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Rolling optimization formation control for multi-agent systems under unknown prior desired shapes☆

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A R T I C L E I N F O

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This paper deals with the optimal formation control problem of multi-agent systems under *a prior* unknown desired shapes. The objective of this paper is to accomplish a rolling optimal formation of multi-agent systems by incorporating trajectory tracking and energy saving control into a unified framework. First, according to the real-time desired position offset between each follower and the leader, the rolling optimization performance indexes are introduced. Then, a distributed rolling optimization algorithm is proposed to realize the desired formation of multi-agent systems under the minimum energy consumption of agents. Finally, several simulation examples are conducted to illustrate the effectiveness of the proposed design algorithm.

1. Introduction

Formation control is one of the most fundamental issues in cooperative control of multi-agent systems (MASs), which enables a team of agents to form and maintain a desired formation structure [1,12,13,29]. Applications of MAS formation control cover a broad range of areas, for example, moving target tracking of autonomous underwater vehicles (AUVs) [2,23,25,37], flying formation of unmanned aerial vehicles (UAVs) [10,11,30,33], collaborative operation of a team of mobile robots [8,9,27], distributed sensing in sensor networks [19,26,41] and distributed energy management in power networks [6,32,35], and so on. According to specific environment of applications, the formation structures mainly includes two cases: 1) the desired shapes are prescribed by leaders or followers in a leader-follower framework; 2) the desired shapes are *a prior* unknown. This paper will focus on the latter case since it is relatively more difficult to implement than the former.

In formation control of MASs, information exchange among neighboring agents via communication networks plays an important role in designing distributed control protocols or algorithms [28,31,38]. Compared with a leaderless formation [3], achieving a leader-follower formation is more challenging because the leader's motion is independent of follower agents and only a small fraction of followers may access to leaders' information [4]. As a consequence, in recent years considerable attention has been paid to the leader-follower cooperative control problems of MASs from various perspectives, see, e.g., [5,16,20–22,36,42] and references therein.

Technically, distributed formation control strategies of MASs mandates necessary support from communication networks. However, in practical implementation the bandwidth of communication networks are often limited [40]. Therefore, it is

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preferable to develop a new distributed control scheme which can realize a desired formation of MASs while improving the capacity of communication. In order to address this issue, event-triggered communication and control schemes have been introduced into networked control systems. The remarkable advantages of event-triggered control schemes in reducing the consumption of communication resources are explicitly presented in [39]. For MASs, distributed event-triggered communication has been proposed in [14,15,17,18,24,34] to achieve consensus tracking while significantly reducing the number of information exchange among neighbors over communication network. An overview of recent advances in event-triggered consensus of MASs can be referred to the survey paper [7].

In most real-world applications, the navigation mileage of mobile agent is regarded as a fundamental technical index. In order to improve the ability of navigation mileage, one of effective strategies is to design an energy-saving control protocol in formation control of MASs. Then, one question naturally arises: is it possible to find an appropriate control law for each follower such that the MAS can achieve the desired formation while minimizing energy consumption of each agent. In addition, in many cases of MAS formation, the desired formation shape cannot be predetermined and it may change over time according to specific environment and operational tasks [13]. For example, the desired formation shapes of soccer robots are unknown in advance and can only be determined by the current positions of both football and players. Therefore, one important issue to be addressed is how to design rolling optimization control schemes which can guarantee the optimal performance index while significantly alleviating consumption of on-board power energy of agents. To the best of the authors' knowledge, few results have been reported in the existing literature to address this issue.

This paper aims to investigate the rolling optimization formation control problem of leader-follower MASs with desired shapes being *a prior* unknown. The real-time rolling optimization quadratic performance index of each follower at the designated time instants is constructed. By optimizing the performance index, a rolling optimization formation control strategy for MASs under unknown prior desired shapes are proposed. The proposed rolling optimization algorithm is highly dependent on the communication topology, which leads to a series of analytical rolling optimization control laws in different time intervals. In order to simplify the network topology of signal exchange for the formation, it is expected that the optimal formation control law of follower i is dependent only on the real-time moving trajectory signals from the leader rather than those from other follower agents. Finally, three examples are given to verify the theoretical results.

2. Problem statement

In this section, some necessary notions from the graph theory will be first reviewed briefly. Then, the problem formulation of this paper will be presented.

The communication topology among agents can be modeled by a directed graph. Let $G=(N,E)$ denote a directed graph, in which N is a finite non-empty set of nodes and E is an edge set of ordered pairs of nodes. The pairs of nodes in a directed graph are ordered. A directed path is a sequence of ordered edges (i, j), where $i, j \in N$. $(i, j) \in E$ represents that agent j can obtain the information from agent i. Define a nonnegative adjacency matrix $A_d=[d_{ij}]_{(M+1)\times(M+1)}$, where $d_{ij}=1$ if $(j, i) \in E$, $d_{ij}=0$ if $(j, i) \notin E$, and $d_{ii}=0$, where $j \neq i$.

Consider a leader-follower MAS with $M+1$ mobile agents, where the dynamics of agent i is described by

$$\begin{cases} \dot{x}_i(t)=A_i x_i(t)+B_i u_i(t) \\ y_i(t)=C_i x_i(t) \\ i=0,1,2\cdots,M \end{cases} \tag{1}$$

where $x_i \in R^{n_i}$ and $u_i \in R^{p_i}$ are state vector and control input of mobile agent i, respectively, $y_i(t) \in R^q$ is output vector which denotes the moving trajectory of mobile agent i, A_i, B_i and C_i are matrices of appropriate dimensions. The control objective of this paper is to design a distributed control law u_i only using the local information from neighbors such that the formation such that MAS (1) achieves the desired formation shapes, namely, the followers track the prescribed reference trajectories.

For MAS (1), if $n_i=3$, it means the motion of agent i has three degrees of freedom, such as UAV and AUV, etc. If $n_i=2$, then agent i will move in a 2-dimension plane, like formation of multiple mobile robots and formation of mobile sensor network, etc. If $A_j=A_i$, $B_j=B_i$, $C_j=C_i$ $(i, j=1,2,\cdots,M)$, then the dynamics of all the agents in the MAS are identical.

Assume that agent 0 is the leader and the desired trajectory $y_s \in R^q$ of agent 0 is known, thereby the actual control law u_0 can be derived such that the trajectory y_0 of mobile agent 0 can approach y_s at a specified decay rate. The responsibility of the leader is to drive the others M followers to achieve the desired formation shapes prescribed by the reference moving trajectory.

When the reference moving signal of follower i is dependent only on the real-time moving trajectory signals from the leader, then the adjacency matrix A_d describing network communication topology of the network of mobile agents can be given by

$$d_{jk}=\begin{cases} 1, & k=1, j=2,3,\cdots,M+1 \\ 0, & \text{others} \end{cases} \tag{2}$$

In fact, different communication topologies can be selected according to specific requirement of formation control performance of MASs. For example, we can also select a network topology, where the reference moving trajectory of agent i is dependent only on the real-time moving trajectory from agent $i-1$. In this case, the adjacency matrix A_d can be described