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Distributed Control in Networked Systems

The September issue, 2009, of the journal **Control Engineering and Applied Informatics (CEAI)** is devoted to the special topic *Distributed Control in Networked Systems.*

Networked systems are changing the world: world is increasingly interconnected and increasingly monitored. Infrastructure systems (electric power, water resources, gas and fuel distribution, transportation, telecommunication, etc.), advanced automotive systems, process control, energy conservation and environmental control and other networked systems are often composed of multiple subsystems defined by complex dynamics and mutual influences, with actuators and sensors linked through communication capabilities and characterized by presence of uncertainty due to changing topology.

The main features of networked structured systems come from their low cost, their flexibility and easy dynamical reconfiguration, their natural reliability and robustness to failure. For such networked systems it is essential to understand how the rules describing the local interactions and the network structure influence the properties of the global emerging system. In designing complex networked systems, control engineers have to solve many new problems arising from their complexity. The high flexibility of communication networks allowed the existence of today's large industrial control, collaborative, and embedded control systems. The web technology on the Internet today appears as a natural, inexpensive way to ensure the communication link in remotely controlled systems, even with the negative impact caused by delays, data loss, data quantization, asynchronous sampling connected to communication networks.

In this context, the design of networked control systems implies a deep knowledge of automatic control, computer science, and communication networks and the skill to capture the interplay among these disciplines. For these complex networked control systems, we work with a C_3 paradigm (Computer, Communication, and Control) in an emerging way.

Most control theory developed so far for this type of systems, traditionally are characterized by centralized design procedures. Hence, even though the local controllers are eventually supposed to operate separately, they are designed in a centralized fashion based on a full global model of the system. This paradigm has conceptual advantages, but also inherent limitations in terms of complexity, scalability issues and communication bandwidth limitations.

The distributed optimization and mathematical decomposition techniques applied to networked control systems could be a good solution to solve many problems. For the multilayered and hierarchical architecture we must develop control theoretic tools for analyzing protocol dynamics in order to guarantee stable and efficient overall behavior. For large networked control systems it is important to evaluate the quality of services provided by the distributed computing system in order to characterize the robustness of controllers.

The revolutionary computing transformation of the 20th century allows us to deal with these problems and to cope with the complexity of the control task using the new emerging paradigm of distributed control. In such a set-up, single units, or local agents, must synthesize local controllers by solving small control subproblems and then they must negotiate their outcomes and requirements in order to achieve the global goal. The main advantages of this new paradigm consists in flexibility, robustness and reduced complexity.

The co-design of control, computing and communication for complex networked control systems requires a new vision on complexity and new concepts and tools that will allow the designers to analyze and simulate how timing affects control performances and to determine the optimal structure of the hybrid distributed system with computing and communication constraints. New methods based on multi-agent systems could be used effectively for designing, modeling, simulating, and analyzing complex structures.

Control structures utilizing agent technology incorporate new forms of coordination and anticipation within behaviors, preceding the action of intelligent agents integrated at different levels of complex systems. By the integration of cognitive processes into complex distributed and hierarchical systems we arrive to a new paradigm, the "C_4 paradigm" which means Computing, Communication, and Cognition for Control. New tools and concepts must be developed to analyze and design the new generation of autonomous hybrid systems based on the C_4 paradigm. We need to understand how the local laws governing the behaviors of the individual intelligent agents influence the global behavior of the networked control system, and how the level of intelligence of the individual agents contributes to increase the autonomy of the entire complex system.

The complexity of the networked control systems requires a theory of networked systems, integrating advanced mathematical tools with heuristics and linguistic representations. New techniques for representation and heterogeneous knowledge processing within large and complex networked systems must be developed.

Hybrid techniques which combine analytical and linguistic tools into associative forms could represent the future instruments to handle complexity.

These advantages calls for the development of systematic distributed control methods for large-scale networked systems. This special issue collects contributions on advanced methods and applications in this area.

A first group of two papers are methodological and contain distributed algorithms to solve centralized model predictive control problems for dynamically coupled linear systems based on local iterative updates, instead of global information exchange.

