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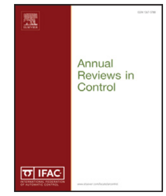

Full Length Article

Predictive control, embedded cyberphysical systems and systems of systems – A perspective☆

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ABSTRACT

Today's world is changing rapidly due to advancements in information technology, computation and communication. Actuation, communication, sensing, and control are becoming ubiquitous. These technological advancements have led to the widespread availability of information and the possibility to connect systems in unforeseen manner. There is a strong desire for smart(er) cities, buildings, devices, factories, health monitoring – a smarter world. However, designing such a smarter world requires addressing also many challenges resulting from the emerging complex interactions and interoperation of systems. How is it possible to handle the increasing complexity during design and maintenance of such systems? How can one guarantee safety and performance of systems operating over networks which are subject to erroneous communication, delays, and failures of sensors and actuators? Is it possible to design control systems which allow for easy reconfiguration or even self-organization, for example by letting subsystems join and leave larger systems via plug and play strategies? Can one guarantee privacy of the controlled subsystems while exchanging information, which is necessary for maintaining overall system performance? We believe that predictive control is a well suited control approach to tackle some of these challenges due to its flexibility with respect to the formulation of the problem and the possibility to directly take constraints, preview information, as well as models of different complexity of the physical world into account. In this perspective we limit our attention to three areas we believe predictive control methods can provide a basis to tackle the appearing challenges: the efficient and easy implementation of predictive control on omnipresent embedded computation hardware, the question of resource and network aware control, as well as control on the network level of systems of systems. We briefly summarize results from these fields and outline some ideas on challenges, which arise.

1. Introduction

Advances in information technology and computation make communication, actuation, sensing, and control ubiquitous. Formerly hard-wired sensors, actuators, and control units are increasingly being connected via flexible, often wireless, communication channels. The deployment over wireless communication allows for significant decrease of installation costs and a higher degree of flexibility (Ikram & Thornhill, 2010). Furthermore, with wireless communication, data and information, which could not be obtained in high quantity or quality before, are becoming available for control, analysis and monitoring. Examples are: real-time traffic data harvested from mobile phones (Calabrese, Colonna, Lovisolo, Parata, & Ratti, 2011), which can be used for traffic control; or the use of ambient sensors in buildings (Bradshaw, 2006; Kitner-Meyer & Conant, 2005) to increase comfort such as air quality and ventilation. Formerly "dumb" devices become "smart" due to the possibility to deploy cheaply embedded control, monitoring, and data processing units (Hristu-Varsakelis & Levine, 2006; Stankovic, 2014).

The widespread availability of data and the possibility to easily exchange information between subsystems offers many options, leading to smart(er) cities, buildings, devices, factories, health monitoring, grids – a smarter world. However, there are also many challenges which need to be tackled (Graham, Baliga, & Kumar, 2009; Stankovic, 2014), especially from the design, as well as from the control, management and maintenance sides: How can one tackle the increasing complexity, (Graham et al., 2009)? Can one guarantee safety and performance of such networked control

☆ This paper is an extended version of Lucia, Kögel, Zometa, Quevedo, and Findeisen (2015b), including a more comprehensive overview of the different fields as well as simulation examples for some of the discussed strategies.

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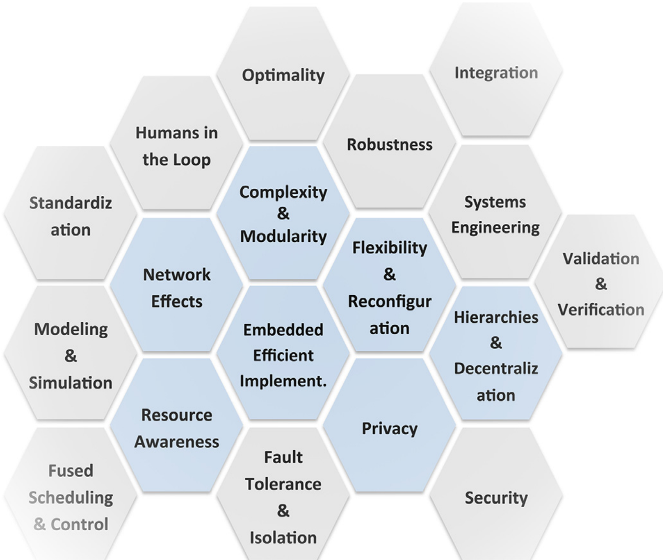

Fig. 1. Important issues and challenges. Highlighted in blue are issues touched in the frame of this work. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

systems subject to erroneous communication, delays, and failures of sensors and actuators? Is it possible to design control systems that allow easy reconfiguration or even self configuration/organization to achieve satisfactory performance and safe operations. How can one guarantee privacy and safe operation of the controlled subsystems while exchanging information? How can one account for the presence of humans in control loops and how can one increase the trust of humans into the controlled system?

