Neurocomputing 171 (2016) 185–193

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Tracking control for polynomial fuzzy networked systems with repeated scalar nonlinearities ☆

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ARTICLE INFO

Article history:
Received 10 March 2015
Received in revised form
7 May 2015
Accepted 18 June 2015
Communicated by Hui Zhang
Available online 2 July 2015

Keywords:
Networked systems
Polynomial fuzzy model
Repeated scalar nonlinearities
Data packet dropouts
Signal quantization
H_∞ control

ABSTRACT

This paper investigates the tracking control problem for nonlinear networked systems with repeated scalar nonlinearities. A polynomial fuzzy model based approach is employed to model the nonlinear systems. A polynomial fuzzy controller is designed to drive the system states to follow those of a given reference model. Imperfect communication links with two typical phenomenons (i.e., data packet dropout and signal quantization) are taken into account. Sufficient conditions are obtained in terms of sum of squares, which guarantee the stochastic stability and H_∞ performance constraint. Finally, a simulation example is given to illustrate the effectiveness of the proposed method.

1. Introduction

The research of nonlinear systems has got considerable progress as many effective approaches have been developed [18,22,24,34,37,38,41,42] . In the literature, the T–S fuzzy model based approach occupies an important part of the area, on account of its high capacity on modeling nonlinear systems as combinations of local linear systems [2,17,19–21,26,29,30,35,40,43,44]. In consequence, efficient results can be developed based on the linear system theory. Recently, the T–S fuzzy model based approach has been generalized into polynomial fuzzy model based (PFMB) approach [32]. The motivations of that work are to simplify the modeling process and obtain more relaxed conditions [15,16,23,27,31]. To mention a few, the stability analysis was presented for polynomial fuzzy systems via piecewise-linear membership functions in [13]. An output-feedback polynomial fuzzy controller was designed to solve the H_∞ tracking control problem in [14]. On the other hand, the study on networked systems has become an active area with the advances of information technology [7,9,25,33]. Since all the components of the systems are on the distributed locations, new challenges, such as data packet dropouts, transmission delay and signal quantization, are introduced in the networked communication channels [5,8,39]. By considering network induced issues, the stabilization problem was studied based on T–S fuzzy model in [10], and the tracking control problem was investigated in [11]. To the authors' knowledge, few results on tracking control for networked polynomial fuzzy systems have beenreported which represents one of the motivations of this paper.

The nonlinear difference equation in the form of $x_{k+1}=A(x_k)\phi(x_k)+B(x_k)u_k$ describes a system with a repeated scalar nonlinearity, where $\phi(x_k)$ is a function in x_k [1,3,4,12]. This type of model represents a class of nonlinearities which is analogous to considering an upper linear fractional transformation with respect to a repeated scalar block as a nonlinear one [1]. With appropriate assumption on the function ϕ, some useful results have been developed. For example, the stability, the l_2-l_2 induced gain, the observability and the controllability were studied in [3], where the function ϕ is assumed to be odd, 1-Lipschitz, and its norm is not larger than 1. Assuming the nonlinear function on each state is not identical and $\phi_i(x_{ik})$ satisfies $\phi_i(x_{ik}) \le |x_{ik}|$, the stability and l_2-l_2 induced gain conditions were proposed in [12]. Moreover, sufficient conditions for l_2-l_2 induced gain and model reduction were investigated in [4]. However, to the authors' knowledge, the tracking control problem for systems with

☆This work was partially supported by the National Natural Science Foundation of China (61203002, 61273106, 61473151), the Program for New Century Excellent Talents in University (NCET-13-0859, NCET-13-0696), the Zijin Intelligent Program of the Nanjing University of Science and Technology (2013 ZJ 0104).
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http://dx.doi.org/10.1016/j.neucom.2015.06.030
0925-2312/

repeated scalar nonlinearities has not been investigated, which remains open and challenge.

In this paper, the H_∞ tracking control problem for networked nonlinear systems with repeated scalar nonlinearities is investigated. A novel lemma is developed to handle the repeated scalar nonlinearities based on a proposed assumption. Polynomial fuzzy model based approach is employed to model the nonlinear systems and a polynomial fuzzy controller is designed to drive the system states to follow those of a given reference model. Imperfect communication links with data packet dropout and signal quantization are taken into account. The control system can represent a class of networked systems with digital communication channel, such as satellite system and unmanned aircraft systems. Sufficient conditions are obtained in terms of sum of squares (SOS) to guarantee the stochastic stability and H_∞ performance constraint. Finally, a simulation example is given to illustrate the effectiveness of the proposed method.

The remaining part of this paper is organized as follows. Section 2 gives the descriptions of the polynomial fuzzy systems with repeated scalar nonlinearities and formulates the problem to be considered. Section 3 analyzes the tracking control problem and the H_∞ performance, then sufficient conditions are developed to solve that problem via the Lyapunov stability theory. A simulation example is exploited to demonstrate the effectiveness of the proposed approach in Section 4 and we conclude this paper in Section 5.

Notations: Some notations are employed in the paper. For instance, "$*$" represents the transposed elements of the symmetric matrix. Identity matrices with appropriate dimensions will be denoted by I. The superscripts "T" and "-1" denote the matrix transpose and inverse respectively. Furthermore, $\mathbb{E}\{x|y\}$ and $\mathbb{E}\{x\}$ signify the mathematical expectation of x conditional on y and the mathematical expectation of x, respectively.

