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T–S fuzzy controller design for stabilization of nonlinear networked control systems

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ABSTRACT

This paper concerns with the problem of stabilization of nonlinear networked systems which are described by type-1 T–S fuzzy model. Based on Lyapunov–Krasovskii theorem, a novel procedure is derived to design a T–S fuzzy controller to asymptotically stabilize the nonlinear networked control system (NCS). The main novelty of the proposed method is to incorporate the grades of memberships of the plant model in the controller synthesis criterion which increases the maximum tolerable delay in the closed loop system. Two comparative examples are presented to verify the applicability and out-performance of the introduced scheme compared to some of existing approaches in the literature.

1. Introduction

Great advantages of growing communication technologies have stimulated industry practitioners to employ data networks in the control loops. Networked control systems (NCSs), wherein the components of the feedback loop share a common information medium, are found in a vast area of real-world applications such as automobiles and aerospace vehicles, large-scale distributed industrial processes and teleoperation systems. Easier installation and maintenance, simpler upgrading and more reliability are the most prominent benefits of these systems over traditional ones with the point-to-point wirings. However, issues such as data loss and latency in communication networks may cause weak performance or even instability in NCSs (L. Zhang et al., 2013; Gupta and Chow, 2010; Hespanha et al., 2007). So, overcoming these challenges has recently attracted many attentions. Various problems including stability analysis and stabilization of linear systems (Farsi and Mahboobi Esfanjani, 2015; Razeghi-Jahromi and Seyedi, 2015; Farnam and Mahboobi Esfanjani, 2014) and nonlinear systems (Al-Hadithi et al., 2015; Postoyan et al., 2014; Greco et al., 2012; Beikzadeh and Marquez, 2015), state estimation (Rezaei et al., 2015), fault detection (You et al., 2014; Peng et al., 2013) and system identification (Wang et al., 2009) have been investigated in the literature of NCSs.

Analysis and design of nonlinear NCSs have been more challenging research topics. In one line of study, the nonlinear controlled system is described by a T–S fuzzy model (Jia et al., 2008; Zhang et al., 2007a, 2007b, 2015; J. Zhang et al., 2013; Peng and Yang, 2010; Chen et al., 2014; Han et al., 2014; Lam and Leung, 2006; Kim, 2013). In this framework, nonlinear dynamics of the systems are represented as a weighted sum of some linear sub-dynamics so that the simple linear control methods can be applied to analysis and synthesis of the closed-loop system. The weights are grades of membership which determine the contribution of each sub-plant or sub-controller to the modeling or controlling tasks. In the most of aforementioned studies, the framework of time-delay systems is employed to formulate the unreliable communications between the components of the closed-loop system; therefore, the rich theory of time-delay systems can be utilized to handle the challenges of NCSs. It is worthy to note that in all of the mentioned papers, the parameters of the controllers were computed via sufficient design conditions which are presented in terms of LMIs that can be easily solved by existing efficient algorithms.

In Jia et al. (2008), considering network-induced delay and out-of-order packets in transmission, Lyapunov–Krasovskii theorem was used to design stabilizing control for a T–S fuzzy NCS. In Zhang et al. (2007a), similar idea was employed to develop a controller which guarantees a certain level of performance for T–S fuzzy system with a time-varying delay and possible packet dropouts. The performance measure was formulated by a cost function and the parameters of the state feedback control law were obtained by solving a set of LMIs. In order to reduce the conservativeness of the sufficient design conditions of Zhang et al. (2007a), the probability distribution of communication delay was taken into account in Peng and Yang (2010) and Chen et al. (2014)

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to obtain delay-distribution-dependent LMIs for controller design. In Zhang et al. (2015), a co-design algorithm was suggested to obtain simultaneously the controller gains and the event-triggering parameters for networked T–S fuzzy system. In Han et al. (2014), first a novel compensation method was proposed for the estimation of missing packets, then a piecewise state feedback controller was developed to asymptotically stabilize the NCS with guaranteed H∞ performance.

The main drawback of the existing methods is that the membership functions of fuzzy plant were not included in the LMIs which leads to conservativeness in the stability and stabilization conditions; while a precious technique was published in Lam and Leung (2005) for stability analysis of delay-free T–S fuzzy systems which incorporates the grades of membership functions in the final stability criterion.

In this paper, inspired by Lam and Leung (2005), fuzzy state feedback controller is developed to stabilize a nonlinear system which is controlled over a packet-delaying and dropping network. Differently from Jia et al. (2008), Zhang et al. (2007a), Peng and Yang (2010), Chen et al. (2014) and Lam and Leung (2006), Zhang et al. (2007b), Kim (2013) in the proposed procedure, the controller gains are obtained by solving a set of LMIs which contain the fuzzy membership grades of the plant model. In contrast to Lam and Leung (2005), the measurement and control signals are transmitted through a communication network, so the Lyapunov–Krasovskii theorem is utilized to extract controller synthesis condition. It is demonstrated that the presence of grades of memberships in the design criterion of T–S fuzzy NCS improves the maximum tolerable delay in the closed loop system. Two numerical examples are presented to illustrate the merits of the suggested method in comparison to the results of rival schemes in Lam and Leung (2006), Zhang et al. (2007b).

