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Brief Papers

Adaptive consensus of nonlinear multi-agent systems with unknown backlash-like hysteresis ☆

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ABSTRACT

In this brief, we consider the consensus problem of high-order nonlinear multi-agent systems with unknown backlash-like hysteresis and unknown control direction. By using backstepping technique, a distributed adaptive control scheme, with the adoption of Nussbaum-type function, is developed to solve this consensus problem. Radial basis function neural network is employed to neutralize the uncertain nonlinear dynamics. The approximation error of the neural networks, together with external disturbance and a bounded term from the hysteresis model, is adaptively estimated and counteracted by a robust term. Under undirected connected communication topology, it is proved that the consensus can be achieved asymptotically with the proposed control protocol. Finally, a numerical example is presented to illustrate the performance of the proposed protocol.

1. Introduction

In the past decade, consensus problem of multi-agent systems has attracted considerable attention in system and control communities. Many well-known results have been reported (see e.g. [1–5]) in the literature. On the one hand, the study of multi-agent systems is interesting since they have a wide range of applications in real world, e.g. robotic systems, scheduling of traffic systems and networked cameras. On the other hand, it is still a challenging topic as agents may come across various uncertainties and work in some extreme environments.

Many researches have been conducted on the consensus problem of multi-agent systems with intrinsic nonlinearities. By assuming that the nonlinearities satisfy the Lipschitz condition with the Lipschitz constants being known, nonlinear multi-agent systems have been considered in [6,7]. In [6], Yu et al. solved the second-order leaderless consensus problem for multi-agent systems with inherent nonlinear dynamics by resorting to a new concept about the generalized algebraic connectivity. In [7], multi-agent systems with first- and second-order nonlinear dynamics were investigated under fixed and switching topologies. While Lipschitz constraints were also imposed on the nonlinearities in [8,9], adaptive control, as a promising tool to deal with nonlinearities, was employed to design control protocols for nonlinear multi-agent systems in [10,11] with the assumption that the nonlinearities can be "linearly parameterized" and the regression matrices are known. As an alternative, the approximate ability of neural networks has been found to be particularly useful in designing controllers for nonlinear systems [12,13]. With this eminent property, neural networks were utilized to solve a large class of consensus problems of nonlinear multi-agent systems, e.g. leaderless first-order nonlinear consensus problem in [14]; leader-following nonlinear consensus problem in [15]; nonlinear multi-agent system with state time-delay in [16]; high-order nonlinear tracking problem in [17]; nonlinear strict-feedback multi-agent systems in [18].

It is noted that all the aforementioned results were obtained on the basis of the actuator of each agent works without any constraint. However, nonlinearities are inevitable in almost all actuators, i.e. the actuators could not carry out exactly what the controllers require. It is widely known that hysteresis commonly exists in many physical systems and devices, such as mechanical actuators, biology optics and electronic relay circuits [19]. Moreover, the performance of system would strongly degrade if the effect of hysteresis on the actuator is neglected in controller design. Actually, some effective control schemes have been

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proposed to design controllers when actuators undergo hysteresis [20–23]. In the literature, there are two ways to deal with hysteresis phenomena, i.e. one is to develop a smooth adaptive inverse to mitigate the effect of hysteresis [24,25], the other one is to treat the effect of hysteresis as a bounded disturbance and detailed characteristic of hysteresis [26,27]. In real physical environment, the actuators of agents in the multi-agent systems may encounter hysteresis phenomena. However, none of these papers has reported hysteresis nonlinearity under multi-agent system setting, which is one of the motivations of this brief. Additionally, the control direction may be uncertain when designing the control algorithm. As an effective tool, the Nussbaum gain technique which originally proposed by Nussbaum [28], has been widely used to facilitate the analysis of the stability of a single system [29]. However, not all the Nussbaum-type functions are feasible for a group of interconnected systems with unknown control direction. Recently, by constructing a novel Nussbaum-type function [11], Chen et al. studied the consensus problem of first-order and second-order multi-agent systems with unknown identical control directions. This function is borrowed in [30], where cooperative output consensus problem for a class of nonlinear multi-agent systems is considered. In [31], another Nussbaum-type function was proposed and proved to be effective to deal with consensus problem of networked systems with unknown control direction.

Motivated by the above discussions, in this brief we consider the consensus problem of high-order nonlinear multi-agent systems with unknown backlash-like hysteresis and unknown control direction. Compared with [11], not only high-order dynamics is considered in our paper, but also the "linearly parameterized" constraint on the nonlinear term is removed. Therefore, our results include that in [11] as special case. By using backstepping technique, the proposed control protocol is proved to guarantee the consensus of the considered multi-agent systems. Moreover, regarding the backlash-like hysteresis input, which have not been considered under multi-agent systems setting, our problem is more challenging and the designed controller is applicable even the actuator suffers from backlash-like hysteresis. The main contributions of this paper are ascribed as follows: (1) Actuator of each agent in the multi-agent systems suffering from backlash-like hysteresis is firstly introduced to consensus problem. Besides, we do not need to acquire the parameters of the hysteresis, which means our controller is adoptable for different kinds of backlash-like hysteresis. (2) An improved robust control strategy is employed in the controller design. With the help of this strategy, the consensus problem of multi-agent system is achieved asymptotically, rather than ultimately uniformly bounded in [14].

