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Letters

Fault detection for interval type-2 fuzzy systems with sensor nonlinearities ☆

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ABSTRACT

This paper deals with the fault detection problem for interval type-2 (IT2) fuzzy systems subject to sensor nonlinearities. By using a general observer-based fault detection filter as a residual generator, the fault detection problem is described as a filter design problem. The fault detection filter is designed to guarantee the prescribed H_∞ performance level. A decomposition approach is employed to handle the characteristic of sensor saturation. Using Lyapunov stability theory, a novel type of IT2 fault detection filter is designed to guarantee that the fault detection system is asymptotically stable with an H_∞ performance. In the design procedure, the parameters of the IT2 filter can be solved by the standard software. The IT2 fuzzy model and IT2 fuzzy filter do not require to share the same lower and upper membership functions. A numerical example is given to demonstrate the feasibility and effectiveness of the proposed method.

1. Introduction

It is well known that fuzzy logic control theory has been proposed as an effective approach to approximate the complex nonlinear systems for the control design objective [1–4]. Over the past years, fuzzy logic control method has been widely used in many practical applications. Recently, the Takagi–Sugeno (T–S) [5] fuzzy systems have attached considerable attention because it is effective to analyze and synthesize nonlinear systems such as chemical processes, automotive systems, robotics systems and many manufacturing processes. The results on stability analysis, controller synthesis and filter design of fuzzy systems were reported in [6–26]. To mention a few, the authors in [21] considered the reliable fuzzy control problem for uncertain suspension systems with actuator faults. Recently, the fault detection problem has been proposed in [27–29]. Based on a residual signal, the residual evaluation function is used to compare with a predefined threshold. An alarm of fault is presented such that the residual evaluation function has a value larger than the threshold. However, it should be mentioned that the above results are under the condition of type-1 T–S fuzzy sets and are available when the grades of membership are certain in the T–S fuzzy systems.

Therefore, it should be pointed out that the control problem of type-1 T–S fuzzy models cannot be addressed if the membership functions contain uncertainty information. Once the nonlinear plant is subject to parameter uncertainties, it will lead to the grades of membership uncertain in value. A basic IT2 fuzzy logic model was proposed in [30], which can be used to handle the nonlinear plants. It has been shown that the IT2 fuzzy logic systems have the superiority performance than the type-1 T–S fuzzy logic models in the aspect of handling parameter uncertainties. The IT2 fuzzy models have attached considerable attention and many control design results have been proposed in [31,32]. Moreover, using the lower and upper membership functions, the authors in [33,34] have dealt with the problem of the IT2 fuzzy systems subject to parameter uncertainties. However, the problem of sensor nonlinearities for IT2 fuzzy systems has not been studied and there are no results about fault detection for IT2 fuzzy systems. It is a valuable research direction to handle the problem of fault detection for IT2 fuzzy systems with sensor nonlinearities.

Motivated by the above discussion, this paper investigates the fault detection problem for the IT2 fuzzy systems subject to sensor

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nonlinearities. The output considered in this paper of IT2 fuzzy systems is a general sector-bounded nonlinearities. The IT2 fuzzy model and IT2 fuzzy fault detection filter do not require to share the same lower and upper membership functions. By using a general observer-based fault detection filter as a residual generator, the fault detection problem is described as a filter design problem. The fault detection filter is designed to guarantee the prescribed H_∞ performance level. A decomposition approach is employed to handle the characteristic of sensor saturation. Using Lyapunov stability theory, a novel type of IT2 fault detection filter is designed to guarantee that the fault detection system is asymptotically stable with an H_∞ performance. In the design procedure, the parameters of the IT2 filter can be solved by the standard software. A numerical example is provided to demonstrate the feasibility and effectiveness of the proposed method. The remaining of this paper is as follows. Section 2 introduces IT2 fuzzy systems, constructs the IT2 filter and presents the fault detection for IT2 fuzzy systems. Section 3 proposes stability conditions based on the Lyapunov stability theory for the IT2 fuzzy systems and Section 4 provides an illustrative example to show the effectiveness of the proposed results. Section 5 concludes this paper.