2. Problem formulation

In this section, we consider a PFMB NCSs as shown in Fig. 1. The system information is extracted from the plant and the reference model is transported into the network channel through the sensor. Once the information is received by the controller, the control signal will be formulated based on a predefined scheme and then transmitted to the actuator after being quantized through the network. The physical plant is modeled as a polynomial fuzzy system with repeated scalar nonlinearities, and a polynomial fuzzy state-feedback controller is designed to drive the states of the plant to follow those of a predefined reference model. As the components of the closed-loop system are distributed on the network, data packets dropout and data quantization will occur.

2.1. Polynomial fuzzy model

The PFMB discrete-time systems with repeated scalar nonlinearities are represented as follows:

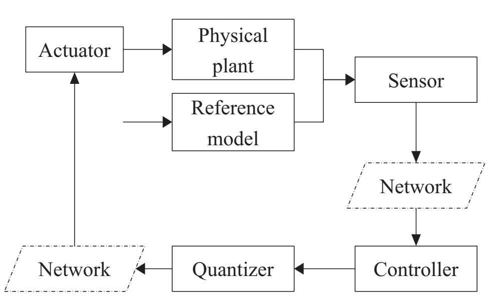

Fig. 1. Diagram of PFMB NCSs.

Plant Rule i : IF $f_1(x_k)$ is N_{i1}, and …, and $f_j(x_k)$ is N_{ij}, and …, and $f_p(x_k)$ is N_{ip}, THEN

$$x_{k+1} = A_i(x_k)\phi(x_k) + B_{2i}(x_k)u_k + B_{1i}(x_k)\omega_k, \tag{1}$$

where $x_k \in R^n$ is the state vector, $u_k \in R^m$ is the control input vector, $\omega_k \in R^c$ is the process disturbance. $A_i(x_k) \in R^{n\times n}$, $B_{2i}(x_k) \in R^{n\times m}$ and $B_{1i}(x_k) \in R^{n\times c}$ are the polynomial system matrices. $i \in 1, 2, \ldots, r$, the scalar r is the number of IF–THEN rules. N_{ij} and $f_j(x_k)$ are the fuzzy set and the premise variable respectively, $j = 1, 2, \ldots, p$. $\phi(x_k)$ is a nonlinear function with respect to x_k. The global model of dynamic system can be inferred from the following representation:

$$x_{k+1} = \sum_{i=1}^{r} w_i(x_k)\left[A_i(x_k)\phi(x_k) + B_{2i}(x_k)u_k + B_{1i}\omega_k\right], \tag{2}$$

where $w_i(x_k) = \mu_i(x_k)/\sum_{i=1}^{r}\mu_i(x_k)$, $\mu_i(x_k) = \prod_{j=1}^{p} N_{ij}(f_j(x_k))$ and $N_{ij}(f_j(x_k))$ is the grade of the membership of $f_j(x_k)$ in fuzzy set N_{ij}. Usually, it is assumed that $\mu_i(x_k) \ge 0$ for $i = 1, 2, \ldots, k$ and $\sum_{i=1}^{r}\mu_i(x_k) > 0$ for all i. Therefore, $w_i(x_k) \ge 0$ (for $i = 1, 2, \ldots, k$) and $\sum_{i=1}^{r} w_i(x_k) = 1$.

Remark 1. If system matrices $A_i(x_k)$, $B_{1i}(x_k)$ and $B_{2i}(x_k)$ are constant matrices and $\phi(x_k) = x_k$, the polynomial fuzzy system will be reduced to the traditional T–S fuzzy system.

2.2. Reference model

A stable reference model is defined as follows:

$$x_{rk+1} = A_r\phi(x_{rk}) + B_r r_k, \tag{3}$$

where $x_{rk} \in R^n$ is the state vector of the reference model, $A_r \in R^{n\times n}$ and $B_r \in R^{n\times m}$ are the system and input matrices, respectively, $r_k \in R^m$ is the reference input vector.

Remark 2. The reference model is required to be stable by choosing appropriate matrices A_r and B_r. However, the matrices are not only limited to be constant matrices, but also polynomial matrices.

2.3. Polynomial fuzzy controller

In order to deal with the tracking problem considered in this paper, a state-feedback polynomial fuzzy controller is presented to drive the states of the system in (2) to follow those of the system in (3). Denote the state error as

$$e_k = x_k - x_{rk},$$

referring to the systems with repeated scalar nonlinearities in (2) and (3), we also define the following error:

$$\hat{e}_k = \phi(x_k) - \phi(x_{rk}),$$

thus, the polynomial fuzzy controller is described as

Controller Rule i: IF $f_1(x_k)$ is N_{i1}, and …, and $f_j(x_k)$ is N_{ij}, and …, and $f_p(x_k)$ is N_{ip}, THEN

$$\hat{u}_k = K_i(\overline{x}_k)\hat{e}_k + G_i(\overline{x}_k)\phi(x_{rk}), \tag{4}$$

where $K_i(\overline{x}_k)$, $G_i(\overline{x}_k) \in R^{n\times m}$ $(i = 1, 2, \ldots, r)$ are the polynomial state-feedback gain matrices with respect to $\overline{x}_k$. $\hat{u}_k$ denotes the output of the controller. Similar to the modeling process of the plant, we have the defuzzification of the fuzzy controller as

$$\hat{u}_k = \sum_{i=1}^{r} w_i(x_k)\left[K_i(\overline{x}_k)\hat{e}_k + G_i(\overline{x}_k)\phi(x_{rk})\right], \tag{5}$$