



Complex Networked Control Systems

INTRODUCTION TO THE SPECIAL SECTION

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We live and operate in a networked world. We drive to work on a network of roads and fly across a web of cities connected by commercial airlines. We communicate using an increasingly elaborate set of devices from phones, to computers, to PDAs, all of which are connected through the Internet. We shop at stores and dine at restaurants connected through food and goods delivery networks, and when we reach for a light switch, we trigger a reaction across the power-delivery network. Our governments are networked as are our financial and societal infrastructures.

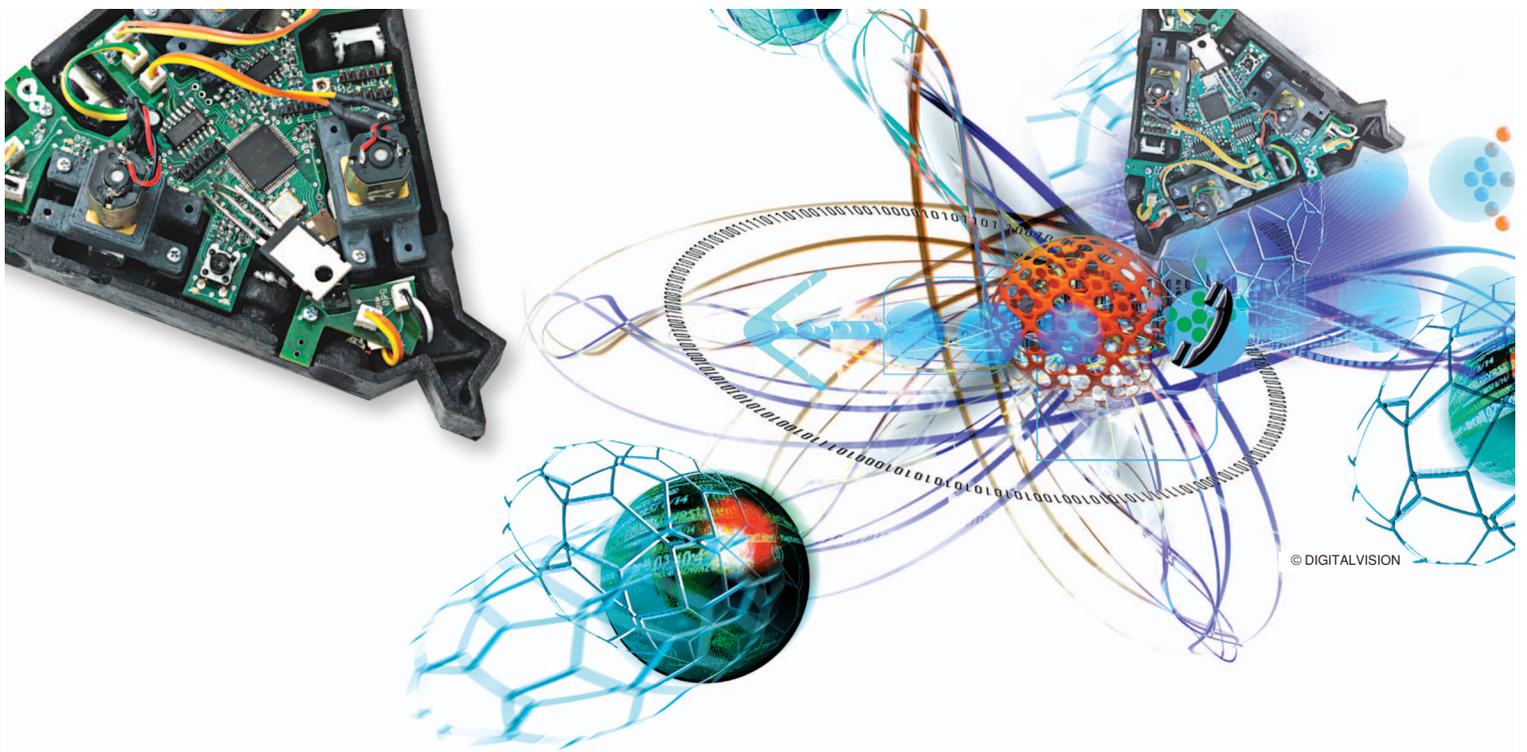
Networks provide a powerful metaphor for describing system behavior from disciplines as diverse as biology, computer science, physics, social science, and engineering. In these fields, complex networks are being studied for the purpose of gaining insight into how properties such as community structure, small-world effects, phase transition, and giant components emerge [1]–[4].

