Neurocomputing 142 (2014) 383–392

Contents lists available at ScienceDirect

Neurocomputing

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

Group consensus for heterogeneous multi-agent systems with parametric uncertainties

Hong-xiang Hu [a,*], Wenwu Yu [b,c,d], Qi Xuan [e], Chun-guo Zhang [a], Guangming Xie [f]

[a] Department of Mathematics, Hangzhou Dianzi University, Hangzhou, 310018, China
[b] School of Electrical and Computer Engineering, RMIT University, Melbourne VIC3001, Australia
[c] Faculty of Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia
[d] Department of Mathematics, Southeast University, Nanjing, 210096, China
[e] Zhejiang Provincial United Key Laboratory of Embedded Systems, Department of Automation, Zhejiang University of Technology, Hangzhou, 310023, China
[f] Center for Systems and Control, State Key Laboratory of Turbulence and Complex Systems, College of Engineering, Peking University, Beijing, 100871, China

ARTICLE INFO

Article history:
Received 29 September 2013
Received in revised form
10 February 2014
Accepted 14 April 2014
Communicated by Y. Liu
Available online 22 May 2014

Keywords:
Heterogeneous agents
Group consensus
Double-integrator system
Euler–Lagrange system

ABSTRACT

In this paper, a group consensus problem is investigated for the heterogeneous agents that are governed by the Euler–Lagrange system and the double-integrator system, respectively, and the parameters of the Euler–Lagrange system are uncertain. To achieve group consensus, a novel group consensus protocol and a time-varying estimator of the uncertain parameters are proposed. By combining algebraic graph theory with the Barbalat lemma, several effective sufficient conditions are obtained. It is found that the time-delay group consensus can be achieved provided that the inner coupling matrices are equal in the different sub-networks. Besides, the switching topologies between homogeneous agents are also considered, with the help of the Barbalat-like lemma, and some relevant results are also obtained. Finally, these theoretical results are demonstrated by the numerical simulations.

1. Introduction

Over the past few years, extensive research has been conducted on distributed coordination of multi-agent systems from various scientific communities [1–8]. Applications of this research include formation control of mobile robots [9–12], design of sensor networks [13–16], optimization-based distributed control [17–20], and so on. Please be referred to [21,22] for a more comprehensive overview of the field.

As one type of distributed coordination problems, group consensus has many civil and military applications in surveillance, reconnaissance, battle field assessment, etc. Research on the group consensus not only helps better understand the mechanisms of natural collective phenomena, but also provides some useful ideas for distributed cooperative control. In the group consensus problem, the whole network is divided into multiple sub-networks with information exchanges between them, and the aim is to design appropriate protocol such that agents in the same sub-networks reach the same consistent states. In [23], Yu and Wang studied the group consensus problem in a multi-agent network with time-varying topologies, and introduced a double-tree-form transformation under which the dynamic equation of agents was transformed into a reduced-order system. In that work, it was assumed that the channels between different groups must exist continuously, thus the protocols proposed in [23] are purely continuous-time ones. Considering that the information exchange between different groups may be intermittent in practice, Hu et al. [24] investigated the group consensus problem with discontinuous information transmissions among different groups, and designed the hybrid protocol to solve it. Recently, Su et al. [25] considered the pinning control problem for cluster synchronization of undirected complex dynamical networks, and proposed a novel decentralized adaptive pinning-control scheme on both coupling strengths and feedback gains. Furthermore, in [26], Su et al. investigated the cluster synchronization of coupled harmonic oscillators with multiple leaders in an undirected fixed network, and it was shown that all oscillators in the same group could asymptotically synchronize with the corresponding leader even when only one oscillator in each group has access to the information of the corresponding leader.

