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A novel single fuzzy approximation based adaptive control for a class of uncertain strict-feedback discrete-time nonlinear systems

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ABSTRACT

This paper investigates the problem of adaptive fuzzy control for a class of uncertain nonlinear strict-feedback discrete-time systems with unknown system functions and control gain functions. Following the idea of single neural network (SNN) approximation, single fuzzy logic system(SFLS) approximation is first proposed and synthesized with "minimal learning parameter (MLP)" technique into a novel adaptive fuzzy control design methodology for the concerned systems. With the help of the MLP technique, the problem of "curse of dimension" is circumvented, and the adaptive mechanism with minimal learning parameterization is achieved. Meanwhile, by employing the SFLC approximation in the adaptive control synthesis, all unknown functions at the intermediate steps are passed down in the controller design process, and only one fuzzy logic system (FLS) is employed to deal with the lumped unknown functions at the last step. Following this approach, the problem of "explosion of complexity" inherent in backstepping method is also avoided, and the designed controllers contain only one actual control law and one adaptive law. Thereby, the number of parameters updated online for the entire discrete-time system is reduced to only one. As a result, the controller is much simpler, the computational burden is much lighter and the learning time tends to much shorter. The closed-loop stability in the sense of semi-globally uniformly ultimately bounded (SGUUB) can be guaranteed via Lyapunov theory. Finally, simulation results via two examples are given to illustrate the performance of the proposed scheme.

1. Introduction

In the past decades, the fuzzy logic system (FLS) have become an active research topic and have obtained widespread attention in the control domain due to its excellent universal approximation ability [1]. In general, FLS is used as function approximator to deal with many uncertainties appearing in the controllers or the investigated systems [2]. In recent years, adaptive fuzzy control has been extensively studied for both continuous-time nonlinear systems and discrete-time ones. For continuous-time systems, much significant development has been achieved [3–7]. For example, in [5], a fuzzy adaptive robust control scheme was proposed based on backstepping design for a class of nonlinear systems with nonlinear uncertainties, unmodeled dynamics, and dynamic disturbances. While in [6], an adaptive fuzzy output feedback control approach was proposed for a class of strict-feedback canonical nonlinear systems without measurements of the states.

It is well-known that the discrete-time systems can be more veritable to describe the practical problems in control systems than the continuous-time systems. Since many industrial control systems include continuous-time signals, sampled-data signals, and digital signals, while both sampled-data control systems and digital control systems are discrete-time control systems, which are more suitable for the real-time implementation of controllers [8]. Hence, the research on control design for discrete-time control systems is much important. Nevertheless, comparing to the continuous-time nonlinear systems indicated in the above mentioned papers, adaptive control is less developed for discrete-time nonlinear systems. The reason lies in that the linearity property of the derivative of a Lyapunov function in the continuous-time case is not persent in the difference of a Lyapunov function in the discrete-time one [9]. As a consequence, many elegant control schemes for continuous-time systems may be not suitable for the discrete-time systems. Thus, the research of control design along with the stability analysis for nonlinear discrete-time systems is much more necessary and challenging. Till now, a lot of researchers have devoted their time and effort into this direction, and some significant progress in adaptive control for nonlinear discrete-time systems has been achieved [10–15]. For example, an adaptive neural network control problem for a class of unknown feedback-linearizable discrete-time system, was

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investigated in [10]. In the proposed method, a layered neural network was used to model the unknown system and generate the feedback control, and the weights of the neural network were updated based on the error between the plant output and the model output. While in [11], a family of two-layer discrete-time neural net (NN) controllers was presented by using a filtered error approach for the control of a class of mnth-order MIMO dynamical system. To solve the noncausal problem, the approach which can "look ahead" and choose the control law to force the states to acquire their desired values was proposed in [12] for parametric-strict-feedback discrete-time systems. But it is hard to extend to more general systems. In [13], both full state and output feedback adaptive neural network (NN) controllers were presented for a class of strict-feedback discrete-time nonlinear systems. The possible controller singularity problem and the noncausal problem were both solved in the discrete-time backstepping design procedure. Subsequently, many elegant adaptive control schemes were studied in [14–24] for discrete-time nonlinear systems based on the approximation property of the neural network.

However, these aforementioned schemes suffered form the explosion of online learning parameters, referred to as "curse of dimensionality". That is, when a FLS (or NN) approximator is constructed to approximate some unknown smooth functions, the number of parameters to be tuned will grow rapidly with the dimension of the argument vector of the functions to be approximated. It imposes that to achieve a better approximation result for the designed system, quite a few number of parameters need to be tuned online in the FLS (NN) approximator-based adaptive control schemes. Consequently, the learning time tends to become unacceptably long, and the time-consuming process is unavoidable during the implementation of these control algorithms. This problem was first solved in [25,26], where "minimal learning parameter (MLP)" algorithms containing much less online learning parameters were constructed by fusion of traditional backstepping technique and T–S fuzzy systems [25] or RBF neural networks [26]. Later on, combined the backstepping technique and MLP algorithms, some adaptive fuzzy control schemes for MIMO nonlinear systems were proposed in [27–29]. By incorporating the "dynamic surface control (DSC)" and "MLP" techniques, some robust adaptive tracking control schemes were developed for a class of uncertain nonlinear systems [30–32], in which both problems of "curse of dimension" and repeated differentiations in the controller design process were circumvented. More recently, a new direct adaptive neural network control algorithm with less adaptive parameters has been developed for a class of uncertain discrete-time nonlinear systems in [33]. Also, several results to reduce the number of the adjustable parameters and lighten the online computation burden were studied in [34–38].