In modern cars and airplanes, as well as in networked homes and office buildings, modern control systems are increasingly incorporating communication networks in feedback loops [5]. Control engineers are thus forced to expand their application domain by incorporating the communication infrastructure into their designs, and by considering the impact of link capacity, latency, and packet loss on the performance of feedback control systems [5], [6]. Significant attention is focused on devising local interaction mechanisms to reproduce the coordinated group behavior observed in biological systems [5], [6], motivated by studies in ecology and theoretical biology that describe the aggregation of animal groups into cohesive groups without centralized coordination. For such control designs to be efficient, we need to better understand how to control physical systems across networks, and to predict whether the network's structure might give rise to specific behaviors [7], [8].

The need for new paradigms for control design is particularly evident in large-scale interconnected multi-agent systems. For such systems, signals need to flow quickly and efficiently, but interconnected components may not be able to store and manipulate the complete state of the system. Although complexity barriers render the design of controllers for high-dimensional systems impractical, the ability to reason about global network properties based on locally available information enables the design of decentralized control laws.

Despite the similarities between the application domains of network theory and control engineering, the necessary links for the transfer of ideas and tools between the two fields have yet to be fully established. This situation is largely due to fundamental differences between the methodologies and goals of the two communities. While control engineers build feedback systems to satisfy closed-loop design specifications, network theorists seek models to explain the observed behavior of existing networks [1]–[3]. As shown in Figure 1, the starting points and objectives of a complex-network theoretician and a control engineer are reversed, even though they face the same problems in trying to understand their target systems. Despite the use of different analysis tools, network properties such as connectivity, efficiency, and robustness are critical to both control design and complex-network modeling.

Network theory provides tools that characterize the growth and topology of distributed networks [1]–[4], [8] in relation to their navigability, congestion, clustering, and robustness to failure [7]. For example, in systems such as social networks and the World Wide Web, not only do short paths exist between every pair of nodes, but such paths can be found under certain conditions using only local information [6], [7], [9]. The presence of such paths implies that distributed sensing and control might be possible over some networks.



By considering the network as a communication service, we identify three properties that critically impact the flow of information and control signals in a networked control system:

- » connectedness, which expresses the existence of a path between the information transmitter and the information receiver
- » navigability, quantified by the difficulty of finding a connecting path; typically, this difficulty depends on whether the path is predetermined, or whether it is discovered in an ad hoc fashion
- » efficiency, as represented by the latency (that is, delay) of each utilized path. This latency, usually a function of the number of hops and the individual link latencies, must be sufficient to guarantee desired end-to-end communication latencies.

All three properties affect the robustness of a network with respect to node or link failures as well as the reliability of network protocols with respect to corruption. In addition, all three properties are critical to the performance of sensor networks and networked control systems. By properly accounting for the structure of networks in the feedback control path of a networked control system, we can detect how topological network properties affect control performance [10]–[14].

The goal of this special issue is to highlight existing conceptual links, while establishing new ones, between complex networks as studied within social science, biology, physics, and mathematics on the one hand, and dynamical models of interconnected systems studied in control theory, on the other. In seeking to understand networks and their effect on control and sensing applications, the following questions are of interest:

- » What mechanisms give rise to networks, and how can such mechanisms be programmed to give rise to a particular network structure?

