time system can be described by:

Plant Rule i:

IF $\xi_1(k)$ is π_{i1} and … and $\xi_s(k)$ is π_{is}, THEN

$$\begin{cases} x(k+1) = A_i x(k) + B_i u(k) + E_i f(k) + D_i d(k), \\ y(k) = Cx(k), \quad i \in \mathcal{I} := \{1, 2, \ldots, q\}, \end{cases} \tag{1}$$

where $x(k) \in \mathbb{R}^n$ is the state, $u(k) \in \mathbb{R}^m$ is the input, $y(k) \in \mathbb{R}^p$ is the system measurement output, $f(k) \in \mathbb{R}^r$ represents actuator or process fault, and $d(k) \in \mathbb{R}^d$ is the disturbance. The number of output channels is greater than or equal to the number of faults, i.e., $p \geq r$. A_i, B_i, C, D_i and E_i are constant real matrices of appropriate dimensions. It is supposed that matrices E_i and C are of full rank, i.e., $\text{rank}(E_i) = r$ and $\text{rank}(C) = p$, and the pair (A_i, C) is observable. $\xi_j(k)$ $(j = 1, \ldots, s)$ are the premise variables, π_{ij} $(i = 1, \ldots, q; j = 1, \ldots, s)$ are fuzzy sets that are characterized by the membership function, q is the number of IF–THEN rules and s is the number of premise variables. The overall fuzzy model achieved by fuzzy blending of each individual linear model is described by

$$\begin{cases} x(k+1) = \sum_{i=1}^{q} h_i(\xi(k))[A_i x(k) + B_i u(k) + E_i f(k) + D_i d(k)], \\ y(k) = Cx(k), \end{cases} \tag{2}$$

where

$$\xi(k) = [\xi_1(k), \ldots, \xi_s(k)], \quad h_i(\xi(k)) = \frac{\sigma_i(\xi(k))}{\sum_{i=1}^{q} \sigma_i(\xi(k))}, \quad \sigma_i(\xi(k)) = \prod_{j=1}^{s} \pi_{ij}(\xi_j(k))$$

and $\pi_{ij}(\cdot)$ is the grade of the membership function of π_{ij}. It is supposed that

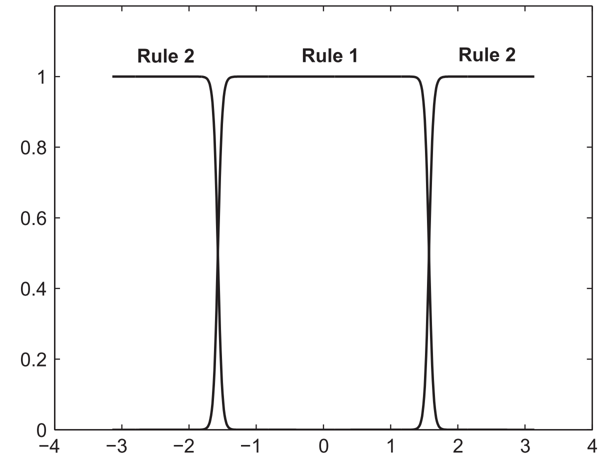

Fig. 1. Membership functions of the two rules.

$$\sigma_i(\xi(k)) \geq 0, \quad i = 1, \ldots, q, \quad \sum_{i=1}^{q} \sigma_i(\xi(k)) > 0$$

for any $\xi(k)$, then $h_i(\xi(k))$ satisfies

$$h_i(\xi(k)) \geq 0, \quad i = 1, \ldots, q, \quad \sum_{i=1}^{q} h_i(\xi(k)) = 1$$

for any $\xi(k)$.

For the sake of clarity, the following notations are defined:

$$h_i = h_i(\xi(k)), \quad A(h) = \sum_{i=1}^{q} h_i(\xi(k))A_i, \quad B(h) = \sum_{i=1}^{q} h_i(\xi(k))B_i,$$
$$E(h) = \sum_{i=1}^{q} h_i(\xi(k))E_i, \quad D(h) = \sum_{i=1}^{q} h_i(\xi(k))D_i,$$

then the T–S fuzzy model (2) becomes

$$\begin{cases} x(k+1) = A(h)x(k) + B(h)u(k) + E(h)f(k) + D(h)d(k), \\ y(k) = Cx(k), \end{cases} \tag{3}$$

Before giving main results, the following a assumption and two lemmas are presented.

Assumption 1. The disturbance distributed matrix $D := D_1 = D_2 = \cdots = D_q$ and matrix (CD) is full column rank.

Remark 1. Assumption 1 is not very restrictive because for many nonlinear systems, the input channel of the external disturbance is unchanged [16]. The condition that the matrix (CD) is full column rank is almost used in the UIO design [23,27].

Lemma 1 (*Iwasaki and Hara [28]*). *Consider a prescribed H_∞ performance level γ, the following discrete-time linear system:*

$$\begin{cases} \mathcal{X}(k+1) = \mathcal{A}\mathcal{X}(k) + \mathcal{B}\mathcal{U}(k) \\ \mathcal{Y}(k) = \mathcal{C}\mathcal{X}(k) + \mathcal{D}\mathcal{U}(k) \end{cases} \tag{4}$$

satisfies the H_∞ performance index $\| \mathcal{Y}(k)\|_2 < \gamma \| \mathcal{U}(k)\|_2$ if there exist a symmetric matrix P and a symmetric positive definite matrix Q such that the following conditions hold:

$$\begin{bmatrix} \mathcal{A} & \mathcal{B} \\ I & 0 \end{bmatrix}^T \Xi \begin{bmatrix} \mathcal{A} & \mathcal{B} \\ I & 0 \end{bmatrix} + \begin{bmatrix} \mathcal{C} & \mathcal{D} \\ 0 & I \end{bmatrix}^T \Pi \begin{bmatrix} \mathcal{C} & \mathcal{D} \\ 0 & I \end{bmatrix} < 0, \tag{5}$$

where

$$\Pi = \begin{bmatrix} \frac{1}{\gamma} I & 0 \\ 0 & -\gamma I \end{bmatrix}$$