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Research article

Finite-time decentralized adaptive neural constrained control for interconnected nonlinear time-delay systems with dynamics couplings among subsystems

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ABSTRACT

The problem of finite-time decentralized neural adaptive constrained control is studied for large-scale nonlinear time-delay systems in the non-affine form. The main features of the considered system are that 1) unknown unmatched time-delay interactions are considered, 2) the couplings among the nested subsystems are involved in uncertain nonlinear systems, 3) based on finite-time stability approach, asymmetric saturation actuators and output constraints are studied in large-scale systems. First, the smooth asymmetric saturation nonlinearity and barrier Lyapunov functions are used to achieve the input and output constraints. Second, the appropriately designed Lyapunov-Krasovskii functional and the property of hyperbolic tangent functions are used to deal with the unknown unmatched time-delay interactions, and the neural networks are employed to approximate the unknown nonlinearities. Note that, due to unknown time-delay interactions and the couplings among subsystems, the controller design is more meaningful and challenging. At last, based on finite-time stability theory and Lyapunov stability theory, a decentralized adaptive controller is proposed, which decreases the number of learning parameters. It is shown that the designed controller can ensure that all closed-loop signals are bounded and the tracking error converges to a small neighborhood of the origin. The simulation studies are presented to show the effectiveness of the proposed method.

1. Introduction

As is well known, time delays can cause performance degradation, and even lead to system instability [1,2]. Uncertain interactions and multivariable nonlinearities have stimulated the study of large-scale systems, such as power systems, transportation networks and traffic systems. In the control design process, the effects of input and output constraints should be properly considered in system performance and security [3,4]. Therefore, in order to achieve finite-time transient performances, this paper will address the problem of finite-time decentralized adaptive constrained control for large-scale nonlinear systems in pure-feedback form subject to unknown unmatched time-delay interconnections and the couplings among the nested subsystems.

In the past few decades, fuzzy or neural adaptive backstepping control methods have been developed to handle the uncertainties for various systems [5–7]. In Ref. [8], neural network approximator was used for vibration control of flexible robotic manipulators. Based on the neural network approximation, Refs. [9,10] presented dynamic learning from adaptive control. Based on terminal sliding mode control method, the position tracking problem was considered in Ref. [11] for permanent magnet linear motor systems. A new chattering-free discrete-time sliding mode control was presented in Ref. [12] via nonsmooth control. Output-feedback fuzzy control was studied in Refs. [13,14] for nonstrict-feedback systems. Approximation-based control was achieved in Refs. [15,16] for uncertain complex nonlinear systems. In particular, decentralized control for physical nonlinear systems with uncertain interactions and complexity has long been an active issue in the control community [17]. In Ref. [18], decentralized adaptive fuzzy control was investigated for large-scale nonlinear systems, and Refs. [19,20] studied the neural-network-based decentralized stabilization problem for large-scale stochastic nonlinear systems. By using one function approximator, Ref. [21] constructed the local controller for interconnected nonlinear time-delay systems. In Refs. [22,23], the switched uncertain nonlinear large-scale systems were considered with arbitrary switching signals. It should be noted that the input and output constraints are factors that affect the performance of the practical

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control system, which need to be considered. To achieve the fast transient performance, the finite-time consensus problem was investigated in Ref. [24] for a group of nonholonomic mobile robots, and a finite-time observer-based distributed control strategy was developed in Ref. [25] for multiple nonholonomic chained-form systems. Recently, to deal with completely unknown system dynamics, approximation-based finite-time control schemes were applied to, finite-time tracking control in Ref. [26] for nonlinear pure-feedback systems, finite-time quantized feedback control in Ref. [27] for nonlinear quantized systems, finite-time adaptive neural tracking control in Ref. [28] for nonstrict-feedback nonlinear systems. However, this novel criterion of finite-time semi-global practical stability (SGPS) only appears in the control of single-variable systems, and particularly, no consideration was given to the effects of time delays and the constraints.

In practical industrial process, the effect of the constraints is a major concern, where most practical systems are usually operated near the boundaries for maximum economic benefit. Actuator saturation is an important input constraint. When the controller input reaches a certain limit, any effect to increase the system output is invalid [15,16,29,30]. Saturation input was used in Ref. [31] for the control design of an upper limb exoskeleton. In Ref. [32], input saturation was considered for decentralized adaptive observer-based control of large-scale nonlinear time-delay systems. Recently, barrier Lyapunov functions (BLFs) have been given to achieve the output constraint requirement [33–35]. By using BLFs, Refs. [36–38] presented input and output constraints, and Refs. [39–41] extended these studies to full-state constrained systems. Ref. [42] developed a fuzzy NN learning algorithm to handle uncertain constrained robot. Most of plants are characterized by multivariable, nonaffine nonlinearity and uncertainty. Time delays are often encountered in the implementation of controller. It is well known that the non-affine nonlinear structure is more general and challenging than the affine nonlinear systems. However, to the best of our knowledge, there is no work done on finite-time adaptive constrained control for uncertain interconnected non-affine nonlinear time-delay systems with the couplings among the nested subsystems.

The goal of this paper is to develop finite-time decentralized adaptive constrained control for a class of interconnected nonlinear systems subject to unknown system dynamics, unknown unmatched time-delay interactions, the couplings among the nested subsystems, input and output constraints. In the control design process, RBF neural networks are used to deal with unknown functions, BLFs are utilized to solve the output constraint problem, and an asymmetric smooth saturation model is employed to ensure input constraints. Then, based on the finite-time stability theory, adaptive control theory, backstepping design technique and Lyapunov-Krasovskii stability theorem, a delay-free finite-time tracking control scheme is presented to ensure the boundedness of the closed-loop system.

