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Distributed adaptive consensus tracking for a class of multi-agent systems via output feedback approach under switching topologies ☆

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ABSTRACT

The consensus tracking problem is discussed for a class of multi-agent systems (MASs) in *non-affine pure-feedback form* via *output feedback approach* under switching directed topologies. Observers are employed to reconstruct state information of the system, and then a consensus tracking control scheme is presented by the backstepping method combining with dynamic surface control (DSC) technique, neural networks (NNs), and graph theory. The main advantage of the proposed strategy is that it only relies on the output signals of individual agents in communication graph and it removes the requirement for exact priori knowledge about parameters of agents. Moreover, by introducing DSC technology, it avoids the well known problem of 'explosion of complexity' that conventional backstepping method suffers from along with the increasement of the degree of individual agents. It is proven that the designed output feedback control scheme guarantees consensus errors are cooperatively semiglobally uniformly ultimately bounded and converge to neighborhood of the origin by suitable choice of design parameters. Simulation results are presented to demonstrate the effectiveness of the proposed control approach.

1. Introduction

Consensus control of multi-agent systems (MASs) has attracted considerable attention from the cybernetic community over the past years, partly due to its board applications in military and civil fields, such as formation control of surface vehicles, wireless sensor networks, and multi robot collaborative equipment. A great number of results about consensus of multi-agent systems have been reported in [1–13]. For instance, consensus problems of first-order and second-order multi-agent systems were studied in [4,7]. And then consensus protocols for linear multi-agent systems with either time-varying delays or with switching topologies were developed in [8,9]. Further, the consensus problems for nonlinear multi-agent systems were studied in [2,6]. Huang et al. considered output regulation problem for second-order [10] and arbitrary relative degree [11] nonlinear multi-agent systems. Wang et al. [12] proposed an output consensus tracking approach for strict-feedback multi-agent systems with mismatched unknown parameters. And a tracking scheme for the agents in semi strict-feedback dynamics form was discussed in [13]. The disadvantage in [12,13] was common that the control laws were complex induced from repeated differentiation of control signals by conventional backstepping method [14]. To overcome the limitation of 'explosion of complexity', a dynamic surface control (DSC) technique was proposed by introducing a first-order filter at each step in [15]. This technique was extended to tracking control of pure-feedback systems combining with NNs, and then the idea gain remarkable progress by numerous scholars, such as [16–20].

Most of the reported results of consensus problem are primarily for MASs with the same-order dynamics. In recent decade, some efforts were taken to develop control strategies for heterogeneous MASs, first for linear systems [21,22]. The output consensus control of a class of heterogeneous uncertain linear MASs [23]. Furthermore, a relevant but more general work was carried out. In [24], a consensus control strategy with relative information was presented by the internal model method for a class of heterogeneous nonlinear systems with relative degree one.

Motivated by the above observations, we restrict our attention to consensus tracking for heterogeneous multi-agent systems in non-affine pure-feedback form via output feedback approach under switching topologies. In detail, the non-affine pure-feedback form of individual agents is transformed into the strict-feedback form

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with the aid of the function transformation and uncertain dynamics are approximated by neural networks. Further, observers are constructed to estimate state information of the system and a first-order low-pass filter is exploited to replace differential operations at each step for individual agents. The main *contributions* of this paper are threefold: (1) Distributed output control laws are proposed and it only relies on output information of individual local agents in topologies. Unlike in [20,30,31], it relaxes the assumptions and there is no requirement of the availableness of inner state information of the neighbor agents. It is worth mentioning that it can reduce the cost related to the on-board sensors and is also useful in industrial applications where inner states can not be or not be easily measured. (2) In [20,29], consensus tracking methods were proposed for individual agents in strict-feedback form, and in [29,30], control approaches were discussed for agents under fixed undirected connected graph. In this paper, we consider the consensus tracking problem for the agents in non-affine pure-feedback form with switching directed topologies. The issue is more general and seems more challenging to design output control law for the system in such form since the control input is implicit for each agent. (3) Uncertainties are taken into account and NNs are employed to approximate unknown dynamics without exact prior knowledge about parameters of the system. Moreover, unlike in [12,13], the limitation of explosion of complexity along with increasement of the degree of individual agents is avoided utilizing the DSC technique.

Throughout the whole paper, $\|\cdot\|$ represents Euclidean norm of vectors or induced norm of matrices. $\lambda_{\min}(\cdot)$ and $\lambda_{\max}(\cdot)$ denote the minimum and maximum eigenvalue of a matrix, respectively.

2. Preliminaries and problem formulation

Consider a class of MASs consisting of one leader and N followers, who are in non-affine pure-feedback form. The dynamics of the ith follower are described as

$$\begin{cases} \dot{x}_{i,1} = f_{i,1}(x_{i,1}, x_{i,2}), \\ \dot{x}_{i,2} = f_{i,2}\left(\underline{x}_{i,2}, x_{i,3}\right), \\ \vdots \\ \dot{x}_{i,n_i-1} = f_{i,n_i-1}\left(\underline{x}_{i,n_i-1}, x_{i,n_i}\right), \\ \dot{x}_{i,n_i} = f_{i,n_i}\left(\underline{x}_{i,n_i}, u_i\right), \\ y_i = x_{i,1}, \end{cases} \tag{1}$$

where the vector $\underline{x}_{i,j} = [x_{i,1}, \dots, x_{i,j}]^{\mathrm{T}} \in \mathbb{R}^j$ with the element $x_{i,j}$ denoting the jth state variable of the ith follower, $i = 1,\dots,N$, $j = 1,\dots,n_i$, $\underline{x}_i = [x_{i,1},\dots,x_{i,n_i}]^{\mathrm{T}} \in \mathbb{R}^{n_i}$; $f_{i,j}(\cdot) \in \mathbb{R}$ are unknown nonlinear smooth functions, representing the jth dynamics of the ith agent; $u_i \in \mathbb{R}$ and $y_i \in \mathbb{R}$ are the input and output of the ith agent, respectively. It is to be assumed that only the output information y_i are available for measurement.