Fig. 1 represents some of the challenges that arise when studying such emerging interconnected systems that exchange information via communication networks.

Related research has been performed under various names, disciplines and perspectives: networked control systems (Gupta & Chow, 2010; Lunze, 2013), internet of things, cyber-physical systems (Johansson, Pappas, Tabuada, & Tomlin, 2014a), wireless sensor networks, systems of systems, ambient intelligence (Encarnacao, 2008; Remagnino, Foresti, & Ellis, 2008), to name just a few. Note that there are settled differences between these definitions, cf. Deka, Andrews, Bryans, Henshaw, and Fitzgerald (2015) and Thompson, Paulen, Reniers, Sontag, and Engell (2015), which for space reasons we do not elaborate on.

We believe that predictive control provides a mean to tackle some of the appearing challenges, as it allows to directly take constraints, preview information, as well as models of different complexity into account. Furthermore, predictive control offers the flexibility to tackle various problem formulations and performance objectives.

In this paper we provide a limited perspective towards predictive control of interconnected systems of systems and cyberphysical systems, focusing on results related to our own expertise and on three aspects we believe predictive control can have significant impact. They span from the efficient and easy implementation on the embedded hardware layer, the control under limited resources and in the presence of network effects, up to the control on the network level, presenting a contract-based control approach which allows for a structured, yet flexible hierarchical design.

Due to the vast and steadily increasing amount of related works, we apologize for not being able to provide a comprehensive review.

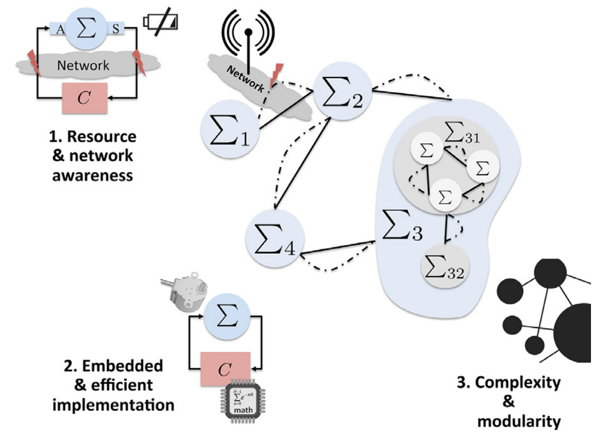

Fig. 2. Physically interconnected system and the challenges touched on in the present work.

1.1. Physically interconnected networked systems

We focus on systems composed of (possibly many) physically interacting systems, which might be connected via the flow of energy, materials, products, forces, etc. Each system might in itself consist of a series of subsystems in the form of a hierarchy, see Fig. 2 (right top). Each system, denoted in the following by Σ, might or might not be controlled. Note that controllers themselves can be regarded as systems. The systems might exchange information via communication channels, denoted by the dashed lines in Fig. 2. This communication can be corrupted, e.g., due to communication loss, resource limitations, delays, or malicious intrusion. Examples for such systems are multifold: power networks, transportation systems, production plants, logistic networks, water distribution networks, communication networks and buildings, to name just a few. One specific example is the control of an air conditioning system of a building: multiple rooms are physically interconnected via their heat exchange, air streams, and persons moving between them. Each room might have its own control unit, e.g., for temperature or air quality control. These units are typically arranged in a hierarchical manner, combining multiple rooms into floors, complete buildings, or series of buildings. Another example is a smart power grid. The power network consists of multiple generators and users, which might be arranged in hierarchies such as regions or local networks. Each of the users, houses, generators, storage units, might have its own control unit. The subsystems might or might not exchange information.

Many challenges and opportunities with respect to the control and the design of such interconnected systems arise. Examples are: the treatment of network effects such as delays and information loss; the analysis and the design of optimal network topologies and structures; fault-tolerant and fault-aware control, which becomes especially important due to the often large number of interacting systems; the issues of privacy and security; the challenge of humans in the loop; output-feedback, validation and verification of the subsystems and the overall network. For a detailed discussion of the appearing challenges we refer to Deka et al. (2015), Thompson et al. (2015), Gupta and Chow (2010) and Lunze (2013).

We focus on three specific issues (represented in Fig. 2) where we believe predictive control can have an impact: the handling of resource and network limitations is considered in Section 2. As computational and memory-limited embedded platforms form the foundation of networked systems, we focus in Section 3 on the efficient and easy implementation of predictive control on such systems. Section 4 considers hierarchical and distributed predictive control approaches for networked systems.