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Swarming of heterogeneous multi-agent systems with periodically intermittent control

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ABSTRACT

This paper investigates a class of heterogeneous swarming systems with periodically intermittent control. It is assumed that agents in the network are nonidentical and potential functions are heterogeneous. Each agent is assumed to obtain information from the leader and the neighbors only on a series of periodically time intervals. The dynamics of the swarm members are affected by inter-individual interactions and the environment. In addition, we consider the first-order integrator system with a class of attraction/repulsion functions. Some sufficient conditions are provided to guarantee exponential stability of the whole system. Although the information from the leader agent and the neighbors is not continuous, all follower agents can track the leader agent in certain error range. A numerical example is shown to illustrate the validity of the above theoretical result.

1. Introduction

The analysis of multi-agent systems has received increasing attention in recent years. In 1974, DeGroot [1] presented a model in which all agents might reach a consensus and form a usual subjective probability distribution for an unknown parameter by taking a weighted average of other agents' opinions. In Vicsek's model [2], all agents had the same speed with different headings, and they could update their headings by averaging the headings of neighbors. Simulation results showed that the group might eventually move in the same direction without centralized coordination.

Swarming is an important branch of coordinated control systems. Gazi et al. [3] developed a swarm aggregation problem with a special interaction function. Their models could reveal some basic features of swarm aggregation. Afterwards, the authors [4] increased the influence of outside environmental profiles on the systems and analyzed the behavior of the swarm on four different cases: plane, Gaussian, quadratic and multi-modal Gaussian functions. Their conclusions showed that the swarm converged to more favorable regions of the profile and diverged from unfavorable regions. As a result, the swarm aggregation problem has received much attention [5–12] and subsequent references therein.

But so far, only a few works have studied the leader-following control with heterogeneous agents. Xiang et al. [13] introduced the Lyapunov V-stability for the heterogenous dynamical network. All nonidentical nodes have a common equilibrium state in the model. Then, Zhao et al. [14] presented asymptotic synchronization of symmetrical dynamical networks with nonidentical nodes. In the paper, it is not necessary to assume that all heterogeneous nodes have the same equilibrium. Next, they [15] addressed the synchronization for general dynamic networks with heterogeneous nodes. He et al. [16] studied the heterogeneous agent dynamics, but they discussed synchronization of only two individuals. Zhong et al. [17] considered the global bounded consensus problem of heterogeneous networked multi-agent systems and they assumed the network topology of communication was with time delay. Their model is consist of nonidentical nonlinear node dynamics. Yang et al. [18] considered the output synchronization problem for heterogeneous networks. They had an assumption

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that all the agents are introspective. Based on this assumption, they proposed a decentralized control scheme to solve the output synchronization problem of a set of network topologies. Obviously, there is a common feature in above multi-agent systems algorithms, that is, each agent can obtain the information of full states from itself and its neighbors all the time. However, the information of some states may not be available. Therefore, intermittent control algorithm emerges. It is that each agent can obtain information from itself and the neighbors only intermittently, but not continuously. Liu et al. [19] investigated the cluster synchronization problem for linearly coupled networks by means of adding periodically intermittent pinning controls. Cai et al. [20] further investigated pinning synchronization of complex network with delayed dynamical nodes by periodically intermittent control. Li et al. [21] studied the exponential stabilization problem for a class of nonlinear systems via periodically intermittent control. Wen et al. [22] investigated the flocking control problem in multi-agent dynamical systems in which each agent could receive intermittent nonlinear measurements of relative velocities from itself and its neighbors. Liu et al. [23] investigated second-order consensus of heterogeneous nonlinear multi-agent systems with time-varying delays. Wang et al. [24] focused on solving the distributed flocking of heterogeneous nonlinear multi-agent systems with preserved network connectivity.

Inspired by these works [16,22,25–27], we consider heterogeneous leader-following problem for multi-agent systems via periodically intermittent control. In the paper, we will show the stability analysis of the leader-following systems with a special class of attraction and repulsion functions. Our study is also related to the above-mentioned works, such as [3–5,16,22]. Compared with [3–5], we assume that the agents in the network are nonidentical and the potential functions are heterogeneous. Moreover, it is assumed that each agent obtains information from the leader and the neighbors only on a series of periodically time intervals. Compared with [16], we investigate multiple heterogeneous dynamical agents with periodically intermittent control. Compared with [22], we increase an interaction between a special leader agent and some nonidentical follower agents. In addition, we consider the first-order integrator system with a class of attraction/repulsion functions. To summarize, the contributions of this paper are twofold. First, we propose a leader-following problem consisting of nonidentical follower agents and different potential functions. The second and more important contribution is that we design an intermittent controller to guarantee the stability of the system. The swarm stability analysis of a heterogeneous leader-following system is much more difficult than that of the homogeneous systems. The challenge here is to design an appropriate Lyapunov function that can simultaneously address the heterogeneous model dynamics and the intermittent controller.

An outline of this paper is as follows. Section 2 describes problem statement. Section 3 contains analysis and result of the heterogeneous leader-following system. Section 4 focuses on some numerical examples to illustrate the validity of the proposed leader-following problem. Section 5 concludes the paper.

