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Research article

Distributed fault-tolerant time-varying formation control for high-order linear multi-agent systems with actuator failures

Yongzhao Hua, Xiwang Dong*, Qingdong Li, Zhang Ren

School of Automation Science and Electrical Engineering, Science and Technology on Aircraft Control Laboratory, Beihang University, Beijing, 100191, P.R. China

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ABSTRACT

This paper investigates the fault-tolerant time-varying formation control problems for high-order linear multi-agent systems in the presence of actuator failures. Firstly, a fully distributed formation control protocol is presented to compensate for the influences of both bias fault and loss of effectiveness fault. Using the adaptive online updating strategies, no global knowledge about the communication topology is required and the bounds of actuator failures can be unknown. Then an algorithm is proposed to determine the control parameters of the fault-tolerant formation protocol, where the time-varying formation feasible conditions and an approach to expand the feasible formation set are given. Furthermore, the stability of the proposed algorithm is proven based on the Lyapunov-like theory. Finally, two simulation examples are given to demonstrate the effectiveness of the theoretical results.

1. Introduction

In recent years, cooperative control of multi-agent systems has attracted great attention from various communities due to its potential practical applications, such as formation control of unmanned aerial vehicles [1,2], coordination control of multiple mobile robotic systems [3,4], attitude synchronization control of satellites [5,6] and so on. Formation control is an important branch of cooperative control, and its objective is to make the states of a group of agents form certain predefined shape. Many formation approaches have been presented in robot control community, including leader-follower, behavior and virtual structure based approaches [7–9]. However, as pointed out in [10], there exist certain disadvantages in these three approaches. The leader-follower formation strategy is heavily dependent on the state of leader and the leader's bias will affect the entire formation. It is difficult to establish the accurate quantitative model and guarantee the stability of the multi-agent system using the behavior based approach. The virtual structure based strategy depends on the centralized coordination and is unable to control a group of agents with a distributed form.

During the past two decades, consensus problems of multi-agent systems have been studied widely [11–18]. If all agents reach an agreement on certain variables of interest, the multi-agent system is said to achieve consensus. More researchers recognize that consensus approaches can be utilized to solve formation control problems with the development of consensus theory. The consensus-based formation strategy only uses the neighbor relative information to construct the local control protocol, which means that this formation approach can be applied in a fully distributed form. Ren [19] proved that consensus-based formation control approaches are more general for second-order multi-agent systems and the leader-follower, behavior and virtual structure based approaches are special cases of consensus-based ones. For first-order and second-order multi-agent systems, consensus based formation control protocols were presented in [20–22]. In many practical situations, the dynamics of each agent is described by high-order differential equations. Constant formation control problems for high-order multi-agent systems were discussed in [23]. Porfiri et al. [24] proposed a simultaneous formation tracking and control approach for a group of agents with high-order dynamics. In [25], time-invariant formation feasibility problems for high-order agents were investigated.

The formations of high-order multi-agent systems in [23–25] are limited to be time-invariant. Considering the task of maneuvering targets surveillance or obstacle avoidance in a complex scene for the multi-agent systems, the desired formation should be time-varying due to the rapid changes of the external environment and the mission requirements. Therefore, the time-varying formation is more practical. In [26], a time-varying formation control approach was presented to deal with the

* Corresponding author.
E-mail addresses: yongzhaohua@buaa.edu.cn (Y. Hua), xwdong@buaa.edu.cn (X. Dong), liqingdong@buaa.edu.cn (Q. Li), renzhang@buaa.edu.cn (Z. Ren).

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influences of the communication time delays. Dong et al. [27] applied the outputs of neighboring agents to construct an output formation control protocol. Considering the directed and switching communication topologies, time-varying formation analysis and design problems were investigated in [28]. Based on adaptive mechanism, Wang et al. [29] studied distributed time-varying formation control problems for a group of high-order agents.

With an increasing number of agents and complex composition for multi-agent systems, actuators in one or more agents may suffer certain failures which can lead to performance deterioration or even system instability. Differing from a single system, the actuator fault in one agent may cause chain reactions and spread over the whole multi-agent system through the communication network. Therefore, in order to improve system reliability and safety, it is significant to research actuator fault accommodation for multi-agent systems. Recently, several different fault-tolerant consensus control protocols for multi-agent systems with actuator failures were proposed in [30–37]. However, to the best of our knowledge, time-varying formation control problems for high-order linear multi-agent systems with actuator failures are still open.

Motivated by the facts stated above, this paper studies the fault-tolerant time-varying formation control problems for high-order linear multi-agent systems with actuator failures. Firstly, the actuator fault model of each agent is established. Then a fault-tolerant formation control protocol is proposed in a fully distributed form. Furthermore, the time-varying formation feasible conditions are given and an algorithm is presented to determine the control parameters of the protocol. Finally, based on Lyapunov-like theory, the stability of the proposed formation protocol is proven.

