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Quantized feedback fuzzy sliding mode control design via memory-based strategy

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ABSTRACT

This paper is concerned with the sliding mode control (SMC) design for a class of Takagi–Sugeno (T–S) fuzzy nonlinear systems subject to model uncertainties and input quantization mismatch. A novel memory-based sliding surface is presented which includes not only the current states but also the past state information of the systems. Sufficient conditions for the design of the switching gains are given via linear matrix inequality(LMI) technique, and then the reaching conditions of the sliding surface is constructed to ensure the reachability of the sliding manifold. Furthermore, an adaptive neuro-fuzzy inference system(ANFIS) is introduced for reducing the high-frequency chattering induced by the signum function term in the sliding mode control. The effectiveness of the proposed methodology is illustrated by Matlab simulations.

1. Introduction

It is well known that the T–S fuzzy model [1] can be utilized to represent many kinds of nonlinear control systems, which is usually a combination of linear time-invariant systems connected by if-then rules. As a result, the conventional linear system theory can be taken for the analysis and synthesis of such nonlinear systems. In the past two decades, many important results on the T–S fuzzy systems have been extensively investigated in the literature. To cite a few, the stability analysis or synthesis problem has been solved [2–8], H_∞ control [9,10], H_∞ filter [11], reliable and fault-tolerant control [12,13], fault detection problem [14], model reduction problem [15] and synchronous control problem [16,17].

On the other hand, signal quantization problem has become an active research topic since a large number of information processing devices are applied in modern engineering fields, and numerous interesting results with respect to quantized feedback control have been issued [18–29]. Among these results, fuzzy quantized feedback control design is one of an important research aspects. For example, in [26], the authors explored the problem of quantized fuzzy adaptive control for a class of uncertain time-delayed nonlinear systems with communication constraint. In [27], fuzzy adaptive quantized output feedback tracking problem is discussed. In addition, in [28], the author discussed the robust H_∞ quantized state feedback control design of the discrete-time fuzzy systems. In [29], the networked control systems with asynchronous samplings and signal quantization in double channels are well established.

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It should be noted that SMC is a very attractive and popular robust control technique since it has good property called as the disturbance rejection with respect to the matched external perturbation [30–36]. For this reason, it is also used to deal with signal quantization problem in the literature, such as, in [37], a time-varying sliding mode control method was proposed to guarantee the robust quantized stabilization of the linear time-invariant systems. In [38], by utilization of the discrete on-line adjustment strategies of the quantized sensitivity, the developed quantized feedback SMC law ensure the asymptotical stability of the whole dynamics. Following this idea, the robust quantized feedback sliding mode fault-tolerant control problem of uncertain linear systems is further presented in [39]. In addition, in [40], dynamical behaviors of quantized feedback SMC systems was investigated. And in [41], for networked control systems with both input and output disturbances, the SMC design problem is discussed using a logarithmic quantizer strategy. Very recently, the discrepancy issue of quantization sensitivity parameters has attracted the attention of scholars [42], and the adaptive sliding mode control method is introduced to deal with the quantization mismatch problem for linear time-invariant uncertain systems [43].

However, to the best of our knowledge, there are few results reported on quantized feedback fuzzy control problem based on SMC technique, especially memory-based SMC strategy. It has shown that better system performance can be obtained by using memory-based control strategy than those memoryless methods [44–46]. Motivated by all the mentioned above, we will investigate the quantized feedback control design via memory-based SMC method for a class of T–S fuzzy systems. The main contributions are listed as follows: (1) The switching gains of the memory-based sliding manifold are obtained by using LMIs for T–S fuzzy systems subject to model uncertainties, external disturbances and input quantization mismatch; (2) The quantized feedback fuzzy sliding mode control law is established for guaranteeing the reachability of the designed memory-based sliding surface in spite of model uncertainties and input quantization mismatch.

