Intelligent Data Centric Systems

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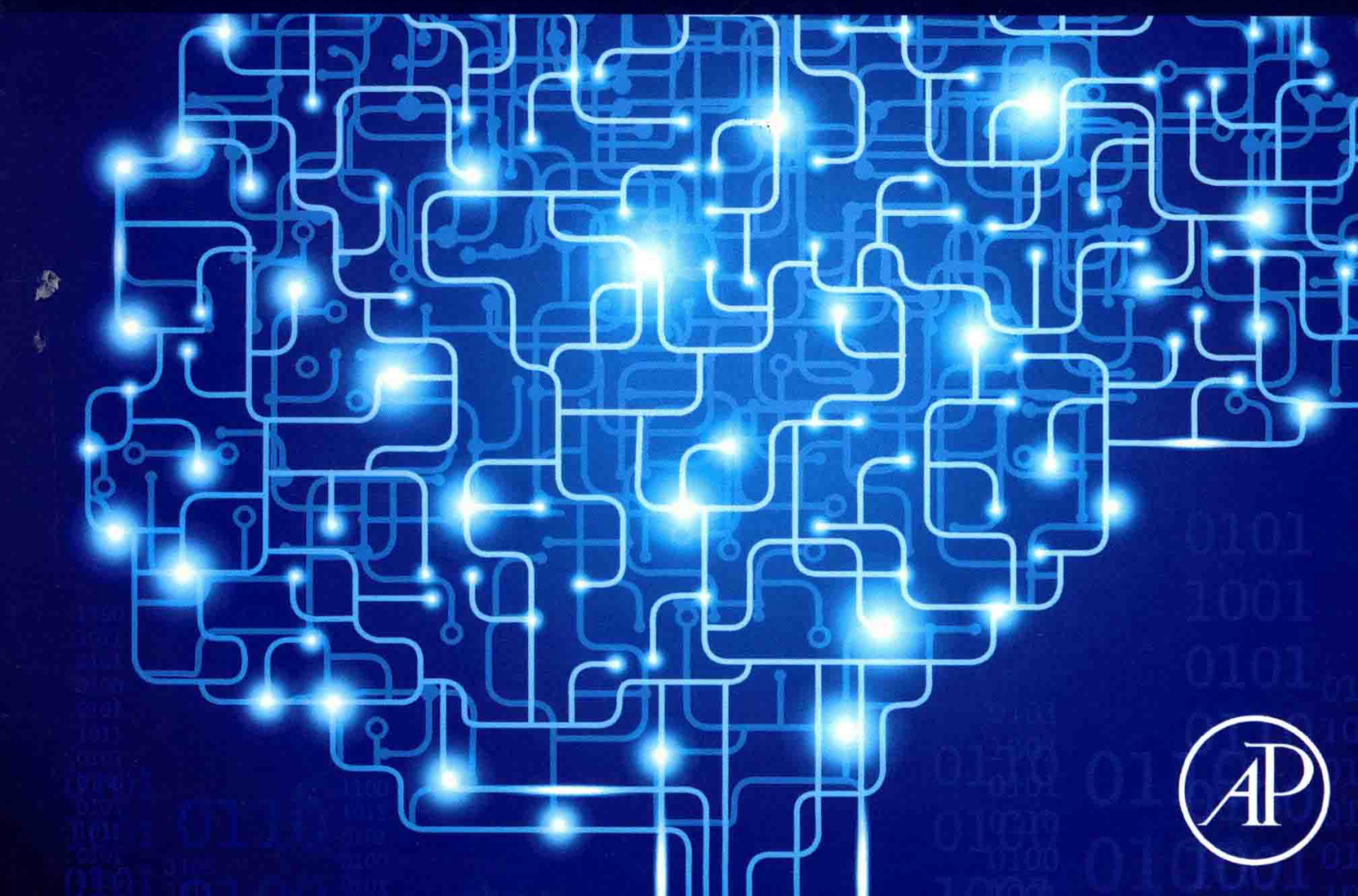
Cyber-Physical Systems

Foundations, Principles and Applications

Edited by Houbing Song, Danda B. Rawat, Sabina Jeschke, and Christian Brecher



Cyber-Physical Systems
Foundations, Principles and Applications

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In Aug. 2012, he joined the Department of Electrical and Computer Engineering, West Virginia University, Montgomery, WV, where he is currently an Assistant Professor and the founding director of the Security and Optimization for Networked Globe Laboratory (SONG Lab, http://www.SONGLab.us), and West Virginia Center of Excellence for Cyber-Physical Systems sponsored by West Virginia Higher Education Policy Commission. He served as an engineering research associate at Texas A&M Transportation Institute in 2007. His research interests lie in the areas of cyber-physical systems, internet of things, cloud computing, big data analytics, connected vehicle, wireless communications, and networking. Dr. Song's research has been supported by the West Virginia Higher Education Policy Commission. Dr. Song was the first recipient of Golden Bear Scholar Award, the highest faculty research award at WVU Tech.

