Guest Editorial
Special Issue on Networked Control Systems

MOTIVATED by the accelerating technological convergence of communications, control, and computing, researchers from a variety of disciplines have become interested in the exciting potential and technological challenges of networked control systems (NCSs). In the broadest terms, these systems are comprised of actuators, sensors, and controllers whose operation is coordinated through some form of communication network. The system elements are typically spatially isolated from one another, operating in an asynchronous manner and communicating over a wide area via both wired and wireless links.

While work to build the foundations of networked control systems technology has accelerated in both industrial and university research centers, many fundamental questions regarding stable operation of interconnected hard real-time systems, signal coding and control information flow, peer-to-peer networking, effects of the network on the performance of control systems, etc. remain to be answered. Nevertheless, there has been a proliferation of industrial control system networking technologies, with names like Profibus, Interbus, ControlNet, and SERCOS (to name only a few). With the caveat that these technologies are evolving extremely rapidly, the reader is referred to [1] for a recent description of industrial control networks.

Industrial control is only one application domain where networked real-time systems are becoming increasingly important. Sensor webs, *ad hoc* networks of autonomous mobile agents (such as UAVs), and arrays of micro-devices (such as microvalve arrays, optical switches, RF switches, MEMS-based spatial light modulators, etc.) all present challenges in coordinating communication and control, and it is our hope that the research described in this Special Issue will help readers to see that there is an emerging theoretical foundation for treating a variety of applied problems.

One common problem to be addressed when considering networked control systems is whether there is sufficient communication bandwidth to feed back information to the controller and then send the control commands to the actuators and the plant. In traditional models of control systems, information from the sensors is assumed to be instantaneously available, as in the case of continuous-time systems, and at the sampling time, in the case of discrete-time systems. There may also be delays in transferring this information to the controller and transmitted signals may be corrupted by noise, but when the information arrives it is assumed to be essentially complete (although possibly corrupted by noise). This is in contrast to the NCSs, where limited channel capacity may severely constrain the bit rate in the feedback signal so as to cause performance degradation and even prevent stable operation. There may also be intermittent gaps in the transmitted feedback information due to dropped packets (which is a common occurrence in wireless digital networks, which are subject to both congestion and fading).

The distributed nature of some networked control systems presents an additional set of challenges. These challenges include deciding about the global state from local information and local processing, and attaining global goals by sensing and acting locally. The formation and stable operation of peer-to-peer and other *ad hoc* networks involves problems which NCSs share with other data networks. There is active interest both in the development of new communication protocols as well as in understanding what is possible with existing technologies such as IEEE 802.11, IEEE 802.15.4, Bluetooth, etc. Within such technological frameworks, research is now broadly focussed on strategies for cooperative control—aimed at issues such as synchronization, localization, routing, and coding. The challenge of NCSs has forced the re-examination of classical results on distributed and decentralized control systems so as to take account of communication and network issues.

When we began work on this Special Issue, the goal was to provide a survey of the state-of-the-art of networked control systems. While several topics are well covered, we will concede that some important areas remain to be treated elsewhere. These include the problem of real-time data-mining that will be associated with large-scale, spatially distributed arrays of RF-networked sensors, real-time data-fusion for heterogeneous and distributed arrays of sensors, and distributed control and communication for peer-to-peer networks to manage device node drop-outs and network reconfiguration strategies, among others. The recent technical literature on information-based control has included a number of references to the term *attention* which—allowing for some minor variations in usage—is a quantitative figure-of-merit for feedback control designs which measures both spatial and temporal complexity. While we believe this is an important topic, it is not discussed in this Special Issue, nor have we included papers which are centrally concerned with the industrial control networks mentioned previously.

Among the topics which are treated in this Special Issue, several unifying themes emerge. A number of the papers accepted treat the relationship between closed-loop stability and communications constraints on the feedback channels. The minimum transmission bit rate that guarantees stability of a feedback loop has received a lot of attention lately. It is not surprising that this rate depends on the fastest unstable pole. Several of the papers appearing here are directly motivated by this result and report current work on approaches for coding and quantization which provide acceptable system performance in the face of data-rate constraints (see, in particular, Fagnani and Zampieri.) While most of the motivating theory to date has treated linear systems,

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we have included some new work on the nonlinear case (Nair *et al.*). Two of the papers (Montestruque and Antsaklis, and Li and Baillieul) emphasize time-varying and random transmission times and asynchronous operation of system components as well as systems in which the feedback channel capacity is time varying.

A number of papers treats stochastic systems operating with data-rate constraints on noisy feedback channels (Tatikonda *et al.*, Tripakis, Sinopoli *et al.*, and Simsek *et al.*). The paper by Elia examines lower bounds on channel feedback capacity for a variety of channel types including single-user Gaussian channels, broadcast channels, multiple access, and interference channels. Most of this work addresses the problem of closed-loop stability in the face of data-rate constraints in the network channels, although questions such as decidability of the question of existence of controllers in networks with unbounded delays are also addressed. Goodwin *et al.* discuss the problem of networked control in which the controller, sensors, and actuators are connected by data-rate limited communications channels, and wherein only a single plant can be addressed at a time. Their approach appears to be suitable for control systems implemented using Profibus, Control Net, and other industrial control network protocols.

Broadly speaking, a second group of papers addresses *ad hoc* network formation and mobility. The paper by Recht and D'Andrea presents a new approach to control design for systems comprised of spatially interconnected elements in which spatial symmetries are described by discrete groups—both abelian and nonabelian. Olfati-Saber and Murray discuss consensus problems for networks of dynamic agents with fixed and switching topologies, using digraph models of interagent connectivity. Mobility is discussed by Fax and Murray who consider information flow and the stability of distributed control of autonomous vehicle formations.

A Special Issue in a journal such as the IEEE TRANSACTIONS ON AUTOMATIC CONTROL can only include a rather small number of papers describing previously unpublished original work that was completed in time for the Special Issue. So, it only represents a view of selected topics in NCSs from a window in time. Although we made every effort to include a variety of approaches, the coverage is by no means complete.

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John Baillieul (M'83–SM'89–F'93) received the B.A. degree (*magna cum laude*) in mathematics from the University of Massachusetts at Amherst, in 1967. He completed graduate studies at the Johns Hopkins University, Baltimore, MD, and the University of Waterloo, Waterloo, ON, Canada, and received the Ph.D. degree in applied mathematics from Harvard University, Cambridge, MA, in 1975. His Ph.D. dissertation was an early work dealing with connections between optimal control theory and what has recently been called "sub-Riemannian geometry."

He is currently a Professor in three departments at Boston University: Aerospace and Mechanical Engineering, Electrical and Computer Engineering, and Manufacturing Engineering. His research deals with robotics, the control of mechanical systems, and mathematical system theory. After publishing a number of papers developing geometric methods for nonlinear optimal control problems, he turned his attention to problems in the control of nonlinear systems modeled by homogeneous polynomial differential equations. His main controllability theorem applied the concept of finiteness embodied in the Hilbert basis theorem to develop a controllability condition which could be verified by checking the rank of an explicit finite dimensional operator. During the mid 1980s, he collaborated with M. Levi to develop a control theory for rotating elastic systems. Much of his present research is devoted to applying the methods of dynamical systems theory and classical geometric nonlinear control theory to problems of current technological interest. Recent developments have led him to work on the interplay between communications and information theory and control.