Compared with existing results, the main advantages of this paper are summarized as: 1) The couplings among the nested subsystems and dynamic interactions including time delays are investigated, and the interconnected systems are in the pure-feedback form. Compared with the decentralized control results [21,22,32] where system functions do not contain dynamic couplings, to design the controller in this paper is a difficult task, especially when unknown unmatched time-delay terms exist. 2) Input saturation and output constraints are concerned for interconnected time-delay systems, and the finite-time performance can be ensured. During the backstepping design, by employing hyperbolic tangent function, novel Lyapunov-Krasovskii functionals are designed to deal with unknown unmatched time-delay interactions. Compared with finite-time control [26–28], this paper investigates the large-scale nonlinear systems with unmatched time-delay interactions involved in the couplings among the nested subsystems. 3) The number of the learning parameters is reduced by updating the estimates of the norm for the unknown network weight vectors. This greatly alleviates the online computation burden and makes the implementation of the algorithm easier.

The remainder of this paper is organized as follows. The problem formulations and preliminaries are shown in Section 2. The decentralized adaptive neural controller is designed and the stability analysis is given in Section 3. Section 4 shows the simulation results to validate the effectiveness of proposed method. Finally, the conclusions are drawn in Section 5.

2. Preliminary knowledge and system formulation

2.1. Preliminaries

Lemma 1. *(Young's inequality [43]) For $\forall(x, y) \in \mathbf{R}^2$, the following inequality holds:*

$$xy \le \frac{\varepsilon^p}{p}\left|x\right|^p + \frac{1}{q\varepsilon^q}\left|y\right|^q \tag{1}$$

where $\varepsilon > 0, p > 1, q > 1, (p-1)(q-1) = 1$.

Lemma 2. [44] For $z_i \in R$, $i = 1, \dots, m$, $0 < c < 1$, *the following result holds*

$$\left(\sum_{i=1}^{m}\left|z_i\right|\right)^c \le \sum_{i=1}^{m}\left|z_i\right|^c \le m^{1-c}\left(\sum_{i=1}^{m}\left|z_i\right|\right)^c \tag{2}$$

Definition 1. [26,27] The equilibrium $x = 0$ *of the nonlinear system $\dot{x} = f(x, u)$ is semi-global practical finite-time stable (SGPFS) if for all $x(t_0) = x_0$, there exists $\varepsilon > 0$ and a settling time $T(\varepsilon, x_0) < \infty$ to make $\|x(t)\| < \varepsilon$, for all $t \ge t_0 + T$.*

Lemma 3. [27] *Given the system $\dot{x} = f(x, u)$, for smooth positive-definite function $V(x)$, there exist scalars $g > 0$, $0 < c < 1$ and $\beta > 0$, having*

$$\dot{V}(x) \le -gV^c(x) + \beta,\ t \ge 0 \tag{3}$$

then the nonlinear system $\dot{x} = f(x, u)$ is SGPFS.

2.2. System representation

Consider the following nonlinear time-delay system:

$$\begin{cases} \dot{x}_{i,j_i} = \varphi_{i,j_i}(\overline{x}_1, u_1, \dots, \overline{x}_{i-1}, u_{i-1}, \overline{x}_{i,j_i+1}) \\ \qquad\qquad + h_{i,j_i}(y(t-\tau)), \\ \dot{x}_{i,n_i} = \varphi_{i,n_i}(\overline{x}_1, u_1, \dots, \overline{x}_{i-1}, u_{i-1}, \overline{x}_i, u_i) \\ \qquad\qquad + h_{i,n_i}(y(t-\tau)), \\ y_i = x_{i,1},\quad i = 1, 2, \dots, m;\ j_i = 1, \dots, n_i - 1. \end{cases} \tag{4}$$

where $\overline{x}_i = [x_{i,1}, x_{i,2}, \dots, x_{i,n_i}]^T \in R^{n_i}$ is the state vector, and $y_i \in R$ is the output of the ith subsystem. $y(t-\tau) = [y_1(t-\tau_1), \dots, y_m(t-\tau_m)]^T \in R^m$ is the delayed output vector and τ_i are unknown constant delay terms. $\overline{x}_{i,j_i} = [x_{i,1}, \dots, x_{i,j_i}]^T \in R^{j_i}$. $\varphi_{i,j_i}(\cdot)$ and $h_{i,j_i}(\cdot)$, $j_i = 1, \dots, n_i$, $i = 1, \dots, m$ are unknown smooth nonlinear functions with $h_{i,j_i}(\cdot)$ representing the interconnected effect between the ith subsystem and other subsystems. u_i denotes the following saturation model.

$$u_i(v_i) = \mathrm{Sat}[v_i] = \begin{cases} u_i^-,\ v_i < u_i^- \\ v_i,\ u_i^- \le v_i \le u_i^+ \\ u_i^+,\ v_i > u_i^+ \end{cases} \tag{5}$$

where u_i^+ and u_i^- are the upper and lower bounds of $u_i(t)$.

Remark 1. *The nonlinear functions $\varphi_{i,j_i}(\cdot)$ in (4) are functions of current states of all i -order subsystems, and thus there exist the couplings among the nested subsystems in (4). The considered systems (4) are unlike the interconnected systems considered in Refs.* [45–47] *where nonlinear function only depends on its own state variables for each subsystems. Ref.* [48] *did not consider time delays. In this paper, the systems described by (4) contain the couplings among the subsystems, and thus it is a more general structure. Moreover, the existence of dynamic interactions and the system*