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Adaptive consensus for high-order unknown nonlinear multi-agent systems with unknown control directions and switching topologies

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ABSTRACT

In this paper, we provide a comprehensive assessment of the consensus of high-order nonlinear multi-agent systems with input saturation and time-varying disturbance under switching topologies. The control directions and model parameters of agents are supposed to be unknown. Our approach is based on transforming the problem of consensus for a network that consists of high-order nonlinear agents to that of perturbed first-order multi-agent systems. The unknown part of dynamics is cancelled using radial basis neural networks. Nussbaum gains and auxiliary systems are respectively employed to overcome the unknown input direction and the saturation. Adaptive sliding mode control is used to compensate for the time-varying disturbance and the imperfect approximation of the developed neural network as well. Through Lyapunov analysis, it is shown that the overall closed-loop system maintains asymptotic stability. Finally, our approach is applied to a group of multiple single-link flexible joint manipulators to highlight better its merit.

1. Introduction

Advances in networked cyber-physical systems and embedded systems technology have created an increasing interest among the control community to study multi-agent systems (MASs). The control techniques developed so far for MASs enable us to apply resilient, cheap, and flexible methodologies to diverse cooperative tasks in many domains including maintenance, surveillance, reconnaissance, search and rescue mission, cooperative construction, and manipulation [6,18,28,31,47].

Consensus is a fundamental cooperative task in MASs where all the agents in a team are supposed to agree on a certain value of interest while each agent updates its states merely on the basis of its own states and the local information from its neighbors. Consensus has applications in a variety of domains, including cooperation of network sensors [35], decision making [26], motion coordination of unmanned aerial vehicles (UAVs) [23,40] and autonomous underwater vehicles (AUVs) [2], attitude synchronization in spacecraft [48], flocking control [33], and load sharing in microgrids [12].

Early studies of consensus mainly focused on the cooperation of agents with first- and second-order dynamics [20,27,29,34]. In [34], the problem of average consensus for first-order integrators under switching topologies and identical time delays was fully developed. The authors in [20] fully discussed the consensus problem of second-order system

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models under jointly-connected switching topologies based on a space decomposition technique. In [29], necessary and sufficient conditions were derived to guarantee consensus in a network of second-order systems over directed topology with a uniform constant delay.

However, first- and second-order kinematics fail to model many practical systems described by high-order differential equations. Hence, several studies concentrated on the consensus problem for linear high-order dynamics [4,11,39,41]. Techniques such as feedback linearization can be used to convert nonlinear systems to linear ones. The perfect cancellation of the nonlinearities requires having an exact model for the system which is not feasible in reality. Therefore, applying the results of linear MASs to unknown nonlinear MASs is not straightforward. However, despite its great importance, there are rather few studies dedicated to the consensus of high-order nonlinear systems [19,21,37,38,45,46]. For example, the authors in [37] developed a consensus framework for a network consisting of uncertain high-order nonlinear systems under jointly-connected switching topologies. The work of [21], investigates consensus problem for high-order stochastic nonlinear systems under fixed topology. In [19], the leader-following consensus for nonlinear homogenous MASs with network induced delays is studied.

Cooperative control of high-order nonlinear MASs can be even more challenging in the presence of input saturation. This practical concern results from the physical constraints of actuators. This issue has been studied in [7,36,43,44]. The study of [36] was dedicated to the semi-global bipartite consensus of general linear MASs with switching topologies. In [43], leader-following output consensus of linear discrete-time MASs subject to actuator saturation and external disturbances was examined. A leader-follower framework for consensus of a group of linear MASs with input saturation was established in [44].

All the aforementioned studies shared the assumption that the control directions are known. Nevertheless, in some practical situations, the controlling effect is not accessible. This issue is already addressed for a single system by using the Nussbaum-type function initially introduced in [32]. Tackling this issue for control of MASs is challenging due to the fact that each agent Nussbaum gain parameter may move in a different direction which impedes using the usual method of contradiction in the establishment of the stability of the overall system [13]. Recently some studies have appeared to overcome this challenge. The authors in [3] investigated adaptive consensus problem of first-order and second-order linearly parameterized systems where the control directions are assumed to have known lower and upper bounds. The problem of adaptive output regulation in the presence of unknown identical control direction was addressed in [13,30] in which the need for prior knowledge of the lower and upper bounds was removed. Researchers in [3,13,30] investigated the special case where all the control directions of the subsystems are identical. Although this condition was relaxed in [1], it still relies on knowing some of the control directions.

The above-mentioned facts motivated us to address the problem of consensus for high-order unknown nonlinear systems with input saturation, time-varying disturbance, and unknown control direction under switching interaction topologies. We develop an approach that converts the problem into the consensus of first-order MASs with bounded perturbation terms and then employs a properly developed stabilizing controller. Radial basis function neural networks are used to approximate the unknown nonlinear part of the system dynamics, while their update rules are derived based on the Lyapunov analysis. In order to deal with the unknown control direction, the Nussbaum-type function is utilized. An auxiliary system is also implemented for each agent to compensate for the input saturation while the effect of the time-varying disturbance and the approximation error of the neural network is counteracted by an adaptive sliding mode control scheme.

Compared to the most relevant study [37], our approach takes into account the effects of both unknown control direction and input saturation. Besides, in the work of [37], the control parameters were determined in such a way that a linear matrix inequality (LMI), which is dependent on the number of agents, should hold. Hence, growing the number of agents in the network would increase the computational burden. To the best of our knowledge, no studies have yet considered the problem at hand in the presence of the all aforementioned practical issues. For example, in [21,37,38,45], the unknown control direction was not addressed. Existing approaches that cope with this difficulty [1,3,13,30], not only neglected the effects of actuator saturation and switching topologies but also required the input directions to satisfy some limiting conditions. As a case in point, in [3], it was supposed that the upper and lower bounds of control effects are known. In [3,13,30], it was assumed that all control directions have an identical sign and in [1] some part of the control coefficients was considered to be known. In Table 1, the differences of our method with those presented in other relevant studies are highlighted. The contributions of this paper can be summarized as follows:

- Consensus for a class of general complex high-order nonlinear MASs with unknown nonlinearity and disturbance is studied.
- The consensus is achieved asymptotically in the presence of jointly connected topology for undirected graphs and uniformly jointly quasi-strongly connected and balanced topology for directed graphs.
- The impact of the actuator saturation in MASs is effectively handled.
- The proposed approach is capable of completely tackling unknown control effects where it allows control effects to have non-identical signs and the need for the knowledge of the boundaries of the control coefficients is removed.

The rest of the paper is organized as follows. In Section 2, required concepts from graph theory and notations are presented. The problem is formulated in Section 3. In Section 4, the control design and main results are presented. Simulations are given in Section 5 and finally, the paper is concluded in Section 6.

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