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A framework of neural networks based consensus control for multiple robotic manipulators

Dongya Zhao [a,*], Wei Ni [b], Quanmin Zhu [a,c]

[a] College of Chemical Engineering, China University of Petroleum, Qingdao, 266580, China
[b] School of Sciences, Nanchang University, Nanchang, 330031, China
[c] Department of Engineering Design and Mathematics, University of the West of England, Coldharbour Lane, Bristol BS16 1QY, UK

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ABSTRACT

A framework for neural networks (NN) based consensus control is proposed for multiple robotic manipulators systems (MRMS) under leader–follower communication topology. Two situations, that is, fixed and switching communication topologies, are studied by using adaptive and robust control principles, respectively. Radial basis function (RBF) NN enhances estimator and observer are developed to estimate system uncertainty and obtain the leader manipulator's control torque online. By using the Lyapunov stability theory, an adaptive consensus control algorithm is designed to tune the weight of the RBF NN online, which can stabilize the consensus error to a small residual set. On this basis, a novel robust control algorithm is presented to eliminate the estimating errors caused by RBF NN, which can achieve asymptotical stability. The stability of the proposed approaches is analyzed by using Lyapunov methods. Finally numerical bench tests are conducted to validate the effectiveness of the proposed approach.

1. Introduction

It has been increasingly important to employ multiple robotic manipulators to execute a commonly or interactively simultaneously shared task in modern manufacturing such as assembling, transporting, painting and welding and so on [1–4]. Such multiple manipulators, if not yet, will have more functions in space and deep seas exploration. The aforementioned industrial applications require large maneuverability and manipulability, in which a single robotic manipulator cannot undertake easily or even impossible. To effectively achieve these largely demanded task functionalities, some effective solutions have been used, such as cooperative or coordinated MRMS and so on [5,6]. One of the effective MRMS cooperative operations is achieved by the joint consensus control [3,4].

Due to the swift development of multi-agent system researches, more and more attentions are paid to the joint consensus control of MRMS. To justify the motivation and necessity of the proposed study, it needs to make a critical survey on the existing representative work, which scrutinizes the achievement and potential hard nut issues. An adaptive synchronized control is presented by using cross-coupling technology, in which the fixed circle communication topology is used [7]. A distributed leaderless consensus algorithm is explored for networked Euler–Lagrange system without considering the gravity effect [8]. A distributed adaptive coordinated control of MRMS is discussed by using NN, which requires fixed communication topologies [9]. A mutual synchronized control is designed for MRMS, which uses NN to compensate system uncertainty and external disturbance [10]. A distributed coordinated tracking control is proposed for Euler–Lagrange systems with a dynamic leader where the fixed leader–follower directed communication topology is used in the controller design [11]. Leader–follower swarm tracking control is considered for networked Lagrange systems [12]. Synchronization of bilateral teleoperators is investigated for two robotic manipulators subjected time delay [13]. A distributed adaptive synchronized control is examined for networked Lagrangian systems [14]. As can be seen above, many results have been obtained by using adaptive and robust control principle under different design conditions. Note that the main purpose of adaptive control or robust control is to overcome system uncertainty and/or external disturbance.

In the robotic manipulators control, system uncertainty and disturbance should be handled properly [15,16]. Otherwise, it may lead to decreased control performance even un-stability. In general, adaptive or robust control approaches are used to deal with them. Slotine et al. proposed a robot adaptive control approach by using the robotic manipulators' property named linear in a set of physical parameters [17]. This is a very smart idea to cope with parameters uncertainty. However, the controller may be very complex as the freedoms of robotic manipulator are large. Spong et al. proposed

* Corresponding author.
E-mail addresses: dongyazhao@gmail.com, dyzhao@upc.edu.cn (D. Zhao).

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robot robust control by assuming that the bounds of the uncertainties are known before the controller design [18]. Though this type control structure is simple it is not so easy to estimate system uncertainty bound in practice. Recently, NN is used in the robot control and achieve many good results [19–21]. The prominent advantage of the NN is that it can approximate any smooth nonlinear function with arbitrary precision [22–24], which can estimate the robotic manipulator uncertainty online with very simple and implemental method. Compared with existing adaptive and/or robust control algorithms, the NN based robot control algorithms are more intelligent and easier to understand and use [25–27].

