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Research article

Distributed robust adaptive control of high order nonlinear multi agent systems

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ABSTRACT

In this paper, a robust adaptive neural network based controller is presented for multi agent high order nonlinear systems with unknown nonlinear functions, unknown control gains and unknown actuator failures. At first, Neural Network (NN) is used to approximate the nonlinear uncertainty terms derived from the controller design procedure for the followers. Then, a novel distributed robust adaptive controller is developed by combining the backstepping method and the Dynamic Surface Control (DSC) approach. The proposed controllers are distributed in the sense that the designed controller for each follower agent only requires relative state information between itself and its neighbors. By using the Young's inequality, only few parameters need to be tuned regardless of NN nodes number. Accordingly, the problems of dimensionality curse and explosion of complexity are counteracted, simultaneously. New adaptive laws are designed by choosing the appropriate Lyapunov-Krasovskii functionals. The proposed approach proves the boundedness of all the closed-loop signals in addition to the convergence of the distributed tracking errors to a small neighborhood of the origin. Simulation results indicate that the proposed controller is effective and robust.

1. Introduction

Multi Agent Systems (MAS) have attracted considerable attention due to its various applications in numerous fields such as sensor networks, electric power systems, telecommunication networks, unmanned air vehicles (UAVs), and flocking models [1–4]. So far, varieties of control approaches have been developed for linear [5–10] and nonlinear [11–14] multi agent systems. In general, the control problem of multi agent systems can be categorized into two classes, namely, the cooperative regulation problem [5,8,10,11,14] and the cooperative tracking problem [6,7,13]. In the first class, distributed controllers are designed for each agent, such that all agents are eventually driven to an unprescribed value which depends on their initial conditions. This problem is known as leaderless consensus or synchronization in the literature [5,8,10,11,14]. In the second class, a leader agent is considered that generates the desired reference trajectory and ignores information from the follower agents. All other agents attempt to follow the trajectory of the leader agent. This problem is known as leader-follower consensus or synchronization to a leader [6,7,13]. However, most of the existing results on nonlinear multi agent systems studied the first and second order systems [11–14]. In fact, in engineering many systems are modeled by higher order dynamics, such as a single-link flexible joint manipulator which is modeled by a fourth order nonlinear system [15]. Therefore, designing controllers for such high order nonlinear systems that distributed on communication graphs become necessary. For linear systems, up to now, considerable attention has been devoted to higher order linear systems [16–18]. However, for nonlinear systems, the results for first and second order systems have been extended to nonlinear systems with higher order dynamics recently [19,20].

Besides, the considered multi agent nonlinear systems in Refs. [11–14,19,20], contained known dynamics or unknown dynamics with linearly parameterized uncertainties. To eliminate this limiting condition, the recent work in Refs. [21–27] utilized Neural Networks (NNs) or Fuzzy Logic Systems (FLSs) to approximate the unknown nonlinearities in multi agent nonlinear systems. However, in the proposed approaches in Refs. [22–26] the number of adaptive laws depends on the number of NN nodes. Consequently,

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when the number of NN nodes is increased to improve approximation, the dimension of the corresponding adaptive parameters is also increased considerably. Hence, online learning time becomes unacceptably large. This problem is called dimensionality curse. In addition, to achieve a close approximation of the nonlinear function, it is important to choose the center vector and width properly. Since the nonlinear functions are unknown, these parameters have to be selected by trial and error and it is difficult to select these parameters for the basis functions. To remove the mentioned restrictive problems, in Ref. [27], the norm of ideal weight vector of NN was estimated instead of the elements of weight vector for individual systems without considering communication on network [27].

In addition, the proposed adaptive control approaches in Refs. [22–24] were proposed for some classes of nonlinear multi agent systems based on the backstepping design method. In Refs. [25,26], the adaptive decentralized control methods were proposed for some classes of uncertain nonlinear multi agent systems based on a Dynamic Surface Control (DSC) approach. The DSC approach is proposed to eliminate the "explosion of complexity" problem by introducing a first order filtering of the input at each stage of the traditional backstepping design method [28,29]. The "explosion of complexity" problem is the complexity of the controller that grows drastically as the order of the system increases, which is caused by repeated differentiation of certain nonlinear functions.

