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Algebraic criteria for second-order global consensus in multi-agent networks with intrinsic nonlinear dynamics and directed topologies

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ABSTRACT

This paper discusses the second-order globally nonlinear consensus in general multi-agent directed networks with both non-time-delay and time-delay couplings. Some easily manageable delay-independent algebraic criteria are presented to unravel the underlying mechanics for reaching the second-order consensus. The obtained results are associated with the underlying network interactive topologies, inner coupling matrices and coupling gains between agents. Theoretical derivation is complemented by its validation on a simulation example.

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1. Introduction

In recent years, there has been an increasing research interest in the dynamical behaviors of isolated nonlinear system [10–12,17,18] or networked control system [49–52,54] with applications [16]. Especially, the design of distributed control algorithms based on agent's local interaction information in multi-agent networks such as rendezvous control of multinonholonomic agents [8], formation control [2,15], and flocking attitude alignment [4,23], has drawn much attention from researchers due to its broad range of applications. The formation control, flocking, and rendezvous, can be unified in the general framework of consensus setting. Consensus, a typical collective behavior in networked systems with a group of autonomous mobile agents, has received considerable attention recently due to its broad applications in biological systems, sensor networks, unmanned air vehicle (UAV) formations, robotic teams, underwater vehicles, etc. The basic idea for information consensus is that each agent shares information only with its neighboring agents under a distributed protocol while the whole group of agents can coordinate so as to achieve a certain global behavior of common interest [5]. It is worth mentioning that different methods to deal with the fuzzy shortest path problems have been presented [9,39,43,55], e.g. fuzzy shortest path in a network by Bellman dynamic programming approach and multiobjective linear programming technique. In the past decade, the consensus problem in the cooperative control community has been extensively studied [6,7,19–22,24–27,29–38,40–42,44,47,48,53], to name a few. Jadbabaie et al. [19] provided a theoretical explanation for the consensus behavior of the Vicsek model by using the graph and matrix theory. Under the assumption that the dynamics of each agent

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was a scalar continuous time integrator, Olfati-Saber and Murray [33] further solved the average consensus problem for the directed balanced network. Ren and Beard [37] extended the results in [19,33] by providing more relaxed conditions. Moreau [30] used a set-valued Lyapunov approach to address the consensus problem with unidirectional time-dependent communication links. Moore and Lucarelli [29] extended the results for single consensus variables to include the cases of forced consensus. Carli et al. [6] discussed the quantized average consensus problem. Hui et al. [15] developed the robust analysis results for nonlinear network consensus protocols. Ballal and Lewis [1] proposed a continuous-time and a discrete-time bilinear trust update scheme for trust consensus. More profound theoretical results have been established for distributed consensus of networked dynamic systems [8,35,38], which are very important in a wide range of practical applications [7,32,44]. Whereas, the scenario for networks of agents with a time-varying asymptotic velocity exists ubiquitously in the study of synchronization [45,46].

When acceleration is considered as the control input, each agent should be modeled as a double integrator dynamics. In this case, the consensus problem becomes more challenging. In many practical applications (e.g. autonomous underwater vehicles, unmanned aerial vehicles), the actuators can affect only the acceleration through the agents' inertias. Particularly, Lee and Spong [23] addressed the stable flocking of multiple agents which had significant inertias and evolved on a balanced information graph. As presented in [23], the agents' inertial effect can even cause unstable group behavior. However, as pointed out in [36], the extension of consensus algorithms for agents from first-order dynamics to second-order (when the control input is added on the driving force/acceleration term) is non-trivial. Protocols or algorithms dealing with the second-order consensus of multi-agent systems with nonlinear dynamics have not been emphasized until the recent works [24–26,40,42,53]. In [53], a kind of measurement for directed strongly connected graph, i.e., general algebraic connectivity, was first defined by Yu et al. The authors built the bridge between the general algebraic connectivity and the performance of reaching an agreement for second-order multi-agent systems with nonlinear dynamics. But the relationship between the generalized algebraic connectivity and the eigenvalues of the Laplacian matrix was not direct. The directed graph containing a directed spanning tree had to be divided into the strongly connected components and the generalized algebraic connectivity of each strongly connected component should be calculated to give sufficient conditions to ensure consensus. The work of [53] was extended to the leader-following case via pinning control by Song et al. in [40] by using pinning control technique, and it is worth mentioning that the above approaches have overcome the restriction, i.e., the interactive network is strongly connected in [53]. In [42], based on the local adaptive strategies, Su et al., have found that if one agent has access to the information of the virtual leader, all agents in the group can synchronize with the virtual leader. In [24], the finite-time second-order robust consensus problem of multi-agent networks with inherent nonlinear dynamics was considered and the convergence time was obtained. In [25], the authors studied the final second-order consensus convergence state of a multi-agent directed network by using a kind of generalized linear local interaction protocols. In [26], by introducing the generalized matrix measure and by applying the tools of contraction and circle analysis, the second-order locally dynamical consensus of multi-agent systems with arbitrarily fast switching directed topologies is theoretically investigated in detail, and some easily verified sufficient conditions are also presented. In [27], the authors discussed the second-order local consensus problem for multi-agent systems with nonlinear dynamics over dynamically switching random directed networks. By applying the orthogonal decomposition method, the state vector of resulted error dynamical system can be decomposed as two transversal components, one of which evolves along the consensus manifold and the other evolves transversally with the consensus manifold. Several sufficient conditions for reaching almost surely second-order local consensus are derived for the cases of time-delay-free coupling and time-delay coupling, respectively. In the above results, the time delay coupling does not be considered. If non-time-delay coupling and time-delay coupling terms exist at the same time, which plays a more important role, the second-order consensus problem of multi-agent systems is still an open problem.

In this paper, we systematically study the second-order global consensus problems in general multi-agent directed networks with both non-time-delay and time-delay coupling terms. Many consensus mathematical models under fixed topology can be seen as special cases of our models. The Lyapunov directed method [46] is used to derive some delay-independent algebraic criteria for reaching the second-order global consensus. These criteria deeply reveal the underlying relationships among the network interactive topologies, inner coupling matrices and coupling gains to obtain the second-order nonlinear consensus. Finally, a numerical simulation example is also provided to illustrate the feasibility and effectiveness of our theoretical results.

The rest of this paper is organized as follows. In Section 2, some preliminaries are provided. Section 3 presents some delay-independent algebraic criteria for second-order global consensus. In Section 4, a numerical example is given to validate the theoretical analysis. Finally, some concluding remarks are stated in Section 5.

2. Preliminaries

This section provides some mathematical preliminaries, supporting lemmas and definitions to derive the main results of this paper.

2.1. Notations

The quite standard notations are used throughout this paper. Let I be an identity matrix with appropriate dimensions. R^n and $R^{m\times n}$ denote, respectively, the n-dimensional real Euclidean space and the set of all $m \times n$ real matrices. Denote $e \in R^n$ a

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