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Distributed adaptive output consensus control of a class of heterogeneous multi-agent systems under switching directed topologies

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ABSTRACT

In this paper, we consider a leader-follower output consensus problem for a class of uncertain heterogeneous non-affine pure-feedback multi-agent systems (MASs) in the presence of time-delay items and input saturation restrictions under switching directed topologies. A distributed adaptive control scheme is constructed by combining Lyapunov–Krasovskii functionals, backstepping methods, neural networks (NNs), auxiliary systems, graph theory, the mean value theorem and the implicit function theory along with the dynamic surface control (DSC) technique. The key advantages of the designed control approach are that there is no requirement of precise knowledge about uncertain dynamics and time-delay items of individual agents and the computational burden can drastically be reduced by employing the DSC technique. Also, norms of unknown weight of neural networks are estimated online instead of weight vectors themselves. In theory, it can be proven that the output signals of follower agents can synchronize with the leader's and all signals in the closed-loop system are cooperatively semiglobally uniformly ultimately bounded (CSUUB) by suitable choice of design parameters. Two simulation examples are presented to demonstrate the effectiveness of the proposed strategy.

1. Introduction

Over the past decade, a large number of cybernetic problems about the cooperative control of multi-agent systems (MASs) have been addressed and been extensively studied due to their potential applications in military and civilian facilities [2,7,9,19,32,34]. Recently, the distributed output consensus problem for multi-agent systems has emerged as an interesting topic and attracted considerable attention from control communities [1,27]. Hong et al. addressed distributed output regulation problems for linear multi-agent systems and designed distributed leader-follower control algorithms using output regulation theory and internal model principle in [10]. Chopra and Spong [4] defined the output synchronization problem and presented solutions for weakly minimum phase systems with relative degree one, and Qu et al. [20,21] solved an output consensus problem under a dynamical communication topology. Kim et al. [12] considered the output consensus prob-

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lem for a class of heterogeneous uncertain linear multi-agent systems. Output consensus analysis and design problems for high-order linear swarm systems with directed interaction topologies were investigated in [28,29]. Nevertheless, the mentioned references [4,10,12,20,21,28,29] reported control approaches with the assumption that the dynamics of agents are in linear form. For a class of nonlinear multi-agent systems, Huang et al. [6] introduced a distributed internal model and converted the cooperative global robust output regulation issue into a global stabilization problem. In [5], Ding reported a consensus control strategy with relative information for network-connected nonlinear systems where the subsystems might have different dynamics with non-sector-bounded nonlinearities. Wang and Wen et al. [26] proposed an output consensus tracking approach for strict-feedback multi-agent systems with mismatched unknown parameters. Afterwards, control methods were discussed for agents with semi-strict feedback heterogeneous dynamics in [18]. However, the conventional backstepping approach [13] used in [18,26] might lead to 'explosion of complexity' with the growth of the order of the system.

To avoid the drawback of traditional backstepping-based methods, a kind of cybernetics technologies named dynamic surface control (DSC) [22] was proposed by introducing a first-order low-pass filter at each step during the design procedure. Furthermore, this approach was combined with neural networks (NNs) to control of single-input-single-output (SISO) uncertain strict-feedback systems in [24]. After that, this technology gained remarkable progress by plenty of scholars. Wang et al. developed a robust stabilization DSC law for SISO non-affine pure-feedback systems in [25]. For a class of multiple-input-multiple-output (MIMO) time-delay systems in strict-feedback form, Li et al. [15] presented an adaptive control scheme by DSC, NNs and Lyapunov–Krasovskii functionals. In [30], Yoo addressed a distributed consensus tracking control problem for multiple strict-feedback systems with unknown nonlinearities under a directed graph topology.

