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Decentralized adaptive neural control of nonlinear interconnected large-scale systems with unknown time delays and input saturation ☆

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ABSTRACT

In this paper, a novel decentralized adaptive neural control scheme is proposed for a class of interconnected large-scale uncertain nonlinear time-delay systems with input saturation. RBF neural networks (NNs) are used to tackle unknown nonlinear functions, then the decentralized adaptive NN tracking controller is constructed by combining Lyapunov–Krasovskii functions and the dynamic surface control (DSC) technique along with the minimal-learning-parameters (MLP) algorithm. The stability analysis subject to the effect of input saturation constrains are conducted with the help of an auxiliary design system based on the Lyapunov–Krasovskii method. The proposed controller guarantees uniform ultimate boundedness (UUB) of all the signals in the closed-loop large-scale system, while the tracking errors converge to a small neighborhood of the origin. An advantage of the proposed control scheme lies in that the number of adaptive parameters for each subsystem is reduced to one, and three problems of "computational explosion", "dimension curse" and "controller singularity" are solved, respectively. Finally, a numerical simulation is presented to demonstrate the effectiveness and performance of the proposed scheme.

1. Introduction

It is well known now that decentralized control strategy is an efficient and effective way in the control of interconnected systems. Unlike a centralized controller, which is difficult to gather feedback signals from those subsystems if some subsystems are distributed distantly, a decentralized controller can be designed independently for local subsystems and make full use of the local available signals for feedback [1]. In particular, decentralized adaptive control is employed for controlling those interconnected large-scale systems with large amount of uncertainties in practice, for example, the power system, the communication system, the network system, the HVAC system, and so on [2,3]. The past two decades have witnessed a remarkable progress in the decentralized adaptive control. The first result on decentralized adaptive control was reported in [4] under the assumption that the relative degrees of all the subsystems should be less than or equal to two. To overcome the limitations both of the difficulty in rigorous design analysis of the overall system and of the poor transient performance of the closed-loop system existed in the traditional adaptive approaches ([4,5] and the references therein), a backstepping-based decentralized adaptive control scheme was first proposed for a class of large-scale systems with unmatched conditions in each subsystem by Wen [6]. Then, some more constructive decentralized adaptive control strategies based on the backstepping design were presented in [7,8,1]. But these methods were built on a strict requirement on the model information of the controlled plants. Recently, some model-free decentralized adaptive control approaches were developed by combining the backstepping technique and the approximation-based fuzzy control schemes [9–12] or neural networks control schemes [13–15]. However, as stated out in [16], that there are two main limitations in the aforementioned approximation-based backstepping control methods, i.e., "computational explosion" problem and "dimension curse" problem. These two problems limit severely the implementation and application of those control algorithms in practice. Fortunately, a novel neural control scheme was developed in [17] for a class of strongly interconnected MIMO systems by fusion of the DSC approach [18,19] and the MLP approach [20,21]. Both the above limitations wereconsequently circumvented elegantly and simultaneously in [17].

In practice, time delay and input saturation constraints are often inevitably met and always result in a new challenge in control design, as well as in decentralized adaptive control design. On the

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one hand, time delay is frequently encountered in models of engineering systems, natural phenomena, and biological systems. Delay may occur in the feedback loop of a plant, either in the states, inputs or outputs [22]. The existence of time delays may degrade the control performance and make the control problem become more difficult. Some of the useful tools in robust stability analysis for time-delay systems are based on the Lyapunovs second method, the Lyapunov–Krasovskii theorem, and the Lyapunov–Razumikhin theorem [23]. Till now, many meaningful results have been obtained either in the analysis of stability [24–27] or in the adaptive control design [23,28–32] with time delays. For example, to handle the completely unknown nonlinear functions with unknown time delays, some novel NN-based adaptive control methods for strict feedback systems have been developed by using the backstepping design and the Lyapunov–Krasovskii functional in [23,28,29,32]. Nevertheless, these time delay free control schemes also suffer from the aforementioned restrictions of either dimensionality curse [32] or computational explosion [28,29], or both of them [23].

On the other hand, input saturation constraint is one of the most important non-smooth nonlinearities which usually appears in many industry control systems. This problem is of great importance because almost all practical control systems have limitations on the amplitudes of control inputs, and such limitations can cause serious deterioration of control performances and even destroy the stability of the control systems [33]. If we ignore it in the control design, it can severely degrade the closed-loop system performance. The analysis and design of control systems with saturation nonlinearities have been studied in [30,31,33–36], and the references therein. For handling the input saturation, the auxiliary design system [34] is introduced to analyze the effect of input saturation in this paper.

The aforementioned results in [1–18] will not be applicable when suffering from the constraints of time delay or input saturation or both of them. Some alternative control methodologies should be developed under the consideration of both of them. However, in the development of decentralized adaptive control in consideration of both time delay and input constraints, only a few results have been obtained, see for examples [30,31,37]. In [30], a novel decentralized adaptive backstepping control scheme is proposed to solve the output tracking of a class of interconnected time-delay subsystems with the input of each loop preceded by an unknown dead-zone. Unknown time-varying delays are compensated by using appropriate Lyapunov–Krasovskii functionals. Furthermore, by introducing a new smooth dead-zone inverse, the proposed control scheme is able to eliminate the effects resulting from dead-zone nonlinearities in the input. It needs more information of the controlled plant. Whereas in [31], a robust fuzzy stabilization controller was proposed by employing Takagi–Sugeno (T–S) fuzzy model to represent nonlinear time-delay system, where a set of fuzzy implications are used to characterize the local dynamics with actuator saturation. And the derived conditions are formulated in terms of linear matrix inequalities (LMIs) so that the synthesis of fuzzy controller and the estimation of stability domain can be carried out efficiently. In [37], a wavelet adaptive observer based control strategy was presented for a class of uncertain MIMO delayed nonlinear systems subjected to actuator saturation. The proposed wavelet adaptive observer performs the task of identification of unknown system dynamics in addition to reconstruction of states of the system. Nevertheless, the above-mentioned methods suffered from either “computational explosion” or “dimension curse”, or both of them.