Generally, the dynamics of agents is an important part of a multi-agent system, which will largely influence their consensus states. However, almost all the aforementioned results were only concerned with distributed coordination of homogeneous multi-agent systems, i.e. all the agents have the same dynamics, which might not be realistic in nature where individual heterogeneity is ubiquitous [27]. In [28], Zheng et al. considered the consensus problem of heterogeneous multi-agent system composed of first-order and second-order agents, for which the consensus protocols have both position and velocity information. It should be noted

* Corresponding author.

http://dx.doi.org/10.1016/j.neucom.2014.04.021
0925-2312/

that all the agents achieve static consensus [29] asymptotically due to the existence of first-order agents. Based on the above results, the finite-time consensus problem of heterogeneous multi-agent systems was proposed in [30]. Liu and Hill [31] investigated the global consensus problem between a multi-agent system and a known objective signal by designing an impulsive consensus control scheme. In their framework, the consensus criteria in the multi-agent system with the uncertainties, heterogeneous agents, and coupling time-delays were studied in terms of linear matrix inequalities (LMIs) and algebraic inequalities. More recently, Liu et al. [32] studied the quasi-synchronization issue of linearly coupled networks with discontinuous nonlinear functions in each heterogeneous node. Here, quasi-synchronization means the synchronization with an error level. By introducing a virtual target, some sufficient quasi-synchronization conditions were presented and explicit expressions of error levels were derived to estimate the synchronization error in [33].

In this paper, we investigate a new group consensus of heterogeneous multi-agent systems, where two types of agents are grouped as two sub-networks. The agents in one sub-network are governed by the Euler–Lagrange system with parametric uncertainties, and those in another sub-network are described by the double-integrator dynamics. Meanwhile, there are time-delays when transmitting information between two sub-networks. Note that the group consensus protocol in [23] cannot be directly applied here due to the inherent nonlinearity of the Euler–Lagrange system. Instead, we design a novel group consensus protocol and a time-varying estimator of the uncertain parameters for the agents governed by the Euler–Lagrange system to achieve group consensus. Furthermore, considering that the interaction topology between agents may change dynamically in practice, we also investigate the group consensus with switching topologies. It is worth noting that there are such heterogeneous multi-agent systems in reality, such as the satellite-based vehicle positioning system in which the dynamics of satellite is described by the Euler–Lagrange system, while the dynamics of vehicle is governed by the double-integrator dynamics.

The rest of the paper is organized as follows. In Section II, some basic definitions in graph theory and mathematical preliminary results are provided. In Section III, a novel group consensus protocol and a time-varying estimator of the uncertain parameters are proposed. Some group consensus results are established, and these results are validated by the simulation experiments in Section IV. Finally, the paper is concluded in Section V.

Notations. Throughout this paper, $(\cdot)^T$ and $(\cdot)^{-1}$ denote transpose and inverse, respectively. $\otimes$ denotes the Kronecker product, and $\|\ \|$ is the Euclidean norm. If ω is a column vector, then $diag(\omega)$ denotes the diagonal matrix with the ith diagonal entry being the ith element of vector ω.

2. Preliminaries

In this section, some basic definitions in graph theory and preliminary mathematical results are firstly introduced for the subsequent use.

2.1. Topology description

For a multi-agent system, information exchange between agents can be modeled by directed or undirected graphs [2,22]. Let $G=(V,\zeta,A)$ be a weighted directed graph of n agents with a set of agents $V=\{\pi_1,\pi_2,\ldots\pi_n\}$, a set of edges $\zeta\subseteq V\times V$, and a non-negative adjacency matrix $A=[a_{ij}]$, which is used to represent the network topology. The agent indexes belong to a finite index set $I=\{1,2,\ldots n\}$, and an edge between two nodes is denoted by $e_{ij}=(\pi_i,\pi_j)$. Moreover, the adjacency elements associated with the edges of the graph are positive, i.e., $(\pi_i,\pi_j)\in\zeta\Leftrightarrow a_{ij}>0$, and the neighbor set of node π_i is denoted by $N_i=\{\pi_j|(\pi_j,\pi_i)\in\zeta\}$. Here, we assume that $a_{ii}=0$ for all $i\in I$, which means $i\notin N_i$ for each agent i. The elements in the corresponding Laplacian matrix $L=[l_{ij}]\in R^{n\times n}$ are defined as

$$l_{ij}=-a_{ij},\ i\neq j,$$
$$l_{ii}=\sum_{j\in N_i}a_{ij}, \tag{1}$$

satisfying that $\sum_{j=1}^{n}l_{ij}=0,\quad\forall i\in I$. A directed path in G from π_i to π_j is a sequence of distinct vertices starting from π_i and ending to π_j with the consecutive vertices being adjacent. Meanwhile, a directed graph is strongly connected, if there is a directed path between any two distinct nodes.

