



Distributed stabilized region regulator for synchronization of a class of multi-agent systems[☆]



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ABSTRACT

In this paper, a stabilized-region regulator method is presented to solve the output synchronization problem for discrete-time multi-agent systems. The topology structure for the information communication of the agents contains a spanning tree. The innovation of our result is that a stabilized region is designed for discrete-time multi-agent systems and the synchronization problem could be solved by choosing the appropriate parameters. A distributed dynamic feedback control law is designed such that the distribution of the eigenvalues of Laplacian matrix could be regulated into the specified region, then some sufficient conditions used to guarantee output synchronization are presented. At last, the result is extended to the uncertain multi-agent systems. Finally, a numerical simulation is given to demonstrate the correctness of obtained results.

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1. Introduction

In the past few years, distributed algorithms have been researched by [1]. Recently, cooperative control of multi-agent systems has attracted increasing attention from various scientific communities. This is partly due to its potential applications in technological fields such as vehicle suspension systems [2], stabilization control [3], impulsive control [4,5], industrial electronics [6], fault-tolerant control [7], and optimal algorithms [8,9]. Among the main research issues on cooperative control problem, the consensus problem plays an important role in investigating the collective behaviors of multi-agent systems due to the fact that many coordination control problems can be translated into the consensus problem.

In consensus problem, each agent communicates the states information of its neighboring agents and then responses according to the distributed consensus protocol, then all the states of the agents reach on the same trajectories with fix or switching topologies [10]. A necessary and sufficient condition for consensus seeking is given in [11], which requires the group decision value to be a linear function of initial states and initial estimated states of all agents in the network. According to the number of leaders existing in a system, consensus problems can be divided into leaderless and leader-following consensus. Noticeable works

focusing on the consensus include [12–18] for the leaderless consensus and [19–29] for the leader-following case. Consensus problem for discrete-time dynamics via the eigenvalues of the graph matrix has been addressed in [16,17] that the eigenvalues should lie into a stabilized region, but the region is depended on the structure of the graph. Then the row stochastic matrix method has been considered in [18] to finish the discrete-time convergence for general linear multi-agent systems. Therefore, for the leader-less case, the machinery for studying the discrete-time consensus is based on the stochastic matrix theory and the structure of the graph, while for the continuous-time case, the graph Laplacian matrix theory becomes a convenient tool. Robust consensus for fractional-order multi-agent systems has been considered in [14] by using algebraic graph theory and LMI method. The aforementioned results usually consider the global information of the graph because the eigenvalues of Laplacian matrix or the row sum of stochastic matrix contain the whole information of the graph. A fundamental problem dealing with the pure consensus protocols has not been emphasized until the recent work [15], which gives a useful result for consensusability of continuous-time multi-agent systems with respect to local information of the agents.

Over the last two decades, considerable researches have been conducted on the cooperative control of multi-agent systems to achieve leader-following problems. Active leader and variable interconnection topology were first studied in [19], in which a neighbor-based state-estimation rule is given for each autonomous agent. Then [20] expanded the conventional observers design to the distributed observers design for a multi-agent

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system where an active leader to be followed moves in an unknown velocity. In [21,22], the cost performance was considered, and adaptive dynamic programming and inverse optimal methods were used in handling this problem. It is worth pointing out that among various control strategies, such as leader–follower, virtual structure and potential function, output regulation is an useful method which could handle the problem that the leader has different dynamics with the followers and the followers always receive the external disturbance such as in [23,26]. Discrete-time tracking problem was considered in [24] by using Riccati design. Unfortunately, so far, very little effort has been devoted to it, and this problem usually depends on the distribution of the eigenvalues of Laplacian matrix.

Different from the aforementioned references, our main result do not subject to whether the eigenvalues of Laplacian matrix spanned in the nearby of a unit. In this note, we propose a novel approach to the investigation of output synchronization problem by using a dynamic feedback control law. This problem has widely application background, such as the energy storage systems (ESSs), which are often proposed to support the frequency control in microgrid systems. Due to the intermittency of the renewable generation and constantly changing load demand, the charging/discharging of various ESSs in an autonomous microgrid needs to be discrete-time case. The properties of stability of the closed-loop systems without considering the disturbance can be obtained by regulating the designed parameters felicitously. With the help of Sylvester equation and internal model method, the outputs of the agents could track the reference output generated by the exosystem. Furthermore, our method can also solve the output synchronization problem for uncertain discrete-time multi-agent systems.

The rest of this paper is organized as follows. In Section 2, some preliminaries are given, and we will formulate our problem. In Section 3, a stabilized region is designed and a distributed dynamic feedback control law is presented. Section 4 extends the result to the uncertain multi-agent systems. Section 5 provides a numerical simulation to validate theoretical results. Conclusions are drawn in Section 6.

2. Preliminaries and problem formulation

Some notations and problem formulation will be addressed in this section.

