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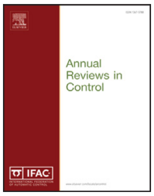

Emerging research topics in control for smart infrastructures☆

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ABSTRACT

As we move deeper into the 21st century, critical infrastructures related to energy and transportation are becoming smart–monitor themselves, communicate, and most importantly self-govern. Various drivers have enabled this transition, including sustainability concerns, scarcity in resources, economic considerations, and rapid growth in enabling technologies of sensor networks, and computational and communication systems. Two notable examples of such infrastructures are smart grids and smart cities. The idea behind a Smart grid is the creation of a dynamic, cyber-physical infrastructure that meets the challenges of intermittency and distributed availability of renewables, and realizes reduced operational costs and emissions, via a flexible, intelligent, and networked grid that plans, controls, and balances supply and demand over an entire region. The concept of a Smart City is gaining popular attention driven by goals of sustainability and efficiency, the needs of enhancing quality of life and affordability, growing urbanization of the world's population, and the explosion of technological advances in communication and computation. While systems and control problems abound in any complex dynamic system, two characteristics that are specific to critical infrastructures are the need to deliver reliable service and the ability to accomplish this goal amidst constrained resources. These in turn lead to new research topics in systems and control including empowered consumers, transactive control, and resilience. The focus of this paper is on these emerging topics. Their role in smart infrastructures, the opportunities they provide, and the research challenges that they bring in are all discussed. Specific illustrations of recent successes are presented that are based on coordinated adjustment of generation and consumption using concepts of multi-agents and multi-timescales in smart grids and socio-technical models of empowered drivers in smart cities.

1. Introduction

The field of control theory and technology pertains to the governance of complex dynamic systems. Enabled in large measures by the drive towards automation, control theory has evolved with the goals of command following and disturbance rejection through on-line measurements of the underlying system. Such information-based decision making has, over the past decades, led to tremendous advances in a wide variety of engineering systems including aerospace, automotive, robotics, process control, and medical devices. The overarching concept that has pervaded the analysis and synthesis of control systems in these applications is decision making using information gathered by these systems, both from physics-based models and on-line measurements. With theoretical advances taking place in control systems, and accompanying advances in sensing and actuation technologies, it can be argued that we have obtained a good understanding, at a systems level, of basic properties of stability, robustness, and reliability. With recent theoretical advances in hybrid, switched, and event-triggered systems, and accompanying advances in real-time and embedded systems, basic properties of networked control systems are well understood as well. With some of the above underpinnings, it can be argued that attention is shifting towards the design of large and smart infrastructures and the fundamental principles of control therein.

Infrastructures are the basic physical and organizational structures and facilities (e.g., buildings, roads, and power supplies) needed for the operation of a society or enterprise. Infrastructures have been around as long as urban centers, supporting a society's needs for its planning, operation, and safety. As we move deeper into the 21st century, these infrastructures are becoming smart, through sensors of various kinds that provide information about the infrastructure as well as decision-makers that effect a change in the infrastructure, and help provide a service of value to the end-user that's infrastructure wide. This service needs to be provided reliably, economically, and in a resilient manner. Examples

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are the delivery of reliable and affordable power, water at a high quality, or transportation at an affordable cost.

Information-based decision-making is a necessary ingredient in several complex systems. As systems become more intricate with increasingly stringent performance specifications, a possible solution is to use sensors and actuators to gather real-time information about the system behavior and its management. As systems increase in scope and size, incorporation and integration of a communication network is mandatory. Associated with this integration is the need for any information gathering or decision-making to occur using coordinated, cooperative, and distributed yet optimal control. And concomitantly present are myriad uncertainties in modeling the system behavior, a host of environmental disturbances, time-variations, and nonlinearities. Given that any smart infrastructure is first and foremost a large and complex system, all of the aforementioned features including uncertainties, nonlinearities, and other disturbances, and the need for pervasive sensors and actuators as well as coordinated, cooperative, and distributed control optimization are also common to and essential for the design of a smart infrastructure. There are, however, two distinguishing aspects to a smart infrastructure that are noteworthy. The first is that the central goal of an infrastructure is to deliver a critical service, such as energy, food, water, healthcare, or transportation. The criticality implies that in addition to meeting the desired performance under nominal times, it is extremely important to deliver essential service in the event of emergencies. This in turn implies that a smart infrastructure should be designed so as to accommodate both normal and emergency situations. The second aspect of an infrastructure is the availability of constrained resources. Whether energy, water, transportation or healthcare, the available resources are limited. As a result, optimal use of resources even as operating constraints increase is mandatory. Given that notion of a *smart* system is one that accomplishes more by using less (Carvallo & Cooper, 2011), a smart infrastructure therefore needs to accomplish its objectives even with limited resources and increasing number of constraints.

