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Distributed adaptive output consensus tracking of higher-order systems with unknown control directions ☆

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ABSTRACT

This paper investigates the distributed adaptive output consensus tracking problem of higher-order subsystems with unknown control directions and unknown dynamic parameters. Only a subset of the subsystems is given access to the desired trajectory information directly, and the subsystems are connected through an undirected and connected graph with a time-invariant topology. A distributed adaptive controller is deduced using the backstepping technique and a Nussbaum-type function to drive all the subsystems to track the desired trajectory asymptotically. Moreover, these controllers are distributed in the sense that the controller design for each subsystem only requires relative state information between itself and its neighbors. It is proven that the output tracking error converges to zero asymptotically and that all the closed-loop system signals are bounded. A simulation is carried out to demonstrate the effectiveness of the proposed control scheme.

1. Introduction

In the past decade, consensus problems in multi-agent systems have attracted significant research attention [1]. Due to its engineering applications in unmanned surface vehicles [2–6], cooperative control of multiple mobile robots [7–9], consensus tracking, as an important research direction of multi-agent systems, has been studied extensively in recent years. For consensus tracking, also called leader-following consensus, there is a leader agent (or a virtual leader) acting as a command generator and ignoring information from all the other agents. Only a subset of the followers is given access to the leader's information directly, and a distributed consensus protocol is proposed to make all the follower agents track the trajectory of the leader using only the local state of the agents and their neighbors. Several valuable results have also emerged and received widespread attention, such as [10–19], to name a few.

In [10,11], Das and Lewis presented distributed adaptive control laws to solve the cooperative tracking problem for unknown nonlinear first-order and second-order integrator systems. The results are generalized to higher-order nonlinear systems in the Brunovsky form by Zhang and Lewis in [12]. However, the design of consensus protocols in [10–12] has a flaw due to the improper choice of the diagonal matrix P. The matrix P is global information in the sense that each subsystem has to know the entire communication graph $\mathcal{G}$ to compute it, which limits its application range. Recently, the problem of robust consensus tracking for a class of first-order and second-order multi-agent dynamic systems with disturbances and unmodeled agent dynamics has been discussed in [13,14], respectively, by developing an identifier for each agent to estimate the unknown disturbances and unmodeled agent dynamics. Moreover, in [15], Wang, Huang, Wen, and Fan have investigated the output consensus problem of tracking a desired trajectory for a class of systems consisting of multiple higher-order nonlinear subsystems with intrinsic mismatched unknown parameters. It is worth noting that most existing results have been obtained for specific systems, as in [10–15] where the controlling effect (also called control gain) of each follower is a known constant or a known function. However, in real practice, the controlling effect is different from unity and not easy to accurately know. Recently, neural network-based leader-following consensus control algorithms for a class of nonlinear multi-agent systems with unknown controlling effects have been presented in [17–19] and received extensive attention from the control community. Ref. [17] studied the synchronization problem of higher-order multi-input/multi-output multi-agent systems with the gain matrix being the unknown function of the states of the agents by using the local filtered error and a radial basis function neural network. However, it is not easy to reduce the bounds of the

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tracking errors by adjusting the control gains. Ref. [18] investigated the leader-following consensus problem of multi-agent systems where the controlling effect of each follower depends on its own state. However, only first-order systems were focused on. In engineering, many systems are modeled by second- and higher-order dynamics, such as the inverted pendulum, a single link flexible joint manipulator [21]. El-Ferik, Qureshi, and Lewis in [19] considered cooperative tracking control of unknown higher-order affine nonlinear systems where the input function $g_i(\cdot)$ is assumed to be unknown. However, the tuning rules proposed for the unknown NN weights result in it being very difficult to guarantee that the estimated weights are always bounded, and thus the second assumption of El-Ferik et al. [19] is hardly valid. Note that the signs of unknown controlling effects are required to be known a priori [17–19]. These signs, called control directions in [22], represent motion directions of the system under any control. In practice, a control direction might not always be known a priori in many applications. Thus, these above-mentioned approaches [10–19] cannot address the consensus problem of multi-agent systems with unknown control directions.

