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Region aggregation analysis for multi-agent networks with multi-equilibria in multi-dimensional coordinate systems via switching strategies

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ABSTRACT

This paper addresses region aggregation issues of multi-agent networks (MANs) that consist of finite number of isolated sub-multi-agent systems (sub-MASs) with multiple equilibria (ME) in multi-dimensional coordinate systems (MDCSs). To investigate aggregation of this kind of MANs via switching strategies, switched systems with ME are used to describe such networks under the case that each agent has a unique equilibrium point and all the equilibria are different from each other. Based on the novel stability concepts of *region stability* (*RS*) and *exponential region stability* (*ERS*) introduced, this paper proposes several RS and ERS results for sub-MASs with ME via the maximum energy function method, and then presents several region aggregation results for such MANs under three suitable assumptions. Also, a numerical example illustrates the effectiveness and practicality of our new results.
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1. Introduction

Multi-agent systems (MASs), an important class of complex systems [1–9], have attracted considerable attention of researchers who study ubiquitously in the fields of natural sciences, social sciences, and engineering technology [10–13] in the past decade. This is because that there are many practical systems, such as online virtual worlds, crowdsourcing system, e-commere platforms, neural networks in computer science, nervous systems in neuroscience, and agent-based mobile robot systems, which can be modeled as MASs. Each agent in these systems presents a single and autonomy individual, such as a mobile robot, or a software entity, or a bird, or a human being. All the agents in MASs show the following interesting common characteristics: autonomy, social ability, reactivity, and pro-activity. So many researchers try to find the innate mechanisms of MASs from many different viewpoints, such as security issues, system analysis and synthesis, system engineering, and then obtain a great amount of results for MASs in the literature, see for example [14–29] and references therein.

From the viewpoint of control theory and engineering, many system analysis and synthesis results are obtained for MASs, such as controllability and observability [19,20], consensus [10,16,18,19,22], tracking control [14], formation control design [25], and other relevant issues' results in [5,14,17,21,28,29]. Among them are plenty of results for different kinds of consensus issues of MASs, such as group consensus [28], finite-time consensus [18], consensus controllability and observability [19], consensus of MASs on time scales [22], and consensus of fractional-order heterogeneous MASs [29]. Especially, leader-following consensus of MASs is a particularly interesting topic investigated by many researchers in [10,16,20,21,29]. According to the classifications introduced in [12], consensus issue is a special kind of formation control of MASs. Since formation control issue is one of the most actively studied topics in the field of MASs, a vast amount of results and several surveys [12,15] for formation control of MASs are presented in the literature. Note that almost all of the above consensus and formation control results on MASs can be investigated by the Lyapunov function method. This is because that both consensus issues and formation control issues are in fact stability of special dynamic systems. On the other hand, since switching phenomena exist ubiquitously in a great amount of practical systems including physical man-made systems, real-life systems, and even biology [30], there also exist switching phenomena in real-life MASs. So many researchers investigate MASs with switching topology and obtain lots of results of consensus issues, formation issues, and the other relevant topics for such kind of MASs [5,17,28].

It is well worth pointing out that almost all consensus results and formation control design results obtained in the literature are based on the assumption that all the locally coordinate systems of agents and the globally coordinate system of the MASs have same

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dimensional states. However, due to the practice and complexity of MANs, in many physical MASs, there might exist an important kind of sophisticated MANs possessing the following characteristics. (1) Each of such MANs is composed of finite number of isolated groups of MASs, which are also called as sub-MASs. (2) The dynamic system of each sub-MAS has more than one equilibrium point [24]. (3) The dimensions of states of agents in different sub-MASs may be different from each other. For instance, from the viewpoint of characteristics of both agents and neuronal cells, each neuron [31] can be viewed as an autonomy agent, and different neurons interact with each other. Millions of such interacted neurons and glial cells [30] organize a complex MAN, i.e., the nervous system that is composed of the following two different sub-MASs: peripheral nervous system (PNS) and central nervous system (CNS). In brain of CNS, each encephalic region can be viewed as a sub-MAS with multiple equilibria (ME) and all the encephalic regions interact with each other and then integrate a higher sophisticated MAN, i.e., the brain. In PNS there are different nervous tissues in arms and legs in which distinct nervous tissues may be observed different-dimensional states. So it is more important and challenging to study such kind of complex MANs. However, to the author's best knowledge, there are few works on any relevant topics of MANs composed of different sub-MASs with ME, not to mention the MANs comprised finite number of sub-MASs in multi-dimensional coordinate systems (MDCS).

In this paper, we will investigate region aggregation of a class of MANs that compose of finite number of isolated sub-MASs with ME in MDCSs. Since aggregation of MASs with a single equilibrium point is one of consensuses of MASs, region aggregation of MANs with ME is similar to multi-consensuses of MANs with ME. Because switching phenomena exist largely in many consensus protocols of MASs, there must exist switching protocols between agents of the kind of MANs with ME in MDCSs. Therefore, to investigate region aggregation of the MANs via switching strategies, we use the formulation of switched systems with ME to describe such complex networks. It is well-known that switched systems have attracted many attention in the control theory and engineering community, and a large amount of system analysis and synthesis results on switched systems are obtained in the literature [4,8,32–41]. Meanwhile, the common Lyapunov function (CLF) method [36], the multiple Lyapunov functions (MLF) method [37], the multiple storage functions (MSF) method [38], the piecewise Lyapunov functions (PLF) method [32,35] and other techniques are developed for analyzing stability of switched systems. However, due to the existence of ME, the above techniques seem to be useless for analyzing stability of switched systems with ME. By means of the maximum energy function (MEF) method developed in [39], we will study region aggregations of the MANs under the case that dynamic system of each agent has a unique equilibrium point and all the equilibria are different from each other. After introducing several novel stability concepts, called *region stability (RS)* and *exponential region stability (ERS)*, we will propose several RS and ERS results for the MANs under a realistic assumption. Then, based on the RS and ERS results obtained, we will present two criteria of region aggregation described as *finite-time exponential region stability (FTERS)* for the MANs under several suitable assumptions. Finally, we will carry out an illustrative example to show the effectiveness and practicality of the results obtained in this paper.