Notation: The superscripts "T" and "-1" stand for matrix transposition and inverse, respectively. R^n denotes the n-dimensional Euclidean space and the notation $P>0(\geq 0)$ stands for a symmetric and positive definite (semi-definite). In symmetric block matrices or complex matrix expressions, we use an asterisk ($\star$) to represent a term that is induced by symmetry and diag$\{\cdots\}$ stands for a block-diagonal matrix. $He(A)$ is defined as $He(A)=A+A^T$ for simplicity. Matrices, if the dimensions are not explicitly stated, are assumed to be compatible for algebraic operations. The space of square-integrable vector functions over $[0,\infty)$ is denoted by $L_2[0,\infty)$, and for $\zeta=\{\zeta(t)\}\in L_2[0,\infty)$, its norm is denoted by $\|\zeta\|_2=\sqrt{\int_{t=0}^{\infty}|\zeta(t)|^2\,dt}$.

2. Problem formulation

2.1. IT2 T–S fuzzy model

Consider the following IT2 fuzzy model that represents a continuous-time nonlinear system with r rules:

Plant Rule i : **IF** $\digamma_1(x(t))$ *is* $\tilde{M}_1^i$ *AND* $\cdots$ *AND* $\digamma_p(x(t))$ *is* $\tilde{M}_p^i$, **THEN**:

$$\dot{x}(t)=A_ix(t)+B_iw(t)+B_{1i}f(t),$$
$$y(t)=\phi(C_ix(t))+D_iw(t)+D_{1i}f(t), \tag{1}$$

where $\tilde{M}_a^i$ is an IT2 fuzzy set of rule i corresponding to the function $\digamma_a(x(t))$, $i=1,2,\ldots,r$; $a=1,2,\ldots,p$; p is a positive integer; $x(t)\in R^n$ is the system state vector, $w(t)\in R^q$ is the disturbance input and $f(t)\in R^m$ is the fault to be detected; $y(t)\in R^l$ is the measure output; A_i, B_i, B_{1i}, C_i, D_i and D_{1i} are the known matrices with appropriate dimensions. The firing strength of the i-th rule is the following interval sets:

$$W_i(x(t))=[\underline{w}_i(x(t)),\ \overline{w}_i(x(t))],\quad i=1,2,\ldots,r, \tag{2}$$

where $\underline{w}_i(x(t))=\prod_{a=1}^{p}\underline{\mu}_{\tilde{M}_a^i}(\digamma_a(x(t)))\geq 0$ and $\overline{w}_i(x(t))=\prod_{a=1}^{p}\overline{\mu}_{\tilde{M}_a^i}(\digamma_a(x(t)))\geq 0$ denote the lower and upper grades of membership, respectively. $\underline{\mu}_{\tilde{M}_a^i}(\digamma_a(x(t)))\geq 0$ and $\overline{\mu}_{\tilde{M}_a^i}(\digamma_a(x(t)))\geq 0$ stand for the lower and upper membership functions, respectively. Therefore, it can be found that $\overline{\mu}_{\tilde{M}_a^i}(\digamma_a(x(t)))\geq\underline{\mu}_{\tilde{M}_a^i}(\digamma_a(x(t)))$ and $\overline{w}_i(x(t))\geq\underline{w}_i(x(t))$ for all i. Then, the IT2 T–S fuzzy system is described as follows:

$$\dot{x}(t)=\sum_{i=1}^{r}\tilde{w}_i(x(t))[A_ix(t)+B_iw(t)+B_{1i}f(t)],$$
$$y(t)=\sum_{i=1}^{r}\tilde{w}_i(x(t))[\phi(C_ix(t))+D_iw(t)+D_{1i}f(t)], \tag{3}$$

where

$$\tilde{w}_i(x(t))=\underline{a}_i(x(t))\underline{w}_i(x(t))+\overline{a}_i(x(t))\overline{w}_i(x(t))\geq 0\ \ \forall i,\quad \sum_{i=1}^{r}\tilde{w}_i(x(t))=1,$$

$0\leq\underline{a}_i(x(t))\leq 1$ and $0\leq\overline{a}_i(x(t))\leq 1$ are nonlinear functions and possess the trait of $\underline{a}_i(x(t))+\overline{a}_i(x(t))=1$ for all i.