Dr. Song is a senior member of IEEE and a member of ACM. Dr. Song is an associate editor for several international journals, including IEEE Access and KSII Transactions on Internet and Information Systems, and a guest editor of several special issues within leading international journals such as IEEE Transactions on Industrial Informatics. Dr. Song was the general chair of four international workshops, including the first IEEE International Workshop on Security and Privacy for Internet of Things and Cyber-Physical Systems (IOT/CPS-Security), held in London, UK and the first/second/third IEEE ICCC International Workshop on Internet of Things (IOT 2013/2014/2015), held in Xi'an/Shanghai/Shenzhen, China. Dr. Song also served as the technical program committee chair of the fourth IEEE International Workshop on Cloud Computing Systems, Networks, and Applications (CCSNA), held in San Diego, USA. Dr. Song has served on the technical program committee for numerous international conferences, including ICC, GLOBECOM, INFOCOM, WCNC, etc. Dr. Song has published more than 100 academic papers in peer-reviewed international journals and conferences.

Danda B. Rawat is an associate professor in the Department of Electrical Engineering and Computer Science at Howard University, Washington DC, USA. Dr. Rawat's research focuses on wireless communication networks, cybersecurity, cyber physical systems, internet of things, big data analytics, wireless virtualization, software-defined networks, smart grid systems, wireless sensor networks, and vehicular/wireless ad-hoc networks. His research is supported by the U.S. National Science Foundation, University Sponsored Programs, and grants from the Center for Sustainability. Dr. Rawat is the recipient of the NSF Faculty Early Career Development (CAREER) Award. Dr. Rawat has published over 100 research articles and 8 books. He serves as editor/guest editor for over 10 international journals. He serves as a web-chair for the IEEE INFOCOM 2016/2017, served as a Student Travel Grant co-chair of the IEEE INFOCOM 2015, Track Chair for wireless networking and mobility of the IEEE CCNC 2016, Track Chair for Communications Network and Protocols of the IEEE AINA 2015, and so on. He served as a program chair, general chair, and session chair for numerous other international conferences and workshops. He is the recipient of the Outstanding Research Faculty Award (Award for Excellence in Scholarly Activity) 2015 from the Allen E. Paulson College of Engineering

and Technology, GSU among others. He is the founder and director of the Cyber-security and Wireless Networking Innovations (CWiNs) Research Lab. Between 2011 and 2016, Dr. Rawat was with Georgia Southern University and Eastern Kentucky University. Dr. Rawat is a senior member of the IEEE and a member of the ACM and the ASEE.

Prof. Dr. rer. nat. Sabina Jeschke is head of the institute cluster IMA/ZLW & IfU at the RWTH Aachen University since 2009. She studied Physics, Computer Science, and Mathematics at the Berlin University of Technology. After research stays at the NASA Ames Research Center/California and the Georgia Institute of Technology/Atlanta, she gained a doctorate on "Mathematics in Virtual Knowledge Environments" in 2004. Following a junior professorship (2005–2007) at the TU Berlin with the construction and direction of its media center, she was the head of the Institute of Information Technology Services (IITS) for electrical engineering at the University of Stuttgart from May 2007 to May 2009, where, during the same period, she was also the director of the Central Information Technology Services (RUS). Her research areas are inter alia distributed artificial intelligence, robotics and automation, traffic and mobility, virtual worlds, and innovation and future research. Sabina Jeschke is vice dean of the Faculty of Mechanical Engineering of the RWTH Aachen University, chairwoman of the board of management of the VDI Aachen and member of the supervisory board of the Körber AG. She is a member and consultant of numerous committees and commissions, alumni of the German National Academic Foundation (Studienstiftung des deutschen Volkes), IEEE Senior and Fellow of the RWTH Aachen University. In Jul. 2014, the Gesellschaft für Informatik (GI) honored her with their award Deutschlands digitale Köpfe (Germany's digital heads). In Sep. 2015 she was awarded the Nikola-Tesla Chain by the International Society of Engineering Pedagogy (IGIP) for her outstanding achievements in the field of engineering pedagogy.

