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Brief paper

Distributed adaptive control for consensus tracking with application to formation control of nonholonomic mobile robots[☆]

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ABSTRACT

In this paper, we investigate the output consensus problem of tracking a desired trajectory for a class of systems consisting of multiple nonlinear subsystems with intrinsic mismatched unknown parameters. The subsystems are allowed to have non-identical dynamics, whereas with similar structures and the same yet arbitrary system order. And the communication status among the subsystems can be represented by a directed graph. Different from the traditional centralized tracking control problem, only a subset of the subsystems can obtain the desired trajectory information directly. A distributed adaptive control approach based on backstepping technique is proposed. By introducing the estimates to account for the parametric uncertainties of the desired trajectory and its neighbors' dynamics into the local controller of each subsystem, information exchanges of online parameter estimates and local synchronization errors among linked subsystems can be avoided. It is proved that the boundedness of all closed-loop signals and the asymptotically consensus tracking for all the subsystems' outputs are ensured. A numerical example is illustrated to show the effectiveness of the proposed control scheme. Moreover, the design strategy is successfully applied to solve a formation control problem for multiple nonholonomic mobile robots.

1. Introduction

Because of its widespread potential applications in various fields such as mobile robot networks, intelligent transportation management, surveillance and monitoring, distributed coordination of multiple dynamic subsystems (also known as multi-agent systems) has achieved rapid development during the past decades. Consensus is one of the most popular topics in this area, which has received significant attention by numerous researchers. It is often aimed to achieve an agreement for certain variables of the subsystems in a group. A large number of effective control approaches have been proposed to solve the consensus problems (see Arcak, 2007; Bai, Arcak, & Wen, 2008, 2009; Hong, Hu, & Gao, 2006; Jadbabaie, Lin, & Morse, 2003; Moreau, 2005; Ren, 2007; Ren & Beard, 2005, for instance). According to whether the desired consensus values are determined by exogenous inputs, which are sometimes regarded as virtual leaders, these approaches are often classified as leaderless consensus and leader-following consensus solutions (see Kaizuka & Tsumura, 2011; Ni & Cheng, 2010; Song, Cao, & Yu, 2010; Zhang, Chen, & Stan, 2011, and the references therein). Besides, many of the early works were established for systems with first-order dynamics, whereas more results have been reported in recent years such as Ni and Cheng (2010), Ren, Moore, and Chen (2007), Seo, Shim, and Back (2009) and Yu, Chen, Ren, Kurths, and Zheng (2011) for systems with second or higher-order dynamics. A comprehensive overview of the state of the art in consensus control can be found in Ren and Cao (2010), in which the results on some other interesting topics including finite-time consensus and consensus under limited communication conditions including time delays, asynchronization and quantization are also discussed.

It is worth mentioning that except for Kaizuka and Tsumura (2011), all the aforementioned results are developed based on the

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assumptions that the considered model precisely represents the actual system and is exactly known. However, such assumptions are rather restrictive since model uncertainties, regardless of their forms, inevitably exist in almost all the control problems. Motivated by this fact, the intrinsic model uncertainty has become a new hot-spot issue in the area of consensus control. In Hu (2011), Liu and Jia (2011) and Yang, Zhang, and Zhang (2011), robust control techniques are adopted in consensus protocols to address the intrinsic uncertainties including unknown parameters, unmodeled dynamics and exogenous disturbances. In addition, adaptive control has also been proved as a promising tool in dealing with such an issue. In Kaizuka and Tsumura (2011), a group of linear subsystems with unknown parameters are considered and a distributed model reference adaptive control (MRAC) strategy is proposed. Different from Liu and Jia (2011) where H_∞ control is investigated, the bounds of the unknown parameters are not required *a* priori by using adaptive control. However, the result is only applicable to the case that the control coefficient vectors of all the subsystems are the same and known. In Nuno, Ortega, Basanez, and Hill (2011), adaptive consensus tracking controllers are designed for Euler–Lagrange swarm systems with non-identical dynamics, unknown parameters and communication delays. However, it is assumed that the exact knowledge of the desired trajectory is accessible for all the subsystems. In Das and Lewis (2010), a distributed neural adaptive control protocol is proposed for multiple first-order nonlinear subsystems with unknown nonlinear dynamics and disturbances. The state of the reference system is only available to a subset of the subsystems. Based on the condition that the basis neural network (NN) activation functions and the reference system dynamics are bounded, the convergence of the consensus errors to a bound can be ensured if the local control gains are chosen to be sufficiently large. The results are extended to more general class of systems with second and higher-order dynamics in Das and Lewis (2011) and Zhang and Lewis (2012). In Yu and Xia (2012), distributed adaptive control on first-order systems with similar structures to those in Das and Lewis (2010) is investigated. By introducing extra information exchange of local consensus errors among the linked agents, the assumptions on boundedness of inherent nonlinear functions can be relaxed. Apart from these, there are also some other results on distributed adaptive control of multi-agent systems, for instance Hou, Cheng, and Tan (2009), Mei, Ren, and Ma (2011), Su, Chen, Wang, and Lin (2011) and Zhao, Zhou, Li, and Zhu (2011). Nevertheless, to the best of our knowledge, results on distributed adaptive consensus control of more general multiple high-order nonlinear systems are still limited. In Wang, Zhang, and Guo (2011), the output consensus tracking problem for nonlinear subsystems in the presence of mismatched unknown parameters is investigated. By designing an estimator whose dynamics is governed by a chain of n integrators for the desired trajectory in each subsystem, bounded output consensus tracking for the overall system can be achieved. However, it is not easy to check whether the derived sufficient condition in the form of LMI is satisfied by choosing the design parameters properly. Moreover, transmissions of online parameter estimates among the neighbors are required, which may increase communication burden and also cause some other potential problems such as those related to network security.

