Neurocomputing 237 (2017) 388–396

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Decentralized event-triggered cooperative control for multi-agent systems with uncertain dynamics using local estimators[☆]

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ARTICLE INFO

Communicated by Guang Wu Zheng

Keywords:
Decentralized consensus control
Uncertain dynamics
Local estimator
Event-triggered control

ABSTRACT

This paper presents a decentralized event triggered cooperative control design for uncertain multi-agent systems under limited communication resources. A local estimator is employed by each agent to generate self-state estimates. The estimated states are directly used in the consensus control design, and the estimator parameters are used in the event condition design. Once an event is triggered, the local estimator is repeatedly reset to its corresponding real state values, such that it can stabilize the uncertain dynamical systems without knowing the exact system model parameters. A theorem for this triggering condition is developed to provide stable thresholds that are robust to model uncertainties and guarantee the asymptotical stability by exploiting the M-matrix, algebraic graph theory and the Lyapunov method. It is rigorously proved that the overall system will achieve the consensus and has no zeno behavior under the introduced triggering condition. Simulation results are provided to show the effectiveness of the proposed decentralized event-triggered cooperative control strategy.

1. Introduction

In recent years, multi-agent systems have attracted a great deal of attention due to their wide applications in practice. The examples include electrical power grids, transportation networks, and wireless sensor networks, to name but a few. Many significant results have been obtained in the control design of multi-agent systems [1–4]. However, increasing demands in applications may enlarge the scales of these networked systems and put more burdens in the network communication and management. It is well known that the communication networks especially wireless networks generally have limited network bandwidths. Thus, how to control multi-agent systems under the limited communication resource has been a critical issue in real applications.

Various techniques have been proposed to deal with this issue, such as Try-Once-Discard (TOD) [5], deterministic or stochastic communication logic [6], and so on. Most communication schemes so far are based on time-triggered control. Generally, periodic time triggered control sends the information in a fixed period. The communication and the task scheduling on control units have to be synchronized in order to ensure the strict time specifications in system design. In addition, if the variation of signal is tiny and negligible, this kind of method will transmit many unnecessary signals through the network. To mitigate the unnecessary waste of communication resource in periodic time-triggered control, an alternative control named event-triggered control is proposed [7], which offers a new point of view on how system states could be sampled or transmitted [8]. In comparison to conventional time-triggered control, the unique feature of event triggered control is that the states of each agent are transmitted to neighbors only when a specific event occurs not by a fixed period. It provides a useful and efficient way to determine whether or not the communication is necessary by verifying the event condition. A comparison between traditional time-triggered control and event-triggered control is presented by [9,10]. It is shown that a considerable reduction of the network resource occupancy is provided by event-triggered control while maintaining a similar control performance with time-triggered control.

Event-triggered control has also been widely used in consensus/synchronization control of multi-agent systems. For examples, in [11], a centralized and a distributed consensus event triggered consensus strategies are developed with a specific threshold consisting of local information. Based on this method, a decentralized event triggered communication strategy is proposed in [12], and the continuous information of neighbors is not required to verify the event condition.

☆ This work was partially supported by the National Natural Science Foundation of China (Grant Nos. 61379111, 61672537, 61672539, 61402538, 61403424, 61602529, 61502055 and 61503048) and the 111 Project (B17048) and the Fundamental Research Funds for Central South University (2015zzts055)
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http://dx.doi.org/10.1016/j.neucom.2017.01.029
Received 2 July 2016; Received in revised form 4 October 2016; Accepted 8 January 2017
Available online 16 January 2017
0925-2312/

To further reduce resource consumption, a new event-triggered synchronization combining both event-triggered control and periodic sampled-data control is proposed in [13,14], in which the event condition is verified only periodically. The common features in these previous works are the use of a Zero-Order-Hold (ZOH) model in the control node and the assumption that there are no uncertainties with plant models.

More recently, a new control framework combining event-triggered control and model-based technology is proposed in [15,16]. This framework allows for considerable reduction of bandwidth and model uncertainties, since an identical global estimator is introduced in each subsystem instead of ZOH to provide the full system state estimates. Every subsystem broadcasts its local information to other subsystems only when the error between estimate and actual state surpasses the threshold. On the basis of this framework, a model-based periodic event-triggered control for linear systems is provided by including a disturbance model in [17]. The work in [18] presents a similar idea to solve the disturbance problem with reduced communication. The model-based event-triggered strategy is extended in [19] to deal with model uncertainties, in which estimation based control is designed for a single network system. In [20], centralized and decentralized approaches of model-based event-triggered control for networked control systems are presented, while each subsystem needs to estimate the states of all subsystems. The neighboring relationship is known to all subsystems and predefined in the sense of dynamical interactions among subsystems and it is required to be symmetric. Moreover, the input matrix parameter is required in the decentralized event condition, and the inter-event time is not analyzed.

