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Review

Decentralized control: Status and outlook

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ABSTRACT

This paper reviews state of the art in the area of decentralized networked control systems with an emphasis on event-triggered approach. The models or agents with the dynamics of linear continuous-time time-invariant state-space systems are considered. They serve for the framework for network phenomena within two basic structures. The I/O-oriented systems as well as the interaction-oriented systems with disjoint subsystems are distinguished. The focus is laid on the presentation of recent decentralized control design and co-design methods which offer effective tools to overcome specific difficulties caused mainly by network imperfections. Such side-effects include communication constraints, variable sampling, time-varying transmission delays, packet dropouts, and quantizations. Decentralized time-triggered methods are briefly discussed. The review is deals mainly with decentralized event-triggered methods. Particularly, the stabilizing controller–observer event-based controller design as well as the decentralized state controller co-design are presented within the I/O-oriented structures of large scale complex systems. The sampling instants depend in this case only on a local information offered by the local feedback loops. Minimum sampling time conditions are discussed. Special attention is focused on interaction-oriented system architecture. Model-based approach combined with event-based state feedback controller design is presented, where the event thresholds are fully decentralized. Finally, several selected open decentralized control problems are briefly offered as recent research challenges.

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1. Introduction

Majority of real-world complex systems is characterized by a great number of measured inputs and outputs. Such systems are usually composed of several local control stations, where each station is responsible only for the working operation of a part of the overall system. The overall control system goal is solved or approximately solved by local control system goals. This approach is referred as decentralization. The control designer determines first the structure of subsystems and their interconnections. Then,

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local systems inputs and outputs are selected. Finally, local controllers are designed so that the overall system stability and performance are satisfied. This general procedure is called decentralized control design. Decentralized control has been a control approach of a choice for large scale complex systems for over four decades. Complex systems arise in every area of concurrent science. It corresponds with an array of different system models. It is rather impossible to look for a general theory covering all their essential features. Even if such theory is feasible, it is not realistic to suppose that it would be developed in the near future. Therefore, the notion of large scale complex system refers at present usually to the necessity to split the given unmanageable (i.e. extremely difficult or impossible) analysis and synthesis problems into effectively manageable subproblems so that their solutions solve the original overall problem. Complex dynamic systems possess a variety of different properties, but several essential common features has been extracted by a long-term experience. Four particular features deserve attention in large scale complex systems such as *large size (dimensionality)* of the system equations, different types of *uncertainties* of models, *information structure constraints*, and *delays*.

The features of complex systems offer diverse challenges how to treat with them. A natural way how to deal with a high dimensionality is to decompose the system into subsystems and their interconnections. Given such a decomposition structure, the control design is performed locally with a subsequent inclusion of the interconnection effect. There are two main ways how to decompose a given system. Physical decomposition tears the system according to their physical properties. However, there are many systems where it is difficult to find appropriate weak couplings. To overcome such a problem, numerical decomposition of the system can be used as an effective tool to treat the dimensionality problem. There are available four well-known system decomposition structures within the notion of numerical decomposition: disjoint decomposition (BD), overlapping decomposition, border block diagonal decomposition (BBD), and epsilon decomposition. A BD structure is the most widely used decomposition resulting in disjoint subsystems and interconnections. Overlapping decomposition is an appropriate tool when some parts of subsystems have a common intersection. A BBD structure refers to an appropriate ordering. It corresponds with diagonal blocks and a two-sided border. An epsilon decomposition employs an appropriate permutation of the elements of the system matrix so that the off-diagonal elements are sufficiently small numbers. Then the stability of the overall system can be reached by the stability of only diagonal system.

Control of large scale complex systems require efficient design methods and algorithms whose implementation necessitates minimal information communication among local systems. It corresponds with the requirement on both wired or wireless decentralized control laws covering a wide range of information structure constraints. A powerful computational tool satisfying this requirement is a convex optimization in the context of Linear Matrix Inequalities (LMIs).

Rapid growth of communication networks inspires an intensive move of system theory to communication networks in the last years. The motivating reasons arise in very different real-world systems such as for instance transportation network, power grids, water distribution networks, large manufacturing systems, telephone networks, internet, global financial networks, ecological networks, mobile autonomous robots, or embedded control systems. Wireless control networks offer several significant advantages and also some drawbacks compared with its wired counterpart. The advantages include low cost operation, flexibility of installation, easy re-configuration, natural reliability, robustness to failures, and adaptation capability. Drawbacks cover time delays, packet loss, finite capacity, problems with data flows, i.e. quality of service, energy saving, which leads to an event based control, and security.

The notion of Networked Control System (NCS) or more precisely digitally networked dynamic system covers three main groups of activities. *Control over networks* deals with the design of feedback strategies adapted to control systems in which control data is exchanged through unreliable communication links. Sensors, actuators, and controllers are remotely positioned and communicate with each other through a communication network. *Control of networks* is mainly concerned with providing a certain level of performance to a network data flow while *multi-agent systems* deal with the study of how network architecture and interactions between network components influence global control goals.

Sampling belongs to the most important issues in NCSs. There are in principle two ways of sampling. Synchronous sampling is inspired by the theory of sampled-data feedback systems. Asynchronous sampling reflects the idea of minimal communication in the loop. The sampling instants are determined by events. An event-triggered condition is usually determined by a preselected threshold. Events are generated by an event generator. It is a mechanism located in the feedback loop between the sensor and the controller which selects the instants of a newly sampled state.

The design of the event-triggered feedback loop includes two different mechanisms. The problem of control design and the problem of control co-design are considered separately. Event-triggered control design means that the controller is designed without considering the event-triggered nature of the feedback, and then subsequently the event-triggered mechanism is designed so that the resulting networked control system is stable and satisfies the requirements on its performance. This is called also emulation-based approach. Event-triggered control co-design means that both controller and event-triggering mechanism are designed simultaneously.

The objective of the paper is to survey recent new methods offering a splitting potential for broadening the scope of decentralized control methods mainly in networked control systems. Both I/O-oriented systems and interaction-oriented systems are based on a disjoint decomposition are included. The paper is supplied with numerous references covering fundamentals of decentralized control as well as control over networks. The presentation is primarily focused on decentralized event-triggering schemes as one of the most progressive future area in decentralized control. In general, there still remains a gap between decentralized control and control over networks.

1.1. Outline of the paper

The paper reviews mainly several basic issues offered by decentralized control of large scale complex systems with an emphasis on event-triggered communication in the feedback loop.

The paper is organized as follows. First, the basic features of decentralized control of wired systems are surveyed. Then, the decentralized time-triggered control is briefly introduced. Finally, event-triggered issues are presented. Centralized event-triggered state control scheme for disturbance attenuation introduce the basic idea of event-triggered control approach is reviewed. Decentralized event-triggered control of networked control systems is reviewed for essential structures of the I/O-oriented systems as well as for interconnected systems with disjoint subsystems and interconnections. The timing problem for multi-channel systems is included explicitly in the design of the decentralized observer-based stabilizing controller, while the co-design is described as the $\mathcal{L}_2$ state feedback controller design together with event-triggering communication scheme. The decentralized event-triggering control design follows within the framework of model-based approach for interconnected systems. Linear continuous-time