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Adaptive fuzzy backstepping dynamic surface control for nonlinear Input-delay systems

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ABSTRACT

This paper investigates the problem of fuzzy adaptive backstepping control for a category of nonlinear strict-feedback systems. Input delay is considered in the design process. Fuzzy logic systems are used to identify the unknown nonlinear functions existing in the systems. To handle the input delay, an integral item is introduced. For the general problem of "explosion of complexity" in adaptive backstepping control approach, dynamic surface control technique is introduced to avoid it. Based on the adaptive backstepping control approach, a fuzzy adaptive controller with adaptive parameters is constructed to guarantee all signals of the closed-loop system are bounded and system states can be regulated to the origin. Finally, simulation results are provided to illustrate the effectiveness of the proposed methodology.

1. Introduction

Time delay frequently occurs in practical applications, which is a necessary factor to be considered in modeling, analysis and synthesis. It can degrade system performance, even lead to instability [1]. Recently, various results have been published [2,3]. The problem of delay-dependent robust stability for uncertain neural systems subject to mixed delay was investigated in [4]. Using the fuzzy-model based linear matrix inequality approach [5], a sampled-data control strategy was developed for a class of delayed nonlinear systems in [6].

As a powerful tool, approximation-based fuzzy or neural adaptive backstepping control plays an important role in handling nonlinear systems. In such framework, fuzzy logic systems (FLSs)/neural network (NN) is used to identify unknown nonlinear functions, and then the corresponding fuzzy/NN adaptive control is developed recursively based on the structural backstepping technique. As discussed in [7], fuzzy/neural adaptive control approach possesses the favorite properties, including tackling nonlinear systems with unmatched conditions and linearly parameterizing unknown nonlinear functions unnecessarily. Thus, such control strategy has been widely applied, such as single-input single-output systems [8–15] and multi-input multi-output systems [16–19]. Liu et al. [20] proposed an adaptive fuzzy control scheme for a class of systems subject to backlash. Considering unknown dead zones, the authors in [21] studied the problem of adaptive fuzzy control for multi-input multi-output systems. An adaptive fuzzy control method for interconnected systems has been given in [22]. Recently, the problem of controller design for delayed systems has been studied based on the fuzzy/NN adaptive backstepping control. Considering unknown delay, an adaptive NN control was proposed for strict-feedback systems in [23]. In a unified framework, the authors in [24] considered time-varying delay, unknown dead zones and gain signs. simultaneously, and investigated the problem of adaptive NN control for multi-input multi-output systems. The authors in [25] provided a novel adaptive NN control scheme for delayed systems, constructing a novel Lyapunov–Krasovskii functional, avoiding the controller singularity and relaxing the constraints on unknown virtual control coefficients. To address the unmeasurable state variables, an output-feedback based adaptive NN control for nonlinear stochastic delayed systems was given in [26]. Using FLSs to approximate unknown nonlinear functions, an output-feedback based adaptive control strategy was presented in [27]. For large-scale systems with delay, an observer-based adaptive NN decentralized control was developed in [28]. Different from the above results, the problem of control design for systems with input delay has been investigated in [29–31]. Using radius basis function NN, an adaptive control scheme was derived for a class of nonlinear systems with state and input delay in [29]. As an extension, results in

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[29] were extended to the unmeasurable state variables case in [30]. Furthermore, the authors in [31] presented an adaptive NN tracking control for multi-input multi-output systems subject to input delay. However, there exists a drawback in adaptive backstepping control method, that is, the problem of "explosion of complexity". And the results mentioned above all suffer from the problem. To avoid such problem, dynamic surface control (DSC) technique has been proposed and widely applied [32,33]. An adaptive NN DSC control for nonlinear strict-feedback systems was proposed in [34]. Wang [35] studied the problem of adaptive NN DSC control for a category of uncertain nonlinear pure-feedback systems. In [36], the DSC technique was combined with adaptive backstepping control method to handle systems subject to unknown delay. It is worth noting that there exist few results for systems with input delay, wherein, the DSC technique is introduced to avoid such problem.

Motivated by the above discussions, the problem of fuzzy adaptive control for a class of strict-feedback systems with input delay is investigated. FLSs are used to identify the unknown nonlinear functions existing in the system. The main contributions of this paper can be summarized as follows. (1) An integral item concerning input signal u is introduced to tackle the delayed input signal. (2) The DSC technique is used to avoid the problem of "explosion of complexity", facilitating reducing complexity. (3) A novel adaptive control scheme is developed based on the adaptive backstepping and DSC methods to ensure that signals of the closed-loop system are bounded and system states can be regulated to the origin. Finally, three examples are given to validate the effectiveness of the approach proposed in this paper.

The rest of the paper is organized as follows. Problem formulation and preliminaries are presented in Section 2. The main results are presented in Section 3. Simulation results to verify the obtained theoretic results are provided in Section 4, while Section 5 concludes the paper.

