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Sabato Manfredi

Multilayer Control of Networked Cyber-Physical Systems

Application to Monitoring, Autonomous and Robot Systems

Springer

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To my mother

Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new design philosophies…, new challenges. Much of this development work resides in industrial reports, feasibility study papers, and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

Traditional distributed control systems are hardwired systems that look after the control of complex physical systems. These complex systems can be compact physically, for example, a cold-rolling steel strip mill, or physically distributed as in a domestic water supply distribution system, for example. Whether compact or distributed, the process control depends crucially on reliable, accurate sensor information, and robust communication with the system's actuators. Hardwired communication links have been the industry solution and for many processes this is viewed as the only secure method of ensuring the integrity of the control communication system.

However, industry is always developing new potential solution technologies and one area where developments have occurred with revolutionary speed is in the control communications field and in particular the use of "wireless communications". Hardwired cabling costs are significant and if the application can be monitored and controlled reliably using wireless technology or even Internet technology, the cabling costs will be avoided. Consequently there has been a substantial growth in the appearance of networked cyber-physical systems. It is not difficult to identify the systems that might benefit from such networked wireless communication systems: vehicular transport networks, distribution networks for water, wastewater, gas, electricity, and environmental monitoring, being some important examples.

The implication of networking for the control–process–sensor structure is a physical and modeling extension to include a new component, namely "the network", and the network has its own dynamics, constraints, and technical problems. This inclusion of a network also causes new "communications" concepts and terminology to be added to those of the control, instrumentation and sensor sciences. This is a growing field and the *Advances in Industrial Control* monograph series has two previous contributions to the analysis and the design of the network–control–process–sensor combination, namely:

- *Internet-based Control Systems* by Shuang-Hua Yang (ISBN 978-1-84996-358-9, 2011)
- *Networked and Distributed Predictive Control* by Panagiotis D. Christofides, Jinfeng Liu, David Muñoz de la Peña (ISBN 978-0-85729-581-1, 2011)

Sabato Manfredi's monograph *Multilayer Control of Networked Cyber-Physical Systems: Applications to Monitoring, Autonomous and Robot Systems* is a valuable additional contribution to the *Advances in Industrial Control* series. It makes explicit the dynamic and constrained nature of the "network" component and shows how to incorporate it into a control system design. His solutions are demonstrated in three simulated application case studies. The monograph is instructive in the way that Dr. Manfredi introduces communications technology and terminology into control systems engineering.

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Preface

Networked Cyber-Physical Systems (NCPSs) consist of computing devices acting synergically by a communication network and interacting with a complex physical process distributed over a given area.

The technological advances in the fields of communication networks and embedded systems have been a major driving force for the widespread, ubiquitous, and emerging NCPS applications ranging from power systems, smart buildings to medical devices to robot autonomous systems.

An NCPS monitors and controls physical variables via sensor, actuator, controller, and robot nodes closed in a feedback loop with the distributed process. Nodes operations are coordinated through a communication network. In this way the performance of NCPS is affected by both the reliability of the network supporting the communication functionality and the efficiency of the control systems interacting with the physical environment. Therefore, the design of NCPS requires basic science foundation synergically drawing on several branches including control theory and computer science.

The book is triggered by the challenging interdisciplinary problem to formulate design approaches for NCPSs. In this respect, the book first introduces a novel multilayer conceptual framework taking into account the communication network and control system features of NCPS. Then a multilayer distributed and cooperative control is devised to simultaneously cope with NCPS network and control requirements. A practical aim of the proposed control approach is to distribute the computational burden among the different devices that cooperatively achieve NCPS' goals.

The intended audience of this book will mainly consist of researchers, research students, and practitioners in automatic control and computer science. The book is also of interest to industrial practitioners in areas such as automation, engineering, sensor networks, robotics, and computer networks. It is suitable for classroom use or as a reference for professionals. Presenting co-design examples that illustrate practical applications derived from theory, the textbook is also suitable for use in upper undergraduate and graduate-level university courses. Nevertheless, I hope that this text will be helpful for readers with very different backgrounds as required to deal with NCPS' design and analysis.

The book is organized in five chapters: Chap. 1 introduces the basic notion of NCPS and the novel multilayer control system conceptual framework to deal with the NCPS design. The multilayer control system is composed of the *network layer control system* and the *application layer control system*. The first one copes with NCPS communication network requirement while the latter with the NCPS control system performance. At each layer a cooperative consensus-based control law is formulated. Chapter 2 presents convergence and stability results, performance and implementation issues of the *network layer control system*. Chapter 3 is devoted to present convergence and stability results, performance, and implementation issues of the *application layer control system*. Design and co-design indications are also provided for the design of the overall multilayer control system. Chapter 4 focuses on the application of the design approaches presented in Chap. 2 to different kinds of autonomous and queuing systems (Content delivery, TCP/ATM and wireless networks). Finally Chap. 5 shows the application of the proposed multilayer control approach to the design of representative NCPSs including monitoring and robots systems. Co-design examples are given in order to illustrate how to take into account the algorithms implementation features in the NCPS design.

Italy Sabato Manfredi
May 2016

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Abbreviations

AIMD	Additive Increase Multiplicative Decrease
AODV	Ad hoc On-Demand Distance Vector
AQM	Active Queue Management
AS	Autonomous System
ATM	Asynchronous Transfer Mode
CCA	Carrier Channel Assessment
CDN	Content Delivery Network
CPS	Cyber-Physical System
CRC	Cooperative Rate Control
DiffServ	Differentiated Services
ECG	Electrocardiogram
ECN	Explicit Congestion Notification
ER	Explicit Rate
FCG	Fetal Cardiac Frequency
IETF	Internet Engineering Task Force
LAN	Local Area Network
MAC	Medium Access Control
NCPSs	Networked Cyber-Physical System
NCS	Networked Control System
NMCS	Networked Monitoring Control System
NMS	Networked Monitoring System
NRS	Networked Robot System
NS	Network Simulator
OSI	Open Systems Interconnection
POC	Point Of Care
QoS	Quality of Service
RAS	Robot Autonomous System
RCP	Rate Control Protocol
RM	Resource Management
RTT	Round Trip Time

SO_2	Oxygen Saturation
TCP	Transmission Control Protocol
VLSI	Very Large Scale Integration
WAN	Wide Area Network
WBAN	Wireless Body Area Network
WMN	Wireless Mesh Network
WNMCS	Wireless Networked Monitoring Control System
WNRS	Wireless Networked Robot System
WSAN	Wireless Sensor Actuator Network
WSN	Wireless Sensor Network