- » How might the emerging network structure be characterized?
- » How do dynamical processes such as sensing, communication, and control take place over networks?
- » What is the relationship between the structure of a network and the dynamics that take place over the network?

These and similar questions motivate the special issue you hold in your hands.

SPECIAL SECTION CONTENTS

This special issue focuses on the study of network architectures and their formation as well as on the description of dynamical processes that take place over networks. The article by Barabasi reviews concepts from social and technological networks and discusses mechanisms that help

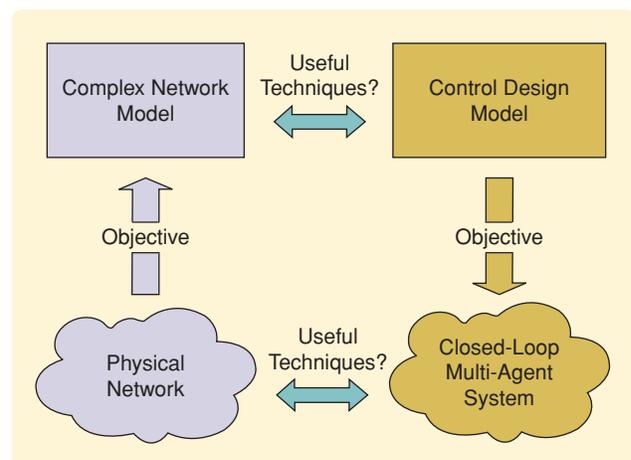


FIGURE 1 A comparison of the complex-network and control-design paradigms. Network theory starts with a physical network and provides a mathematical model to predict its properties. Control theorists, on the other hand, start with a control design model and create physical networks to achieve feedback-control objectives.

explain the emergence of small-world networks and power-law characteristics. The article also motivates the study of human dynamics as an example of a dynamical process that takes place over a network structure, explaining the bursty behavior of various human activities in terms of a priority queuing system.

Next, Klavins describes self-assembly as a mechanism that spontaneously arranges a collection of particles into a coherent network. This article considers active self-assembly, where particles are locally programmed using a graph grammar to join together into a global system with a prescribed behavior. The article applies this approach to an experimental system called *the programmable parts testbed*.

The article by Barooah and Hespanha focuses on distributed estimation in sensor networks. Specifically, the authors show how a set of sensor nodes can infer a global measurement of a quantity of interest from the collective and distributed measurements of local quantities. Such distributed algorithms have applications to localization, time-synchronization, and consensus. In a similar vein, the article by Martinez, Cortes, and Bullo addresses the challenge of obtaining specified global behavior for a collection of particles using only local information. While the article by Barooah and Hespanha focuses on sensing applications, Martinez, Cortes, and Bullo use system-theoretic and networking concepts to establish stability and convergence of distributed motion-coordination algorithms.

Finally, the article by Paley, Leonard, Sepulchre, Grunbaum, and Parrish uses coupled-phase oscillator models to study the collective motion of engineered and biological systems. The authors use these models to design distributed motion coordination and control algorithms as well as to study the schooling behavior of fish.

A common thread throughout the five articles is the role of distributed processing and control, as well as the search for network-growth mechanisms that give rise to a desired structure and behavior. Whether we seek to understand how natural networks evolve or how the structure of such networks can be emulated in man-made systems, it is clear to us that the links between networks and controls are emerging and getting stronger.

CONCLUDING REMARKS

The articles of this special section reflect the emergence of links among control-systems and network-theory researchers. While we have attempted to select broad and representative research, the articles of this issue are targeted to readers of *IEEE Control Systems Magazine*. The authors have done a masterful job in adapting their work to the *IEEE Control Systems Magazine* readership and style, and they deserve all of the credit for the quality of this special issue.

ACKNOWLEDGMENTS

The work of C.T. Abdallah is supported in part by NSF grant CNS 0626380 under the FIND initiative. Bert Tanner is supported in part by the NSF Career grant 0447898.

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