The following notations will be used in this paper. $\mathbb{R}^n$ denotes the n-dimensional Euclidean space; X^T represents the transpose of matrix X; I and 0 represent the identity and zero matrices in appropriate dimension, respectively. The notation $X > 0$ ($X \geq 0$) means that matrix X is real symmetric and positive definite (semi-positive definite). $|\cdot|$ denotes the standard Euclidean norm of a vector, or the induced norm of a matrix, respectively. In symmetric block matrices, a star $\star$ is used to represent a term that is induced by symmetry. Finally, the symbol He(X) represents $X + X^T$.

2. Problem statement and preliminaries

In this paper, we consider a class of nonlinear uncertain systems depicted by T–S fuzzy model with q plant rules via fuzzy modeling techniques as follows.

Plant Rules i:

IF $\theta_1(t)$ is M_{1i}, $\theta_2(t)$ is M_{2i}, ..., $\theta_p(t)$ is M_{pi},

THEN

$$\dot{x}(t) = (A_i + \Delta A_i(t))x(t) + B(\Phi(u(t)) + f(t, x(t))) \tag{1}$$

where $\theta_i(t)$, $i = 1, 2, \ldots, p$, are the premise variables, and M_{ji}, $j = 1, 2, \ldots, p$, $i = 1, 2, \ldots, q$, are the fuzzy sets, q is the number of the fuzzy sets. $x(t) \in \mathbb{R}^n$ and $u(t) \in \mathbb{R}^m$ are the system states and control inputs, respectively. $A_i \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$ are the known system characteristic matrix and control input matrix, respectively. $\Delta A_i(t)$ and $f(t, x)$ represent mismatched uncertainties, matched uncertainties and external disturbances, respectively. $\Phi(u) \in \mathbb{R}^m$ is the quantization control input.

The form of the quantizer $\Phi(s)$ is taken as follows:

$$\Phi(s) = \tau_d(t)\text{round}\left(\frac{s}{\tau_c(t)}\right) \triangleq \tau_d(t)q\left(\frac{s}{\tau_c(t)}\right) \tag{2}$$

where $\tau_c(t)$ and $\tau_d(t)$ are the quantization sensitivity parameters of the coder and decoder sides, respectively. The notation round(s) represents the mathematical function which rounds the nearest integers from the negative infinity direction.

During the running process, the quantized information $q(\frac{s}{\tau_c(t)})$ is generated at the coder side and then is sent through a digital channel to the decoder side. As a consequence, the decoder generates the signal $\tau_d(t)q(\frac{s}{\tau_c(t)})$, i.e., the quantization operator $\Phi(s)$. Usually, it is assumed that $\tau_c(t) \equiv \tau_d(t)$, for $\forall t \geq 0$. As a matter of fact, such assumption is unreasonable to some extension since the stochastic noisy and imperfect implement of the hardware in practical situations. Thus we will consider the quantization discrepancy issue of the quantization sensitivity occurred in the control input channels. In other words, the relationship $\tau_c(t) \equiv \tau_d(t)$ does not maintain in some times. It is called quantization mismatch problem here.

Once signal quantization phenomenon occurs in the control input channel, the following coder/decoder mismatch relation is modeled:

$$\Phi(u) = \tau_d(t)q\left(\frac{u(t)}{\tau_c(t)}\right) \tag{3}$$

and suppose that $r(t) = \frac{\tau_d(t)}{\tau_c(t)}$, then

$$\Phi(u(t)) = r(t)q_{\tau_c(t)}(u(t)) = r(t)(u(t) + e_{\tau_c}(t)) \tag{4}$$

where $q_{\tau_c}(u(t)) = \tau_c(t)q(\frac{u(t)}{\tau_c(t)})$ and quantization error $e_{\tau_c}(t) = q_{\tau_c}(u(t)) - u(t)$ satisfying

$$|e_{\tau_c}(t)| \leq \nabla\tau_c(t) \tag{5}$$