Neurocomputing 168 (2015) 646–654

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Hybrid subgroup coordination of multi-agent systems via nonidentical information exchange ☆

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ARTICLE INFO

Article history:
Received 8 September 2014
Received in revised form
1 April 2015
Accepted 17 May 2015
Communicated by W. Lu
Available online 11 June 2015

Keywords:
Multi-agent systems
Multiple coordination
Hybrid subgroup coordination
Nonidentical information exchange

ABSTRACT

Multiple coordination corresponds to a diversified synchronous regime where different subgroups in one multi-agent system may emerge several distinct collective behaviors respectively. This paper is devoted to propose and analyze hybrid subgroup coordination of multi-agent systems under generic directed topologies. Due to unanticipated practical situations, agents in one subgroup are supposed to achieve a synchronous scenario asymptotically, such as average of agents' initial states or its bounded region, while there is no agreement between any two distinct subgroups. Certain assumptions are imposed on the underlying topology for agents to evolve into several subgroups. Explicit distributed control algorithms are designed by adopting nonidentical extra-subgroup and intra-subgroup information exchange, and detailed convergence analysis is presented based on techniques of graph and matrix. Relevant simulation work is further carried out to illuminate the developed theoretical results.

1. Introduction

MASs (multi-agent systems) represent a kind of complex dynamical systems that consist of a collection of interactive autonomous or semi-autonomous agents, connected through an underlying network [1–4]. Examples of agents are ubiquitous in the real world, such as animals gathering toward nest sites in the nature [5–7], mobile robots that are mechanized to perform search and rescue tasks [8–10], and UAVs (Unmanned Aerial Vehicles) formation flying to supervise forest fires or manoeuvred to track hostile targets in the battle plans [11,12]. Concerning MASs, the main research could be the exploration of collective behaviors that networked agents may emerge, which mathematically is to analyze state agreement problems in networked systems [1–5]. Under such cases, many literatures focus on distributed cooperative controls of MASs, and several modes of collective behaviors have been derived, such as flocking or formation control [5,6,10], and consensus or synchronization [8,9,13–19,32].

Roughly speaking, consensus (or synchronization) is a fundamental collective behavior of MASs [8,9,13–19,23–28,32,33], which has been intensively examined due to its broad applications, such as cooperative manipulation in mobile robot systems, collaboration in social networks, and synchronization in nature [9,32–34,36]. Several technical terms have been derived, such as average consensus or synchronization [8,9,13–19,32], bounded consensus or synchronization [8,9,29,30,34], and group consensus or cluster consensus [21–28]. Most related literatures concern only with the single consensus that states of agents converge to one common value. Instead, few concentrate on multiple collective behaviors of MASs, like group/cluster consensus or multistability [21–28,31], where networked agents are somehow partitioned to reach more than one consensus value. Nonetheless in the real world, agents may have to make immediate response to randomly occurring situation, which is likely to cause some anti-synchronization issues [34], bounded consensus or synchronization [29,30]. For practical requirements, a team of UAVs could be partitioned into path planning, and each subgroup may take on distinctive dynamic behaviors [10–12,34].As examples, a coupled multi-pendula system may take on some oscillatory motion [29]; or in a musical theater, the outburst of rhythmic applause is possibly pulselike [35].

However, in addition to flocking behavior [5,6] or group/cluster consensus [27,24], it is important and necessary to introduce some other collective behaviors, especially in terms of multi-cases. This

☆This work was supported in part by the National Natural Science Foundation of China under Grants 61170031, 61272114, 61370093 and 61473128, and the Doctoral Foundation of Ministry of Education of China under Grant 20130142130010, and the 973 National Basis Research Program of China under Grant 2011CB013301.
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http://dx.doi.org/10.1016/j.neucom.2015.05.060
0925-2312/

phenomenon stimulates us to explore other diversified cooperative scenarios. While seeking multiple coordination in a MAS, one simple case could be that agents within one subgroup achieve a consensus asymptotically, yet agents in another subgroup reach a state agreement at a small region, which is akin to mixed consensus and anti-consensus. Different from the conventional studies on standard consensus [13–19], or group/cluster consensus [20–28,31], herein we resort to a new term: hybrid subgroup coordination. We introduce the concept of hybrid coordination to exactly describe the multiple coordination of MASs. Comparing with group/cluster consensus and bounded consensus/synchronization, hybrid subgroup coordination considered here represents a more inclusive class of collective behaviors that MASs may emerge.

In fact, most related work is established on the premise that information exchange among networked agents is carried out through agents' real-state signals, see, e.g., [1–4,13–19,32], which is both beneficial to operate and effective to ensure desired dynamic behaviors in control systems. Yet due to the network feature of MASs, there may exist geographical constraints or communication difficulties with respect to distinct subgroups. Under this circumstance, the propagation of state information among agents may not be performed through the acquisition of real-state signals straightforwardly, but by means of some signal-processing techniques. Intrigued by this issue, we propose an alternative interactive scenario in terms of extra-subgroup and intra-subgroup, namely, nonidentical information exchange. On the other hand, as is common in signal processing, the sinusoidal signal usually plays a typical kind of bounded external control signal, and it has advantages of information transmission [8–11], see Fourier Transform in practical signal-processing applications and others. Many literatures resort to the sine function to model nonlinear phenomena in physics and biology [31,34–36]. Hence this paper utilizes the sinusoidal signal to guarantee desired communication among agents. In order to distinguish the extra-subgroup information from the intra-subgroup one, we adopt the classic sinusoidal signal, namely a converted real state, to undertake desirable extra-subgroup information exchange, while necessary information exchange within one subgroup is boosted by the real state.

