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H_∞ filtering for T–S fuzzy networked systems with stochastic multiple delays and sensor faults

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ABSTRACT

This paper deals with the problem of H_∞ filter design for a class of nonlinear networked systems based on T–S fuzzy model with multiple stochastic time-varying delays, and sensor faults and packet dropouts are considered simultaneously. A sequence of stochastic and independent variables, which obey the Bernoulli distribution, are introduced to depict stochastic time-varying delays. The possible of sensor failure can be described by unrelated random variables taking values on an interval, and the packet dropouts are described as a set of Bernoulli distributed white noises. The approach of piecewise quadratic Lyapunov function is applied to reduce the conservatism. The filter parameters are obtained by solving a set of linear matrix inequalities. Finally, a simulation example is provided to illustrate the effectiveness of the proposed filter design approach.

1. Introduction

It is generally known that the issue of state/signal estimation has been discussed in the areas of control and signal processing. One of the most famous methods is Kalman filtering, which was put forward in [1]. However, it is very difficult to know the knowledge of noises as a prior, which is required in Kalman filtering in some practical systems. In order to solve this problem, H_∞ filtering approach was introduced. One of the advantages of using H_∞ filter over Kalman filter is that no distribution characteristic on the noise is needed. Besides, H_∞ filtering provides stronger robustness over Kalman filtering. Owing to those advantages, much attention has been paid to the H_∞ filtering, and various results on this topic have been reported in literature (see, e.g., [2–9,24,30,34] and references there in).

During the past few years, fuzzy systems based on Takagi–Sugeno (T–S) model have been well investigated in [2,3,6,8–10,12,14–20,26–30,33]. The T–S fuzzy model is made up of a set of local linear models which are smoothly connected by nonlinear fuzzy membership functions. It has been proved that the approach is an efficient one to approximate complex nonlinear systems with arbitrary precision [10]. Recently, some results on the design of filters for T–S fuzzy systems with the approaches based on common quadratic Lyapunov functions have been reported, see, e.g., [11,13]. However, it has been known that the methods tend to be conservative, and even more, a common quadratic Lyapunov function might not exist especially for highly nonlinear complex systems. In [15], a convex piecewise affine controller design method is proposed based on a new dilated LMI characterization, where the system matrix is separated from Lyapunov matrix such that the controller parametrization is independent of the Lyapunov matrix. In [16], delay-dependent H_∞ controller has been designed for T–S fuzzy systems based on a switching fuzzy model, and H_∞ performance is guaranteed by adopting an approach of piecewise Lyapunov function. To reduce the conservatism, stability analysis of fuzzy systems based on the piecewise quadratic Lyapunov functions has been considered in [6,15]. Similar work can be found in [17,19], and references therein.

It is well known that one of the most important issues that lead to the systems performance deterioration is time-delay. So far, the stability and filter design problems for networked systems or T–S fuzzy systems with network-induced delays have been investigated by many researchers [11,13,19–24,26,27,31–34,36]. In [19], H_∞ controller for discrete-time T–S fuzzy systems with time-varying state delays has been investigated. A fuzzy controller has been designed for nonlinear impulsive fuzzy systems with time-delay in [20]. Since network delays are usually time-varying and stochastic, recently, the delays have been modeled in various probabilistic

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ways [21–23]. On the other hand, packet dropouts have attracted much attention because it may result in the bad performance, and even instability of the system [23–25]. Robust H_∞ filtering for a class of nonlinear networked systems with randomly occurring distributed delays, missing measurements and sensor saturation has been discussed in [23], where the occurrence probability of the packet dropout phenomenon obeys an individual and certain probabilistic distribution taking values on 0 and 1. In [24], Dong et al. consider robust H_∞ fuzzy output feedback control with multiple probabilistic delays and multiple packet dropouts, where the packet dropout phenomenon occurs randomly.

Besides, sensor faults always occur in the practical control systems, which may affect the performance of systems. Therefore, there is a practical interest to consider the sensor faults. Up to now, a great deal of literatures have been reported on the sensor faults [34–39]. In [37], the control problem of a class of T–S fuzzy systems with stochastic sensor faults has been studied. The fault statistics of each sensor is individually quantified and stochastic sensor faults and non-ideal network quality of services are coupled in a unified framework. To the best of the authors' knowledge, the problem of networked H_∞ filtering for T–S fuzzy systems with stochastic sensor faults, packet dropouts and multiple stochastic time-varying delays being considered simultaneously has not been fully investigated, which motivates us to study on this problem. The main contributions of this paper can be concluded as follows: (i) networked H_∞ filtering with multiple stochastic time-varying communication delays, stochastic sensor faults and packet dropout phenomena are simultaneously considered in the T–S fuzzy systems framework; (ii) an approach of piecewise quadratic Lyapunov functional is adopted to reduce the conservatism of the results.

By concluding the above discussion, in this paper, our aim is to provide the T–S fuzzy-model-based piecewise H_∞ filter design for networked control systems, which include multiple stochastic time-varying communication delays, sensor faults and successive data missing phenomenon. Both the sensor faults and packet dropouts in the measurement equation are considered. Moreover, packet dropouts are described by a Bernoulli random process.

The rest of the paper is organized as follows. System descriptions and problem formulations are presented in Section 2. In Section 3, fuzzy filter is designed with piecewise quadratic Lyapunov function. A simulation is conducted to demonstrate that the performance of the system can be guaranteed with the proposed approaches in Section 4 and the conclusion is provided in Section 5.