2. Problem formulation and preliminaries

2.1. Problem formulation

Consider the following nonlinear system with input delay:

$$\begin{aligned}\dot{x}_i &= x_{i+1} + f_i(\bar{x}_i) + d_i(x,t), \quad i = 1,2,\ldots,n-1,\\ \dot{x}_n &= u(t-\tau) + f_n(\bar{x}_n) + d_n(x,t),\\ y &= x_1,\end{aligned} \tag{1}$$

where $x = \bar{x}_n = [x_1, x_2, \ldots, x_n]^T \in R^n$ and $y \in R$ are state vector and output, respectively. $\bar{x}_i = [x_1, x_2, \ldots, x_i]^T$. $f_i(\bar{x}_i)$ is unknown but smooth nonlinear continuous functions. $f_i(0,0,\ldots,0) = 0$. τ denotes the input delay, $d_i(x,t)$ is the bounded external disturbance. $u(t-\tau)$ is the system input with delay τ.

Control objective: The control objectives of this paper are as follows:

1. All signals of system in (1) are bounded.
2. System states x can be regulated to the origin.

The following assumptions are given to facilitate analyzing and designing system (1).

Assumption 1. The external disturbance satisfies $|d_i(x,t)| \le \mathcal{D}_i$.

2.2. Fuzzy logic systems

In order to tackle the unknown nonlinear function, the FLSs are introduced in this section. The details are described as follows:

Rule j: IF x_1 is M_{j1}, and x_2 is M_{j2} and, …, and x_n is M_{jn}, THEN y is N_j, $\quad j = 1,2,\ldots,\Lambda$,

where $x = [x_1, x_2, \ldots, x_n]^T$ is the system input; y is the system output; the fuzzy sets and membership functions are represented by M_{jl}, N_j, $u_{M_{jl}}(x_l)$ and $u_{N_j}(y)$, respectively. Λ stands for the number of fuzzy rules.

With the common techniques including singleton, center average defuzzification and product inference, the final output can be described as follows:

$$y(x) = \frac{\sum_{j=1}^{\Lambda} \tilde{y}_j \prod_{l=1}^{n} u_{M_{jl}}(x_l)}{\sum_{j=1}^{\Lambda} \prod_{l=1}^{n} u_{M_{jl}}(x_l)}, \tag{2}$$

where $\tilde{y}_j = \max_{y \in R} u_{N_j}(y)$.

The membership functions are defined as $\phi_j = \frac{\prod_{l=1}^{n} u_{M_{jl}}(x_l)}{\sum_{j=1}^{\Lambda} \prod_{l=1}^{n} u_{M_{jl}}(x_l)}$. Define $\eta = [\tilde{y}_1, \tilde{y}_2, \ldots, \tilde{y}_\Lambda]^T = [\eta_1, \eta_2, \ldots, \eta_\Lambda]^T$ and $\phi(x) = [\phi_1(x), \phi_2(x), \ldots, \phi_\Lambda(x)]^T$. Then, the final output in (2) can be expressed as follows:

$$y(x) = \eta^T \phi(x). \tag{3}$$

The following lemma is used to set relationship between the unknown nonlinear function and the FLSs.

Lemma 1 (*Li et al. [37]*). *In view of the continuous function f(x), which is defined on the compact set Ω, for any constant $\zeta > 0$, the FLSs (3) have the following property:*

$$\sup_{x \in \Omega} \left| f(x) - \eta^T \phi(x) \right| \le \zeta,$$

where ζ stands for the estimation error.

3. Adaptive control design

The adaptive controller and adaptive laws are derived in this section. In order to avoid the general problem of "explosion of complexity", DSC technique is integrated into the framework of adaptive backstepping control. An integral item concerning input signal u is constructed to tackle input delay. Based on the above techniques, an adaptive fuzzy controller with adaptive parameters are developed to realize the control objective.

To begin with, the change of coordinates is as follows:

$$\begin{aligned}z_1 &= x_1,\\ z_i &= x_i - \chi_i, \quad i = 2,3,\ldots,n-1,\\ z_n &= x_n - \chi_n + \int_{t-\tau}^{t} u(s)\, ds,\end{aligned}$$

where χ_i will be defined later.

The i-th control signal and the adaptive law are given as follows.

We choose the first virtual control signal α_1 and the adaptive law $\hat{\theta}_1$ as follows:

$$\alpha_1 = -c_1 z_1 - \frac{z_1 \hat{\theta}_1 \phi_1^T \phi_1}{2\rho_1^2} - \frac{z_1}{2}, \tag{4}$$

$$\dot{\hat{\theta}}_1 = \frac{z_1^2 \lambda_1 \phi_1^T \phi_1}{2\rho_1^2} - \eta_1 \hat{\theta}_1, \tag{5}$$

where $c_1 > 0$, $\rho_1 > 0$ and $\eta_1 > 0$ are constants to be designed and $\hat{\theta}_1$ will be defined later.

Define the i-th virtual control signal α_i and the adaptive law $\hat{\theta}_i$ as follows:

$$\alpha_i = -c_i z_i - \frac{z_i \hat{\theta}_i \phi_i^T \phi_i}{2\rho_i^2} - \frac{z_i}{2} + \dot{\chi}_i, \tag{6}$$