Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-18 (2016) 564–569

An Event-Triggered Control Approach to Cooperative Output Regulation of Heterogeneous Multi-Agent Systems ⋆

Wenfeng Hu, Lu Liu, Gang Feng

Department of Mechanical and Biomedical Engineering
City University of Hong Kong, Kowloon, Hong Kong
(Tel:852-34425426, E-mail: wenfenhu@163.com,
luliu45@cityu.edu.hk, megfeng@cityu.edu.hk)

Abstract: This paper presents a novel distributed event-triggered control approach to cooperative output regulation of heterogeneous multi-agent systems. First, we propose a basic event-triggered control scheme. Next, building on this result, we propose a distributed self-triggered control scheme, such that continuous monitoring of measurement errors can be avoided. With these proposed control schemes, Zeno behavior can be excluded for each agent by introducing a fixed timer in the triggering mechanism. An example is finally provided to demonstrate the effectiveness of the proposed control schemes.

Keywords: Cooperative output regulation, event-triggered control, heterogeneous multi-agent systems, self-triggered control.

1. INTRODUCTION

Nowadays, more and more attention has been drawn to the cooperative control of large scale networked dynamical systems called multi-agent systems, which is due to the wide applications of multi-agent systems. Recently, the authors in Wang et al. (2010), Kim et al. (2011), Su and Huang (2012), and Su et al. (2013) addressed the cooperative output regulation problem of linear multi-agent systems with an exosystem. It is noted that in the distributed setting of multi-agent systems, the cooperative output regulation problem is more challenging than conventional output regulation of a single system (Huang, 2004). More results on cooperative output regulation problem of nonlinear multi-agent systems can be found in Dong and Huang (2014) and Xu et al. (2014).

In these aforementioned literatures, multi-agent systems with continuous time dynamics are considered and it is usually assumed that the communication among neighboring agents and controller update are continuous. Such control schemes might become infeasible in some applications of multi-agent systems, considering the fact that each individual agent may only have limited on-board computing and power resources. Event-triggered strategies have attracted attention of many researchers due to their ability to reduce the communication load. Event-triggered strategies have been applied to solve the so-called consensus problem of multi-agent systems. Particularly, in Dimarogonas et al. (2012), Seyboth et al. (2012), and Meng and Chen (2013), multi-agent systems with single- or double-integrator dynamics were considered. The authors in Garcia et al. (2014), Guo et al. (2014), Forni et al. (2014), Zhu and Jiang (2015), and Hu et al. (2016) further generalized the event-triggered strategies to multi-agent systems with general linear dynamics.

A key issue in event-triggered control is how to design the triggering mechanism, which is expected to be both distributed and independent. As the control tasks become more complicated, and agent dynamics are assume to be more general, the design of event-triggered control schemes becomes more difficult. Another key issue in designing event-triggered control schemes is the exclusion of Zeno behavior. Zeno behavior is used to describe a scenario that an infinite number of events occur in a finite time. To exclude it, a strictly positive minimum inter-event time should be guaranteed, which is very difficult sometimes. To address one or some of these problems, some progress has been made recently. In Meng and Chen (2013) and Guo et al. (2014), the event-triggered control schemes were developed based on sampled-data transmission strategies, such that the inter-event times can be lower bounded by at least one sampling period. In Forni et al. (2014), Tallapragada and Chopra (2014), and Fan et al. (2015), a fixed timer (or a dwell time) was introduced in the triggering mechanism to guarantee the existence of a positive minimum inter-sampling time.

In the abovementioned works, event-triggered strategies have been mainly utilized to address the consensus problem of various multi-agent systems. The existing approaches to consensus problem can not be adopted to design a Zeno-free event-triggered control scheme for the cooperative output regulation problem. The different agent dynamics in heterogeneous multi-agent systems make the event-triggered control even more challenging. These observations motivate our study.

⋆ This work was supported by the Research Grants Council of the Hong Kong Special Administrative Region of China under Project CityU/11209514. Corresponding author: Lu Liu, Tel: 852-34425426, E-mail: luliu45@cityu.edu.hk.

10.1016/j.ifacol.2016.10.225

The main contributions of this paper can be summarized as follows. First, inspired by Su and Huang (2012), a dynamic controller is proposed for each agent, and a virtual layer is constructed for communication. Second, a novel event-triggered control scheme is proposed to solve the cooperative output regulation problem of heterogeneous multi-agent systems. By introducing a fixed timer in the triggering mechanism, Zeno behavior can be excluded for each agent. Third, a self-triggered control scheme is further developed to avoid continuous monitoring of measurement errors, which is suffered by the event-triggered control scheme. Compared with the control scheme in Su and Huang (2012), which assumes continuous communication and control update, the self-triggered control scheme in this paper only needs intermittent communication. Compared with the triggering mechanism in Hu and Liu (2016), a positive minimum inter-event time can be explicitly given in this paper.

The rest of the paper is organized as follows. Some preliminaries and problem formulation are introduced in Section 2. In Section 3, both event-triggered and self-triggered control schemes are presented for cooperative output regulation of heterogeneous multi-agent systems. An example is provided to illustrate the effectiveness of the proposed control schemes in Section 4 and conclusions are drawn in Section 5.

