Panos J. Antsaklis and J. Baillieul, “Scanning the Issue: Special Issue on Technology of Networked Control Systems," Proceedings of the IEEE, Vol.95, No. 1, pp. 5-8, January 2007. In Special Issue on 'Technology of Networked Control Systems,' Panos J. Antsaklis and J. Baillieul Eds., Proceedings of the IEEE, Vol.95, No. 1, pp. 5-312, January 2007.

Special Issue on Technology of Networked Control Systems

BY PANOS ANTSAKLIS, *Fellow IEEE*
Guest Editor

JOHN BAILLIEUL, *Fellow IEEE*
Guest Editor

Networked control systems are control systems comprised of the system to be controlled and of actuators, sensors, and controllers, the operation of which is coordinated via a communication network. These systems are typically spatially distributed, may operate in an asynchronous manner, but have their operation coordinated to achieve desired overall objectives.

Control systems with spatially distributed components have existed for several decades. Examples include control systems in chemical process plants, refineries, power plants, and airplanes. In the past, in such systems the components were connected via hardwired connections and the systems were designed to bring all the information from the sensors to a central location where the conditions were being monitored and decisions were made on how to control the system. The control policies then were implemented via the actuators, which could be valves, motors, etc. What is different today is that technology can put low-cost processing power at remote locations via microprocessors and that information can be transmitted reliably via shared digital networks or even wireless connections. These technology driven changes are fueled by the high costs of wiring and the difficulty in introducing additional components into the systems as the needs change.

This special issue provides information on current and future research directions in the emerging field of Networked Control Systems.

The changes in the scope and implementation of control systems have caused two main changes in the emphasis in control system analysis and design. The first has to do with the explicit consideration of the interconnections; the network now must be considered explicitly as it affects significantly the dynamic behavior of the control system. The second change has to do with a renewed emphasis on distributed control systems. Because of these changes in control systems, several new concerns need to be addressed. Several areas such as communication protocols for scheduling and routing have become important in control when considering, for example, stability, performance, and reliability. Algorithms and software that are capable of dealing with hard and soft time constraints are very important in control implementation and design and so areas such as real-time systems from computer science are becoming increasingly important. There is also some reordering of priorities and importance of control concepts due to changes in importance to control applications. There had also been renewed emphasis on methodologies for increased autonomy that allows the system to run without feedback information for extended periods of time. At a more fundamental level, control theorists have been led to re-examine the open- (feedforward) versus closed-loop (feedback) control issues.

Technology advances, together with performance and cost considerations, are fueling the proliferation of networked control systems and, in turn, are raising fundamentally new questions in communications, information processing, and control dealing with the relationship between operations of the network and the quality of the overall system's operation. A wide range of research has recently been reported dealing with problems related to the distributed characteristics and the effect of the

Digital Object Identifier: 10.1109/JPROC.2006.887291

digital network in networked control systems. The current state of the art of such research is the subject of the 12 papers in the present Special Issue of the Proceedings of the IEEE.

The first paper titled "Control and Communication Challenges in Networked Real-Time Systems" is written by the Guest Editors and provides a rather comprehensive overview of the field of networked control systems including a snapshot of the current state of research and possible future directions. It also discusses in more detail the contents of the rest of the papers in the Special Issue and provides additional references. In this field, recent theoretical advances and target applications are intimately intertwined, and the common goal of papers in the Special Issue is to describe key aspects of this relationship. An additional aim is to provide a bridge between networked control systems and closely related work dealing with sensor networks and wireless communication protocols.

The remaining 11 papers are organized in three sections: a section on the "current state of the technology of networked control systems," a section on "foundations of networked real-time systems," and a section on "wireless networks—the backbone of networked control systems." These are now briefly discussed.

I. CURRENT STATE OF TECHNOLOGY OF NETWORKED CONTROL SYSTEMS

The present section includes four papers. In the first paper of this section, "The Emergence of Industrial Control Networks for Control Diagnostics and Safety," Moyne and Tilbury describe the emergence of networks for control, diagnostics, and safety, and present mechanisms for designing and analyzing network control solutions. Network performance characteristics such as delay, delay variability, and determinism are characterized. Future trends in manufacturing control networks are discussed, such as the move to wireless for all categories of data exchange.

In the next paper, "Collective Motion, Sensor Networks, and Ocean Sampling," Leonard *et al.* report on an on-going project aimed at developing a mobile sensor network which can be used in a wide variety of adaptive ocean sampling applications. The focus is on optimized data collection using networks of sensor-enabled mobile agents. The paper mentions a number of such applications where a key feature of optimal sensing is the use of motion-control which is optimized to make the data acquisition as effective as possible.

Cantoni *et al.* in the third paper of the section titled "Control of Large Scale Irrigation Networks" considers a control problem involving sensors and actuators distributed over a large area, an irrigation network. Feedback control schemes that involve only local, i.e., gate-to-gate, information exchange are discussed. Analysis identifies a key design tradeoff between local performance objectives and the nature of disturbance propagation through the network. Using classical loop-shaping ideas and recent tools for structured controller synthesis, an optimal control approach is proposed for systematically dealing with this tradeoff. The results of preliminary field trials are provided to demonstrate the validity of the modeling and control design framework described.

