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Cooperative output feedback adaptive control of uncertain nonlinear multi-agent systems with a dynamic leader ☆

Zhouhua Peng [a,*], Dan Wang [a], Hongwei Zhang [b], Yejin Lin [a]

[a] School of Marine Engineering, Dalian Maritime University, Dalian 116026, PR China
[b] School of Electrical Engineering, Southwest Jiaotong University, Chendu 610031, PR China

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ABSTRACT

This paper considers the cooperative tracking problem of uncertain nonlinear multi-agent systems with unmeasurable states and a dynamic leader whose input is unknown to all follower agents. By approximating the uncertain nonlinear dynamics via neural network and constructing a local observer to estimate the unmeasurable states, distributed output feedback adaptive controllers are proposed, based on the relative observed states of neighboring agents. It is proved that with the developed controllers, the state of each agent synchronizes to that of the leader for any undirected connected graphs even when only a fraction of the agents have access to the state information of the leader, and the tracking errors are guaranteed to be uniformly ultimately bounded. A sufficient condition to the existence of the controllers is that each agent is stabilizable and detectable. The main advantage, compared with existing results, lies in the fact that cooperative tracking of nonlinear systems can be achieved in the presence of unmeasurable states without knowing the input of the leader. Two illustrative examples are given to show the efficacy of the proposed methods.

1. Introduction

Recent years have witnessed a compelling interest in consensus problem of multi-agent systems for broad applications in engineering such as formation flight of aerial vehicles, formation control of mobile robots, cooperative control of marine vehicles. The key of consensus is to design a distributed control law based on local interactions such that the group agree on some value of interest [1–5]. In the literature, a great deal of effort has been made on two consensus problems of multi-agent systems. One is *leaderless consensus*, and the other is *leader–follower consensus* where there exists an active leader who acts as a trajectory generator for the group to follow [5]. In some literature, the leader–follower consensus is also called as *distributed tracking* [6], *consensus tracking* [7], or *cooperative tracking* [8].

During the past few years, consensus control of multi-agent systems has been widely studied from different perspectives. In [9], a neighbor-based observer is proposed for tracking control of first-order linear multi-agent system under fixed and variable topologies. In [10], a consensus algorithm is developed for first-order linear systems with a time-varying leader dynamics. In [11,12], distributed output regulation approaches are proposed for linear multi-agent systems. In [13], consensus of linear multi-agent systems and synchronization of complex networks are unified in a framework. In [6], distributed tracking control of linear multi-agent systems with a leader of bounded unknown input is considered. In [14], leader–follower consensus algorithms are developed for both fixed and switching interaction topologies. In [15], a framework for cooperative tracking is proposed, including state feedback, observer and output feedback. In [16], finite-time state consensus problem for linear multi-agent systems is discussed. In [17], partial state consensus is investigated for networks of second-order linear dynamic agents. In [18], consensus problem of continuous-time second-order multi-agent systems via sampled data is considered. In [19], consensus seeking of discrete-time linear time-invariant multi-agent systems with communication noises is studied. In [20], observer-based consensus protocols are developed for second-order multi-agent systems under fixed and stochastically switching topology. Note that all aforementioned results are based on the exact linear system model, which may not be adequate to describe the practical agent dynamics in many real-world applications.

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* Corresponding author.
E-mail address: zhouhuapeng@gmail.com (Z. Peng).

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Recently, consensus control of nonlinear systems has drawn great attention [8,21–28]. Consensus control of nonlinear multi-agent systems with unknown nonlinear dynamics is firstly considered in [21], where distributed adaptive controller is designed to achieve robust consensus. Distributed tracking of first-order nonlinear systems on strongly connected graphs is studied in [22], where neural network (NN) is employed to account for the unknown nonlinear dynamics. This result is extended to second-order uncertain nonlinear systems in [23]. Neural network-based leader-following control of first-order multi-agent systems with uncertainties is presented in [24], and this result is extended to second-order case using a backstepping technique. Robust consensus tracking of second-order nonlinear multi-agent systems is discussed in [25], where continuous consensus protocols are developed to enable global asymptotic tracking performance. Distributed tracking control of high-order nonlinear systems is provided in [8], where the communication graph does not require to be connected. Synchronized tracking control of high-order nonlinear systems using state and output information is considered in [28]. Adaptive coordinated tracking of multiple manipulators with uncertainties can be found in [26,27]. In these works [8,21–27], state feedback is particularly efficient for nonlinear systems to achieve consensus. However, in many real world systems, only the measured output information rather than the full state information can be available for feedback. Therefore, from a practical perspective, observer-based output feedback control is of great importance.

In this paper, we focus on the cooperative tracking control of uncertain nonlinear multi-agent systems with an unknown input of the leader over an undirected network. It is assumed that a fraction of agents have access to the state of the leader and the input of the leader is bounded. As for the cooperative state feedback tracking control of uncertain nonlinear systems, the unknown input of the leader can be considered as a disturbance to be rejected by the NN. However, this cannot be done in the context of the output feedback case due to the fact that the unknown input cannot be merged into the uncertain part. By approximating the uncertain nonlinear dynamics via NN and constructing a local observer to estimate the unmeasurable states, cooperative output feedback adaptive controllers, with static and dynamic coupling gains, respectively, are developed. Two Riccati equations are employed to show the uniform ultimate boundedness of the observer errors and tracking errors. It is shown that synchronization to the leader can be reached for nonlinear systems in the presence of unmeasurable states and unknown input of the leader. A sufficient condition to the existence of such controllers is that each agent is stabilizable and detectable. It is worth noting that the static tracking controller depends on the eigenvalues of the communication graph and the upper bound of the control input of the leader. This restriction is removed by using adaptive coupling strategy which results in fully distributed observer-based tracking controllers.