Notations: The notations throughout the paper are fairly standard. The superscript "T" stands for matrix transpose; $\mathbb{R}^n$ denotes the n-dimensional Euclidean space; $\mathbb{R}^{m\times n}$ is the set of all real $m \times n$ matrices; and I_n represents $n \times n$ identity matrix; and $0_{m\times n}$ represents $m \times n$ zero matrix, respectively. $P>0$ means that P is a real symmetric and positive definite. We use an asterisk ($*$) to represent a term that is induced by symmetry in symmetric matrices, and $diag\{\cdots\}$ stands for a block-diagonal matrix, respectively. $\mathbb{E}\{x\}$ and $\mathbb{E}\{x|y\}$ stand for the expectation of x and the expectation of x conditional on y, and $\lambda_{max}(A)$ and $\lambda_{min}(A)$ denote the largest and the smallest eigenvalue of the square matrix A, respectively. $\mathcal{L}_2[0,\infty)$ denotes the space of square-integrable vector functions over $[0,\infty)$.

2. System descriptions and problem formulations

In this section, we use a T–S fuzzy model to represent the nonlinear physical plant. The measured information received from the plant is transmitted via the shared communication channel, where the sensor faults and the randomly occurring data missing phenomena happen. In what follows, physical plant will be modeled.

2.1. T–S fuzzy model of nonlinear physical plant

Consider a discrete T–S fuzzy model with r fuzzy rules, and the i-th fuzzy rule is as follows R^i : IF $\xi_1(k)$ is W_{i1}, and…, $\xi_g(k)$ is W_{ig} THEN

$$\begin{cases} x(k+1)=A_i x(k)+A_{di}\sum_{m=1}^{q}\alpha_m(k)x(k-\tau_m(k))+B_i w(k) \\ y(k)=C_i x(k) \\ z(k)=L_i x(k) \end{cases} \tag{1}$$

where R^i ($i\in\Re\triangleq 1,2,\ldots,r$) denotes the i-th fuzzy inference rule, r is the number of fuzzy implications. $\xi(k)=(\xi_1(k),\xi_2(k),\ldots,\xi_g(k))\in\mathbb{R}^g$ is the premise variable vector and assumed to be measurable. W_{ij} ($j=1,2,\ldots,g$) are the fuzzy set, $x(k)\in\mathbb{R}^n$ is the state vector, $y(k)\in\mathbb{R}^m$ is the system measurement output, and $z(k)\in\mathbb{R}^p$ is the signal to be estimated, $w(k)\in\mathbb{R}^q$ is the external disturbance input vector belonging to $\mathcal{L}_2[0,\infty)$, and $\tau_m(k)$ ($m=1,2,\ldots,q$) are randomly time-varying communication delays. (A_i, A_{di}, B_i, C_i, L_i) stands for the ith local model of the fuzzy system.

The stochastic variables $\alpha_m(k)$ ($m=1,2,\ldots,q$) in (1) are Bernoulli distributed white noise sequences and satisfy

$$Prob\{\alpha_m(k)=1\}=\overline{\alpha}_m \quad \text{and} \quad Prob\{\alpha_m(k)=0\}=1-\overline{\alpha}_m$$

Assumption 1. The communication delays $\tau_m(k)$ ($m=1,2,\ldots,q$) are time-varying and satisfy $\tau_1\le\tau_m(k)\le\tau_2$, where τ_1 and τ_2 are constant positive scalars representing the lower and upper bounds on the communication delays, respectively.

By using a singleton fuzzifier, product fuzzy inference, and center-average defuzzifier, the T–S fuzzy system (1) can be described as follows:

$$\begin{cases} x(k+1)=\sum_{i=1}^{r}h_i(\xi(k))\left[A_i x(k)+A_{di}\sum_{m=1}^{q}\alpha_m(k)x(k-\tau_m(k))+B_i w(k)\right] \\ y(k)=\sum_{i=1}^{r}h_i(\xi(k))C_i x(k) \\ z(k)=\sum_{i=1}^{r}h_i(\xi(k))L_i x(k) \end{cases} \tag{2}$$

where

$$h_i(\xi(k))=\frac{\prod_{j=1}^{g}W_{ij}(\xi(k))}{\sum_{i=1}^{r}\prod_{j=1}^{g}W(\xi(k))} \tag{3}$$

Therefore, for all k, $h_i(\xi(k))$ satisfies

$$h_i(\xi(k))\ge 0,\qquad \sum_{i=1}^{r}h_i(\xi(k))=1 \tag{4}$$

In what follows, for simple to write, we rewrite Eq. (2) as

$$\begin{cases} x(k+1)=A(h)x(k)+A_d(h)\sum_{m=1}^{q}\alpha_m(k)x(k-\tau_m(k))+B(h)w(k) \\ y(k)=C(h)x(k) \\ z(k)=L(h)x(k) \end{cases} \tag{5}$$

where

$$\begin{bmatrix} A(h) & A_d(h) & B(h) \\ C(h) & 0 & 0 \\ L(h) & 0 & 0 \end{bmatrix}=\sum_{i=1}^{r}h_i\begin{bmatrix} A_i & A_{di} & B_i \\ C_i & 0 & 0 \\ L_i & 0 & 0 \end{bmatrix}$$