In the last paper of the section "The Role of Network-Centric Systems in Military Operations in Urban Terrain," Godbole *et al.* focuses on small unmanned aerial vehicles (UAVs) and on their use for reconnaissance and surveillance missions in cities and towns. These vehicles have limited endurance and payload capability and are integrated within an information and communication network. The paper discusses recent developments in urban UAVs, potential areas of application in the military domain, recent research results, and network-oriented scalable system concepts for the near-term operational use of these vehicles for urban operations.

II. FOUNDATIONS OF NETWORKED REAL-TIME SYSTEMS

Five papers are grouped together in this section. The paper by Nair *et al.* titled "Feedback Control under Data Rate Constraints: An Overview," presents a tutorial exposition of the major theoretical results in the area of data rate-limited control. The main contributions are reviewed, including the so-called data rate theorem, which gives the smallest feedback data rate required to be able to stabilize an unstable linear system. For nonlinear systems, the topics discussed include results on input-to-state and semi-global stability and the concept of topological feedback entropy. Recent results and open problems are described.

Hespanha *et al.* in the second paper titled "A Survey of Recent Results in Networked Control Systems," presents results on estimation and controller synthesis aimed at spatially distributed control systems in which the operational challenges arise from the nature of the wireless communication links between sensors, actuators, and controller. The paper addresses the effects of channel limitations in terms of packet rates, sampling, network delay, and packet dropouts.

In the third paper, "Foundations of Control and Estimation over Lossy Networks," Schenato *et al.* propose a mathematical framework to optimally design networked control systems using the common UDP and TCP protocols over lossy physical layer links. This work discusses stability criteria and provides numerical tools to find stabilizing controllers under different communication protocols. The paper also discusses the fundamental limitations of control in the presence of limited information in the form of losses.

Ghosh *et al.* in "Bio-Inspired Networks of Visual Sensors, Neurons, and

Oscillators" focuses on the role of network for the purpose of sensing, encoding, and decoding with the eventual goal of target localization, control, and actuation. The paper proposes "optimal sensor placement" as one way to solve the calibration problem enabling one to rapidly fuse the associated sensor data. The roles of communication, packet drops, and variable delays are important areas of design that are the subject of future research in the study of networks of mobile visual sensors.

In the last paper of this section "Consensus and Cooperation in Networked Multiagent Systems," Ofati-Saber *et al.* discusses consensus problems in networked dynamic systems that have emerged as a fundamental problem and unifying theme in performing various cooperative tasks in multiagent systems including flocking, formation control, rendezvous in space, synchronization of coupled oscillators, and information fusion in sensor networks. The paper illustrates the concept of "cooperation" among dynamic systems via a detailed discussion of formation control for networked multivehicle systems.

III. WIRELESS NETWORKS—THE BACKBONE OF NETWORKED CONTROL SYSTEMS

The last section of this special issue includes two papers. Oh *et al.* in "Tracking and Coordination of Multiple Agents Using Sensor Networks: System Design, Algorithms, and Experiments" illustrate the main challenges in developing a real-time control system for pursuit–evasion games with the aid of a large scale sensor network. Novel algorithms based on multiple layers of data fusion and on a real-time hierarchical coordination architecture are proposed and successfully demonstrated in a large-scale outdoor wireless sensor-actuator network.

In the last paper, Chiang *et al.* in "Layering As Optimization Decomposition: A Mathematical Theory of Network Architectures," discuss the "layered" protocol stack as a fundamental enabling idea of modularized network design. Network design has traditionally been carried out based only on heuristics, and the paper surveys the conceptual framework of layering and shows that it provides a unifying analytic foundation for current network architectures. The paper approaches the issue of distributed network resource allocation with modularized design through optimization theory and decomposition theory. Using a first-principles approach to network design, the authors illuminate a promising synergy between the control of networks and networked control systems.

This special issue aims to provide the reader with a picture of the current research and future research directions in the emerging field of networked control systems, which is as comprehensive as possible. Leading researchers in the field were first contacted over two years ago, and the present special issue has been made possible only because of the significant time and effort the authors have invested. We would like also to recognize the contributions of the reviewers who helped the authors refine and focus the ideas in their manuscripts. Without their help this issue would not have been the same. Finally, we would like to thank the Managing Editor Jim Calder and Publications Editor Margery Meyer for their continuing support. ■

ABOUT THE GUEST EDITORS

Panos Antsaklis (Fellow, IEEE) is a graduate of the National Technical University of Athens (NTUA), Greece, and received the M.S. and Ph.D. degrees from Brown University, Providence, RI.