In this paper, we shall present a backstepping based distributed adaptive consensus tracking control scheme for a class of nonlinear systems with mismatched uncertainties as similar to Wang et al. (2011). Suppose that only part of subsystems can acquire the exact information of the desired trajectory. Inspired by Bai et al. (2008, 2009) and Yu and Xia (2012), the time-varying reference is assumed to be linearly parameterized. The main differences between our proposed scheme and the existing representative approaches can be summarized as follows. (i) The communication status among subsystems is represented by a directed graph. Thus the control protocols in Bai et al. (2008, 2009) by employing the graph symmetry property are not applicable to solve our problem. (ii) The nonlinearities accompanied with unknown parameters in each subsystem's dynamics cannot be assumed bounded in advance as those activation functions in Das and Lewis (2010, 2011) and Zhang and Lewis (2012). To bypass this difficulty, an error variable is defined in each subsystem by introducing local estimates of the reference' uncertainties. Based on this, an alternative form of the Lyapunov function is constructed. Then the coupling terms related to local consensus errors and other subsystems' parameter estimation errors can be eliminated in computing the derivative of the Lyapunov function. Moreover, the parameter update laws can be designed totally in distributed manner without further information exchange of synchronization errors among subsystems as required in Yu and Xia (2012). (iii) By introducing additional local estimates to account for the uncertainties involved in its neighbors' dynamics, the extra transmissions of online parameter estimates required in Wang et al. (2011) among linked subsystems can be avoided. It is shown that with the proposed distributed control scheme, not only the boundedness of all closed-loop signals is ensured, but also asymptotically consensus tracking of all the subsystems' outputs can be achieved with the proposed control scheme.

Apart from these, the proposed design strategy is successfully applied to solve a formation control problem for multiple nonholonomic mobile robots. Such a challenging problem can be regarded as a generalized problem of one-dimensional output consensus tracking by considering demanding distances on 2-D plane. Note that the considered robots are uncertain underactuated mechanical systems with both dynamic and kinematic models, which brings new difficulties in designing distributed adaptive controllers. Therefore, only a few results have been reported in this area so far. In Do and Pan (2007), formation control of multiple unicycle-type mobile robots at the dynamic model level is investigated. A path-following approach by combining the virtual structure technique is presented to derive the formation architecture. In Do (2008), a formation control scheme is proposed for multiple mobile robots and no collision between any two robots is guaranteed. In the two schemes, all the robots require the exact information of the reference trajectory. In Dong (2011), the flocking control of a collection of nonholonomic mobile robots is proposed, where only part of the robots can obtain exact knowledge of the reference directly. However, the system model considered is limited at the kinematic level. Motivated by these, we investigate the formation control problem for multiple nonholonomic mobile robots at dynamic model level with unknown parameters under the condition that only part of the robots can access the exact information of the reference directly. It is proved that the formation errors of the overall system can be made as small as desired by adjusting the design parameters properly with the combination of our proposed distributed control strategy and the transverse function technique in Morin and Samson (2003).

2. Problem formulation

Similar to Wang et al. (2011), we consider a group of N nonlinear subsystems which can be modeled as follows.

$$\begin{aligned} \dot{x}_{i,q} &= x_{i,q+1} + \varphi_{i,q}(x_{i,1}, \ldots, x_{i,q})^T \theta_i, \quad q = 1, \ldots, n-1 \\ \dot{x}_{i,n} &= b_i \beta_i(x_i) u_i + \varphi_{i,n}(x_i)^T \theta_i \\ y_i &= x_{i,1}, \quad \text{for } i = 1, 2, \ldots, N \end{aligned} \tag{1}$$

where $x_i = [x_{i,1}, \ldots, x_{i,n}]^T \in \Re^n$, $u_i \in \Re$, $y_i \in \Re$ are the state, control input and output of the ith subsystem, respectively. $\theta_i \in \Re^{p_i}$