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Iterative learning control approach for a kind of heterogeneous multi-agent systems with distributed initial state learning

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ABSTRACT

In this paper, leader–follower coordination problems of a kind of heterogeneous multi-agent systems are studied by applying iterative learning control (ILC) scheme in a repeatable control environment. The heterogeneous multi-agent systems are composed of first-order and second-order dynamics in two aspects. The leader is assumed to have second-order dynamics and the trajectories of the leader are only accessible to a subset of the followers. To overcome the strict identical initial condition commonly used in ILC, the distributed initial state learning controller for each follower is designed, thus each follower agent can take arbitrary initial state. Distributed iterative learning protocols guarantee that all follower agents can achieve perfect tracking consensus for both fixed and switching communication topologies, respectively. In addition, the proposed scheme is also extended to achieve formation control for heterogeneous multi-agent system. Finally, simulation examples are given to illustrate the effectiveness of the proposed methods in this article.

1. Introduction

Multi-agent systems have been actively studied over the last decade partly due to its broad applications in many areas, such as the formation control of robotic systems, the cooperative control of unmanned aerial vehicles, the target tracking of sensor networks and the congestion control of communication networks, and so on. As one of the most typical collective behaviors of multi-agent systems, consensus problem, which is fundamental to distributed coordination, has been studied as an active research area in many fields. Many consensus algorithms have been proposed and consensus criteria have been obtained for the first-order [1–5] and the second-order [6–9] multi-agent systems, respectively, under fixed topology, switching topology, varying topology or time delays.

Unfortunately, numerous existing results on the consensus problem are mostly given for the homogeneous multi-agent systems, i.e., agents with identical dynamics. However, the dynamics of the agents coupled with each other are quite different because of various restrictions or the common goals with mixed agents in the practical systems, for example, taking dynamic environments and uncertainty external to the multi-robot system itself into account, heterogeneous systems with robots in different shapes and abilities are more applicable than the homogeneous systems in real world. Recently, some efforts have been made to solve the consensus problem of heterogeneous multi-agent systems, which consist of the agents with different dynamics [10–17]. In [10], the authors considered the consensus problem of heterogeneous multi-agent system with linear consensus protocol and saturated consensus protocol, respectively. The article [11] considered robust output regulation of uncertain

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heterogeneous multi-agent systems in the case that all agents have non-identical nominal dynamics. In the article [12], the authors considered the consensus problem of heterogeneous multi-agent system where the second-order integrator agents cannot obtain the velocity measurements for feedback. Consensus problem of a heterogeneous multi-agent system with agents modelled by first-order and second-order integrators with fixed and switching topology was presented in [13]. And the finite-time consensus problem of the heterogeneous multi-agent system with first-order and second-order integrators was considered in [14]. Under the influences of disturbances, the problem of dynamical tracking control for heterogeneous multi-agent systems with different algorithms was considered in the article [15]. Output synchronization of a network of heterogeneous linear state-space models under time-varying and directed interconnection structures was investigated in [16]. The authors in [17] studied the output consensus problem for a class of heterogeneous uncertain linear multi-agent systems. The objectives of [16,17] are to achieve output synchronization among all systems and the output of each agent has the same dimensions.

While most of the aforementioned papers have been focused on the consensus of multi-agent systems in the one-dimensional system framework evolving along the time axis. By now, many researchers have considered the multi-agent consensus and formation problems by iterative learning control from the viewpoint of two-dimensional systems [18–24]. The tracking control problems for multi-agent systems with linear systems were considered in [18–21]. In [22], a distributed D-type iterative learning scheme was developed for the formation control problem of the multi-agent system. A distributed adaptive iterative learning control was presented for leader-following consensus problem in [23]. It is worth pointing out that the literatures [18–23] only solved the consensus problems of homogeneous multi-agent systems by iterative learning control method. The literature [24] studied consensus tracking problem for both homogeneous and heterogeneous multi-agent systems under the fixed communication topology.

