Principles of Cyber-Physical Systems

This unique introduction to the foundational concepts of cyber-physical systems (CPSs) describes key design principles and emerging research trends in detail. Several interdisciplinary applications are covered, with a focus on the wide-area management of infrastructures, including electric power systems, air transportation networks, and health care systems.

Design, control, and optimization of cyber-physical infrastructures are discussed, addressing security and privacy issues of networked CPSs, presenting graph-theoretic and numerical approaches to CPS evaluation and monitoring, and providing readers with the knowledge needed to operate CPSs in a reliable, efficient, and secure manner. Exercises are included at the end of each part of the book.

This is an ideal resource for researchers and graduate students in electrical engineering and computer science, as well as for practitioners using CPSs in aerospace and automotive engineering, medical technology, and large-scale infrastructure operations.

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Principles of Cyber-Physical Systems

An Interdisciplinary Approach

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107066618
DOI: 10.1017/9781107588981

First published 2020

A catalogue record for this publication is available from the British Library.

ISBN 978-1-107-06661-8 Hardback

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Preface

Cyber technologies are becoming pervasive in engineered physical systems ranging in scale from micro-robots that travel in the bloodstream to multi-continent transportation networks. The tight interfacing of cyber and physical components in engineered systems permits profound (and sometimes magical) advancements in their functionalities, but at the same time brings forth unique challenges in system operation, analysis, and design. The potentially transformative benefits that come from melding cyber and physical capabilities, and the attendant challenges, are rapidly driving research and development efforts in wide-ranging fields (e.g., medicine, transportation, power transmission, retail). As these cyber-physical systems (CPSs) become increasingly common in our daily lives, tools and techniques for characterizing and designing their operations are increasingly needed. This is because such tools will (1) permit keen analysis and improvement of the intricate interactions between cyber and physical aspects of a particular complex system; and yet (2) transcend system-specific details to provide general insight into CPSs. In short, a foundational theory for CPSs is spanning important disciplines but yielding concrete advances in deployment and operation of particular systems.

The interfacing of cyber technologies with physical systems is not new: Computers have been used in conjunction with electromechanical systems almost from the inception of the digital age, and such fields as telecommunications and manufacturing have a rich history of exploiting digital technologies to enhance physical-system function. What is new, however, is (1) the increasingly wide penetration of cyber-capabilities into physical devices; (2) the growing diversity of uses of cyber-capabilities in these systems; (3) the increasing sophistication of the computer–machine interface; and (4) the advent of integrated technologies whose functionalities supersede those of physical and cyber systems in isolation. It is this growing pervasiveness and sophistication of CPSs that motivates the development of a new foundational theory, one which provides generic insight into interfaced cyber and physical capabilities across disciplines. At its essence, such a foundation requires understanding of how information-transmission and processing capabilities (the hallmarks of cyber systems) can be interfaced with physics-based functionalities. A wide array of interesting and difficult questions arise in engineering these dual-purpose systems, including analysis of their dynamics, stability analysis, performance design, robustness and security characterization, equity, implementation of the cyber-physical interface, and deployment, among others.

The analysis and design of CPSs has drawn wide attention in academia, government, and industry in recent years. In particular, industrial and governmental organizations in several domains – automobile manufacturing, surgical/medical device design, and transportation-system management, to name just a few – are engaged in research and development efforts to build and optimize CPSs. At the same time, university engineering and computer-science programs are beginning to foster scholarship on CPSs, through introduction of new courses, involvement in and support of research projects, faculty-hiring initiatives, etc. As research and development on CPSs continues to expand, there is a growing recognition that knowledge in several fields needs to be integrated and enhanced to develop foundational methods/tools for CPSs and to take these methods to industrial practice. Such foundational integrated work on CPSs crucially requires forums that: (1) provide comprehensive tutorial content on basic CPS principles and concepts; and (2) introduce state-of-the-art research on focused topics that are necessary for advancing the field.

The purpose of this publication is to meet these dual needs for tutorial content and focused research advancement, in a way that is useful for both academic researchers and industrial practitioners. With this goal in mind, we have sought to develop a text that can serve both as a compendium of interesting and important research results, and as a textbook for a graduate or advanced undergraduate course on CPSs. To this end, we have invited leading researchers on CPSs from several disciplines to contribute chapters to the book that contain up-to-date research progress. While these chapters capture new research, we have also asked the authors to include tutorial content to provide a comprehensive introduction to their direction of research; this content includes significant literature review, examples and exercises, illustrations, and homework problems, so that the book is instructional for classroom use. Additionally, we as editors have included sectional overview materials, a scoping chapter for future work on cyber-physical infrastructures, and some discussions and annotations, so as to achieve a cohesive story with smooth transitions and completeness. The two of us hail from different disciplines (controls engineering and computer science) and are collaborating on multidisciplinary research on CPSs; we have sought to draw on our ongoing collaboration to compose an interdisciplinary yet cohesive perspective. In short, it is our intention that the textbook covers the state-of-the-art with regard to influential CPS research, while also meeting the need for a cohesive framework for CPS concepts and principles.