Nevertheless, the problem of "explosion of complexity" still exists universally in above mentioned methods due to the employment of the backstepping technique. The main reason is the use of multiple approximators. That is, in every step of the adaptive control approaches based on backstepping design procedure, the approximators must be employed to construct the virtual control laws or the actual control law. The use of multiple approximators makes the controller design procedure much more complex and the controller computational burden growing up. More recently, to solve the problem by use of multiple approximators, a novel idea of single neural network (SNN) approximation was first proposed in [39] for adaptive control of a class of strict-feedback continuous-time nonlinear systems. The main idea of SNN approximation is to use only one approximator to approximate the lumped unknown function in the system at the last step of the controller design procedure. Soon later, this idea was extended to adaptive control design for adaptive control of a class of uncertain pure-feedback nonlinear systems in [40]. But these schemes focused on continuous-time systems, and have not been applied to the control design for discrete-time systems.

In this paper, motivated by above observations, a single fuzzy-logic-system approximation based adaptive control scheme incorporating the "minimal learning parameters (MLP)" technique is proposed for a class of uncertain discrete-time nonlinear systems in strict-feedback form. Comparing to the existing methods, all the unknown functions of the virtual control laws does not need to be approximated online at intermediate steps, and only one fuzzy logic system is employed to approximate the lumped unknown function in the system at the last step. That is, only one actual control law needs to be constructed. Additionally, with the help of MLP technique, the number of parameters updated online for entire system is reduced to only one, no matter how many rules are used in the constructed fuzzy system and how many input variables exist in the investigated system. The problem of "curse of dimensionality" is thus avoided and the adaptive mechanism with minimal learning parameterization is achieved. By using the Lyapunov analysis method, all the signals in the closed-loop system are guaranteed to be SGUUB, and the tracking error converges to a small neighborhood of the origin. Two simulation examples are utilized to illustrate the effectiveness and advantages of the proposed scheme.

The rest of this paper is organized as follows. Section 2 describes the problem formulation and the necessary preliminaries. The systematic design procedure along with the stability analysis via Lyapunov theory is given in Section 3. Simulation results via two examples are shown in Section 4. This paper ends with conclusion in Section 5.

2. Problem formulation and preliminaries

2.1. Problem formulation

Consider the following single-input and single-output (SISO) discrete-time nonlinear system in strict-feedback form

$$\begin{cases} x_i(k+1)=f_i(\overline{x}_i(k))+g_i(\overline{x}_i(k))x_{i+1}(k), \ i=1,2,\ldots,n-1, \\ x_n(k+1)=f_n(\overline{x}_n(k))+g_n(\overline{x}_n(k))u(k) \\ y_k=x_1(k) \end{cases} \tag{1}$$

where $\overline{x}_i(k)=[x_1(k),x_2(k),\ldots,x_i(k)]^T\in R^i$, $i=1,2,\ldots,n$ are the state variables, $u(k)\in R$ is the system input, $y_k\in R$ is the system output, $f_i(\overline{x}_i(k))$ and $g_i(\overline{x}_i(k))$, $i=1,2,\ldots,n$ are unknown smooth functions.

The control objective is to design an adaptive fuzzy controller for the system (1) such that: (i) all the signals in the closed-loop system are semi-globally uniformly ultimately bounded (SGUUB) and (ii) the system output follows the desired reference signal $y_d(k)$. In this note, it needs to make the following assumptions with respect to the systems (1).

Assumption 1. The desired reference signal $y_d(k)\in\Omega_y$, $\forall k>0$ is a bounded known smooth function with $\Omega_y:=\{\chi|\chi=x_1\}$.

Assumption 2. The sign of $g_i(\overline{x}_i(k))$, $i=1,2,\ldots,n$ are known and there exist constants $\underline{g_i}>0$ and $\overline{g}_i>0$ such that $\underline{g_i}\le|g_i(\overline{x}_i(k))|\le\overline{g}_i$, $\forall\overline{x}_n(k)\in\Omega\subset R^n$.

Without losing generality, we assume that $g_i(\overline{x}_i(k))$ and $g_n(\overline{x}_n(k))$ are positive in this paper. i.e., $\underline{g_i}\le g_i(\overline{x}_i(k))\le\overline{g}_i$.

Definition 1. Ref. [13], the solution of (1) is semi-globally uniformly ultimately bounded (SGUUB), if for any Ω, a compact subset of R^n and all $\overline{x}_n(k_0)\in\Omega$, there exist an $\varepsilon>0$ and a number $N(\varepsilon,\overline{x}_n(k_0))$ such that $\|\overline{x}_n(k)\|<\varepsilon$ for all $k\ge k_0+N$.