Motivated by the aforementioned references, we will restrict our attention to present a distributed adaptive leader-follower output consensus scheme for a class of uncertain heterogeneous non-affine pure-feedback multi-agent systems in the presence of time-delay items and input saturation constraints. The main contributions of this paper are nontrivial as follows: (1) First of all, the discussed objects are extended to general nonlinear systems in non-affine pure-feedback form with both time delays and input saturation constraints. The task of designing control laws for such nonlinear systems consisting of heterogeneous agents seems more formidable and challenging than the results reported in [25,30,33]. (2) In addition, there is no requirement of priori knowledge about uncertain dynamics and time-delay items of individual agents. In contrast to fixed and/or undirected topologies discussed in [26,30], the communication interactions among agents are under switching directed topologies and trajectory information of the leader are only available for part of followers, that is, not all of them. (3) Last but not the least, norms of neural network weights is taken as estimated parameters instead of weight vectors themselves which reduces the number of online updated parameters and the DSC approach is introduced to avoid the so-called problem of 'explosion of complexity', which leads to a much simpler and more concise control strategy than traditional backstepping-based methods.

2. Preliminaries and problem formulation

Consider a class of MASs consisting of one leader and N followers, which are in non-affine pure feedback form with unknown time-delay functions and input saturations. The dynamics of the ith follower are:

$$\begin{cases} \dot{x}_{i,j}(t) = f_{i,j}\big(\bar{x}_{i,j}(t), x_{i,j+1}(t)\big) + h_{i,j}\big(\bar{x}_{i,j}(t-\tau_{i,j})\big) + \Delta_{i,j}(\bar{y}(t), t),\ j = 1, \ldots, \ n_i - 1, \\ \dot{x}_{i,n_i}(t) = f_{i,n_i}\big(\bar{x}_{i,n_i}(t), u_i(t)\big) + h_{i,n_i}\big(\bar{x}_{i,n_i}(t-\tau_{i,n_i})\big) + \Delta_{i,n_i}(\bar{y}(t), t), \\ x_i(t) = \varpi(t),\ t \in \big[-\tau_{\max}, 0\big], \\ y_i(t) = x_{i,1}(t), \end{cases} \tag{1}$$

for $i = 1, \ldots, N,$ where $x_{i,\,k}(t)$, $k = 1, \ldots, n_i$, is available and denotes state variable of the ith follower, $\bar{x}_{i,k}(t) = [x_{i,1}(t), \ldots, x_{i,k}(t)]^{\mathrm{T}} \in \mathbb{R}^k$, and $x_i(t) = [x_{i,1}(t), \ldots, x_{i,n_i}(t)]^{\mathrm{T}} \in \mathbb{R}^{n_i}$; $f_{i,\,k}(\cdot)$ and $h_{i,\,k}(\cdot)$ are unknown nonlinear smooth functions; $\Delta_{i,k}(\bar{y}(t), t)$ represents uncertain disturbances, which is an unknown continuous function; $\varpi(t) \in \mathbb{R}^{n_i}$ is a smooth and bounded initial state vector function; $\tau_{\max}$ is the upper bound of $\tau_{i,\,k}$; $u_i(t) \in \mathbb{R}$ and $y_i(t) \in \mathbb{R}$ are the input and output of the ith follower, respectively; $\bar{y}(t) = [y_1(t), \ldots, y_N(t)]^{\mathrm{T}} \in \mathbb{R}^N$; $u_i(t)$ is the design control input with $u_{i,\,0}(t)$ subjected to the condition of saturation

$$u_i = \mathrm{sat}(u_{i,0}) = \begin{cases} u_{i,\max}, & \text{if } u_{i,0} > u_{i,\max}, \\ u_{i,0}, & \text{if } u_{i,\min} \le u_{i,0} \le u_{i,\max}, \\ u_{i,\min}, & \text{if } u_{i,0} < u_{i,\min}, \end{cases} \tag{2}$$

and define that

$$\Delta u_i = u_i - u_{i,0}, \tag{3}$$

where $u_{i,\,\max}$ and $u_{i,\,\min}$ are the known upper saturation limitation and lower saturation limitation, respectively.

Remark 1. It should be mentioning that time-delay functions and input saturation efforts are simultaneously appeared in (1) and the two phenomena are commonly encountered in industrial applications. The pure-feedback forms of individual followers (1), in practice, are employed to describe dynamics of numerous physical systems [11,17,25], such as robotic systems, air vehicles, biochemical processes, and so on. What's more, the degree and structure of each agent may not be the