In this paper, based on the above observations, we extend the MLP-DSC scheme proposed in [17] to a class of interconnected large-scale nonlinear time delay systems with input saturation constrains. A stable adaptive NN tracking control scheme with small computation load will be developed based on the Lyapunov–Krasovskii functions. Both the tracking performance and the UUB stability of the closed-loop system are guaranteed. The main features of the proposed scheme are: (1) Only one online learning parameter is contained in the proposed controller of each subsystem, which is independent of the order of each subsystem. (2) Thecomputational load in our proposed controller can be reduced drastically in comparison with the relevant existing controller without the limitations of “dimensionality curse” and “complexity explosion”, which facilitate its implementation in applications. (3) The RBF NNs are only used to approximate those unknown system functions, and the unknown gain functions are not required to be approximated. Consequently, the potential controller singularity problem can be overcome.

This paper is organized as follows. Section 2 contains the problem formulation and some necessary preliminary results. In Section 3, the control design and its stability analysis are given. In Section 4, a numerical simulation example is used to demonstrate the performance of the scheme. The final section contains conclusions.

2. Problem formulation and preliminaries

2.1. Problem formulation

Consider a class of interconnected large-scale nonlinear systems comprising N subsystems, where the ith subsystem is given as

$$\begin{cases} \dot{x}_{i,j} & = f_{i,j}(\overline{x}_{i,j}) + g_{i,j}(\overline{x}_{i,j})x_{i,j+1} + \Delta_{i,j}(Y) \\ & \quad + h_{i,j}(\overline{x}_{i,j}(t-\tau_{i,j})) \\ & \cdots \\ \dot{x}_{i,n_i} & = f_{i,n_i}(\overline{x}_{i,n_i}) + g_{i,n_i}(\overline{x}_{i,n_i})u_i + \Delta_{i,n_i}(Y) \\ & \quad + h_{i,n_i}(\overline{x}_{i,n_i}(t-\tau_{i,n_i})) \\ y_i & = x_{i,1}, \quad i = 1, \vdots, N, \quad j = 1, \ldots, n_i - 1 \end{cases} \tag{1}$$

where $x_i = [x_{i,1}, \ldots, x_{i,n_i}]^T \in R^{n_i}$ denotes the vector of state variables, and $y_i \in R$ is the output of the ith subsystem. $\overline{x}_{i,j} = [x_{i,1}, \ldots, x_{i,j}]^T \in R^j$; $Y = [y_1, \ldots, y_N]^T \in R^N$. $f_{i,j}$, $g_{i,j}$ and $h_{i,j}$ are unknown nonlinear smooth functions, where $g_{i,j}$, $j = 1, \ldots, n_i - 1$ are referred to virtual control gain functions, and g_{i,n_i} is called the actual control gain function. $\tau_{i,j}$ are unknown time delays of the states. $\Delta_{i,j}(Y): R^N \to R$ are unknown continuous functions representing the interconnections among subsystems. $u_i \in R$ represents the control input with saturation constrains.

In this paper, considering the presence of input saturation constraints on u_i as

$$-u_{im} \le u_i \le u_{iM} \tag{2}$$

where u_{im} and u_{iM} are the known lower limit and upper limit of the input saturation constraints of u_i, respectively. Thus,

$$u_i = sat(v_i) = \begin{cases} u_{iM} & \text{if } v_i > u_{iM} \\ v_i & \text{if } -u_{im} \le v_i \le u_{iM} \\ -u_{im} & \text{if } v_i < -u_{im} \end{cases} \tag{3}$$

where v_i is the designed control input of ith subsystem.

The control objective is to design a decentralized adaptive NN state-feedback tracking controller in (3) for the ith subsystem (1), such that (i) all the signals in the closed-loop large-scale system remain UUB and (ii) the output y_i follows the desired trajectories $y_{i,r}$ as expected.

The following assumptions are needed in this paper.

Assumption 1. $g_{i,j}$ are strictly positive, and there exist unknown positive constants g_m and g_M, such that $0 < g_m \le g_{i,j} \le g_M$.

Assumption 2. The reference signal $y_{i,r}(t)$ is a sufficiently smooth function of t and $y_{i,r}$, $\dot{y}_{i,r}$, $\ddot{y}_{i,r}$ are bounded, that is, there exists a positive constant $B_{i,0}$, such that $y_{i,r}^2 + \dot{y}_{i,r}^2 + \ddot{y}_{i,r}^2 \le B_{i,0}$. And denote $\Pi_{i,0} := \{(y_{i,r}, \dot{y}_{i,r}, \ddot{y}_{i,r}) : y_{i,r}^2 + \dot{y}_{i,r}^2 + \ddot{y}_{i,r}^2 \le B_{i,0}\}$.