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Research article

Surrounding control of nonlinear multi-agent systems with non-identical agents

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ABSTRACT

In this paper, the surrounding control problem of a group of non-identical agents is considered, where a team of followers achieves an equidistant distributed formation to surround a team of moving leaders. An adaptive design method is presented for multi-agent systems where the dynamics of agents are supposed to be nonlinear with unknown parameters. First, an estimator for the center of the leaders is introduced. Then, two distributed adaptive controllers based on the estimated center are proposed for each follower. The stability and parameter convergence of the proposed protocols are shown by using algebraic graph theory and Lyapunov theory. Finally, a numerical example is provided to validate the theoretical results.

1. Introduction

Cooperative control of a network of autonomous agents has been an emerging research direction and attracted many attentions from many scientific communities, especially the systems and control community. A group of autonomous agents, by coordinating with each other via communication or sensing networks, can accomplish some tasks that cannot be performed by a single agent. Cooperative control of multi-agent systems has potential applications in broad areas such as consensus [1–4], swarming [5], formation control [6], synchronization [7] and containment [8,9]. Surrounding control is an interesting field in distributed cooperative control. In surrounding control, a group of followers achieve a surrounding formation around a team of leaders using local information. For example, surveillance using sensor-enabled robot [10], the rescue of a wounded soldier by a group of robots and helicopters [11], and protection of unmanned ground vehicles (UGVs) by armed robotic vehicles (ARVs) [12] can be mentioned.

The surrounding control problem requires all the followers to surround some leaders which are either stationary or moving. The surrounding control of stationary leaders with identical dynamics is studied in [12]. When the geometric center of the leaders is not available, an estimator is firstly built and then an estimator-based control algorithm is constructed to guarantee that the followers surround the leaders eventually.

The surrounding problem can be considered as an inverse of containment problem, where a group of agents are driven to be contained in a convex hull formed by the leaders. The containment control is studied in [13], where the network topology is modelled by a directed graph. In [14] the containment problem is investigated for high-order linear time-invariant singular swarm system with time delays, and [15] proposes a non-smoothing control approach to solve the distributed robust containment tracking problem for uncertain linear dynamics. The distributed containment problem based on the output measurements approach of higher-order multi-leader multi-agent systems is considered in [16].

The surrounding problem is also closely related to the target-enclosing problem, where it achieves an enclosing formation around targets by a group of agents. The target-enclosing problem under a target-agent framework has been intensively investigated and many control methods have been implemented to solve such problems. For example, cyclic pursuit approach is given in [17,18] to achieve a target-capturing task, and for a moving target-capturing task, [19] proposes a consensus-based method. Model Predictive Control (MPC) methods are presented in [20] for enclosing a moving target. There are also some researches in the lack of information about the system. The coordination of multi-agent systems by simultaneous decentralized control is proposed in [21]. In [22–26], authors implement a simultaneous estimation and control strategy in achieving enclosing control for targets.

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The enclosing problem of a stationary or moving target with unknown position by one agent is considered in [22]. Also this idea is extended to the case where one agent encloses a group of targets in [23]. The enclosing control problem when a group of agents encloses one target is also solved in [24] by the estimator-control method. The problem of enclosing a group of moving targets by a team of agents is addressed in [25], where the same number of agents and targets with identical geometry are considered. In [26], the estimator-control method is applied to solve enclosing control problem for moving targets by a group of agents, where the number of agents can be different from the number of targets.

Most of the aforementioned results on the surrounding or enclosing problem are presented for the homogeneous multi-agent systems, in which all the agents are governed by identical dynamics. Because of various restrictions in practical systems, the dynamics of the agents can be different from each other. Also, a group of agents with different dynamics are more applicable than identical agents. Recently, the heterogeneous multi-agent systems are intensively discussed in consensus and containment problems. For example, consensus of multi-agent systems with non-identical dynamics for agents in networks with jointly connected topologies is studied in [27], and containment control of non-identical agents is considered for nonlinear multi-agent systems in [28]. An adaptive control method is presented in these papers for solving the consensus and the containment problem, respectively.

This paper considers a distributed surrounding control problem for moving leaders and non-identical agents governed by unknown nonlinear dynamics where the unknown dynamics of all agents are parameterized by some basis uniformly bounded functions. To design a control input for each follower, the geometric center of the leaders should be known [12]. Generally, since each follower might have access to only a subset of leaders, a decentralized estimator is required to be constructed at each follower to estimate the geometric center of leaders. Then, the estimated center is used to design the control input for the followers, which results in a system with coupled estimation and control. In comparison with [12] where the leaders are stationary, and [25], where the dynamics of agents are linear and identical, in this paper it is assumed that the dynamics of all agents, either followers or leaders, are non-identical. The contribution of this paper is mainly in two aspects. First, a finite time center estimator is introduced to estimate the center position of the leaders. Second, two distributed adaptive surrounding control strategies are proposed for a group of non-identical agents with unknown nonlinear dynamics to surround the leaders in the network.