Furthermore, one of the serious problems that often occurs in many practical systems and brings uncertainties to the systems is actuator fault. Actuator faults often cause undesired system behavior and sometimes lead to instability or even catastrophic accidents [30,31]. The desired control design is expected to compensate the actuator faults by effectively compensating the uncertainties. In recent years, there have been remarkable efforts in reliable control of systems with actuator faults [32–50]. The adaptive controllers were presented for linear systems in Refs. [32–37] and for nonlinear systems in Refs. [37–50] in the presence of actuator faults.

Due to the development of high techniques and increasing complexity of the multi agent systems, the design of a reliable control system even in the presence of faults has been regarded as a challenging problem in multi agent systems. To the best of the authors' knowledge, relatively few papers have been published regarding fault compensation problem for multi agent systems [51–55]. However, the control gains of the considered systems in Refs. [51–55] should be "1" or be known functions.

In this paper, a distributed robust adaptive approach is proposed for a class of high order nonlinear multi agent systems with unknown nonlinearities and actuator faults. The main contributions of this paper, compared with the existing results [32–55], are as follows:

(1) The robust adaptive control approach is proposed for high order nonlinear multi agent systems.
(2) The control gains of the considered multi agent systems are unknown nonlinear functions.
(3) By using the Young's inequality, only few parameters need to be tuned regardless of NN nodes number. As a result, the computational burden is significantly alleviated and a simpler distributed adaptive NN control scheme is obtained than [32–55].
(4) In contrast with the previous literature of multi agent systems, in this paper the actuators of the considered systems may fail during the operation.
(5) The considered actuator faults not only reduce the system gain and degrade the system performance but also insert some uncertainties to the system which complicates the controller design.
(6) The proposed design method does not require a priori knowledge of the bounds of the uncertainties.
(7) The proposed design method proves the boundedness of all the closed loop signals in addition to the convergence of the distributed tracking errors to a small neighborhood of the origin.

The reminder of this paper is organized as follows. In section 2, the related works are explained in more details. In section 3, some preliminaries and the model description are given along with the necessary assumptions. Sections 4 and 5 are devoted to distributed controller design and its stability analysis. In sections 6 and 7, simulation results and conclusions are given, respectively.

2. Related works

Although a great development has been achieved for the adaptive control of nonlinear systems and multi agent systems, the aforementioned control approaches assume that all the considered systems are in good operating conditions [1–29]. Indeed, some faults such as actuators and sensors usually exist in the real processes [30,31]. Due to the importance of the actuator fault compensation problem in industrial systems, there have been remarkable efforts in reliable control of systems with actuator faults until now [32–50]. The adaptive controllers were presented for linear systems in Refs. [32–37] and for nonlinear systems in Refs. [37–50] against actuator faults. In Ref. [32], a model reference adaptive controller was proposed for a class of linear systems in the presence of linearly parameterized stuck faults. In Refs. [33,34], the direct adaptive control schemes were developed to solve the robust fault-tolerant control problem for linear systems with mismatched parameter uncertainties, disturbances and actuator faults including loss of effectiveness, outage and stuck. In Ref. [35], a robust model reference adaptive tracking controller was considered for linear systems containing modeling uncertainties, unknown additive disturbances and actuator fault. In Ref. [36], an adaptive state feedback coordinated decentralized control scheme was proposed for a class of dynamic systems with state delay in subsystems and in the interconnections and in the presence of unknown actuator faults in each subsystem.

For nonlinear systems, in Refs. [37,38], the adaptive compensation control schemes were designed and analyzed for some classes of nonlinear systems in the presence of linearly parameterized actuator faults. In Ref. [39], an adaptive backstepping control scheme is presented for parametric strict feedback nonlinear systems with actuator faults including loss of effectiveness, outage and constant stuck faults. In Ref. [40], an adaptive actuator fault compensation controller was presented for a class of uncertain stochastic nonlinear systems with unmodeled dynamics. The considered actuator faults in Ref. [40] cover loss of effectiveness faults as well as constant stuck faults. In Ref. [41], an adaptive fuzzy control method was presented for accommodating actuator faults in a class of uncertain nonlinear systems in strict feedback form. The considered actuator faults in Ref. [41] were completely known. In Refs. [40,41], the unknown nonlinearities were estimated by using FLSs. In Ref. [42], a neural network based adaptive control approach was proposed for a class of nonlinear systems in the presence of constant faults in actuators. In Ref. [42], the unknown nonlinearities were estimated by using neural networks. In Ref. [43], the problem of adaptive fault-tolerant control was considered for a class of nonlinear time delay systems with disturbance against unknown loss of effectiveness faults in actuators. In Ref. [44], the controller design problem was considered for a

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