Motivated by what mentioned above, this paper is devoted to investigating multiple coordination of MASs with generic directed topologies, which as much as we know has not been thoroughly studied yet. The major contribution of this paper is to present the hybrid subgroup coordination to describe multiple coordination of MASs, which could be more inclusive than that group/cluster consensus or multi-consensus in the existing literatures. Without loss of generality, and for the purpose of multi-agent partition, we impose some connectivity conditions on the underlying directed topology, which ensures that agents have the ability of evolving into two distinct subgroups. In order to realize hybrid subgroup coordination, we introduce a novel information exchange scenario, namely nonidentical extra-subgroup and intra-subgroup information exchange. In some sense, it yields less conservatism in designing controllers while the extra-subgroup interaction is promoted by a converted sinusoidal signal of agents, not the real one. It is shown that a MAS can realize hybrid subgroup coordination if each underlying subgraph is strongly connected and balanced, and the asymptotic behavior of each subgroup is varying by network links and dynamical evolution of agents.

The paper is outlined as follows: Section 2 briefly puts forward the problem of this paper where the concept of hybrid subgroup coordination is defined. While Section 3 elaborates the main results, where after the presentation of some mathematical preliminaries we propose an explicit hybrid cooperative control algorithm with detailed convergence analysis. Furthermore, Section 4 gives some crucial simulation support. Finally, Section 5 concludes the paper.

2. Problem formulation

This section mainly presents the multiple coordination problem of first-order MASs under directed topologies. A concept of hybrid subgroup coordination is properly introduced and defined to describe diversified collective behaviors of MASs.

2.1. Prerequisites

First, some useful notations are defined. Let $\|\cdot\|$ be the Euclidean norm. For any $B \in \Re^{n\times n}$, $\lambda_2(B)$ denotes the second smallest eigenvalue of B, while $\lambda_{\max}(B)$ and $\lambda_{\min}(B)$ denote the maximum and the minimum eigenvalues of B, respectively. $1_n = (\underbrace{1,1,\ldots,1}_{n})^T$. $E_{n\times m} = 1_n 1_m^T$.

Consider a MAS consisting of n agents, its interactive topology is described by a directed connected graph $G=\{V,E\}$, where $V=\{1,2,\ldots,n\}$ and $E=\{(i,j) \mid i,j \in V\}$ are the vertices set and edges set, respectively. The weighted adjacency matrix of graph G is given as $A=[a_{ij}]_{n\times n}$, where $a_{ij}\neq 0$ if $(i,j)\in E$ otherwise $a_{ij}=0$, and $a_{ii}=0$ for all $i\in V$. $N_i=\{j\in V \mid (i,j)\in E\}$ denotes the neighboring set of agent i, $i=1,2,\ldots,n$.

Let $x_i(t)\in\Re$ be the state of agent $i\in V$ at time t. Each agent is modeled as

$$\dot{x}_i(t)=u_i(t), \quad t\geq 0, \tag{1}$$

where $u_i(t)\in\Re$ denotes a distributed cooperative control algorithm that needs to be determined and usually is constituted of interactive information between neighboring agents.

Generally speaking, the standard consensus of MAS (1) is said to be achieved if states of all agents reach an agreement, namely, $x_1=x_2=\cdots=x_n$, in other words, MAS (1) falls into an asymptotically synchronous regime as

$$\lim_{t\to\infty}\|x_i(t)-x_j(t)\|=0, \quad \forall i,j\in V. \tag{2}$$

To realize consensus in the form of (2), we resort to the following controller:

$$u_i(t)=\sum_{j\in N_i} a_{ij}\left[x_j(t)-x_i(t)\right], \quad t\geq 0. \tag{3}$$

By controller (3), each agent will evolve towards a weighted average of its own state and its neighbors' states. Some conditions on the communication topologies are derived to guarantee consensus of MAS (1) with controller (3), such as the communication topology G is a strongly connected digraph (see Corollary 1 in [13]).

As mentioned before, consensus is the most fundamental collective behavior of MASs, see [13–19,23–28] and references therein. However, in many real-world applications, such as a team of mobile robots performing some specific tasks or UAVs under constraints of geographical environment, networked agents may be subject to some communication issues that would cause difficulties in information transmission. To overcome this, networked agents are likely to evolve into several subgroups, and a MAS may emerge multiple coordination. Group consensus and cluster consensus are two typical kinds of this multiple coordination. In this paper, we aim to examine a more inclusive collective behavior that networked agents take on several different synchronous regimes with respect to different subgroups.