The book is divided into four parts which each address a major conceptual theme in the design and operation of CPSs. Specifically, the chapters in Part I discuss challenges in uncertainty modeling, analysis, and mitigation for CPSs. Part II explores the notion of CPS structure, broadly defined, and explores how structure can be exploited in control and management of CPSs. The chapters in Part III address the growing need for threat assessment and resolution across the cyber and physical components of CPSs, and hence introduce principles related to security, privacy, and vulnerability. Finally, Part IV describes the development of frameworks and testbeds for addressing CPS challenges. Core conceptual and analytical results are presented throughout the book, but are also supported by myriad application case studies that reflect the authors'

individual specializations. Besides the four main parts, the editors have included a concluding chapter, which overviews major challenges in management and control of large-scale infrastructure networks. This concluding chapter shows how the major themes of the book can tie together in addressing an engineering grand challenge, namely management of terrestrial-scale infrastructures, and serves as a call-to-action to CPS researchers to focus on wide-area management of infrastructures.

The field of CPSs has grown extremely rapidly over the last 10 years or so: An extraordinary number of conference and journal articles have been published on the topic, new conferences and journals have been initiated, several companies have introduced focused research and development efforts in the area, and – importantly – several other books have been written on the subject. The wealth of recent work on the subject is a strong motivation for this book, but at the same time means that we should distinguish the contributions of this book from other texts. Because of the huge scope and newness of CPS research, intrinsically each text and survey manuscript has a different perspective on the field. We believe that this book encompasses a wide range of core concepts as well as applications of CPSs, and should be of interest widely to academics and practitioners in the field. At the same time, however, we would like to highlight two distinguishing features of our book.

First, this book diverges from the bulk of the literature on CPSs in that there is a central focus on large-scale infrastructures like power-transmission networks and global transportation systems. CPSs as a field grew out of the embedded computing literature, and hence naturally the field's original focus was on physical devices with embedded cyber systems, and in turn on networks of such devices (which constitute the Internet of Things). This book overviews research in these directions, but also recognizes the complementary challenge of operating legacy infrastructures with integrated cyber systems as a keystone CPS problem. We believe that the need for focused research and tutorial content is particularly pronounced in the management of cyber-physical critical infrastructures, like transportation, electric power, and water-distribution systems, among many others. The efficient operation of such infrastructures in a complex and adversarial world constitutes a grand challenge problem for engineers today. Diverse cyber technologies are being integrated into these infrastructures, and are enabling revolutionary changes in their operations. Yet fully harnessing these new technologies requires detailed co-modeling and analysis of the infrastructures' physical-world processes and its cyber systems. For most infrastructures, modeling, analysis, and management are undertaken by domain experts who are well-versed in the physical processes and legacy systems involved in the infrastructure, but typically have limited technical knowledge of computing systems. On the other hand, most computer scientists lack specialized knowledge about the physical processes in infrastructures. Also, the historical development of infrastructure systems often dictates that there is limited interface between computer scientists and domain experts. Given this lack of comprehensive expertise, conceptual and mathematical frameworks are needed that facilitate co-analysis of the cyber and physical systems and allow efficient operation/management. This book aims to provide the conceptual and mathematical frameworks needed for operation and management of CPSs.

Second, a special focus of this book is on coalescing research in computer science and systems/controls engineering to address CPS challenges. Several of the chapters introduce techniques that leverage both systems/controls engineering concepts and computer science constructs, or develop new algorithmic capabilities that merge the fields. These efforts show that coalesced methods can support advanced control and design of CPSs, including for performance-shaping and threat assessment and mitigation. The coalesced methods are crucial for the analysis and design of cyber-physical *networks* (whether infrastructures like power and transportation networks, or communicating-agent systems like multi-vehicle teams or networked devices in a smart building/home). This book demonstrates the application of coalesced methods in these diverse network-focused applications.

It is our hope that the material in the book will be useful for researchers and practitioners across many areas of specialization, who encounter analysis and engineering design problems that involve tightly interfaced cyber and physical components. Target audiences include:

- practitioners in industry engaged in building cyber-physical capabilities, who require a comprehensive overview of foundational methods in the field;
- academic and industrial researchers interested in developing interdisciplinary techniques for the analysis and management of CPSs, such as epidemiologists seeking to integrate cyber decision-making capabilities into hospital-management procedures or public-health initiatives;
- graduate and advanced undergraduate students in engineering and computer science, especially those focused on modeling, algorithms, and systems/control. Specifically, we envision that these students would read the text as part of a graduate or advanced undergraduate course on CPSs.

The book has been designed to allow readers to easily port the introduced concepts and principles to their application area of interest.