For general linear multi-agent systems with model uncertainties, the design of event-triggered control appears to be more challenging for several reasons. First, the event-triggering strategy should be fully distributed for ease of implementation. Second, each agent prefers the asynchronous control in order to further reduce the transmission load. Third, to deal with model uncertainties, the state estimation is needed for each agent by only using its local neighboring agents' information. In this paper, we propose a new decentralized event-triggered cooperative control for a general class of linear uncertain multi-agent systems. Particularly, to deal with model uncertainties and to reduce the communication load, a local estimator instead of global estimator is designed for each agent to provide its own states' estimates based on the estimated state model of system matrices A_i and B_i. The accurate input matrix parameter is no longer needed in the decentralized event design. The decentralized cooperative control law for each agent is based on the use of its own estimated states and those transmitted from its neighbors under an event-triggered sampling mechanism. That is, an event for broadcasting the exact state values will be triggered once the error between the last transmitted value and the real value exceed the threshold value At the same time, the values of estimators will be reset to the real state values. The main contributions of the paper are twofold: first, a novel model based event-triggered cooperative control with local estimator instead of global estimator, in which the neighboring relationship of every agent is not needed, is presented for general linear multi-agent systems. Second, a new triggering condition based on local model is designed to further deal with model uncertainties. A theorem for this triggering condition is developed to provide stable thresholds that are robust to model uncertainties and guarantee the asymptotical stability by exploiting the M-matrix, algebraic graph theory and the Lyapunov method. It is rigorously proved that the asymptotic consensus can be achieved under the proposed event-triggered cooperative control protocol. It is also demonstrated that the inter-event times of each agent is strictly positive, which implies the Zeno behavior can be excluded.

2. Preliminaries and problem statement

2.1. Graph theory

We use a graph to represent the communication topology in networked multi-agent systems. Let $G(V, E, \mathcal{A})$ denote a weighted directed graph, where $V = \{1, 2, \ldots, N\}$ is a set of N nodes and $E = \{(i, j) \in V \times V\}$ is an edge set of adjacent two nodes, $\mathcal{A} = [a_{ij}]$ is the weighted adjacency matrix. An edge of G is $(i, j) \in E$, then $a_{ij} > 0$. For undirected graph, $a_{ij} = a_{ji}$. The set of neighbors of the node i is denoted by $N_i = \{j \in V: (i, j) \in E\}$. The degree matrix of Graph G is denoted by $D = diag\{d_1, d_2, \ldots, d_N\}$, where $d_i = \sum a_{ij}$. Then the Laplacian matrix L is defined as $L = D - \mathcal{A}$. For connected graphs, L has one zero eigenvalue $\lambda_1(G)$, and denote the smallest non-zero eigenvalue as $\lambda_2(G)$.

2.2. System model

The networked multi-agent systems studied in this paper consist of N agents with general linear dynamics described by

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t), \ \ i = 1, 2, \ldots, N \tag{1}$$

where $x_i \in R^n$ denotes the state of agent i, $u_i \in R^m$ denotes the control input of agent i, $A_i \in R^{n\times n}$, and $B_i \in R^{n\times m}$ are constant matrices but unknown or partially known for control design due to various possible uncertainties and disturbances in the system.

Remark 1. As shown in (1), the individual agents may assume different system dynamics. Apparently, the multi-agent systems with the first-order integrator and the double integrator dynamics are special cases of (1). That is, if $A_i = 0$, $B_i = I$, the dynamics of system can be written as $\dot{x}_i(t) = u_i(t)$. If $A_i = [0, 1; 0, 0]$, $B_i = [0, 1]^T$, then the agent model becomes the double integrator $\ddot{x}_i = u_i$.

In this paper, a new event-triggered decentralized cooperative control is designed to make the networked multi-agent systems (1) reach consensus in the presence of model uncertainties and limited communication resources.

3. Decentralized cooperative control based on event triggered sampling

In this section, we present the proposed cooperative control design for networked multi-agent systems with model uncertainties. It is assumed that the communication graph is fixed, directed, and strongly connected. In the standard control design for networked agents, communication requirements may come from two aspects: first, the control design for agent i needs the transmitted state information from its neighbors in order to accomplish coordinated tasks (consensus in this paper); second, it also needs its own state measurements to be wirelessly transmitted to its control module which may be located at a distance location from the sensing/measurement module. The typical example includes the control of power networks. That is, the control of such types of networked multi-agent systems imposes a heavy demand on communication bandwidth. The proposed decentralized event-triggered cooperative control aims at relaxing the constraint on communication bandwidth as well as dealing with model uncertainties.

The basic control system architecture for agent i is shown in Fig. 1. It can be seen that agent i contains two fundamental modules: actuator and sensor. In the actuator module, design is done for both the controller and the local estimator. In the sensor module, design is done for the event generator. The event generator is used to determine when the true state value of agent i should be transmitted to the actuator modules of its own and its neighbors. Specifically, based on the measurement of the real state value $x_i(t)$, the event generator computes the error between $x_i(t)$ and the last transmitted state value. If the error exceeds the specified threshold, a triggering signal will be