2.1. Notation

Let R and C be the set of real numbers and complex numbers, respectively. $R^{n \times n}$ is denoted as the real $n \times n$ matrix. 1_N is the column vector of all ones, and $\mathbf{0}$ is the zero matrix with appropriate dimensions. Let $\lambda_{\max}$ and $\lambda_{\min}$ denote respectively, the maximum and minimum eigenvalue of a real matrix, and $\sigma(A)$ means the singular value of A .

2.2. Graph theory

Our notation from graph theory is standard and follows the notation in [30].

The topology structure of a communication network can be expressed by a digraph. Let $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$ be a weighted digraph with the set of vertices $\mathcal{V} = \{1, 2, \dots, N\}$, the set of edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$, and a weighted adjacency matrix $\mathcal{A} = [a_{ij}]$ with non-negative adjacency elements a_{ij} . If the directed edge $(j, i) \in \mathcal{E}$, agent j is called a neighbor of agent i with $a_{ij} > 0$, and agent i can receive information from agent j ; otherwise, $a_{ij} = 0$. The neighbor index set of agent i is denoted by $\mathcal{N}_i = \{j \in \mathcal{V} | (j, i) \in \mathcal{E}\}$. A directed path is a sequence of edges in a digraph of the form $(i_1, i_2), (i_2, i_3), \dots, A$

digraph has a directed spanning tree if there exists at least one node, called the root node, having a directed path to all the other nodes.

2.3. Problem formulation

Consider a group of $N+1$ agents with general linear dynamics, consisting of N identical followers and a leader. The dynamics of N agents are described by

$$\begin{cases} x_i(k+1) = Ax_i(k) + Bu_i(k) + E_i\omega(k), \\ y_i(k) = Cx_i(k), i = 1, 2, \dots, N, \end{cases} \quad (1)$$

in which $x_i(k) \in R^n$, $y_i(k) \in R^p$ are the states and measurable outputs, $u_i(k) \in R^u$ is the control input. Assume that (A, B, C) is stabilizable and detectable. $E_i\omega(k)$ is the disturbance generated by the leader, which is also called the exosystem, given as follows:

$$\begin{cases} \omega(k+1) = S\omega(k), \\ y_r(k) = Q\omega(k), \end{cases} \quad (2)$$

in which $\omega(k) \in R^q$, and $y_r \in R^p$ is the reference output.

The information exchange of the above $N+1$ agents can be expressed by the digraph $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$, in which $\mathcal{V}$ is the set of vertices $\mathcal{V} = \{0, 1, 2, \dots, N\}$. Nodes $i = 1, 2, \dots, N$ are the N followers and node 0 is defined as the leader node. $a_{i0} > 0$ if node i could receive the information from the leader node, and in this paper we assume that the leader node cannot receive the information from the other nodes, i.e., $a_{0i} = 0$. Therefore, the weighted adjacency matrix of $\mathcal{G}$ is expressed as follows:

$$\mathcal{A} = \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathcal{A}_0 1_N & \mathcal{A}_s \end{pmatrix},$$

where $\mathcal{A}_0 = \text{block diag}\{a_{10}, a_{20}, \dots, a_{N0}\}$, and $\mathcal{A}_s$ is the adjacency matrix of $\mathcal{G}_s$ with the set of vertices $\mathcal{V} = \{1, 2, \dots, N\}$. Then Laplacian matrix of $\mathcal{G}$ is defined as $\mathcal{L} = [l_{ij}]$ with $l_{ij} = -a_{ij}, i \neq j$, and $l_{ii} = \sum_{k=0}^N a_{ik}$, i.e., the Laplacian matrix can be written as

$$\mathcal{L} = \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ -\mathcal{A}_0 1_N & \mathcal{H} \end{pmatrix},$$

in which $\mathcal{H} = \mathcal{A}_0 + \mathcal{L}_s$.

The following basic assumptions are necessary to solve the synchronization problem:

Assumption 1. The pair (Q, S) is detectable.

Remark 1. This assumption is only concerned with the asymptotic property of the closed-loop system by the measurement output feedback.

Assumption 2. S has no eigenvalues in the interior of the unit circle in the z -plane.

Remark 2. In fact, assumption 2 does not involve a loss of generality. If the partial eigenvalues of S are in the interior of the unit circle in the z -plane, S can be transformed into the stable and unstable parts by the appropriate transformation, and the stable part could be neglected in the distributed tracking problem because the tracking error and the disturbance generated by the stable exosystem will be converge to zero as time k tend to infinite.

Assumption 3. For all $\lambda \in \sigma(S)$,

$$\text{rank} \begin{pmatrix} A - \lambda I_n & B \\ C & 0 \end{pmatrix} = n + p.$$

Assumption 4. The digraph $\mathcal{G}$ contains a spanning tree and node 0 as its root.

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