Many actual applications will inevitably result in the nonlinear characteristic of sensors. Here, the function $\phi(u)$ in system (3) is assumed to belong to $[K_1,K_2]$, for some given diagonal matrices $K_1\geq 0$ and $K_2\geq 0$ with $K_2>K_1$, and satisfies the following sector condition:

$$(\phi(u)-K_1u)^T(\phi(u)-K_2u)\leq 0,\quad \forall u\in R^l. \tag{4}$$

2.2. IT2 fuzzy filter design

An IT2 fuzzy filter with r rules is constructed as follows:

Rule j : **IF** $g_1(x(t))$ *is* $\tilde{N}_1^j$ *AND* $\cdots$ *AND* $g_l(x(t))$ *is* $\tilde{N}_l^j$, **THEN**:

$$\dot{\hat{x}}(t)=A_{fj}\hat{x}(t)+B_{fj}y(t),$$
$$z_f(t)=C_{fj}\hat{x}(t), \tag{5}$$

where $\tilde{N}_\beta^j$ is an IT2 fuzzy set of rule j corresponding to the function $g_\beta(x(t))$, $j=1,2,\ldots,r$; $\beta=1,2,\ldots,l$; l is a positive integer; A_{fj}, B_{fj} and C_{fj} are the filter parameters to be designed. The firing strength of the j-th rule is the following interval sets:

$$M_j(x(t))=[\underline{m}_j(x(t)),\overline{m}_j(x(t))],\quad j=1,2,\ldots,r,$$

where $\underline{m}_j(x(t))=\prod_{\beta=1}^{l}\underline{\mu}_{\tilde{N}_\beta^j}(g_\beta(x(t)))\geq 0$ and $\overline{m}_j(x(t))=\prod_{\beta=1}^{l}\overline{\mu}_{\tilde{N}_\beta^j}(g_\beta(x(t)))\geq 0$ stand for the lower and upper grades of membership, respectively. $\underline{\mu}_{\tilde{N}_\beta^j}(g_\beta(x(t)))\geq 0$ and $\overline{\mu}_{\tilde{N}_\beta^j}(g_\beta(x(t)))\geq 0$ denote the lower and upper membership functions, respectively. Here, $\overline{\mu}_{\tilde{N}_\beta^j}(g_\beta(x(t)))\geq\underline{\mu}_{\tilde{N}_\beta^j}(g_\beta(x(t)))$ leading to $\overline{m}_j(x(t))\geq\underline{m}_j(x(t))$ for all j. The overall IT2 fuzzy filter is proposed as follows:

$$\dot{\hat{x}}(t)=\sum_{j=1}^{r}\tilde{m}_j(x(t))[A_{fj}\hat{x}(t)+B_{fj}y(t)],$$
$$z_f(t)=\sum_{j=1}^{r}\tilde{m}_j(x(t))C_{fj}\hat{x}(t), \tag{6}$$

where

$$\tilde{m}_j(x(t))=\frac{\underline{\beta}_j(x(t))\underline{m}_j(x(t))+\overline{\beta}_j(x(t))\overline{m}_j(x(t))}{\sum_{k=1}^{r}(\underline{\beta}_k(x(t))\underline{m}_k(x(t))+\overline{\beta}_k(x(t))\overline{m}_k(x(t)))}\geq 0,\quad \forall j,$$
$$\sum_{j=1}^{r}\tilde{m}_j(x(t))=1,$$

in which $0\leq\underline{\beta}_j(x(t))\leq 1$ and $0\leq\overline{\beta}_j(x(t))\leq 1$ are predefined functions and possess the trait of $\underline{\beta}_j(x(t))+\overline{\beta}_j(x(t))=1$ for all j.

To improve the performance of the fault detection system, we add a weighting matrix function into the fault $f(s)$. Here, $f_w(s)=W(s)f(s)$, where $f(s)$ and $f_w(s)$ denote, respectively, the Laplace transforms of $f(t)$ and $f_w(t)$. One state-space realization of $f_w(s)=W(s)f(s)$ can be described as

$$\dot{x}_w(t)=A_wx_w(t)+B_wf(t),$$
$$f_w(t)=C_wx_w(t),$$
$$x_w(0)=0, \tag{7}$$