2. Problem formulation

We consider a multi-agent system with $N+1$ agents, labelled $0,1,2,\ldots,N$. Let an agent indexed by 0 be the leader agent and the corresponding remain individuals labelled by $1,2,\ldots,N$ denote the follower agents. We assume all individuals to move in a n-dimensional Euclidean space.

The leader agent is totally positive in this paper, in other words, the leader agent could affect intermittently the dynamics of the follower agents but could not be impacted by the follower agents. The motion of the leader is based only on the environment function, as follows:

$$\dot{x}_0(t) = -\nabla_{x_0}\sigma_0(x_0(t)), \tag{1}$$

where $x_0(t)\in\mathbb{R}^n$, $\sigma_0(x_0(t))$ and $\nabla_{x_0}\sigma_0(x_0(t))$ are respectively the states, the scalar potential function (the environment function) and the gradient function of the leader agent.

Each follower agent may also be influenced by the leader and its neighboring followers only on a series of periodically time intervals. The motion of each follower is affected by both inter-individual interactions and the environment. Each follower agents is described by

$$\dot{x}_i(t) = \begin{cases} -\nabla_{x_i}\sigma_i(x_i(t)) + k_{i0}(x_0(t)-x_i(t)) + \sum\limits_{j\in N_i} w_{ij}\, g\big(x_i(t)-x_j(t)\big), \\ \quad t\in[mT, mT+\omega] \\ -\nabla_{x_i}\sigma_i(x_i(t)), \quad t\in(mT+\omega,(m+1)T) \end{cases} \tag{2}$$

for all $i=1,2,\ldots,N$, where $x_i(t)\in\mathbb{R}^n$, $\sigma_i(x_i(t))$ and $\nabla_{x_i}\sigma_i(x_i(t))$ are respectively the states, the scalar potential field and the gradient field of the agent i. $T>0$ denotes the control period, $\omega>0$ denotes the control width and $\omega<T$. Moreover, $m=0,1,2,\ldots$. $k_{i0}\ge 0$ is the coupling factor with $i=1,2,\ldots,N$. In addition, $N_i\subseteq\{1,\ldots,N\}\backslash\{i\}$ includes neighboring follower agents of the agent i. $g(\cdot)$ is the attractive function for long distances and the repulsive function for short distances. $W=[w_{ij}]\in\mathbb{R}^{N\times N}$ is the coupling weight matrix with $w_{ij}\ge 0$, $w_{ii}=0$ for all i,j and the corresponding Laplacian is L. L has an eigenvalue 0 and the associated multiplicity is 1 [28].

Let the error vector $e_i(t)$ be $x_i(t)-x_0(t)$, then

$$\dot{e}_i(t) = \begin{cases} -\tilde{f}_i(x_i(t),x_0(t)) - k_{i0}e_i(t) + \sum\limits_{j\in N_i} w_{ij}\, g\big(e_i(t)-e_j(t)\big), \\ \quad t\in[mT, mT+\omega] \\ -\tilde{f}_i(x_i(t),x_0(t)), \quad t\in(mT+\omega,(m+1)T) \end{cases} \tag{3}$$

where $\tilde{f}_i(x_i(t),x_0(t)) = \nabla_{x_i}\sigma_i(x_i(t)) - \nabla_{x_0}\sigma_0(x_0(t))$, and $e(t)=(e_1(t),e_2(t),\ldots,e_N(t))^T$.

Assumption 1. There exist constants $l_i>0$ such that for $x_0(t)$ and all $x_i(t)$, $\|\tilde{f}_i(x_i(t),x_0(t))\|_p \le l_i^p\|e_i(t)\|_p$, where $i=1,2,\ldots,N$.

3. Main results

In order to analyze the leader-follower system, we use some mathematical tools, such as Lyapunov function, matrix norm, and so on. We will consider a special class of attraction and repulsion functions described by [5]

$$g(y) = -y[g_a(\|y\|) - g_r(\|y\|)], \tag{4}$$

where $g_a:\mathbb{R}^+\to\mathbb{R}^+$ represents the attraction term, whereas $g_r:\mathbb{R}^+\to\mathbb{R}^+$ represents the repulsion term, and $\|y\|=\sqrt{y^Ty}$ is the Euclidean norm.

Assumption 2. There exist constants $a,b>0$ such that $g_a(\|y\|)=a$, $g_r(\|y\|)\le\frac{b}{\|y\|}$ for any $y\in\mathbb{R}^n$. That is, the attraction function is fixed linear and the repulsion function is bounded.

Theorem 1. *Let Assumptions 1 and 2 hold. Under the attraction/repulsion function (4), there exist a nonsingular matrix P and a matrix measure $\mu_p(\cdot)(p=1,2,\infty)$ such that $\Xi\omega+\chi_{\max}(T-\omega)<0$, the group of follower agents (2) and the leader agent (1) can achieve exponentially stable.*

Among of the above, $\Xi=\zeta_{\max}+\|-aP\|_p\|L\otimes I\|_p\|P^{-1}\|_p$, $\zeta_{\max}=\max\{\zeta_1,\zeta_2,\ldots,\zeta_N\}$, $\zeta_i=\mu_p(-k_{i0}I)+l_i^p\|P\|_p\|P^{-1}\|_p$, $\chi_{\max}=\max\{\chi_1,\chi_2,\ldots,\chi_N\}$, $\chi_i=l_i^p\|P\|_p\|P^{-1}\|_p$.