Though NN based robot control algorithms are gradually improved their uses in MRMS are just started. The existing results are focused on the NN based adaptive control such as [9,10]. It is interesting and useful to construct a NN based consensus control framework for MRMS. The main purpose of this paper is to give a universal and systematical solution for MRMS consensus control by using NN. Specifically, the NN based adaptive and robust consensus controller design methods are presented in this paper by considering the directed, fixed and/or switching leader–follower communicating topologies. The main differences of the proposed approach with the exiting results [9,10] are the controller deigning method and communicating topologies. The NN robust control and switching communicating topology are addressed in this paper. They are not considered in [9,10]. It should be mentioned that a neruo-agents based synchronized control algorithm has been developed for MRMS [28]. It is an adaptive type control algorithm. The main contribution of paper focuses on the NN based consensus control framework, by which adaptive, robust etc. type consensus control algorithms can be designed easily. Then the proposed approaches extend the existing achievements in control structure and algorithm design.

The rest of this study is organized as follows. In Section 2, the problem is formulated and some indispensable preliminaries are given. In Section 3, the universal framework of NN based consensus control is proposed and the corresponding stability analysis is also given. In Section 4, illustrative examples are presented to validate the performance of the design scheme. Finally, in Section 5, some concluding remarks are given.

Some notations will be used in the following sections. In this paper $||\cdot||$denotes the Euclidean norm of vectors and/or matrices. For a matrix $\mathbb{A}$, Frobenius matrix norm is defined as $||\mathbb{A}||_F^2 \triangleq \sum_{ij}|a_{ij}|^2 = \mathrm{tr}(\mathbb{A}^T\mathbb{A}) = \mathrm{tr}(\mathbb{A}\mathbb{A}^T)$, $\lambda_{\max/\min}(\mathbb{A})$ denotes the maximum/ minimum eigenvalue of a symmetric matrix $\mathbb{A}$.

2. Preparation problem formulation and preliminaries

In this section, some basic concepts on robotic manipulator dynamics, algebraic graph theory and RBF NN are introduced to lay a foundation for MRMS consensus control. The control objective will be summarized after defining the leader–follower consensus error.

2.1. Dynamics of the manipulators

Consider one leader and n identical follower m-link fully actuated robotic manipulators. Their dynamic equations can be given as:

$$M(q_0)\ddot{q}_0 + C(q_0,\dot{q}_0)\dot{q}_0 + G(q_0) = \tau_0 \tag{1}$$

$$M(q_i)\ddot{q}_i + C(q_i,\dot{q}_i)\dot{q}_i + G(q_i) = \tau_i + f_i,\ i = 1,\cdots,n, \tag{1a}$$

where the subscript 0 and i denote the leader and the n follower manipulators, respectively, $q_0,\dot{q}_0,\ddot{q}_0 \in R^m$, and $q_i,\dot{q}_i,\ddot{q}_i \in R^m$ are the joint position, velocity and acceleration of the leader/follower manipulators, respectively, $M(\cdot) \in R^{m\times m}$ is a symmetric positive definite inertia matrix, $C(\cdot) \in R^{m\times m}$ represents Coriolis and centripetal matrix, $G(q_i) \in R^m$ is a gravitational force vector, $\tau_0, \tau_i \in R^m$ are joint torque vectors, f_i denotes the system uncertainty and load disturbance which is defined as $f_i = -\Delta M(q_i)\ddot{q}_i - \Delta C(q_i,\dot{q}_i)\dot{q}_i - \Delta G(q_i) + \tau_d$, where $\tau_d \in R^m$ is the external disturbance for force. The leader/follower manipulators have different states but have the same dynamic parameters.

