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Distributed adaptive controllers for cooperative output regulation of heterogeneous agents over directed graphs[☆]

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ABSTRACT

This paper considers the cooperative output regulation problem for linear multi-agent systems with a directed communication graph, heterogeneous linear subsystems, and an exosystem whose output is available to only a subset of subsystems. Both the cases with nominal and uncertain linear subsystems are studied. For the case with nominal linear subsystems, a distributed adaptive observer-based controller is designed, where the distributed adaptive observer is implemented for the subsystems to estimate the exogenous signal. For the case with uncertain linear subsystems, the proposed distributed observer and the internal model principle are combined to solve the robust cooperative output regulation problem. Compared with the existing works, one main contribution of this paper is that the proposed control schemes can be designed and implemented by each subsystem in a fully distributed fashion for a class of directed graphs.

1. Introduction

Cooperative output regulation of multi-agent systems is to have a group of autonomous agents (subsystems) interacting with each other via communication or sensing to asymptotically track a prescribed trajectory and/or maintain asymptotic rejection of disturbances. The cooperative output regulation problem is closely related to the consensus problem and other cooperative control problems as studied in Li and Duan (2014) and Ren, Beard, and Atkins (2007) and the references therein. A central work in cooperative output regulation is to design appropriate distributed controllers, using local state or output information of each agent and its neighbors. In recent years, many interesting results are reported on cooperative output regulation, e.g.,in Ding (2015), Isidori, Marconi, and Casadei (2014), Li, Feng, Guan, Luo, and Wang (2013), Meng, Yang, Dimarogonas, and Johansson (2013), Su and Huang (2012), Su, Hong, and Huang (2013), Wang, Hong, Huang, and Jiang (2010) and Xiang, Wei, and Li (2009). In particular, several state and output feedback control laws are proposed in Li et al. (2013), Meng et al. (2013), Su and Huang (2012) and Xiang et al. (2009) to achieve cooperative output regulation for multi-agent systems with heterogeneous but known linear subsystems. The robust cooperative output regulation problem of uncertain linear multi-agent systems is studied in Su et al. (2013) and Wang et al. (2010), where internal-model-based controllers are designed. In Ding (2015) and Isidori et al. (2014) cooperative global output regulation is discussed for several classes of nonlinear multi-agent systems.

Although many advances have been reported on the cooperative output regulation problem, some challenging issues remain unresolved. For instance, control design presented in Su and Huang (2012), Su et al. (2013) and Wang et al. (2010) explicitly depends on certain nonzero eigenvalues of the Laplacian matrix associated with the communication graph. However, it is worth mentioning that any nonzero eigenvalue of the Laplacian matrix is global information of the communication graph. Using these global information of the communication graph prevents fully distributed implementation of the controllers. In other words, the controllers given in the aforementioned papers are not fully distributed. In

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Li et al. (2013), fully distributed adaptive controllers are proposed, which implement adaptive laws to update the time-varying coupling weights between neighboring agents. Similar adaptive protocols have been also presented in Li, Ren, Liu, and Xie (2013), Li, Wen, Duan, and Ren (2015) and Yu, Ren, Zheng, Chen, and Lü (2013) to solve the consensus problems. It is worth noting that the adaptive controllers in Li et al. (2013) are applicable to only the case where the graph among the agents are undirected and that the adaptive protocols in Li et al. (2013), Li et al. (2015) and Yu et al. (2013) are designed for homogeneous multi-agent systems. To design fully distributed controllers to achieve cooperative output regulation for heterogeneous multi-agent systems with general directed graphs is much more challenging, due to both the heterogeneity of the agents and the asymmetry of the directed graphs, and is still open, to the best knowledge of the authors.

This paper extends the fully distributed control design to the cooperative output regulation problem for linear multi-agent systems with a directed communication graph, heterogeneous linear subsystems, and an exosystem whose output is available to only a subset of subsystems. Both the cases with nominal and uncertain linear subsystems are studied. A distributed adaptive observer-based controller is designed to solve the cooperative output regulation problem for multi-agent systems with nominal linear subsystems. The distributed adaptive observer, which utilizes the observer states from neighboring subsystems, is constructed for the subsystems to asymptotically estimate the state of the exosystem. The case with uncertain linear subsystems is further studied. The proposed distributed adaptive observer and the internal model principle are combined to design distributed controllers to solve the robust cooperative output regulation problem. The proposed control schemes in this paper, in contrast to the controllers in Su and Huang (2012), Su et al. (2013) and Wang et al. (2010), can be designed and implemented by each subsystem in a fully distributed fashion, and, different from those in Li et al. (2013), are applicable to directed graphs.

2. Cooperative output regulation problem

In this section, we consider a network consisting of N heterogeneous subsystems and an exosystem. The dynamics of the ith subsystem are described by

$$\begin{aligned} \dot{x}_i &= A_i x_i + B_i u_i + E_i v, \\ e_i &= C_i x_i + D_i v, \quad i = 1, \ldots, N, \end{aligned} \tag{1}$$

where $x_i \in \mathbf{R}^{n_i}$, $u_i \in \mathbf{R}^{m_i}$, and $e_i \in \mathbf{R}^{p_i}$ are, respectively, the state, the control input, and the regulated output of the ith subsystem, and A_i, B_i, C_i, and D_i are constant matrices with appropriate dimensions. In (1), $v \in \mathbf{R}^q$ represents the exogenous signal which can be either a reference signal to be tracked or the disturbance to be rejected. The exogenous signal v is generated by the following exosystem:

$$\dot{v} = Sv, \qquad y_v = Fv, \tag{2}$$

where $y_v \in \mathbf{R}^l$ is the output of the exosystem, $S \in \mathbf{R}^{q\times q}$, and $F \in \mathbf{R}^{l\times q}$.

