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Adaptive control for a class of uncertain strict-feedback nonlinear systems based on a generalized fuzzy hyperbolic model

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Abstract

In this study, we propose an effective method for designing an adaptive controller for a class of uncertain strict-feedback nonlinear systems with unknown bounded disturbances. During the controller design process, all of the unknown functions are accumulated at the intermediate steps to approximate the last step. In addition, only one generalized fuzzy hyperbolic model is used to approximate the total unknown functions for the system. Thus, only the actual control law needs to be implemented and one adaptive law is proposed for the overall controller design process. As a result, the controller design is much simpler and the computational burden is reduced greatly. Using Lyapunov techniques, we obtain the uniformly ultimately bounded stability of all the signals for the closed-loop system. Our simulation results verified the theoretical analysis and they illustrated the superior performance of the method proposed in this study.

Keywords: Adaptive control; Generalized fuzzy hyperbolic model; Lyapunov function; Strict-feedback

1. Introduction

Studies of nonlinear systems have been performed widely, including stability analysis [1–3], controller design [4,5], and synchronization problems [6–8]. In particular, the design of controllers is a key problem in control theory. In recent years, adaptive control design has advanced significantly for nonlinear systems such as Brunovsky systems [9], feedback-linearized systems [10], strict-feedback systems [11], and stochastic nonlinear systems [12]. In addition, methods for adaptive control design have been proposed using different techniques, including feedback linearization [10], inversion control [13], backstepping [11,14], sliding mode control [15,16], the fuzzy basis function vector approach [17], and adaptive fuzzy output feedback control approach [18]. During the controller design process, the following problems make the designed controllers increasingly complex and the computational burden grows: (1) re-

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peated derivations of certain nonlinear functions mean that the differential explosion phenomenon is inevitable during the controller design process; and (2) the use of multiple approximators increases the amount of calculations required. In order to eliminate the problem of differential explosion, the dynamic surface control (DSC) technique was developed by adding a first-order low-pass filter to the conventional backstepping design procedure [19–25]. However, the controller design process is still very complex using this approach. Thus, to reduce the complexity of the controller, we propose the design of an adaptive controller based on the generalized fuzzy hyperbolic model (GFHM) for a class of uncertain strict-feedback nonlinear systems in this study.

To the best of our knowledge, there are many function approximators, including neural networks [26–32], fuzzy logic systems, the fuzzy hyperbolic model (FHM), and GFHM [33,34]. It has been proved that they can approximate an unknown nonlinear function with arbitrary precision by selecting appropriate parameters. In addition, it has been proved that the GFHM is a universal approximator. The GFHM has many merits compared with the Takagi–Sugeno fuzzy model, including the following: (1) when using the GFHM, there is no need to identify the premise structure during the modeling process; and (2) the GFHM can reduce the calculation cost, especially when many fuzzy rules are needed to approximate nonlinear complex systems. Thus, an adaptive controller can be designed based on the GFHM for a class of uncertain strict-feedback nonlinear systems.

In contrast to existing methods, we propose an adaptive control method based on the GFHM for a class of uncertain strict-feedback nonlinear systems, where filters do not need to be introduced. The unknown functions of the virtual control laws in do not need to be approximated during the intermediate steps and only one GFHM is used to approximate the total unknown functions in the last step. Thus, all of the virtual controllers do not require online implementation and only the actual control law needs online implementation. Using this approach, the two problems mentioned above are eliminated, so the controller structure is much simpler and the computational burden is reduced greatly. The main contributions of this study are as follows.

1. Unlike the conventional backstepping method, which needs n approximators and n adaptive laws, only the actual control law requires online implementation, where only one approximator and one adaptive law are needed in the proposed method.
2. The structure of a controller designed using this approach is much simpler compared with that obtained by existing methods.
3. The computational burden can be greatly reduced using the proposed approach compared with existing methods.

The remainder of this paper is organized as follows. In Section 2, we characterize a class of SISO [A1] nonlinear systems with perturbation. In Section 3, we provide a simple presentation of the GFHM. In Section 4, adaptive control based on the GFHM is described. The stability analysis is given in Section 5. The simulation results obtained by the proposed approach are verified in Section 6. In Section 7, we give our conclusions.

2. Problem statement and preliminaries

2.1. Problem statement

The class of SISO nonlinear systems can be expressed by the following state-space representation:

$$\begin{cases} \dot{x}_i = f_i(\bar{x}_i) + x_{i+1} + d_i, i = 1, 2, \cdots, n-1 \\ \dot{x}_n = f_n(\bar{x}_n) + u + d_n, \\ y = x_1, \end{cases} \tag{1}$$

where $x_i(t) \in R$ is the state, $\bar{x}_i = [x_1, x_2, \ldots, x_i]^T$, $u \in R$ is the input, $y \in R$ is the output, $f_i(\cdot)$ $i = 1, 2, \ldots, n$ are unknown smooth nonlinear functions, and d_i are the bounded uncertain constant disturbances. Thus, a constant $d^* > 0$ exists such that $|d_i| \le d^*$.

Assumption 1. If $x_i(t), i = 1, 2, \ldots, i$ is bounded, then the nonlinear function $f_i(\bar{x}_i)$ is bounded.