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Control design of interval type-2 fuzzy systems with actuator fault: Sampled-data control approach

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ABSTRACT

This paper focuses on designing sampled-data controller for interval type-2 (IT2) fuzzy systems with actuator fault. The IT2 fuzzy system and the IT2 state-feedback controller share different membership functions. Firstly, considering the mismatched membership functions, the IT2 fuzzy model and the IT2 state-feedback sampled-data controller are constructed. Secondly, based on Lyapunov stability theory, an IT2 state-feedback sampled-data controller is designed such that the closed-loop system is asymptotically stable. The actuator failure is considered in the control systems. The resulting closed-loop system is reliable since the designed controller can guarantee the asymptotic stability and H_∞ performance when the actuator experiences failure. The existence condition of the IT2 fuzzy H_∞ sampled-data controller can be expressed by solving a convex optimization problem. An inverted pendulum model is utilized to demonstrate the effectiveness of the proposed new design techniques.

1. Introduction

Over the past decades, Takagi–Sugeno (T–S) fuzzy model [33,34] has been widely used to handle a class of nonlinear systems [38–40,47–49]. Complex nonlinear systems can be possibly represented as a weighted sum of some simple linear subsystems by using T–S fuzzy rules [8,33,34] and its weightings are characterized by the type-1 membership functions. Since the work by [34], considerable investigations [4–7,9–11,13,17,22–24,27,29–31,35–37,42–46] have been carried out on the stability, stabilization and filter design of type-1 T–S fuzzy systems, and the references therein. The authors in [35] designed a fuzzy controller for T–S fuzzy systems and the existence condition of the controller was derived in terms of linear matrix inequalities (LMIs). Owing to the growing complexity of automated control systems, there have been considerable researches to resolve the reliable and fault-tolerant control problems for dynamic systems with actuator or sensor faults. The authors in [4] studied the problem of fuzzy controller design with time delays and actuator faults. The authors in [20] considered the reliable fuzzy H_∞ controller design for active suspension systems with actuator delays and faults. On

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the other hand, some references have shown that the problem of sampled-data fuzzy control are significant in the practical applications [9,15,19,50]. There are two main approaches to solve the problems of stability and stabilization for sampled-data fuzzy systems by constructing a sampled-data system in discrete-time system or continuous-time system. For example, in [15], the authors considered the problem of sampled-data fuzzy control for T–S fuzzy control systems. It should be mentioned that the results on sampled-data fuzzy controller design and fault-tolerant controller design for T–S fuzzy systems are based on parallel distributed compensation (PDC) concept. It means that the fuzzy system and the fuzzy controller should share the same premise membership functions. That is to say, the membership functions contain no uncertainties. This will bring some conservative results if the membership functions contain uncertainties and the PDC design concept is still used for designing the controller.

In order to represent and capture the uncertainties more effectively, the authors in [14] proposed the type-2 fuzzy sets. Based on the type-2 fuzzy set theory, the type-2 fuzzy logic system was developed in [26]. In [1–3,12,25,32,41], it is pointed out that the type-2 fuzzy logic systems have the potential to provide better performance than type-1 fuzzy logic systems. In [41], the authors shown that the type-2 fuzzy logic system coped well with the complexity of the plant, and can handle the modeling uncertainty better than its type-1 counterpart. The authors in [2] proposed a novel interval type-2 (IT2) fuzzy controller architecture to resolve nonlinear control problems of vehicle active suspension systems. Recently, several previous works have reported for IT2 fuzzy systems [16,18,21] in the T–S fuzzy model framework. In [18], the authors proposed an IT2 T–S fuzzy model to represent the nonlinear systems with uncertainties. An IT2 fuzzy state-feedback controller in [18] was designed to stabilize the proposed IT2 T–S fuzzy model. The IT2 membership functions were used in [16] to capture the uncertainties in the plants and designed a state-feedback controller for the IT2 T–S fuzzy systems. However, there is no result about sampled-data control for IT2 fuzzy systems with actuator fault, which motivates this study.