The rest of this paper is organized as follows. Section 2 gives preliminaries including the model formulation, notation, assumptions, a proposition, and definitions. Section 3 proposes several main region aggregation results on the MANs. An illustrative example is carried out to show the effectiveness and practicality of the new results in Section 4, which is followed by the conclusion and discussions in Section 5.

2. Preliminaries and problem formulation

2.1. Preliminaries

2.1.1. Notation

Let $\mathbb{N}$ denote the set of all natural numbers, and let $\mathbb{N}_+$ denote the set of all positive integers. Let $[K]$ denote the set $\{1, 2, \ldots, K\}$, where $K \in \mathbb{N}_+$. Let $\mathbb{R}^n$ denote the n-dimensional Euclidean space. Let $\|\cdot\|$ denote the Euclidean norm in $\mathbb{R}^n$. Let $\mathbb{R}^{m\times n}$ denote the space of all $m \times n$ matrices. Let the superscript "T"denote matrix transposition. Let $\langle \cdot, \cdot \rangle$ denote the inner product. Let $\mathrm{d}(x, y) = \|x - y\|$, $\mathrm{d}(x, \Omega) = \inf_{y \in \Omega}\{\|x - y\|\}$, and $\mathrm{d}(Q_1, Q_2) = \inf_{x \in Q_1, y \in Q_2}\{\|x - y\|\}$ denote the distance between two points x and y in $\mathbb{R}^n$, the distance from point x to set Ω in $\mathbb{R}^n$, and the distance from set Q_1 to set Q_2 in $\mathbb{R}^n$, respectively. Let $\partial\Omega$ denote the boundary of the set Ω. Let $\mathbb{V}_1 \oplus \mathbb{V}_2$ denote the direct sum of vector spaces $\mathbb{V}_1$ and $\mathbb{V}_2$. Let $\mathcal{C}(\mathbb{D})$

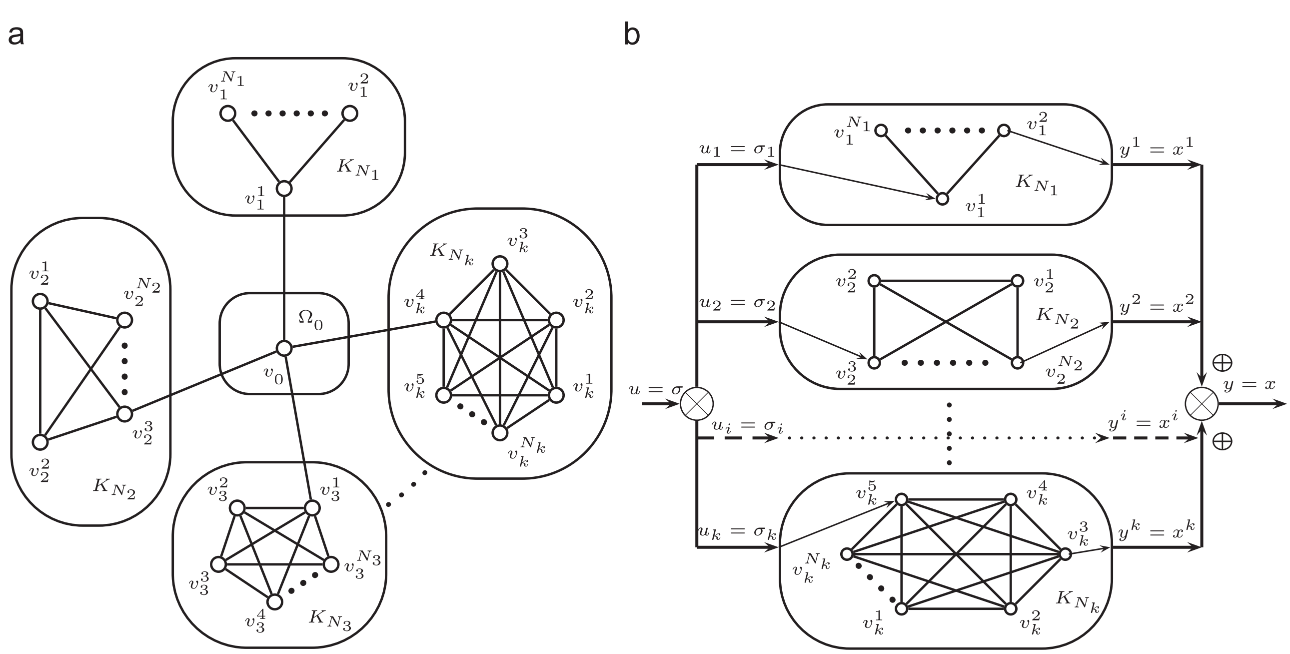

Fig. 1. (a) MAN $\mathcal{G}(\mathcal{V}, \mathcal{E}(t))$ and (b) input–output graph $\mathcal{G}(\mathcal{V}, \mathcal{E}(t))$. Note that the other edges between the plotted vertices and the omitted vertices are not drew in (a) and (b).

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