By defining x_0 and x_i as: $x_0 = [q_0^T, \dot{q}_0^T]^T, x_i = [q_i^T, \dot{q}_i^T]^T$ can be written as:

$$\dot{x}_0 = Ax_0 + b_0 + BM^{-1}(q_0)\tau_0 \tag{2}$$

$$\dot{x}_i = Ax_i + b_i + B[M^{-1}(q_i)(\tau_i + f_i)] \tag{2a}$$

where $A = \begin{bmatrix} 0_m & I_m \\ 0_m & 0_m \end{bmatrix}$, $B = \begin{bmatrix} 0_m \\ I_m \end{bmatrix}$, $b_0 = \begin{bmatrix} 0 \\ M_0^{-1}[-C_0\dot{q}_0 - G_0] \end{bmatrix}$, $b_i = \begin{bmatrix} 0 \\ M_i^{-1}[-C_i\dot{q}_i - G_i] \end{bmatrix}$, subscript 0 and i denote the leader and the follower manipulator, respectively. For example, M_0^{-1} means $M^{-1}(q_0)$.

Assumption 1. $||f_i|| \le \alpha_1$, $||\tau_0|| \le \alpha_2$ where $\alpha_1 > 0$ and $\alpha_2 > 0$ are bounded positive numbers.

2.2. Concepts on graph theory and leader–follower system

A leader–follower system consists of one leader and n followers. Let $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ be an undirected graph, in which $\mathcal{V} = \{1,2,\cdots,n\}$ is the set of nodes, representing the n robotic manipulators. ε is the set of edges. An edge of $\mathcal{G}$ is represented by an ordered pair (i,j). $(i,j) \in \mathcal{E}$ if and only if manipulators i and j can exchange information between each other. The graph $\mathcal{G}$ is undirected, which means that the edge (i,j) and (j,i) in $\mathcal{E}$ are considered to be the same. Two nodes i and j are neighbors to each other if $(i,j) \in \mathcal{E}$. The set of neighbors of nodes i is denoted by $\mathcal{N}_i = \{j | j \in \mathcal{V},\ (i,j) \in \mathcal{E}, j \ne i\}$. A path is a sequence of connected edges in a graph. A graph is connected if there is a path between every pair of nodes. A component of graph $\mathcal{G}$ is a connected subgraph which is maximal. The leader is represented by node 0. Only the neighbors of leader 0 can measure some of the leader's states but not vice versa. Define $\overline{\mathcal{G}}$ to be a graph which consists of the graph $\mathcal{G}$, node 0 and edges pointing from node 0 to its neighbors.

The time varying graph denotes that the edges among the nodes vary with time. Consider all possible graphs $\{\overline{\mathcal{G}}_p | p \in \mathcal{P}\}$, in which $\mathcal{P}$ denotes an index for all graphs defined on nodes$\mathcal{V} = \{0,1,2,\cdots,n\}$. Similarly, let $\{\mathcal{G}_p | p \in \mathcal{P}\}$ be the subgraphs defined on the nodes $\mathcal{V} = \{1,2,\cdots,n\}$. The time varying property can be described by switching signal $\sigma : [0,\infty) \to \mathcal{P}$, which means that at each time t the underlying graph is $\overline{\mathcal{G}}_{\sigma(t)}$.

For the adjacency matrix $\mathcal{A} \in R^{n\times n}$ of a graph $\mathcal{G}$ on nodes $\mathcal{V} = \{1,2,\cdots,n\}$, its entry is 1 if (i,j) is an edge of $\mathcal{G}$ and 0 if it is not or $i = j$. The degree matrix of D of $\mathcal{G}$ is a diagonal matrix whose ith diagonal elements is $\sum_{j=1}^n a_{ij}$. The Laplacian of $\mathcal{G}$ is defined to be a matrix $\mathcal{L} = -\mathcal{A} + \mathcal{D}$ and has the following property.

Lemma 1. *[29]: The graph $\mathcal{G}$ is connected if and only if the Laplacian $\mathcal{L}$ of $\mathcal{G}$ has a simple zero eigenvalue.*

2.3. Concepts on RBF neural networks

RBF NN has some desirable features such as local adjustment of weights and mathematical tractability, which attracts larger numbers of attentions in researches and applications. RBF NN based adaptive controls [30,31] and robust controls [32,33] are designed