The following lemma gives a property of strongly connected graph.

Lemma 1. *([34]). Suppose that $G(A)$ represents a directed graph and L is the corresponding Laplacian matrix, then $G(A)$ is strongly connected if and only if there exists a positive column vector $\omega=[\omega_1,\cdots,\omega_n]^T$, such that $\omega^T L=0$. Furthermore, the matrix $((diag(\omega)L+L^T diag(\omega))/2)$ is positive semi-definite.*

2.2. System model

In our framework, there are two kinds of dynamics in the heterogeneous multi-agent systems.

Firstly, the agents in one sub-network are described by the Euler–Lagrange dynamics, which has the form

$$M_i(q_i)\ddot{q}_i+C_i(q_i,\dot{q}_i)q_i+g_i(q_i)=\tau_i,\quad i\in I_1=\{1,\ldots,n\}, \tag{2}$$

where $q_i\in R^p$ is the vector of generalized coordinates, $M_i(q_i)\in R^{p\times p}$ is the symmetric positive-definite inertia matrix, $C_i(q_i,\dot{q}_i)q_i\in R^p$ is the vector of Coriolis and centrifugal torques, $g_i(q_i)$ is the vector of gravitational torque, and $\tau_i\in R^p$ is the group consensus protocol on the i th agent. Owing to the structure of Euler–Lagrange systems [35], Eq. (2) exhibits certain fundamental properties as follows:

(P1). For any $i\in\{1,\ldots,n+m\}$, there are positive constants $k_{\underline{M}}$, $k_{\overline{M}}$, $k_{\overline{C}}$, and $k_{\overline{g}}$ such that $k_{\underline{M}}I_p\le M_i(q_i)\le k_{\overline{M}}I_p$, $\|C_i(q_i,\dot{q}_i)\|\le k_{\overline{C}}\|\dot{q}_i\|$, and $\|g_i(q_i)\|\le k_{\overline{g}}$.

(P2). The matrix $\dot{M}_i(q_i)-2C_i(q_i,\dot{q}_i)$ is skew symmetric.

(P3). The Euler–Lagrange systems can be linearly parameterized, that is

$$M_i(q_i)x+C_i(q_i,\dot{q}_i)y+g_i(q_i)=Y_i(q_i,\dot{q}_i,x,y)\theta_i,\quad\forall x,y\in R^p, \tag{3}$$

where $Y_i(q_i,\dot{q}_i,x,y)$ is the regression matrix and θ_i is an unknown vector associated with the i th agent.

According to (P3), θ_i should be estimated by using the information from the regression matrix Y_i.

Then, the agents in another sub-network are governed by the double-integrator dynamics:

$$\begin{cases}\dot{x}_i(t)=v_i(t),\\ \dot{v}_i(t)=u_i(t)-\Lambda_2 v_i(t),\end{cases}\qquad\forall i\in I_2=\{n+1,\cdots,n+m\}, \tag{4}$$

where $x_i(t),v_i(t)\in R^p$, and the matrix $-\Lambda_2\in R^{p\times p}$ is Hurwitz. Here the term $-\Lambda_2 v_i$ represents the velocity damping term [29]. It should be especially noted that in [29], the damping force is in proportion to the magnitude of velocity, which is not required here and thus make our results more general. Besides, $u_i(t)\in R^p$ is the control input or the group consensus protocol.

The following lemmas will be used to derive the main results of this paper.

Lemma 2. *([36]). Let $\phi: R\to R$ be a uniformly continuous function on $[0,\infty)$. Suppose that $\lim_{t\to\infty}\int_0^t\phi(\tau)d\tau$ exists and is finite, then $\phi(t)\to 0$ as $t\to\infty$.*