When the control directions are unknown, the adaptive control problem becomes much more difficult. The first result was given in [23] by Nussbaum for a class of first-order linear systems, where the so-called Nussbaum-type gain was originally proposed. Up to now, a great number of interesting results, such as those of [24–27], have been obtained by exploiting the special properties of Nussbaum-type gain. Nevertheless, to the best of our knowledge, the results regarding the distributed adaptive consensus control of more general multiple nonlinear systems where the signs of control directions are unknown are still limited. In [20], Shi and Shen have discussed the cooperative control problem of uncertain higher-order nonlinear multi-agent systems on directed graphs with fixed topology, where the control gains are influenced by the state of each agent, and the control directions are unknown. By the Nussbaum-type gain technique and the function approximation capability of neural networks, a distributed adaptive neural network-based controller was proposed to drive all the followers to track the leader, with the tracking errors being semi-globally uniform ultimate bounded. However, a major problem with this is that Lemma 4 in Shi and Shen [20], which plays a fundamental role in its stability analysis, is only focused on the cases involving a single Nussbaum-type function gain and cannot be extended to cases containing more than one Nussbaum-type gain directly [24]. Also due to the above reason, it is not clear how to use the existing Nussbaum-type functions to solve the distributed adaptive consensus problem with theoretical proof, although they might work well in practice or simulation. In [28], Peng and Ye have investigated the cooperative regulation problem (also called leaderless consensus) with unknown high-frequency gain signs. They constructed a sub-Lyapunov function for each agent to ensure that only a Nussbaum-type item is incorporated, and thus the situation that the Lyapunov function contains more than one Nussbaum-type gain can be avoided. However, only first-order systems without unknown dynamic parameters were focused on. Also due to its particular method of analyses, it is not easy to extend the proposed method to solve consensus tracking control of higher-order systems with unknown dynamic parameters and unknown control directions. More recently, in [29], Chen, Li, Ren, and Wen have also dealt with the adaptive consensus of multi-agent systems with unknown control directions and unknown dynamic parameters. A novel Nussbaum-type function was proposed to overcome these obstacles of the Lyapunov function containing more than one Nussbaum-type gain. However, they only solved the leaderless consensus problem with first- and second-order subsystems. In addition, the unknown dynamic parameters only appear in the last equation of each subsystem. That is, the uncertainties must satisfy the matching condition in [29]. How to design a distributed consensus tracking controller for higher-order uncertain nonlinear systems with unknown control directions and unknown dynamic parameters is quite challenging and to the best of our knowledge is still open. The main difficulty lies in that the control directions are unknown, which renders the construction of distributed controller far from being easy, and that the uncertain dynamics does not satisfy the matching condition, which makes the controller design for higher-order nonlinear subsystems much more complicated.

In this paper, we study the output consensus tracking problem of higher-order uncertain nonlinear systems with unknown control directions and unknown dynamic parameters. The backstepping technique is adopted to deduce the distributed control laws, and the projection algorithm is taken to guarantee that the estimates of the unknown parameters are always bounded. Compared with existing works in the literature, the main contributions of note lie in the following aspects. First, the higher-order systems discussed in this paper are more general than the systems in most results available regarding the distributed consensus control with unknown dynamic parameters and unknown control directions. Second, all the agents' outputs synchronize to the desired trajectory asymptotically, though only a subset of the agents can obtain the desired trajectory information directly.

The rest of this paper is organized as follows. In Section 2, some notions and preliminaries regarding algebraic graph theory are briefly introduced, and the output consensus problem of tracking a desired trajectory is presented. Section 3 derives the proposed distributed adaptive consensus protocol in detail and presents the main results. In Section 4, simulation results are provided to demonstrate the effectiveness of the proposed technique. Conclusions with future work on the problem of consensus tracking follow in Section 5.

2. Problem statement

2.1. Basic graph theory and notations

In this subsection, some notions and terminologies regarding algebraic graph theory are briefly introduced, which can also be found in [30].

Let $\mathcal{G}=\{\mathcal{V},\mathcal{E}\}$ denote an undirected graph, where $\mathcal{V}=\{1,\dots,N\}$ is the set of nodes corresponding to each subsystem and $\mathcal{E}\subseteq\mathcal{V}\times\mathcal{V}$ is the set of edges. $(i,j)\in\mathcal{E}$ indicates that subsystem j can obtain information from subsystem i, and necessarily $(j,i)\in\mathcal{E}$ for an undirected graph, but not necessarily vice versa for a directed graph. In this paper, self-loops are not allowed in the graph, that is, $(i,i)\notin\mathcal{E}$. $N_i=\{j\in\mathcal{V}\,|\,(j,i)\in\mathcal{E}\}$ denotes the neighbors of subsystem i. The matrix $A=[a_{ij}]\in R^{N\times N}$ denotes the adjacency matrix of $\mathcal{G}$, where $a_{ij}=1$ if and only if $(j,i)\in\mathcal{E}$, else $a_{ij}=0$. It is assumed that the topology is fixed, which means that A is time-invariant. The matrix $L=D-A$ is called the Laplacian matrix of $\mathcal{G}$, where $D=\mathrm{diag}(d_1,\dots,d_N)$ is the in-degree matrix with $d_i=\sum_{j=1}^{N}a_{ij}$. A path from subsystem i to subsystem j is a sequence of successive edges in the form $\{(i,l),(l,m),\dots,(k,j)\}$. The undirected graph $\mathcal{G}$ is strongly connected if, for every pair of distinct subsystems i and j, with $i\neq j$, there is a path from i to j. Let b_i denote the communication between subsystem i and the desired trajectory, where $b_i=1$ means that subsystem i has access to the desired trajectory, else $b_i=0$. In our problem, we assume that the graph $\mathcal{G}$ is undirected and strongly connected and that there exists at least one agent connected to the desired trajectory, i.e., $\sum_{i=1}^{N}b_i\geq 1$.