He is the H. Clifford and Evelyn A. Brosey Professor of Electrical Engineering and Concurrent Professor of Computer Science and Engineering at the University of Notre Dame, Notre Dame, IL. He served as the Director of the Center for Applied Mathematics of the University of Notre Dame from 1999 to 2005. His research addresses problems of control and automation and examines ways to design engineering systems that will exhibit a high degree of autonomy in performing useful tasks. His recent research focuses on networked embedded systems and addresses problems in the interdisciplinary research area of control, computing, and communication networks, and on hybrid and discrete-event dynamical systems. He has authored a number of publications in journals, conference proceedings, and books, and he has edited six books on intelligent autonomous control, hybrid systems and on networked embedded control systems. In addition, he has coauthored the research monographs "Supervisory Control of Discrete Event Systems Using Petri Nets" (Kluwer Academic 1998, with J. Moody) and "Supervisory Control of Concurrent Systems: A Petri Net Structural Approach" (Birkhauser 2006, with M.V. Iordache) and the graduate textbook *Linear Systems* (McGraw-Hill 1997 and Birkhauser 2005, with A. N. Michel). He is currently a member of the subcommittee on Networking and Information Technology of the President's Council of Advisors for Science and Technology (PCAST) that advises the President of the United States on Science and Technology federal policy issues regarding technology, scientific research priorities, and math and science education.

Dr. Antsaklis serves on the editorial boards of several journals, and he currently serves as AEAL of the IEEE Transactions on Automatic Control. He has been a Guest Editor of special issues in IEEE Transactions of Automatic Control and the Proceedings of IEEE. He has served as Program Chair and General Chair of major systems and control conferences including the Conference on Decision and Control, and he was the 1997 President of the IEEE Control Systems Society (CSS). He has been a plenary and keynote speaker in a number of conferences and research workshops. He currently serves as the President of the Mediterranean Control Association. He serves in the Scientific Advisory Board for the Max-Planck-Institut fur Dynamik Komplexer Technischer Systeme, Magdeburg, Germany. He is a Distinguished Lecturer of the IEEE Control Systems Society, a recipient of the IEEE Distinguished Member Award of the Control Systems Society, and an IEEE Third Millennium Medal recipient. He was the 2006 recipient of the Brown Engineering Alumni Medal of Brown University.

John Baillieul (Fellow, IEEE) holds professorial appointments in three departments at Boston University, Boston, MA: he is Professor of Aerospace/Mechanical Engineering, Professor of Electrical and Computer Engineering, and Professor of Manufacturing Engineering. He is currently Chairman of Aerospace/Mechanical Engineering. He has also served as Associate Dean for Academic Programs in the B.U. College of Engineering. After receiving the Ph.D. degree from Harvard University in 1975, he joined the Mathematics Department of Georgetown University. During the academic year 1983–1984 he was the Vinton Hayes Visiting Scientist in Robotics at Harvard University, and in 1991 he was visiting scientist in the Department of Electrical Engineering at MIT. Prof. Baillieul has been an active member of the IEEE Control Systems Society for many years. From 1984 through 1985 he was an Associate Editor of the IEEE Transactions on Automatic Control, and in 1987 he served as Program Chairman of the IEEE Conference on Decision and Control in Los Angeles. He is past Associate Editor of the IEEE Robotics and Automation Society Newsletter and was a member of the editorial board of the journal Bifurcation and Chaos in Applied Sciences and Engineering. He was Editor-in-Chief of the IEEE Transactions on Automatic Control for six years from 1992 through this past June. Currently, he is on the editorial boards of the Proceedings of the IEEE, the IEEE Transactions on Automatic Control, *Communications in Information and Systems*, and the journal *Robotics and Computer Integrated Manufacturing*. He has been named Fellow of the IEEE for his contributions to nonlinear control theory, robotics, and the control of complex mechanical systems. He is a recent recipient of the IEEE Third Millennium Medal for various professional contributions. He is past IEEE Control Systems Society Vice-President for Technical Activities and IEEE CSS Vice-President for Publications. He currently is serving as CSS President. At the level of the corporate IEEE, Prof. Baillieul's service has included four years as TAB Transactions Chair (1998 through 2001), member at large of the Publications Services and Products Board (PSPB) (1999–2004, 2006 –), Chair of the PSPB Strategic Planning Committee (2001–2002), and Chair of the PSPB Finance Committee (PSPB Treasurer, 2004). During 2005, he chaired the PSPB Ad Hoc Committee on the IEEE Press of the Future. Committee recommendations were distilled into a business plan which the IEEE Press Board and the PSPB are now working to execute. Currently, he is IEEE Vice President of Publication Services and Products.

His research deals with robotics, the control of mechanical systems, and mathematical system theory. His Ph.D. dissertation, completed at Harvard University under the direction of R. W. Brockett in 1975, was an early work dealing with connections between optimal control theory and what has recently been called sub-Riemannian geometry. 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. Such systems describe, for example, the controlled dynamics of a rigid body. 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, Baillieul collaborated with M. Levi to develop a control theory for rotating elastic systems. Recently, he has written a number of papers on motion planning and control of kinematically redundant manipulators, and he has become interested in problems associated with anholonomy in planning motions for robots which have elastic joints and other components which store energy. 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. In particular, he is working on applications of mathematical control theory to fluid structure interactions, microelectromechanism dynamics, adaptive optics, and network mediated control of large scale device arrays. Recent developments in this research has led him to work on the interplay between communications and information theory and control.