In this paper, under a repeatable operation environment, leader-following coordination problems of a kind of heterogeneous multi-agent systems are studied by applying iterative learning control approach. Compared with [18–23], this paper considers the heterogeneous multi-agent systems composed of first-order and second-order dynamics. The leader is assumed to have second-order dynamics, and the trajectories are only known to a subset of the followers. Although the systems of each agent in [24] are not identical and the state dimensions are different, the controller used only the output information of each agent and the output of each agent has the same dimensions. In addition, the paper [24] can obtain output consensus and cannot achieve state synchronization among all systems. In this paper, we require that all states of each follower should track that of the leader and makes the first step to analyze state consensus of heterogeneous multi-agent systems by using iterative learning control. Therefore, the main contributions of this paper are summarized as follows:

(i) We require that all states of each follower in heterogeneous multi-agent systems should track that of leader. Then, we should design different protocols for follower agents with different dynamics (see Eq. (6)). Therefore, it is quite different from protocols design in [24].
(ii) Different from [24], each follower agent can take arbitrary initial state owing to the distributed initial state learning controller and the strict identical initial condition used in [24] is not required in this paper (see Remark 3);
(iii) Some sufficient conditions for the consensus are established to guarantee all follower agents to achieve the asymptotic tracking consensus in the iteration domain and perfect tracking consensus in the time domain for both fixed and switching communication topologies;
(iv) The proposed scheme is also extended to achieve the formation control.

The remainder of the paper is organized as follows. In Section 2, some preliminaries and the agent model are briefly outlined. The main results of ILC schemes for heterogeneous multi-agent consensus and formation control problems with fixed and switching topology are proposed in Sections 3 and 4, respectively. In Section 5, the effectiveness of the consensus algorithms proposed in this paper is demonstrated by the simulations. Finally, conclusions are drawn in Section 6.

2. Problem formulation

Let $G = (V, E, A)$ denote an undirected graph, where $V = \{v_1, \dots, v_n\}$ is the set of vertices and $E \subseteq V \times V$ is the set of edges. $A = [a_{ij}] \in R^{n\times n}$ is the weighted adjacency matrix of the graph G. If there is an edge between agent i and j, i.e., $(v_j, v_i) \in E$, then $a_{ij} = a_{ji} > 0$, and otherwise $a_{ij} = a_{ji} = 0$. Moreover, we assume that $a_{ii} = 0$. The set of neighbors of node v_i is $N_i = \{v_j : (v_j, v_i) \in E\}$. The Laplacian matrix of digraph G is $L = D - A$, where $D = \mathrm{diag}\{d_1, \dots, d_n\}$ with $d_i = \sum_{j=1}^{n} a_{ij}$. For the undirected graph G, the weighted adjacency matrix A is symmetric and the graph G is connected if there is a path between any two vertices. The graph G is allowed to have several components, within every such component all the agents are connected via undirected edges.

In what follows, we mainly concern the $\bar{G}$ associated with the system consisting of n followers whose topology graph denoted by G and the leader (labelled by 0). Denote b_i as the connection weight between agent i and the leader. If the ith follower can obtain the information from the leader, then $b_i > 0$, otherwise $b_i = 0$. It is obvious that $H = L + B$ is a symmetric matrix associated with $\bar{G}$, where L is the Laplacian matrix of G and $B = \mathrm{diag}\{b_1, \dots, b_n\}$. In order to give the following significant lemma, we define that: by "graph $\bar{G}$ is connected", it means that at least one agent in each connected component of graph G can obtain the information from the leader.

Notations: Throughout this paper, let R be the set of real numbers. $I_m = \{1, 2, \dots, m\}$, $I_n/I_m = \{m+1, m+2, \dots, n\}$. The graph $\bar{G}$ consists of n agents and one leader and the graph $\bar{G}_1$ consist of the first m agents and the leader.

Lemma 1 ([25])**.** *If graph $\bar{G}$ is connected, then the symmetric matrix H associated with $\bar{G}$ is positive definite.*