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Distributed containment control for asynchronous discrete-time second-order multi-agent systems with switching topologies☆

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ABSTRACT

A distributed containment control problem for asynchronous discrete-time second-order multi-agent systems with switching topologies is studied in this paper, where asynchrony means that each agent only receives the state information of its neighbors at certain discrete time instants determined by its own clock that is independent of other agents. Based on a novel containment control protocol, the asynchronous system is transformed into a matrix-vector form, which implies that the asynchronous containment control problem can be converted to a convergence problem of the product of infinite time-varying nonnegative matrices whose all row sums are less than or equal to 1. Then the relations between switching communication topologies and the composite of binary relation are exploited to solve this convergence problem. Finally, we obtain a sufficient condition that all the followers can enter and keep moving in the convex hull formed by the leaders if the union of the effective communication topologies across any time intervals with some given length contains a spanning forest rooted at the leaders. Moreover, some simulation examples are presented for illustration.

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1. Introduction

In the last ten years, distributed coordination of multi-agent networks has been a huge concern for scientists in different fields due to its wide applications in biological science and computer science, and so on. Consensus, as a fundamental problem in multi-agent coordination, refers to the agreement of certain quantity of interests through only local state information with agents' neighbors. Up to now, the consensus problem and its variants have been studied comprehensively and deeply in the literatures [1–11]. In these papers, it is assumed that all the agents can receive the state information from its neighbors to update its own state at the same time. However, a central synchronizing clock to all the individuals in the multi-agent systems may not be available due to technology limitations and environment disturbances. These relatively restrictive conditions in real applications naturally evoke intense interest in the consensus problem under asynchronous setting in recent

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years. Asynchrony implies that each agent receives the state information of its neighbors at the certain time instants determined by its clock that is independent of those of the other agents, and then asynchronous consensus problem of multi-agent systems usually generalizes the synchronous case. As the pioneering work, asynchronous consensus problem of agents with first-order continuous-time dynamics was studied in [12]. Due to the extensive applications of second-order dynamics in practice, Qin et al. [13] investigated the stationary asynchronous consensus of second-order discrete-time dynamics and Zhang et al. [14] discussed the asynchronous consensus of second-order continuous-time dynamics with arbitrary sampling. Gao and Wang [15] studied the asynchronous consensus problem of continuous-time second-order multi-agent systems under an assumption that the communication topology is strongly connected and balanced.

The consensus problems with single or multiple leaders are important problems of the distributed coordination of multi-agent system. In the single-leader case, the objective is to drive the states of the followers to track the state of the single leader, and some interesting results have been reported in [16–19]. In the multi-leader case that is called containment control, the objective is to make all the followers enter the convex hull formed by the multiple leaders according to properly designed protocols. The study of containment control problem is motivated by some interesting natural and social phenomena, for example, the female moths who are called as leaders intermittently release a pheromone, namely bombykol, to appeal to male moths who are called as followers. As a result, it can often be seen in nature that the male moths swarm in the strict geometric configurations formed by the female moths, such as horizontal rectangle structure [20]. In a social network, when making decisions or forming opinions, individuals tend to communicate with their parents, friends or colleagues and accept suggestions from their social counterparts. Social relationships such as friends, kinship and other relationships can influence the decisions they make. Some people who may show greater influence in other people's decisions can be called social leaders, others who are more inclined to accept the opinions of neighbors are called social followers. Based on these considerations, the authors of [21] studied the containment control problem of opinion dynamics in social networks and finally obtained a very interesting result that the social followers' states will converge to the convex hull formed by the social leaders. Starting with the early work [22], which proposed a stop-and-go strategy to achieve the containment control for agents interacting over undirected network topology, the containment control problem of multi-agent systems has been extensively studied by researchers in different fields and backgrounds in recent years. Accordingly, a lot of valuable research results in different investigation scenarios, such as only position information [23], time-delays [24,25], sampled-data control [26] and heterogeneous communication topology [27], have been made public. The above works about the containment control problem are concerned with a simple setting that the communication topology is time-invariant. For this relatively complicated case with switching topologies, some valuable results have also been presented in the literatures [28–30]. The first-order containment control problem with directed switching topologies was studied in detail in [28], and the second-order containment control with switching topologies has received a lot of attention in [29]. Based on an assumption that the input matrix has full row rank, Mu et al. [30] investigated the containment control of general linear discrete-time multi-agent systems with dynamic digraph.

As we know, a central synchronizing clock to all the individuals in the multi-agent systems may not be available due to technology limitations and environment disturbances in practice, and further, the synchronous situation can be regarded as a special case of asynchronous situation. However, many existing research results that focus on the containment control problem of multi-agent systems are based primarily on the synchronous situation [23–30], few papers have paid attention to the containment control problem in asynchronous setting except our previous work [31]. It is noteworthy that [31] studied asynchronous containment control under fixed topology. Due to disturbances and/or subject to communication range limitations, the communication links between the agents may be unreliable in real system, as a result, it is more important to consider the multi-agent system with switching topologies, which generalize the fixed topology situation as a special case. This consideration prompt us to study the asynchronous containment control problem for discrete-time second-order multi-agent systems with switching topologies in this paper, in which asynchronous setting means that each agent only receives the state information of its neighbors at certain discrete time instants determined by its clock that is independent of those of the other agents.

It is shown from the existing literature which studied the containment control with fixed topology [23–27,31] that all the followers finally enter the convex hull formed by the leaders, and then their final states can be expressed by the Laplacian matrix of fixed communication topology and the states of the leaders. Thus, the key method used in [23–27,31] is transforming the asynchronous system into an equivalent synchronous error system by subtracting the followers' final states. Due to the time-varying characteristics of switching topologies, the final states of the followers may keep changing with the change of the communication topologies, therefore it is impossible to derive the corresponding error system, which implies that the techniques used in [23–27,31] are not applicable to study the asynchronous containment control problem with switching topologies in this paper. In addition, the methods used to analyze the synchronous containment control problem with switching topologies in [28–30] also cannot be employed to solve the current problem of this article due to the complexity of asynchronous setting considered in this paper. To solve this problem, we will propose a new approach that is based on the composite of binary relation in this paper and obtain a sufficient condition that relies solely on the communication topologies.

To make a thorough investigation into this expanded problem, the remaining paper is organized as follows. Some basic concepts about graph and matrix are introduced in Section 2 and the model formulation is presented in Section 3. In Section 4 a sufficient condition is given to guarantee that all the followers can enter and keep moving in the convex hull

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