For the first time, a cooperative output feedback adaptive control (COFAC) architecture is developed for uncertain nonlinear multi-agent systems with a dynamic leader whose input is unavailable to each agent. Previous works related to this paper include [8,13–15,21–24,28,29], and the differences are listed as follows. First, compared with the agent dynamics in [8,21–24, 28,29], the agent model considered in this paper is more general and takes the first-order, second-order, and high-order nonlinear systems as special cases. By employing two Riccati equations, the restriction on the agent dynamics is relaxed. Besides, the controllers proposed in [8,21–24,26,27] are based on the state feedback, while this paper focuses on the output feedback problem which means that the design methods given in [8,21–24,26,27] cannot be directly applied. Second, in contrast to the observer-based cooperative tracking controllers developed for linear systems in [13–15], the controllers designed in this paper are for nonlinear systems. Since the "separation principle" is generally not valid for nonlinear system, this development is nontrivial. The main advantage of the proposed scheme is that the NN identification of the individual uncertain dynamics is decoupled from the network topology, which is useful for practical implementations since the uncertain nonlinear dynamics can be suppressed by the local NN.

This paper is organized as follows. Section 2 introduces some preliminaries and formulates the control problem. Section 3 presents the cooperative output feedback control design and stability analysis. The above result is extended to the cooperative output feedback control design with dynamic coupling in Section 4. Two examples are given in Section 5 for illustrations. Conclusions are drawn in Section 6.

2. Preliminaries and problem formulation

2.1. Preliminaries

2.1.1. Notation

Let the Euclidean norm, the Frobenius norm, the minimum singular value, the maximum singular value, and the trace be denoted by $\|\cdot\|$, $\|\cdot\|_F$, $\underline{\sigma}(\cdot)$, $\overline{\sigma}(\cdot)$, and $\mathrm{tr}\{\cdot\}$, respectively. Let $\mathrm{diag}\{\lambda_1,\dots,\lambda_N\}$ be a diagonal matrix with λ_i being the ith diagonal element. An identity matrix of dimension N is represented by I_N. Let the Kronecker product be denoted by $\otimes$ with the properties $(A\otimes B)^T=A^T\otimes B^T$, $\alpha(A\otimes B)=(\alpha A)\otimes B=A\otimes(\alpha B)$, $(A\otimes B)(C\otimes D)=(AC)\otimes(BD)$, where A,B,C,D are matrices and α is a scalar.

2.1.2. Graph theory

Consider a network of multi-agent systems consisting of N agents and one leader. If each agent is considered as a node, the neighbor relation can be described by a *graph* $\mathcal{G}=\{\mathcal{V},\mathcal{E}\}$, where $\mathcal{V}=\{n_1,\dots,n_N\}$ is a node set and $\mathcal{E}=\{(n_i,n_j)\in\mathcal{V}\times\mathcal{V}\}$ is an edge set with the element (n_i,n_j) that describes the communication from node i to node j. The neighbor set of the node i is denoted by $\mathcal{N}_i=\{j|(n_j,n_i)\in\mathcal{E}\}$. Define an adjacency matrix $\mathcal{A}=[a_{ij}]\in\mathbb{R}^{N\times N}$ with $a_{ij}=1$, if $(n_j,n_i)\in\mathcal{E}$, and $a_{ij}=0$, otherwise. Define the in-degree matrix as $\mathcal{D}=\mathrm{diag}\{d_1,\dots,d_N\}$ with $d_i=\sum_{j\in\mathcal{N}_i}a_{ij}$. The Laplacian matrix $L=[l_{ij}]\in\mathbb{R}^{N\times N}$ associated with the graph $\mathcal{G}$ is defined as $L=\mathcal{D}-\mathcal{A}$. If $a_{ij}=a_{ji}$, for $i,j=1,\dots,N$, then the graph $\mathcal{G}$ is *undirected*. A *path* in a graph is an ordered sequence of nodes such that any two consecutive nodes in the sequence are an edge of the graph. An undirected graph is *connected* if there is a path between every pair of nodes. Finally, define a leader adjacency matrix as $\mathcal{A}_0=\mathrm{diag}\{a_{10},\dots,a_{N0}\}$, where $a_{i0}>0$ if and only if the ith agent has access to the leader information; otherwise, $a_{i0}=0$. For simplicity, denote $L+\mathcal{A}_0$ by H.

Lemma 1 (*Hong et al.* [9]). *If the graph $\mathcal{G}$ is undirected and connected, and at least one agent has access to the leader. Then, H is positive definite.*

2.2. Problem formulation

Consider a network of uncertain nonlinear multi-agent systems consisting of N agents and a leader. The dynamics of the ith agent is given by

$$\begin{cases}\dot{x}_i=Ax_i+B[u_i+f_i(x_i)],\\ y_i=Cx_i,\end{cases}\tag{1}$$

where $x_i=[x_{i1},\dots,x_{in}]^T\in\mathbb{R}^n$ is the system state; $u_i\in\mathbb{R}^m$ is the control input; $f_i(x_i)\in\mathbb{R}^m$ is an unknown matched uncertainty;