2. PROBLEM FORMULATION

2.1 Algebraic Graph Basics

In a multi-agent system without a leader, the communication graph can be denoted by $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with the agent set $\mathcal{V} = \{1, \cdots, N\}$ and the edge set $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$. If $(i, j) \in \mathcal{E}$, they are called adjacent agents, and agent i is called the child agent while agent j is the father agent. In a graph, if $(i, j) \in \mathcal{E} \Leftrightarrow (j, i) \in \mathcal{E}$, the graph is called undirected. All the father agents of agent i constitute its neighbor set, denoted by $\mathcal{N}_i$. A path is a sequence of distinct adjacent agents in a graph. If there is a path between any two agents of the graph $\mathcal{G}$, then $\mathcal{G}$ is called connected. Each graph is uniquely associated with an adjacency matrix $\mathcal{A} = (a_{ij})_{N\times N}$, whose (ij)th entry is 1 if and only if $(i, j) \in \mathcal{E}$, and 0 otherwise (with the assumption that $(i, i) \notin \mathcal{E}$). The degree matrix is $\mathcal{D} = \mathrm{diag}(|\mathcal{N}_1|, \cdots, |\mathcal{N}_N|)$, where $|\mathcal{N}_i|$ denotes the cardinality of the set $\mathcal{N}_i$. The Laplacian matrix of $\mathcal{G}$ is defined as $L = \mathcal{D} - \mathcal{A}$.

In a multi-agent system with a leader, we use vertex 0 to be associated with the leader and vertices $\{1, \cdots, N\}$ to be associated with other agents. Then, the communication graph among all agents and the leader can be described by $\bar{\mathcal{G}} = \left(\bar{\mathcal{V}}, \bar{\mathcal{E}}\right)$, where $\bar{\mathcal{V}} = \mathcal{V} \cup \{0\}$ and $\bar{\mathcal{E}} \subseteq \bar{\mathcal{V}} \times \bar{\mathcal{V}}$. The new adjacency matrix $\bar{\mathcal{A}} \in R^{(N+1)\times(N+1)}$ is defined as $a_{i0} = 1$, $i = 1, \cdots, N$, if and only if the controller of agent i can use the information from the leader, and $a_{i0} = 0$ otherwise, while all other elements are the same as those of $\mathcal{A}$. We define $\Delta = \mathrm{diag}(a_{10}, \cdots, a_{N0})$, and let $H = L + \Delta$.

Remark 1. It is well known that, for undirected graphs, matrix H is positive definite if and only if graph $\bar{\mathcal{G}}$ is connected. For simplicity, define $\lambda_m = \lambda_{min}(H)$ and $\lambda_M = \lambda_{max}(H)$, where $\lambda_{min}(H)$ and $\lambda_{max}(H)$ are used to represent the smallest and largest eigenvalue of matrix H, respectively.

2.2 Problem Formulation

In this paper, we consider the following linear multi-agent system with N heterogeneous agents in Su and Huang (2012),

$$\begin{aligned} \dot{x}_i &= A_i x_i + B_i u_i + E_i v \\ \tilde{e}_i &= C_i x_i + D_i u_i + F_i v, \ \ i = 1, \cdots, N \end{aligned} \tag{1}$$

where $x_i \in R^{n_i}$, $u_i \in R^{m_i}$, and $\tilde{e}_i \in R^{p_i}$ are the state, input, and error output of agent i, respectively. A_i, B_i, E_i, C_i, D_i, and F_i all have compatible dimensions. $v \in R^q$ is the exogenous signal representing a class of reference inputs to be tracked and/or a class of disturbances to be rejected. It is generated by the following exosystem,

$$\dot{v} = Sv, \tag{2}$$

where $S \in R^{q\times q}$. All agents and the exosystem constitute a fixed undirected graph, denoted as $\bar{\mathcal{G}}$.

Definition 1. (Cooperative Output Regulation Problem). Given systems (1), (2) with graph $\bar{\mathcal{G}}$, develop a distributed controller, such that the following two properties are satisfied

1) The overall closed-loop system consisting of (1), (2) and the controller is asymptotically stable if $v = 0$.

2) For any initial conditions $x_i(0)$ and $v(0)$, the following condition holds

$$\lim_{t\to\infty} \tilde{e}_i(t) = 0, \ \ i = 1, \cdots, N.$$

The objective of this paper is to develop, for agent i, $i = 1, \cdots, N$, a controller with intermittent communication, such that the cooperative output regulation problem of linear multi-agent system (1) and exosystem (2) can be solved.

To achieve this, the following assumptions are needed.

Assumption 1. S has no eigenvalues with negative real parts.

Assumption 2. The pairs (A_i, B_i), $i = 1, \cdots, N$, are stabilizable.

Assumption 3. There exist solution pairs (Π_i, Γ_i) for the following linear matrix equations

$$\begin{aligned} A_i\Pi_i + B_i\Gamma_i + E_i &= \Pi_i S \\ C_i\Pi_i + D_i\Gamma_i + F_i &= 0, \quad i = 1, \cdots, N. \end{aligned} \tag{3}$$

Assumption 4. Graph $\bar{\mathcal{G}}$ is undirected and connected.

Remark 2. Assumption 1 is made only for convenience and loses no generality, see Huang (2004). Assumptions 1-4 are also needed for cooperative output regulation problem for linear multi-agent systems in Su and Huang (2012).

3. MAIN RESULTS

In this section, we will address the cooperative output regulation problem of heterogeneous linear multi-agent systems by proposing a dynamic controller and a novel triggering mechanism. First, we develop a basic event-triggered control scheme. Then, based on the result, an enhanced self-triggered control scheme is proposed, such that continuous monitoring can be avoided, and thus only intermittent communication is required.