The rest of this paper is organized as follows. Section 2 presents the problem of stabilization of T–S fuzzy NCS subject to data delay and loss. Section 3 is dedicated to present the main results of the paper. The simulation examples are given in Section 4 to demonstrate the effectiveness of the proposed technique. At last, Section 5 concludes the paper.

Notations: $\mathfrak{R}$ denotes real numbers set. I is identity matrix of appropriate dimensions. The symbol $P>0$ (respectively, $P\geq 0$) means that P is real symmetric and positive definite (respectively, positive semidefinite). The superscript T stands for matrix transposition.

2. Problem description and preliminaries

In this section, the fuzzy model of the considered networked control system is explained and some useful facts are recalled from literature.

2.1. Fuzzy model of plant

Almost all nonlinear systems can be described by T–S fuzzy models to high degree of precision. Actually, it is proved that T–S fuzzy models are universal approximators of any smooth nonlinear dynamical system (Fantuzzi and Rovatti, 1996; Buckley, 1992). Therefore, considered nonlinear plant can be described by a T–S fuzzy model as follows:

Rule i: If $\theta_1(x(t))$ is w_1^i, $\theta_2(x(t))$ is w_2^i, … and $\theta_g(x(t))$ is w_g^i, Then

$$\dot{x}(t)=A_i x(t)+B_i u(t)$$

where, w_j^i is the fuzzy set of rule i corresponding to the function $\theta_j(x(t))$, for $j=1,2,\ldots,g$ and $i=1,2,\ldots,r$; in which g is a positive integer and r is the number of if–then rules. $x(t)\in\mathfrak{R}^{n\times 1}$ is the system state vector and $u(t)\in\mathfrak{R}^{m\times 1}$ is the input vector. $A_i\in\mathfrak{R}^{n\times n}$ and $B_i\in\mathfrak{R}^{n\times m}$ are known system and input matrices, respectively.

The inferred dynamical system is represented as follows:

$$\dot{x}(t)=\sum_{i=1}^{r} h_i(x(t))(A_i x(t)+B_i u(t)) \tag{1}$$

where nonlinear function $h_i(x(t))$ is defined as

$$h_i(x(t))=\frac{\Pi_{j=1}^{g}\mu_j^i(\theta_j(x(t)))}{\sum_{i=1}^{r}\Pi_{j=1}^{g}\mu_j^i(\theta_j(x(t)))} \tag{2}$$

in which, $\mu_j^i(\theta_j(x(t)))$ is the grade of membership corresponding to the fuzzy set w_j^i. Note that $0\leq h_i(x(t))\leq 1$ for $i=1,2,\ldots,r$ and $\sum_{i=1}^{r}h_i(x(t))=1$.

It is worth noting that in general, there are two main directions to construct T–S fuzzy models like (1): first, fuzzy identification using input–output data (Sugeno, 1988; Sugeno and Kang, 1988); second, derivation from nonlinear equations of system for the plants that are represented readily by analytical models. The latter scheme is based on the ideas of "sector nonlinearity", "local approximation in fuzzy partition space" or combination of them (Kawamoto et al., 1992; Ying, 2000).

2.2. Fuzzy model of networked control system

In the NCS depicted in Fig. 1, the information is exchanged with packets through a network where the data packets encounter variable delay and random dropout. In what follows, considering the effects of network-induced delay and loss in data transmission, the closed-loop system is modeled as a fuzzy differential equation with bounded time-varying delay.

In the considered NCS, the controller and the actuator are event-driven and sampler is clock-driven. The actual input of the system (1) is realized via a zero order hold (ZOH) device. The sampling period is assumed to be a positive constant T and the information of ZOH may be updated between sampling instants.

The updating instants of ZOH are denoted by t_k and τ_{sc} and τ_{ca} are the time-delays from the sampler to the controller (feedback) and from the controller to the ZOH (feedforward) at the updating instant t_k, respectively. So, the successfully transmitted data in the NCS at the instant t_k experience round trip delay $\tau_k=\tau_{sc}+\tau_{ca}$ which does not need to be restricted inside one sampling period. Regarding the role of ZOH, for a state sampled at $t_k-\tau_k$, the corresponding control signal would act on the plant from t_k unto t_{k+1}. Therefore, the fuzzy control input for $t_k\leq t<t_{k+1}$, is written as the following:

$$u(t)=\sum_{j=1}^{r} h_j(x(t_k-\tau_k))K_j x(t_k-\tau_k) \tag{3}$$

where $K_j\in R^{m\times n}$, $j=1,2,\ldots,r$ are the feedback gains to be determined; t_{k+1} is the next updating instant after t_k and the variable delay, τ_k is bounded as $\tau_k\leq\tau_{\max}$.

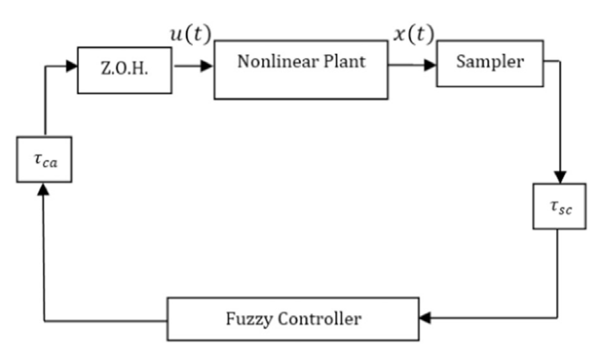

Fig. 1. Considered networked control system.