In this paper, we consider the problem of state-feedback sampled-data controller design for IT2 fuzzy systems with actuator fault. The IT2 fuzzy system can deal with uncertain grades of membership well if parameter uncertainties of nonlinear plants are considered, and the IT2 fuzzy controller can provide better performance. The IT2 fuzzy systems and the IT2 sampled-data controller do not share the same membership function. When the actuator fault of IT2 fuzzy control system is considered, the IT2 fuzzy controller can stabilize the IT2 system well. Firstly, considering the mismatched membership functions, the IT2 fuzzy system and the IT2 state-feedback sampled-data controller are constructed. Secondly, based on Lyapunov stability theory, an IT2 state-feedback sampled-data controller is designed such that the closed-loop system is asymptotically stable for all possible actuator failures. The existence condition of the IT2 fuzzy H_∞ sampled-data controller can be expressed by a convex optimization problem. Finally, an inverted pendulum model is used to illustrate the effectiveness of the proposed results. The rest of the paper is organized as follows: The problem to be addressed is formulated in Section II and the main results are presented in Section III. A practical example is provided in Section IV to show the effectiveness of the developed results and we conclude the paper in Section V.

Notations: The notations used throughout the paper are fairly standard. R^n stands for the n-dimensional Euclidean space and $R^{n\times m}$ denotes the set of all $n \times m$ real matrices; $\mathrm{He}(A)$ is defined as $\mathrm{He}(A) = A + A^T$; $P > 0 (\geqslant 0)$ stands for a symmetric and positive definite (semi-definite); $L_2 - L_\infty$ represents the space of square-integrable vector functions over $[0,\infty)$; $\mathrm{diag}\{\ldots\}$ stands for a block-diagonal matrix and the superscript "T" and "-1" stand for matrix transposition and inverse, respectively; in symmetric block matrices, we use an asterisk ($\star$) to represent a term that is induced by symmetry.

2. Problem formulation

In this section, we consider the following IT2 fuzzy system:

Plant Rule i : IF $f_1(x(t))$ *is* W_{i1} *and* $\cdots$ *and* $f_b(x(t))$ *is* W_{ib}, THEN

$$\begin{aligned} \dot{x}(t) &= A_i x(t) + B_i u^f(t) + B_{1i} w(t), \\ z(t) &= C_i x(t) + D_i u^f(t) + D_{1i} w(t), \end{aligned} \tag{1}$$

where W_{is} is the IT2 fuzzy set of the corresponding to the function $f_s(x(t)), i = 1,2,\ldots,r, s = 1,2,\ldots,b, r$ is the number of plant rules, b is the number of premise variables, $x(t) \in R^n$ denotes the state vector, $u^f(t) \in R^m$ stands for the input vector, $z(t) \in R^p$ is the controlled output and $w(t) \in R^q$ is the disturbance input that belongs to $L_2[0,\infty)$. $A_i, B_i, B_{1i}, C_i, D_i$ and D_{1i} are the known real constant matrices with appropriate dimensions. The following interval set expresses the firing strength of the i-th rule.

$$\tilde{\theta}_i(x(t)) = \left[\prod_{s=1}^{b} \underline{\mu}_{W_{is}}(f_s(x(t))), \prod_{s=1}^{b} \overline{\mu}_{W_{is}}(f_s(x(t)))\right] = \left[\underline{\theta}_i(x(t)), \overline{\theta}_i(x(t))\right], \; i = 1,2,\ldots,r,$$

where $\overline{\theta}_i(x(t))$ and $\underline{\theta}_i(x(t))$ $\left(\overline{\theta}_i(x(t)) \geqslant \underline{\theta}_i(x(t)) \geqslant 0\right)$ denote the upper and lower grades of membership, $\overline{\mu}_{W_{is}}(f_s(x(t)))$ and $\underline{\mu}_{W_{is}}(f_s(x(t)))$ $\left(\overline{\mu}_{W_{is}}(f_s(x(t))) \geqslant \underline{\mu}_{W_{is}}(f_s(x(t))) \geqslant 0\right)$ stand for the upper and lower membership functions, respectively. The nonlinear system in (1) can be represented by the following IT2 T–S fuzzy systems: