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Event-triggered output feedback control for distributed networked systems

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ABSTRACT

This paper addresses the problem of output-feedback communication and control with event-triggered framework in the context of distributed networked control systems. The design problem of the event-triggered output-feedback control is proposed as a linear matrix inequality (LMI) feasibility problem. The scheme is developed for the distributed system where only partial states are available. In this scheme, a subsystem uses local observers and share its information to its neighbors only when the subsystem's local error exceeds a specified threshold. The developed method is illustrated by using a coupled cart example from the literature.

1. Introduction

The advancement of computational and communication technology, and accessibility with open standard interfaces have relaxed the hard-requirement of simple algorithms at sensing and actuation devices. In turn, this has encouraged to design intelligent and smart sensing and actuation devices for control applications. These distributed smart devices can be configured from controllers with appropriate sensing and control schemes to meet the distributed control objectives. In addition, the wireless technology has enabled to realize a type of distributed control systems embedded with wireless nodes, thus asking for resource efficient control and communication algorithms. Such systems require to limit the use of sensing, communicating and control to the time instances when the system needs attention. Recall that the classical sampled-data control is based on periodic sensing, control calculation, and actuation irrespective of whether there is change in sensing or new control calculation is needed [1]. Many simulation and experimental studies show that event-triggered control strategy is capable of reducing the number of control calculations with satisfactory closed-loop performance, see, e.g., [2–5], the stable control algorithms in distributed networked control paradigm are rare. In this regard, we have studied the problem of event based output-feedback control in the context of distributed networked systems.

Event-triggered control (ETC) is a control strategy that is especially suited for applications where communication resources are scarce [6]. By updating and communicating sensor and actuator data only when needed for stability or performance purposes, ETC is capable of reducing the amount of communications, while still retaining a satisfactory closed-loop performance. In an event-triggered scheme, a control task is triggered by the violation of the so-called "event condition", which is usually based on the actual state of the system. Because the event-triggered control enables the task periods to vary with the system state, it can generate longer task periods than the time-triggered control. Hence, it can improve the effective usage of system resources. Furthermore, it leads to a better overall system performance, i.e., a trade-off between the control performance (tracking, stabilization, and disturbance rejection), software performance (processor load), and other aspects (communication bus load and system cost [7]).

Furthermore, since sensor and actuator nodes can be physically distributed, centralized event-triggering mechanisms are often prohibitive and, therefore, we will propose a decentralized event-triggering mechanism. This event-triggering mechanism invokes transmission of the outputs in a node when the difference between the current values of the outputs in the node and their previously transmitted values becomes large compared to the current values and an additional threshold.

Through a parallel research development, in [10], a boiler-turbine coordinated multivariable control system is proposed

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based on improved sliding mode controller (ISMC). A new Lyapunov–Krasovskii functional is constructed in [11]. Based on the derived condition, the reliable H_∞ control problem is solved, and the system trajectory stays within a prescribed bound during a specified time interval. The work in [12] deals with the control theory design of a speed soft sensor for induction motor where the sensor is based on the physical model of the motor. Given that packet loss is inevitable in wireless sensor networks (WSNs) and networked control systems (NCSs), then if the node loses measurement data, then the estimation performance will degrade. In [13], a novel filter based on consensus algorithm for packet loss is designed in order to increase estimation accuracy and reliability.

1.1. Limitations in existing literature

A majority of the literature on event-triggered control is based on the state-feedback control methods [8]. In many control applications complete state measurement may not be available for feedback. In case full state is not available, the output-feedback controllers are required. The problem of event-triggered output-feedback control is still open problem.

To truly realize the benefits of event-triggering, one would need an event-triggered output feedback controller, in which triggering is done solely on the basis of observed sensor measurements, rather than state estimates [9].

This paper studies the problem of event-triggered output feedback control in the scenario of distributed networked control systems. Extension of existing state-feedback event-triggered communication and control methods to output-feedback scheme is not straightforward [8]. Another requirement of the event based scheme is to keep a minimum-time between two subsequent events [8] in addition to the stability of the overall scheme. The sensors, actuators and controller nodes in a networked system can be physically distributed, thus a distributed triggering is required instead of centralized scheme. This encourages to investigate the event-based methods for communication and control in the distributed networked framework.

1.2. Relevance of output feedback

One objective in the control theory is to achieve good control performance with resource efficient control scheme. State-feedback control scheme requires full states of the plant. State Feedback allows a rich and sophisticated approach to design a controller. For example

- One can position the poles anywhere at the desired location (but at cost of high control gains), in the left half plane.
- One can use design tools like LQR regulator directly.

The first advantage of full state feedback is that it gives complete control over placement of the closed loop eigenvalues. Second, if a Kalman filter or observer is required to construct the states for feedback, the separation theorem guarantees that the system closed loop eigenvalues consist of the filter eigenvalues together with the controller eigenvalues, each computed as if they were operating separately. Finally, the method can be extended to multi-variable control by use of LQG optimal control theory.

In fact state feedback allows us to position the closed loop poles anywhere we want by using any pole placement methods (Ackermann, etc); the problem is that we should have a very reliable process model because the state estimation calculated by the state observer will be based on that and the state feedback gains too, so if there is a mismatch between the real process and our model the poles can go unstable in worst case. The control algorithms based on the actual process response (output) are far more robust and reliable than those based on process models, unless we have a way to keep the model precisely updated.

We should recall that, there are some cases when we should use state feedback instead of output feedback. For example, when there are unstable modes that are uncontrollable from the output, but can be controlled by other states. Such cases are exceptional for output feedback control methods.

The remainder of the paper is organized as follows. Section 2 discusses the related literature. Problem formulation is presented in Section 3, which is followed in Section 4 by presenting the Event-Triggered Output Feedback Control and the main results. Section 5 gives simulation example to illustrate the results provided in Section 4. Section 6 provides some final conclusions and directions for the future work.

2. Related work

Little work has been done for event-triggered output feedback control. It is worth to mention that most of the prior work about the event-triggered and self-triggered control concentrates on the state-feedback controllers. So far, only few studies have been carried for the output-feedback controllers. An event-triggered implementation based on a dynamic output-feedback controller was shown in [14]. Recently, a dynamic output-feedback control system under a modified event-triggering mechanism was modeled as an impulsive system in [8]. Conditions on its stability and L_∞ gain performance were derived in terms of LMIs. A guaranteed minimum inter-event time was also presented.

In [15], an observer structure from [16] is combined with the self-triggered state-feedback controller proposed in [17] to form an output feedback configuration. Here, the event triggering is designed on the basis of the Lyapunov function between the sampling events. In [18], previous work of [15] is extended to the case of acyclically interconnected systems. Ref. [8] proposed an event-triggering mechanism that invokes execution of the control task when the difference between the measured output or the control input of the plant or controller, respectively, and its previously sampled value becomes large compared to its current value and an additional threshold. Ref. [19] examined output feedback control of wireless networked control systems where there are separate links between the sensor-to-controller and controller-to-actuator. The proposed triggering events only rely on local information so that the transmissions from the sensor and controller subsystems are not necessarily synchronized. An upper bound on the optimal cost attained by the closed-loop system is established for the weakly coupled case. Ref. [20] investigated both reduced and full order observers for linear system with event-triggered sensing scheme. Global uniform ultimate bounded stability of the closed-loop systems is established with the event-triggered scheme.

In [21], an observer based output-feedback control scheme is presented in event-triggered framework. This scheme uses a state observer in the event generator and shows that the communication frequency is bounded. This work can be extended by including a disturbance estimator to the observer that will enable the event generator and the control input generator to have an estimate of the disturbance. The additional information about system disturbances can be used to further increase the inter-sampling time of event triggering. Other event-triggered methods based on output information instead of full state information are discussed in [8,22,23], and [24]. The Luenberger state observer of the event generator in [21] is assumed to continuously receive the measured output. In [8], the measured output is directly used to update the control signal at event times and there is no observer as compared to [21]. While in [22,23] and [24], Event based Kalman filter is used