To achieve cooperative output regulation, the subsystems need information from other subsystems or the exosystem. The information flow among the N subsystems can be modeled by a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{v_1, \ldots, v_N\}$ is the node set and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the edge set, in which an edge is represented by an ordered pair of distinct nodes. If $(v_i, v_j) \in \mathcal{E}$, node v_i is called a neighbor of node v_j. A directed path from node v_{i_1} to node v_{i_l} is a sequence of adjacent edges of the form $(v_{i_k}, v_{i_{k+1}})$, $k = 1, \ldots, l-1$. A directed graph contains a directed spanning tree if there exists a root node that has directed paths to all other nodes.

Since the exosystem (2) does not receive information from any subsystem, it can be viewed as a virtual leader, indexed by 0. The N subsystems in (1) are the followers, indexed by $1, \ldots, N$. Assume that the output y_v of the exosystem (2) is available to only a subset of the followers. Without loss of generality, suppose that the subsystems indexed by $1, \ldots, M$ $(1 \le M \ll N)$, have direct access to the exosystem (2) and the rest of the followers do not. The followers indexed by $1, \ldots, M$, are called the informed followers and the rest are the uninformed ones. The communication graph $\mathcal{G}$ among the N subsystems is assumed to satisfy the following assumption.

Assumption 1. For each uninformed follower, there exists at least one informed follower that has a directed path to that uninformed follower.

For the case with only one informed follower, Assumption 1 is equivalent to that the graph $\mathcal{G}$ contains a directed spanning tree with the informed follower as the root node. For the directed graph $\mathcal{G}$, its adjacency matrix $\mathcal{A} = [a_{ij}] \in \mathbf{R}^{N\times N}$ is defined by $a_{ii} = 0$, $a_{ij} = 1$ if $(v_j, v_i) \in \mathcal{E}$ and $a_{ij} = 0$ otherwise. The Laplacian matrix $\mathcal{L} = [\mathcal{L}_{ij}] \in \mathbf{R}^{N\times N}$ associated with $\mathcal{G}$ is defined as $\mathcal{L}_{ii} = \sum_{j\neq i} a_{ij}$ and $\mathcal{L}_{ij} = -a_{ij}$, $i \neq j$.

Because the informed subsystems indexed by $1, \ldots, M$, can have direct access to the exosystem (2), they do not have to communicate with other subsystems to ensure that e_i, $1, \ldots, M$, converge to zero. To avoid unnecessarily increasing the number of communication channels, assume that the informed subsystems do not receive information from other subsystems, i.e., they have no neighbors except the exosystem. In this case, the Laplacian matrix $\mathcal{L}$ associated with $\mathcal{G}$ can be partitioned as $\mathcal{L} = \begin{bmatrix} 0_{M\times M} & 0_{M\times(N-M)} \\ \mathcal{L}_2 & \mathcal{L}_1 \end{bmatrix}$ where $\mathcal{L}_2 \in \mathbf{R}^{(N-M)\times M}$ and $\mathcal{L}_1 \in \mathbf{R}^{(N-M)\times(N-M)}$. Under Assumption 1, it is known that all the eigenvalues of $\mathcal{L}_1$ have positive real parts (Cao, Ren, & Egerstedt, 2012). Moreover, it is easy to verify that $\mathcal{L}_1$ is a nonsingular M-matrix (Qu, 2009).

The objective of the cooperative output regulation problem is to design appropriate distributed controllers based on the local information available to the subsystems such that (i) the overall closed-loop system is asymptotically stable when $v = 0$; (ii) for any initial conditions $x_i(0)$, $i = 1, \ldots, N$, and $v(0)$, $\lim_{t\to\infty} e_i(t) = 0$.

To solve the above cooperative output regulation problem, the following assumptions are needed, which are standard in the classic output regulation problem (Huang, 2004).

Assumption 2. The matrix S has no eigenvalues with negative real parts.

Assumption 3. The pairs (A_i, B_i), $i = 1, \ldots, N$, are stabilizable.

Assumption 4. The pair (S, F) is detectable.

Assumption 5. For all $\lambda \in \sigma(S)$, where $\sigma(S)$ denotes the spectrum of S, $\operatorname{rank}\left(\begin{bmatrix} A_i - \lambda I & B_i \\ C_i & 0 \end{bmatrix}\right) = n_i + p_i$.

Since the exogenous signal v is not available to the subsystems for feedback control, the subsystems need to implement some observers to estimate v. For the informed subsystems that have direct access to the output y_v of the exosystem (2), they can estimate v by using the following observers:

$$\dot{\xi}_i = S\xi_i + L(F\xi_i - y_v), \quad i = 1, \ldots, M, \tag{3}$$

where the feedback gain matrix $L \in \mathbf{R}^{p\times l}$ is chosen such that $S + LF$ is Hurwitz. Denote by $\bar{\xi}_i = \xi_i - v$ the estimation errors. From (2) and (3), it is easy to see that $\dot{\bar{\xi}}_i = (S + LF)\bar{\xi}_i$, $i = 1, \ldots, M$, implying that $\lim_{t\to\infty} \bar{\xi}_i(t) = 0$, $i = 1, \ldots, M$.