Available online at www.sciencedirect.com

ScienceDirect

Fuzzy Sets and Systems 248 (2014) 122–137

FUZZY sets and systems

www.elsevier.com/locate/fss

Adaptive fuzzy iterative learning control with initial-state learning for coordination control of leader-following multi-agent systems ☆

Junmin Li *, Jinsha Li

Department of Applied Mathematics, Xidian University, Xi'an 710071, PR China

Received 8 December 2012; received in revised form 20 October 2013; accepted 22 October 2013

Available online 25 October 2013

Abstract

We propose a distributed adaptive fuzzy iterative learning control (ILC) algorithm to deal with coordination control problems in leader-following multi-agent systems in which each follower agent has unknown dynamics and a non-repeatable input disturbance. The ILC protocols are designed with distributed initial-state learning and it is not necessary to fix the initial value at the beginning of each iteration. A fuzzy logical system is used to approximate the nonlinearity of each follower agent. A fuzzy learning component is an important learning tool in the protocol, and combined time-domain and iteration-domain adaptive laws are used to tune the controller parameters. The protocol guarantees that the follower agents track the leader for the consensus problem and keep at a desired distance from the leader for the formation problem on $[0, T]$. Simulation examples illustrate the effectiveness of the proposed scheme.

Keywords: Multi-agent system; Fuzzy system; Adaptive iterative learning control; Nonlinear system

1. Introduction

In the past few decades, cooperative control of multi-agent systems has attracted attention for industrial, military, and consumer applications [1–3]. The fundamental problem for multi-agent systems is consensus, whereby all agents eventually reach an unprescribed common value [4–6]. For the leader-following consensus problem, the leader agent acts as a command generator and all other agents attempt to follow the leader [7–10]. In particular, for the formation control problem, distributed protocols are designed for each agent such that all agents reach and maintain some desired formation or group configuration [11,12].

In the real world, practical systems usually have complicated and nonlinear dynamics, and can even have some uncertainties. Robust control and adaptive control can be used to deal with these problems. Recently, adaptive control has been applied to the consensus problem for multi-agent systems [13–15]. Hu studied the problem of robust consensus tracking for a class of second-order multi-agent dynamic systems with disturbances and an unmodeled agent dynamics [13]. Das and Lewis investigated synchronization to a desired trajectory for multi-agent systems with

☆ This work was supported by the National Natural Science Foundation of China under Grant No. 60974139, and the Fundamental Research Funds for the Central Universities under Grant No. 72103676.

* Corresponding author.
E-mail addresses: jmli@mail.xidian.edu.cn (J.M. Li), jinsha0321@163.com (J.S. Li).

0165-0114/$ – see front matter
http://dx.doi.org/10.1016/j.fss.2013.10.010

second-order integrator dynamics and unknown nonlinearities and disturbances [14]. Zhang and Lewis considered adaptive cooperative tracking control of higher-order nonlinear systems with unknown dynamics [15].

The traditional adaptive approach suffers from the assumption of linearity in parameters; when system nonlinearity cannot be linearly parameterized, a neural network or fuzzy system approximator is often used to solve adaptive nonlinear control problems owing to their universal approximation [16,17]. A fuzzy system and wavelet network have been applied to iterative learning control (ILC) for unknown nonlinear dynamic systems [18,19]. An adaptive iterative learning controller based on a fuzzy neural network was proposed for a repetitive control task for a robotic system [20]. Precup et al. proposed three fuzzy control solutions focused on a unified design method and new Takagi–Sugeno proportional–integral fuzzy controllers incorporating ILC algorithms [21]. Olivares et al. described fuzzy feed-forward ILC for repetitive situations [22].

Many researchers have considered multi-agent consensus and formation problems using ILC [23–26]. Meng and Jia studied multi-agent cases involving linear systems [23–25]. Liu and Jia developed an iterative learning scheme for formation control of a multi-agent system with unknown nonlinear dynamics [26]. They considered the case without a leader, and the nonlinear dynamics of each agent was identical and without disturbance. It should be noted that their result is not valid when disturbance is considered. The authors assumed that $f(x_i(t))$ is an unknown nonlinear global Lipschitz continuous function in terms of $x_i(t)$ and applied contraction mapping theory.

Here we consider the coordination of leader-following multi-agent systems on the finite interval $[0, T]$. Our analytical method was motivated by Chien's study [18]. For each follower agent, an iterative learning protocol is derived using communication information from its neighbors, which differs from typical ILC algorithms that are based on tracking errors for a prescribed fixed target [18]. Then we apply Chien's method [18] to a distributed leader-following multi-agent system. We consider disturbance and each follower agent has distinct dynamics $f_i(x_i(t))$ that is an unknown real local Lipschitz continuous nonlinear function. To deal with the unknown dynamics of each follower agent, a fuzzy approximator is used in the protocol design. In addition, the trajectory of the leader is only available to a portion of the follower agents. It should be noted that the identical initial condition commonly used in ILC is inapplicable for distributed multi-agent systems. Moreover, to combine the characteristics of ILC and multi-agent systems, we use distributed initial-state learning. The distributed adaptive fuzzy ILC protocols consist of a feedback component and a fuzzy learning component and guarantee that the follower agents track the leader uniformly on $[0, T]$ for consensus problem. We extend the proposed scheme to achieve formation control for multi-agent systems. We then analyze the results based on Lyapunov stability theory.

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

2. Preliminaries and problem formulation

2.1. Graph theory

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 agents i and j, that is, $(v_j, v_i) \in E$, then $a_{ij} = a_{ji} > 0$, otherwise $a_{ij} = a_{ji} = 0$. Moreover, we assume that $a_{ii} = 0$. The set of neighbors of node v_i is $N_i = \{v_j\colon (v_j, v_i) \in E\}$. 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.

In what follows, we mainly consider $\bar{G}$ associated with a system consisting of n followers whose topology graph is denoted by G and a leader (labeled as 0). Let b_i denote the connection weight between agent i and the leader. If the ith follower agent can obtain 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 $B = \mathrm{diag}\{b_1, \dots, b_n\}$.

For the following significant lemma, we first provide the following definition: "graph $\bar{G}$ is connected" means that at least one agent in the connected graph G can obtain information from the leader.

Lemma 1. *(See [27].) If graph $\bar{G}$ is connected, then the symmetric matrix H associated with $\bar{G}$ is positive definite.*