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Cooperative control of multi-agent systems with unknown control directions

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ABSTRACT

This paper deals with the cooperative control problem of high-order multi-agent systems with unknown control directions. Adaptive backstepping technology is utilized to handle the difficulties caused by the unknown control direction in every order's dynamics. By using a conditional inequality related to multiple terms of the Nussbaum-type function at each step, the consensus problem for systems with undirected and connected topology is solved. Then, it is shown that cooperative asymptotic regulation problem can be addressed by the same design procedure. The agents can achieve consensus and converge to the equilibrium asymptotically as well. Simulation examples are provided finally to demonstrate the effectiveness of the proposed design methods.

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1. Introduction

Cooperative control in networks of autonomous mobile agents is extensively studied over the past few years due to its extensive applications in sensor networks, mobile robots, spacecraft formation flying, and other areas. As one of the most fundamental research topics in the field of cooperative control of multi-agent systems, consensus plays an important role in achieving collective behavior through local interactions of agents. Consensus means that the states of all agents reach an agreement on a common value by using local information of each agent's neighbors. Following some pioneering works [1–4], various consensus problems of multi-agent systems have been studied recently, such as consensus of systems with second-order dynamics [5–8], high-order dynamics [9] and linear dynamics [10,11], consensus of agents with time-delay [12–15], agreement over random networks [16–19], and distributed containment control [20–22], just to mention a few.

Control directions, namely, the signs of the control coefficients, represent the motion directions of the system. In most existing works, a common assumption is that signs of the control coefficients are known and assumed to be positive without loss of generality. However, in many applications, control directions might not always be known in priori. For instance, when not all state variables are measurable, and when there exist large uncertainties in systems, it is difficult to detect the control directions directly [23]. The standard way to handle the unknown control directions is the Nussbaum gain approach, which was first proposed in [24]. Later, the Nussbaum gain approach has been extensively used to various adaptive control problems for single system in [25–27]. Recently, for a group of interacting systems involved an unknown control direction, a sub-Lyapunov function for each subsystem was constructed in [23,28], where only one Nussbaum-type function was employed. However, there are few results on the cooperative control problem for multi-agent systems with unknown control directions. Very recently, [29] discussed consensus problem of first-order multi-agent systems with unknown control directions by using the sub-Lyapunov function method. Note that the sign and amplitude of each agent's control direction are

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all unknown and the sign of each agent can be different. However, the method proposed in [29] is not valid for second-order or high-order system. For second-order linearly parameterized multi-agent systems with unknown identical control directions, consensus problem was solved in [30] by constructing a new Nussbaum-type function to estimate the unknown control direction of each agent and establishing a novel lemma to deal with the multiple terms of the proposed Nussbaum-type function. It is worth noting that only the control direction in the second-order dynamics is unknown, whereas the control direction in the first-order dynamics is known and the control gain is assumed to be 1. If the control directions at every order are unknown or even high-order system are considered, the controller design and consensus analysis will become more difficult. It is worth noting that some interesting results on cooperative control of nonlinear system with unknown control directions can be found in [31–33]. In [31] and [32], adaptive neural networks-based control approach is used, where switching topology and fixed topology are considered, respectively. In [33], output consensus of heterogenous agents is studied with two distributed Nussbaum-type control laws.

In this paper, we consider the cooperative control problem for high-order multi-agent systems with unknown control directions. Since that each order's control direction is unknown, adaptive backstepping technology is utilized. By using a conditional inequality related to multiple terms of the Nussbaum-type function at each order, the consensus problem for systems with undirected and connected topology is solved. Then, it is shown that cooperative asymptotic regulation problem can be addressed by the same design procedure. The agents can achieve consensus and converge to the equilibrium asymptotically as well. The main contributions of this paper are summarized as follows: 1) This paper makes one of the first few attempts to deal with the cooperative control problem of high-order multi-agent systems with unknown control directions; 2) Each order's control direction is unknown; 3) To accomplish the consensus analysis with backstepping technology, a conditional inequality related to multiple terms of the Nussbaum-type function is used at each step; 4) The cooperative asymptotic regulation problem can be solved by the same approach. Although nonlinear system are not considered in our paper, the approach used in the paper is more simpler than that in [31–33]. Furthermore, both cases of consensus and decentralized asymptotic regulation are addressed in the paper.