The rest of the paper is organized as follows. In Section 2, some basic preliminary results, which include some basic concepts and useful results of graph theory are assembled. The distributed surrounding control problem is given in Section 3. The main results are established in Section 4 when an estimator for the center position of leaders is given and the surrounding control for non-identical unknown nonlinear dynamics of agents is proposed in two scenarios. Numerical simulation is provided in Section 5 to validate the theoretical results and also a comparison between the proposed methods are presented. Finally, the conclusions are drawn in Section 6.

1.1. Notation

Throughout this paper, let $\mathbf{C}$ and $\mathbf{R}$ be the set of complex number and real number, respectively, and $\mathbf{R}^p$ be the p-dimensional real vector space. For a given vector or matrix X, X^T denotes its transpose. The identity matrix of order n is denoted by I_n. $\mathbf{1}_n$ is an $n \times 1$ vector with elements one, and $\mathbf{0}$ is a zero matrix with appropriate dimension. For a complex number S, $|S|$ denotes its magnitude. Symbol $\otimes$ represents the Kronecker product.

2. Preliminaries

The communication network of a multi-agent cooperative system can be modeled by a graph. For a group of n agents, a directed graph G is a pair (V, E), where $V = \{v_1, \ldots, v_n\}$ is a nonempty finite set of vertices and $E = \left\{ e_{ij} = (v_i, v_j) \right\} \subset V \times V$ is a set of edges. If $\left(v_i, v_j \right) \in E$, then v_j is said to be a neighbor of v_i. The set of neighbors of vertex v_i is denoted by $N_i = \left\{ v_j \middle| (v_i, v_j) \in E \right\}$. A graph with the property that $(v_i, v_j) \in E$ implies $(v_j, v_i) \in E$ for any $v_i, v_j \in V$, is an undirected graph. A path from vertex v_i to vertex v_j is a sequence of ordered edges of the form $(v_{i_k}, v_{i_{k+1}}) \in E$, $k = 0, \ldots, l-1$, where $v_{i_0} = v_i$ and $v_{i_l} = v_j$. An undirected graph is connected if there exists a path between any distinct vertices. The adjacency matrix $A = [a_{ij}] \in \mathbf{R}^{n\times n}$ associated with G is defined by $a_{ij} > 0$ if $(v_i, v_j) \in E$, and $a_{ij} = 0$ otherwise. The Laplacian matrix $L = [\ell_{ij}] \in \mathbf{R}^{n\times n}$ is defined as $\ell_{ii} = \sum_{i\neq j} a_{ij}$ and $\ell_{ij} = -a_{ij}$, $i \neq j$. For undirected graphs, both A and L are symmetric.

In this paper, we consider a multi-agent system with n followers and m leaders. Let G_n and G_{n+m} be the graphs used to model n followers and $n+m$ agents' interaction topology, respectively. The set of followers is denoted by V_F while the set of leaders is denoted by V_L. N_i is used to denote the set of neighbors of the follower i with respect to the follower's set.

To describe the movement of followers to achieve the surrounding of the leaders, we use the matrix $B = [b_{ik}] \in \mathbf{R}^{n\times m}$ that is defined as $b_{ik} = 1$ if follower i is connected to the leader k, and $b_{ik} = 0$ otherwise. Also, the connection weight of the leader k is denoted by B_k, which is a diagonal matrix with diagonal elements $b_{1k}, b_{2k}, \ldots, b_{nk}$.

3. Problem statement

Consider a multi-agent system consisting of n non-identical followers and m non-identical leaders. The dynamics of n followers are represented by

$$\dot{x}_i(t) = f_i(x_i, t) + u_i(t), \quad i \in V_F, \tag{1}$$

where $x_i(t) \in \mathbf{C}$ is the position state of ith follower, $u_i(t) \in \mathbf{C}$ is the control input, and $f_i(x_i, t)$ is an unknown nonlinear function which is assumed to be continuous in t and Lipschitz in x_i. We assume that leaders are moving and their dynamics are described by

$$\dot{r}_k(t) = v_k(t), \quad k \in V_L, \tag{2}$$

where $r_k(t) \in \mathbf{C}$ denotes the position of the kth leader and $v_k(t) \in \mathbf{C}$ is its velocity and assumed to be unknown.

Throughout the paper, we make the following assumptions:

Assumption 1. The graph G_n is assumed to be undirected and connected, and in the graph G_{n+m} each of m leaders can communicate with at least one follower.

Assumption 2. In the set of neighbors of each follower, there exists at most one leader.

Assumption 3. For the leader group V_L, the movement of each leader around the center of the leaders is bounded. That is, there exists $M \in \mathbf{R}^+$ such that.

$$M = \sup_{k=1:m} \left\{ \left| r_k(t) - \bar{r}(t) \right| \right\}. \tag{3}$$

where, $\bar{r}(t) = \frac{1}{m}\sum_{k=1}^{m} r_k(t)$.

The goal is to find decentralized control signals u_i, $i = 1, 2, \ldots, n$ in a way that all followers asymptotically form