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Reliable guaranteed cost sampling control for nonlinear time-delay systems

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Abstract

The problem of reliable guaranteed cost sampling control is investigated for nonlinear time-delay systems in this paper. Sufficient conditions for the existence of state feedback controller are derived in terms of linear matrix inequities (LMIs), which guarantee asymptotic stability with the provided performance index for the normal and possible actuator faults cases. The related optimization problem is also offered to minimize the guaranteed cost performance bound. Illustrative examples are given to show the validity of the present control scheme.

Keywords: Fuzzy control; Sampling control; Reliable control; Linear matrix inequality (LMI)

1. Introduction

In the last decade, fuzzy control was developed for dealing with the various complex industrial plants. Abundant results about the stability analysis and synthesis problem of T–S fuzzy systems with time delay were studied by many researchers in [2–6,11,14,18,24]. Besides the simplest stabilization problem, there have been various methods to obtain certain performance criteria. Among these methods, the guaranteed cost control is an efficient approach that stabilizes the controlled systems while providing an upper bound on a given performance index, such as [4,6,11,14]. Generally, we assumed that all control components are in good working conditions. However, while some actuator faults occurring, the considered performance may be degraded. To improve system reliability, we can select some reliable control strategies such that the closed-loop system can be operating well even if some actuator faults occur. There are also some results about reliable guaranteed cost fuzzy control [20,21].

In the digital controller design, to improve the inter-sampling performance, the hybrid model is generally built via a zero-order-hold (ZOH). Recently, various approaches were applied in the field of sampled-data control, such as [7,16,13]. In the meantime, there are also some results about the intelligent sampled-data controller design [8,12,15,17,23]. However, the reliable guaranteed cost demand has not been considered by the aforementioned literature.

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In this paper, we propose a reliable guaranteed cost nonuniform sampling control scheme for nonlinear time-delay systems via fuzzy control approach. Its objective is to find a nonuniform sampling controller such that the bound of the given guaranteed cost function is obtained by solving a series of LMIs.

The remainder of this paper is organized as follows: basic problem formulation is introduced in Section 2. The reliable guaranteed cost nonuniform sampling controller via state feedback is designed in Section 3. Section 4 provides illustrative examples to demonstrate the effectiveness of the proposed scheme. Finally, concluding remarks are made in Section 5.

In the following sections, the identity matrices and zero matrices are denoted by I and 0, respectively. X^T denotes the transpose of matrix X. R^n denotes the n-dimensional Euclidean space. The notation $*$ always denotes the symmetric block in one symmetric matrix. The standard notation $>$ ($<$) used to denote the positive (negative)-definite ordering of matrices. Inequality $X > Y$ shows that the matrix $X - Y$ is positive definite.

2. Problem formulation

Consider the following T–S fuzzy systems with time delay and it is structured by fuzzy rules, which describes local linear input–output relations of nonlinear systems.

Plant Rule i

IF $\theta_1(t)$ is N_{i1}, ..., and $\theta_p(t)$ is N_{ip}

THEN

$$\dot{x}(t) = A_i x(t) + A_{d_i} x(t-d) + B_i u(t),\ i = 1, 2, \ldots, r$$

where r is the number of fuzzy rules, $x(t) \in R^n$ denotes the state vector, $u(t) \in R^m$ is the control input, A_i, $A_{d_i} \in R^{n\times n}$ and $B_i \in R^{n\times m}$ are known constant matrices, respectively, of the i-th subsystem, d is the constant bounded time delay in the state and it is assumed to be $0 < d \le \bar{\tau}$, $\theta_1(t)$, $\theta_2(t)$, ..., $\theta_j(t)$ are the premise variables, N_{ij} is the fuzzy set ($j = 1, 2, \ldots, p$), the initial condition function will be illuminated in the latter paragraph. By using singleton fuzzifier, product inference and center-average defuzzifier, the dynamic fuzzy model is expressed by

$$\dot{x}(t) = \sum_{i=1}^{r} h_i(\theta(t))[A_i x(t) + A_{d_i} x(t-d) + B_i u(t)],$$

where $h_i(\theta(t)) = \mu_i(\theta(t))/\sum_{i=1}^{r}\mu_i(\theta(t))$, $\mu_i(\theta(t)) = \Pi_{j=1}^{p} N_{ij}(\theta_j(t))$ and $N_{ij}(\theta_j(t))$ is the grade of membership function $\theta_j(t)$ in N_{ij}. Notice $\mu_i(\theta(t)) \ge 0$ and $\sum_{i=1}^{r}\mu_i(\theta(t)) > 0$ for all t. Then, we have $h_i(\theta(t)) \ge 0$ and $\sum_{i=1}^{r} h_i(\theta(t)) = 1$.

According to the conventional parallel distributed compensation (PDC) concept and considering the sampling actions, we offer the following reliable nonuniform sampling controller via state feedback:

Controller Rule i

IF $\theta_1(t)$ is N_{i1}, ..., and $\theta_p(t)$ is N_{ip}

THEN

$$u_F(t) = \omega_L K_i x(t_k),\quad t_k \le t < t_{k+1},\qquad i = 1, 2, \ldots, r$$

where r is the number of controller rules, $t_k (k = 0, 1, 2, \ldots)$ is the sampling instant, and $x(t_k)$ is the state vector of plant at the instant t_k, which is a piecewise constant function, by using a ZOH, $K_i \in R^{m\times n}$ is the controller gain matrix, the scaling factor $\omega_L (L = 0, 1, \ldots, l_p,\ l_p \le 2^m - 1)$ describes the fault extent, while $\omega_{Lj} = 0 (1 \le j \le m)$ means that the j th actuator is invalid and $\omega_{Lj} = 1 (1 \le j \le m)$ means that the jth actuator is valid, and satisfies

$$\omega_L \in \Omega \triangleq \{\mathrm{diag}[\omega_{L1}, \omega_{L2}, \ldots, \omega_{Lm}],\qquad \omega_{Lj} = 0 \text{ or } 1,\ j = 1, 2, \ldots, m\}.$$

Thus, the fuzzy controller can be expressed as follows:

$$u_F(t) = \sum_{i=1}^{r} h_i(\theta(t))\omega_L K_i x(t_k),\qquad t_k \le t < t_{k+1}. \tag{1}$$

There maybe exist some other actuator fault models such as [5,22]. If the appropriate fault information is known and the possible faults cases are finite, the proposed approach can be extended easily to the other models.