Notations. Throughout this paper, for real symmetric matrices X and Y, the notation $X \geq Y$ (respectively, $X > Y$) means that the matrix $X - Y$ is positive semi-definite (respectively, positive definite). $\mathbb{R}^n$ denotes the set of $n \times 1$ real vectors. $\mathbb{R}^{n\times n}$ denotes the set of $n \times n$ real matrices. I denotes an identity matrix of appropriate dimension. $\mathbf{1}_N \in \mathbb{R}^N$ be the vector with all entries being 1. The notation '$*$' is used as an ellipsis for terms that are induced by symmetry.

2. Preliminaries

In this section, some basic concepts and definitions about graph theory and model formulations are briefly introduced.

Let $\mathcal{G} = \{\mathcal{V}, \mathcal{E}, \mathcal{A}\}$ be an undirected graph with the set of nodes $\mathcal{V} = \{v_1, v_2, \ldots, v_N\}$, the set of edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$, and an adjacency matrix $\mathcal{A} = (a_{ij})_{N\times N}$. A path is sequence of edges with the form $(v_1, v_2), (v_2, v_3), \ldots$. An undirected graph is connected if there is path between every pair of distinct nodes. The elements of the adjacency matrix $\mathcal{A}$ are defined as $a_{ij} > 0$ if and only if there is an edge (v_j, v_i) in $\mathcal{G}$; otherwise, $a_{ij} = 0$, and $a_{ij} = a_{ji}$. Define the degree matrix as $\mathcal{D} = diag\{d_i\}_{N\times N}$ with $d_i = \sum_{j=1}^{N} a_{ij}$ and the Laplacian matrix as $\mathcal{L} = \mathcal{D} - \mathcal{A}$. For the undirected and connected graph $\mathcal{G}$, $\mathcal{L}$ is symmetric.

Consider a group of N agents with the following dynamics:

$$\begin{aligned} \dot{x}_{i,k} &= b_{i,k} x_{i,k+1} \\ \dot{x}_{i,n} &= b_{i,n} u_i \end{aligned} \tag{1}$$

where $i = 1, \ldots, N$, $k = 1, \ldots, n-1$; $x_i = [x_{i,1}, \ldots, x_{i,n}]^T$, $x_i \in \mathbb{R}^n$ and $u_i \in \mathbb{R}$ are the state and the control input, and $b_{i,q}$, $i = 1, \ldots, N, q = 1, \ldots, n$ ($b_{i,q} \neq 0$) are unknown constant parameters.

Assumption 1. $b_{i,q}$, $q = 1, \ldots, n$ from different agents have the identical unknown sign. That is, the sign of $b_{i,1}$, $i = 1, \ldots, N$ are the same, the sign of $b_{i,2}$, $i = 1, \ldots, N$ are the same, ..., the sign of $b_{i,n}$, $i = 1, \ldots, N$ are the same.

Definition 1. Consensus in multi-agent system (1) is achieved if for any initial conditions,

$$\lim_{t\to\infty} |x_{i,q} - x_{j,q}| = 0, \quad \forall i, j = 1, \ldots, N, q = 1, \ldots, n$$

Remark 1. A Nussbaum-type function $\mathcal{N}(\cdot)$ is the one with the following properties [24]:

$$\begin{aligned} \lim_{k\to\infty} sup \frac{1}{k} \int_0^k \mathcal{N}(\tau) d\tau &= \infty \\ \lim_{k\to\infty} inf \frac{1}{k} \int_0^k \mathcal{N}(\tau) d\tau &= -\infty \end{aligned}$$

To overcome the obstacle of the multiple Nussbaum-type function terms coexisting in the same condition inequality, the author in [30] constructed a new Nussbaum-type function for solving the consensus problem of first-order and second-order multi-agent systems:

$$\mathcal{N}_0(k) = cosh(\lambda k) sin(k) \tag{2}$$

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