Remark 1. The form in (1) can be employed to described plenty of practical military and civil systems such as air space crafts, unmanned surface vehicles, and robotic systems [14]. More generally speaking, it is worth emphasizing that parts of nonlinear systems can be transformed, by a proper change of coordinate, into the pure-feedback form as shown in (1).

For the sake of conciseness, we omit t in the delay-free terms throughout the whole paper, and the following assumption is addressed.

Assumption 1. The reference signal y_{d} is smooth and $y_{\mathrm{d}}, \dot{y}_{\mathrm{d}}, \ddot{y}_{\mathrm{d}}$ are bounded, that is to say, there exists a positive constant ϱ_{i0} satisfying that $y_{\mathrm{d}}^2 + \dot{y}_{\mathrm{d}}^2 + \ddot{y}_{\mathrm{d}}^2 \le \varrho_0$.

Remark 2. In practice, the energy of command generators are limited. In this case, Assumption 1 is substantially common and it can be found in exiting literature, such as [17].

Remark 3. Compared with the multi-agent system studied in [20], the control scheme presented in this paper extends the related results to a more generalized architecture whereas authors in [20] only focused on the control problem for a class of nonlinear systems in strict-feedback form. What is more, state observers will be introduced to reconstructed system states and we remove the assumption in [20], that inner states $x_{i,1}$ and $x_{i,2}$ are available for the neighbor agents, which makes the stability analysis more challenging and research work more complex.

The communication topology of the information flow between the $N+1$ agents is described by a directed graph and we consider the scenario in which the individual agents, whose state information are available by themselves. A graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ has a spanning tree, where $\mathcal{V}$ and $\mathcal{E}$ is described as a node set and an edge set, respectively, $\mathcal{V} = \{\upsilon_0, \upsilon_1, \dots, \upsilon_N\}$, $\mathcal{E} = \{(\upsilon_i, \upsilon_j) \in \mathcal{V} \times \mathcal{V}\}$ with (υ_i, υ_j) denoted that Node i can obtain information from Node j. The leader is denoted as 0 and the followers are from 1 to N. Also, the neighbor set of Node i is defined as $\mathcal{N}_i$. $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{(N+1)\times(N+1)}$ is the adjacency matrix with $a_{ij} = 1$, if $(\upsilon_j, \upsilon_i) \in \mathcal{E}$; and a_{ij} is zero, otherwise. What is more, a diagonal matrix $\mathcal{B} = \mathrm{diag}[b_1, \dots, b_N]$ is introduced to represent the accessibility of the leader to the Node i with $b_i = 1$, if possible; and $b_i = 0$, otherwise. We define a subgraph $\overline{\mathcal{G}} = \{\overline{\mathcal{V}}, \overline{\mathcal{E}}\}$ to illustrate the communication relationships among followers, where $\overline{\mathcal{V}} = \{\upsilon_1, \dots, \upsilon_N\}$, and $\overline{\mathcal{L}} = \overline{\mathcal{D}} - \overline{\mathcal{A}}$ is the Laplacian matrix of the subgraph. $\overline{\mathcal{D}} = \mathrm{diag}[d_1, \dots, d_N]$, $\overline{\mathcal{A}} = [a_{ij}] \in \mathbb{R}^{N\times N}$ is the adjacency matrix with $a_{ij} = 1$, if $(\upsilon_j, \upsilon_i) \in \overline{\mathcal{E}}$; and a_{ij} is zero, otherwise. The more details can be found in [20] and the references therein.

The preliminaries about the radial basis function (RBF) neural networks are omitted for the sake of space limitation. Readers may refer to relevant publications, such as [25,26], for more details. In the following sections, $\theta_{i,j}^*$ and W_i^* are unknown ideal constant weight vectors of RBF neural networks, $\varphi_{i,j}(Z_{i,j})$ and $G_i(Z_i)$ are Gaussian function vectors with appropriate dimensions where input vectors $Z_{i,j}$ and Z_i will be given later. Approximation errors $\varepsilon_{i,j}$ and ξ_i are bounded satisfying that $|\varepsilon_{i,j}| \le \varepsilon_{i,j}^*$ and $|\xi_i| \le \xi_i^*$, where $\varepsilon_{i,j}^*$ and ξ_i^* are unknown positive constants.

The definition about cooperatively semiglobally uniformly ultimately bounded (CSUUB) can be found in [20], and the control objective of this paper is to design a distributed adaptive control strategy for the system (1) to force the output y_i of followers to synchronize with the output of the leader while all signals in the closed-loop system are CSUUB.

3. Output feedback control law design and stability analysis

In this section, state observers will be constructed to estimate the inner states of MASs in form (1). Then, a distributed adaptive consensus output feedback tracking scheme will be presented to achieve the control objective stated in Section 2.

3.1. Observer design

For the ith subsystem of (1), we define

$$F_{i,j}(\underline{x}_{i,j}, x_{i,j+1}) = f_{i,j}(\underline{x}_{i,j}, x_{i,j+1}) - x_{i,j+1}, \tag{2}$$