The thesis of this paper is that the above two features of a smart infrastructure lead to the following three emerging research topics in control: Empowered Consumers, Transactive Control, and Resilient Control. The first topic addresses the fact that resources are constrained and therefore active decision making in managing consumption. The second addresses the opportunity provided by the first topic which enables several *actuators* and provides an architecture for coordinating their actions and enabling global optimization using local outcomes related to financial transactions. The third is a direct consequence of the need to address the two objectives of a smart infrastructure, of satisfactory behavior in the nominal case and at the same time resilient performance in the face of emergencies.

The first of these emerging topics concerns the consumer, to whom the underlying infrastructure has to provide a service. In contrast to the traditional role of the consumer, which is typically a passive one, the role of the consumer in a smart infrastructure is more central, and notably an active one. Given that the major problem in a smart infrastructure is one of managing resources and making them available at the right location and at the right time, there is a distinct paradigm shift taking place in this topic. The end-user is empowered with making decisions, based on frequent, real-time, and distributed information available about the overall infrastructure. The questions that arise related to such a decision making as well as the collection of pertinent information and its processing, the requisite tools, methodologies, and challenges are all problems that fall within the broad rubric of systems and control.

If one can view the first topic of empowered consumers as an actuator, Transactive Control, the second emerging research topic in a smart infrastructure, can be viewed as a control input to this actuator. Given that in a smart infrastructure, the consumer plays an active role and can carry out decisions that impact the infrastructure dynamics, the question that arises is about the actual signal that the consumer responds to. Defined broadly as a mechanism through which system and component-level decisions are made through economic transactions negotiated between the components of the system (Annaswamy & Nudell, 2015), Transactive Control is now being explored in depth in the context of a smart grid infrastructure, and is beginning to be explored in the context of smart cities as well (Sengupta, Amin, Annaswamy, Moura, & Bulusu, 2015). Given that transactive control provides an opportunity for designing a closed-loop, the specific feedback mechanism of the underlying transactions needs to be suitably designed, and accommodate both the behavioral model of the consumers and economic objectives of the infrastructure manager. A plethora of challenges remains to be addressed, as a result, pertaining to cooperation and coordination of multiple consumers and organizations, constraints on all entities that are involved in the underlying transactions, and dynamic modeling and accommodation of multiple time-scales associated with the problem.

The third topic is resilience of the infrastructure. A distinguishing feature of any infrastructure is not only its ability to deliver a service, but to deliver it in a reliable and resilient manner. The former can be argued as a robustness property under nominal disturbances. Resilience refers the capacity of an infrastructure to recover from setbacks, adapt well to change, and continue to operate in the face of adversity (Ovens, 2015), that is, its ability to withstand severe disturbances, both random failures and targeted adversarial attacks, and still continue to function. In the presence of empowered users, who can directly impact the control actions within the system, it is critical to engineer resilience into the infrastructure. However, the tight coupling of the continuous and the discrete dynamics in a smart infrastructure make the design and analysis of a resilient controller particularly challenging. An obvious challenge arises from the scale of the infrastructure; while each individual system may have a small state space, the coupling between these systems leads to a very large number of interacting states. Additionally, the faults and attacks in one part of the infrastructure can propagate to adversely affect other systems. A more subtle challenge is balancing the diverse requirements and constraints of the composite system. The optimal control strategy for an individual system may not align with the global requirements leading to compromises.

As alluded to above, there are many examples of critical infrastructures. In this paper we focus on two of them, the first of which is a Smart Grid, an end-to-end cyber-enabled electric power system, from fuel source, to generation, transmission, distribution, and end use, that has the potential to (i) enable integration of intermittent renewable energy sources and help decarbonize power systems, (ii) allow reliable and secure two-way power and information flows, (iii) enable energy efficiency, effective demand management, and customer choice, and (iv) provide self-healing and resiliency not only from physical anomalies but also cyber-attacks. The need for such a change is precipitated by the need for reducing greenhouse gas emissions, staggering growth in energy demand and aging electricity infrastructure.

One of the most promising concepts that is being explored to realize the smart grid vision is Demand Response (DR), a concept which allows demand to be adjustable (Hansen, Knudsen, & Annaswamy, 2016; Kim, Yin, & Kiliccote, 2013; Olsen, Goli, Faulkner, & McKane, 2012), to cope with variations in RERs. A fairly vast literature exists on Demand Response, its potential, and associated challenges and opportunities (Biegel et al., 2013; Hansen, Knudsen, & Annaswamy, 2014; Petersen, Hansen, Bendtsen, Edlund, & Stoustrup, 2013). The concept of introducing flexible consumption in

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