Dang Doan, Tamas Keviczky, Ion Necoara, Moritz Diehl and Bart De Schutter, in *A distributed version of Han's method for DMPC using local communications only,* proposed a distributed model predictive control scheme, based on a parallel algorithm to solve a class of separable convex problems developed by Han and Lou, that is able to handle linear time-invariant dynamics with linear dynamical couplings, and the presence of coupled linear constraints. The main advantage of this new method consists in the fact that each local controller only needs to communicate with its direct neighbors to exchange predictions, which are iteratively updated by the local controllers. Results on convergence to the global optimum, recursive feasibility, and stability are established for the new algorithm.

Ion Necoara and Ioan Dumitrache, in *An accelerated optimization algorithm for distributed model predictive control,* present a dual-based decomposition method to solve separable convex problems. The paper provides convergence results and efficiency estimates for the new distributed algorithm which improves with one order of magnitude the bounds on the number of iterations of the classical dual subgradient algorithm. The new method is suitable for application to distributed model predictive control for systems with coupled dynamics or constraints but decoupled cost since it is highly parallelizable, each subsystem uses local information and the coordination between the local MPC controllers is performed via the Lagrange multipliers corresponding to the couplings.

The next group of three papers is focused on distributed control applications in transportation systems, energy an telecommunication networks.

Alina Tarau, Bart De Schutter and Hans Hellendoorn, in *Centralized, decentralized, and distributed model predictive control for route choice in automated baggage handling systems*, consider and compare centralized, decentralized, and distributed model predictive control algorithms for routing individual bags in a baggage handling system of an airport. Although the best performance of the system is obtained when using centralized MPC, such a control scheme becomes intractable when the number of junctions in the transportation network is large due to high computational effort. However, simulations show that decentralized or distributed model predictive control offer a balanced trade-off between computation time and performance.

Guillaume Sandou, in *Metaheuristic strategy for the hierarchical predictive control of large scale energy networks,* presents an hierarchical predictive control strategy for controlling energy networks. Models of such systems are highly non-linear due to the energy propagation modeling and moreover, some of the control variables are binary ones which makes the corresponding on-line optimization problem extremely difficult to solve. Therefore a hierarchical scheme is developed, where in the first stage, a global predictive control law is defined to compute the global amount of energy to be produced by each production site and then in the second stage, this energy is dispatched between the production units of each site by a local predictive law. Due to the complexity of the corresponding optimization problem, the global law is computed by a Particle Swarm Optimization method whereas the local law is computed by ant colony and genetic algorithm.

Paschalis Tsiaflakis and Marc Moonen, in *Distributed spectrum coordination for DSL broadband access networks,* provide a survey of recent results on distributed spectrum coordination techniques for broadband access networks. Digital subscriber line (DSL) technology is the dominating broadband internet access technology. The main issue for data rate performance improvement of current DSL broadband access is crosstalk interference. Distributed spectrum coordination is considered as a key technology to tackle this crosstalk problem and consists in combining local procedures that can react fast on the channel environment with a centralized control that steers towards a better global network behavior. The authors show how state-of-the-art techniques from mathematical programming can be used to design very efficient distributed spectrum coordination algorithms, that scale with the amount of message passing from a selfish local behavior to a social network behavior.

Finally, Jose Garcia and Jairo Espinosa, in *Moving Horizon Estimators for Large-Scale Systems,* present a review on state estimation schemes applied to large-scale systems. The attention is focused on Moving Horizon Estimation schemes due to the addressing of the estimation problem in an optimal way, and its inherent capability to handle the process constraints. Moreover, compared to other optimal estimation schemes such as those based on Kalman filters, this approach allows to incorporate a cost function. The authors describe the main existing results on large-scale state estimation schemes, outlining their merits and limitations. and attention is also given on the challenge to design distributed Moving Horizon Estimation schemes that are scalable, robust and flexible.

Despite the fact that the compilation of papers presented here can only be a restricted sample of the very diverse control theoretic and optimization research currently taking place at the interface between theory of networked systems and the underlying distributed control methods, the guest editors hope that it will contribute in stimulating further work in this exciting multidisciplinary area, of importance for our future.

We thank all our contributors.

Guest Editors
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