Compared with the existing results on formation control, the main contributions of the current paper are threefold. Firstly, the expected time-varying formation can still be achieved even though the actuators in one or more agents undergo certain unknown bias faults and loss of effectiveness faults. In [26–29], fault-tolerant control problems were not considered, and the expected formation could not be achieved by the multi-agent systems with actuator failures. Without considering the actuator faults, the time-varying formation related terms in [26–29] can be compensated by the control input directly. Since the actuator efficiency factors are assumed to be unknown and time-varying in the current paper, it is more difficult to deal with the fault-tolerant formation problems. Secondly, each agent has generalized high-order linear dynamics and the formations can be time-varying. In [19–22], the agent is described by the first-order or second-order model. In [23–25], the dynamics is high-order but only time-invariant formations can be accomplished. There exist the formation information and the derivative of it in the design and analysis of the fault-tolerant formation control protocol. Thus, the time-varying formation control is more challenging, and the results of fault-tolerant consensus control in [30–37] cannot be extended to handle the formation problems directly. Thirdly, neither the bounds of the actuator faults nor any global knowledge about the communication topology is required in the proposed formation protocol. In [34–36], the fault bounds were considered to be known and used to design the consensus control protocols. However, these bounds are difficult to obtain in practical applications. Using the adaptive estimate mechanism, the control protocol in this paper does not need the values of these bounds. The formation control protocols in [26–28] all used the minimum nonzero eigenvalue of the Laplacian matrix, but it is global information since every agent has to know the Laplacian matrix. By introducing the adaptive coupling weights, the minimum nonzero eigenvalue is not required. Different from assigning an adaptive coupling weight to each edge in [29], the proposed formation control protocol applies the time-varying weight to each agent.

The rest of this paper is organized as follows. In Section 2, some basic concepts on graph theory and the problem description are given. Main results are presented in Section 3. Two simulation examples are provided in Section 4. Section 5 concludes the paper.

The following notations will be used throughout this paper. Let I_n represent an identity matrix with dimension n and $\mathbf{1}$ stand for an appropriate column vector consisting of 1. The superscript T stands for the transpose for real matrices and $\text{diag}\{\cdot\}$ denotes a diagonal matrix. Let $\lambda_{\min}(\cdot)$ and $\lambda_{\max}(\cdot)$ represent the minimum and maximum eigenvalues of a positive definite matrix. For a vector $x(t) \in \mathbb{R}^n$, $\|x(t)\|$ represents its two norm.

2. Preliminaries and problem description

In this section, the basic graph theory and the problem description are given.

2.1. Basic graph theory

The communication topology of multi-agent systems can be described by a graph $G = \{V, E, W\}$, where $V = \{v_1, v_2, \ldots, v_N\}$ is the set of nodes, $E \subseteq \{(v_i, v_j): v_i, v_j \in V;\ i \neq j\}$ stands for the set of edges, and $W = [a_{ij}] \in \mathbb{R}^{N\times N}$ denotes the adjacency matrix with nonnegative weights a_{ij}. An edge of graph G is denoted by $e_{ij} = (v_i, v_j)$. The weight $a_{ij} > 0$ if and only if $e_{ji} \in E$, and $a_{ii} = 0$ for $i \in \{1, 2, \ldots, N\}$. Let $N_i = \{v_j \in V: (v_j, v_i) \in E\}$ represent the set of neighbors of node v_i. The in-degree matrix of G is denoted by $D = \text{diag}\{\deg_{in}(v_1), \ldots, \deg_{in}(v_N)\}$ with $\deg_{in}(v_i) = \sum_{j=1}^{N} a_{ij}$. Let $L = D - W$, where L is the Laplacian matrix of the graph G. A graph is said to be undirected if $e_{ij} \in E$ implies $e_{ji} \in E$ and $a_{ij} = a_{ji}$. If there is a path between any two different nodes, then the undirected graph is said to be connected.

Lemma 1 (*[11]*). *Let $L \in \mathbb{R}^{N\times N}$ be the Laplacian matrix of an undirected graph G, then*

(*i*) *L is symmetric and positive semi-definite and has at least one zero eigenvalue with associated eigenvector* $\mathbf{1}$, i.e., $L\mathbf{1} = 0$.

(*ii*) *If G is connected,* 0 *is a simple eigenvalue of L and all the other* $N-1$ *eigenvalues are positive. Moreover, assume that λ_i denotes the eigenvalue of L and $0 = \lambda_1 < \lambda_2 \le \cdots \le \lambda_N$, if $\mathbf{1}^T y(t) = 0$, then $y^T(t) L y(t) \ge \lambda_2 y^T(t) y(t)$.*

2.2. Problem description

Consider a multi-agent system consisting of N agents on an undirected graph G. Each agent can be regarded as a node in G, and the interaction strength from agent j to agent i can be denoted by the weight a_{ij}. It is assumed that G is connected.

To formulate the fault-tolerant time-varying formation problem, the actuator fault model should be established firstly. For agent i $(i \in \{1, 2, \cdots N\})$, the fault model is defined as

$$u_i^F(t) = \rho_i(t) u_i(t) + u_{bi}(t), \tag{1}$$

where $u_i(t) \in \mathbb{R}^m$ is the actuator input, $u_i^F(t) \in \mathbb{R}^m$ is the output of the actuator with failures, $u_{bi}(t) \in \mathbb{R}^m$ is the unknown actuator bias, $\rho_i(t) = \text{diag}\{\rho_{i1}(t), \rho_{i2}(t), \ldots, \rho_{im}(t)\}$ and $0 < \rho_{ij}(t) \le 1$ denotes the unknown efficiency factor of the actuator channel j $(j = 1, 2, \ldots, m)$. Both bias fault and loss of effectiveness fault are considered in this paper. If $\rho_{ij}(t) = 1$ and $u_{bij}(t) \neq 0$, there exists bias fault in the actuator channel j. In the case where $0 < \rho_{ij}(t) < 1$ and $u_{bij}(t) = 0$, the actuator suffers from the loss of effectiveness fault. When $0 < \rho_{ij}(t) < 1$ and $u_{bij}(t) \neq 0$, the actuator has both bias