The rest of the paper is organized as follows. In Section 2, some preliminaries on graph theory and model formulation are given. Controller scheme and its effectiveness is discussed in Section 3. In Section 4, a numerical example is given to verify the theoretical analysis. Section 5 is the conclusion and brief description of our future work.

2. Preliminaries and problem formulation

2.1. Graph theory

The relationship among N agents in the multi-agent system is modeled by an undirected graph $\mathcal{G}=\{\mathcal{V},\mathcal{E},\mathcal{A}\}$ of order N with a set of nodes $\mathcal{V}=\{1,2,\ldots,N\}$, a set of edges $\mathcal{E}\subseteq\mathcal{V}\times\mathcal{V}$ and an adjacency matrix $\mathcal{A}=[a_{ij}]\in\mathbb{R}^{N\times N}$ with nonnegative weights. In an undirected graph, edges are denoted by unordered pairs of nodes $e_{ij}=(i,j)$, which implies that node i and node j can exchange information with each other. The communication strength between node i and node j is represented by a_{ij}, i.e., $e_{ij}\in\mathcal{E}\Leftrightarrow a_{ij}>0$ and $a_{ij}=0$, otherwise. The set of neighbors of node i is denoted by $\mathcal{N}_i=\{j\in\mathcal{V}:(i,j)\in\mathcal{E}, j\neq i\}$. The Laplacian matrix L of graph $\mathcal{G}$ is defined by $L=D-\mathcal{A}$, where $D=\mathrm{diag}\{d_1,\ldots,d_N\}$ and $d_i=\sum_{j\in\mathcal{N}_i}a_{ij}$ is the degree of node i. A sequence of edges $(i_1,i_2),(i_2,i_3),\ldots,(i_{k-1},i_k)$ is called a path from node i_k to node i_1. A graph is connected if there exists a path between any two distinct nodes.

2.2. Problem formulation

The multi-agent system under consideration consists of N agents. The ith agent is modeled by the following differential equations:

$$\dot{x}_{i,m}=x_{i,m+1},\quad m=1,\ldots,M-1,$$
$$\dot{x}_{i,M}=b_iH(u_i)+f_i(x_i)+\delta_i(t), \tag{1}$$

where $x_{i,m}\in\mathbb{R}$ is the mth state of agent i; $x_i=[x_{i,1},\ldots,x_{i,M}]^T$ is the state vector of agent i; $f_i(x_i)$ is a continuous vector function containing unknown parameters and δ_i represents the external disturbance; $u_i\in\mathbb{R}$ is the control input; b_i is an unknown constant representing the direction of the control input and it is assumed that the signs of all b_i are the same and $0<b_{\min}\le|b_i|\le b_{\max}$; $H(u_i)$ denotes the backlash-like hysteresis effect on the actuator, which has the following property:

$$\frac{dH}{dt}=\alpha\left|\frac{du_i}{dt}\right|(\gamma u_i-H)+\beta\frac{dH}{dt} \tag{2}$$

where α, β, and γ are constants, and $\gamma>0$ is the slope of the line satisfying $\gamma>\beta$. Based on the analysis in [20], the expression of $H(u_i)$ can be written explicitly as

$$H(u_i(t))=\gamma u_i(t)+d(u_i) \tag{3}$$

$$d(u_i)=[H(u_i(0))-\gamma u_i(0)]e^{-\alpha(u_i(t)-u_i(0))\mathrm{sgn}(\dot{u}_i)}+e^{-\alpha u_i\,\mathrm{sgn}(\dot{u}_i)}\int_{u_i(0)}^{u_i(t)}[\beta-\gamma]e^{\alpha\xi\,\mathrm{sgn}(\dot{u}_i)}\,d\xi, \tag{4}$$

where $d(u_i)$ is bounded as shown in [20]. To show that (2) is able to model a class of backlash-like hysteresis, the parameters in (2) are chosen as $\alpha=1,\beta=0.345$ and $\gamma=3.1635$ and the solution is shown in Fig. 1. Obviously, the hysteresis is not a one-to-one function. This means that for a given determined control input u_i, the corresponding hysteresis output is uncertain and it is associated with the direction of the derivative of the control input.

Remark 1. In the existing literature, consensus problem of nonlinear multi-agent systems has been extensively investigated and

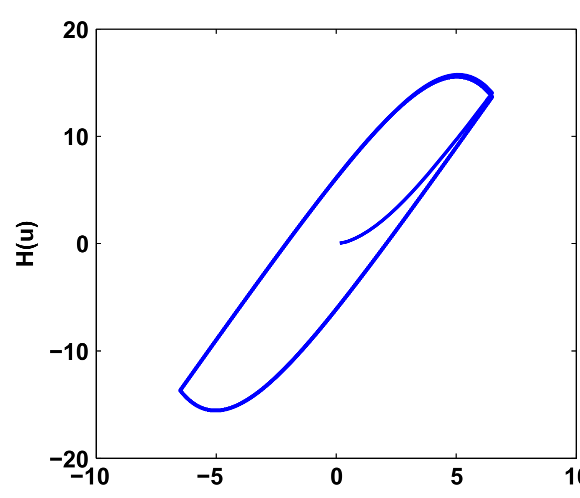

Fig. 1. Hysteresis curve.