Prof. Dr.-Ing. Christian Brecher has been the Ordinary Professor for Machine Tools at the Laboratory for Machine Tools and Production Engineering (WZL) of the RWTH Aachen as well as the Director of the Department for Production Machines at the Fraunhofer Institute for Production Technology IPT since Jan. 1, 2004. Further, he is CEO of the Cluster of Excellence "Integrative Production Technology for High-Wage Countries," which is funded by the German Research Foundation (DFG). After finishing his academic studies in mechanical engineering, he started his professional career first as a research assistant and later as a team leader in the department for machine investigation and evaluation at the WZL. From 1999 to Apr. 2001, he was responsible for the department of machine tools in his capacity as a Senior Engineer. After a short spell as a consultant in the aviation industry, Professor Brecher was appointed in Aug. 2001 as the Director for Development at the DS Technologie Werkzeugmaschinenbau GmbH, Mönchengladbach, where he bore the responsibility for construction and development until Dec. 2003. Prof. Brecher has received numerous honors and awards including the Springorum Commemorative Coin, the Borchers Medal of the RWTH Aachen, the Scholarship Award of the Association of German Tool Manufacturers (Verein Deutscher Werkzeugmaschinenfabriken VDW) and the Otto Kienzle Memorial Coin of the Scientific Society for Production Technology (Wissenschaftliche Gesellschaft für Produktionstechnik WGP). Currently he is chairman of the scientific group for machines of CIRP, the International Academy for Production Engineering.

Foreword

Cyber-Physical Systems (CPS) have been a critical driving force for economic development during the beginning of the 21st century. An organized effort to define CPS research and development and to establish a sponsored research program commenced 10 years ago. In 2006, the Computer and Network System Division (CNS) of the US National Science Foundation (NSF) reviewed its research programs and decided to initiate a new direction by emphasizing engineering systems that are built from and depend upon the integration of computational and physical components. Consequently, the Computer System Research (CSR) program of CNS was revised and CPS became a thematic research area in CSR program. With the support from the NSF Directorate for Computer & Information Science & Engineering (CISE), the first call-for-proposal of this new research program was announced in Fall 2006 (NSF 07-504).

This first CPS research program received enthusiastic response from all academic, industrial, and governmental sectors. The first workshop about CPS research and development was held in Austin, Texas, in October 2006, with a mission to define the agenda of CPS research and development for the nation. The effort was quickly recognized by the President's Council of Advisors on Science and Technology (PCAST). In PCAST's 2007 report, CPS was given a top priority for substantial research investment. In 2008, the NSF elevated its support for CPS research by launching a fully fledged research program (NSF 08-611), which has now become a core NSF program jointly supported and managed by multiple agencies, including the Department of Homeland Security, the Department of Transportation, the National Aeronautics and Space Administration, the National Institutes of Health, and the Department of Agriculture. Many other countries and organizations have launched similar efforts, triggering a large-scale, globally organized effort on CPS research, education, and development. Consequently, the CPS community has had tremendous growth. Currently, in the United States alone, thousands of researchers and developers are actively working in this emerging field.

This book covers recent advances on Cyber-Physical System research and development, which I believe is the best way to celebrate the 10th anniversary of launching the first CPS program. The papers collected for this book not only report the results in CPS research and development accomplished in the last decade, but they also address open challenging research issues yet to be explored for the success of CPS long-term development.

W. Zhao
Chair professor and rector (president) of the University of Macau
Former director of NSF Computer and Network Systems Division

Preface

Cyber-physical systems (CPSs) are transforming the way people interact with engineered systems, just as the Internet transformed the way people interact with information. CPSs integrate cyber components (namely, sensing, computation, control, and networking) into physical components (namely, physical objects, infrastructure, and human users), connecting them to the Internet and to each other. CPSs are characterized by much higher capability, adaptability, scalability, resiliency, safety, security, and usability. CPS will drive innovation and competition in an ever-growing set of application domains, and enable a smart and connected world to address grand societal challenges.

Tremendous progress has been made in advancing CPS science, technology and engineering over the past decade since the term "CPS" emerged in 2006. An increasing number of scientists and engineers motivated by CPS are building a research community committed to advancing research and education in CPS and to transitioning CPS science and technology into engineering practice. However, there is not a book to present the state-of-the-art and the state of the practice of CPS from the perspective of systems science and engineering. This book serves the purpose of preparing scientists and engineers from various backgrounds for making CPS a reality.

This edited book, *Cyber-Physical Systems*: *Foundations*, *Principles*, *and Applications*, aims to present the scientific foundations and engineering principles needed to realize CPS, and various CPS applications. Towards this goal, this book is organized into three parts: Foundations, Principles, and Applications.

Part 1 is composed of nine chapters. In addition to the opportunities and challenges of CPS (Chapter 1), this part presents various scientific foundations of CPS, including real-time control and adaptation for CPS (Chapters 2 and 3), energy harvesting (Chapter 4), communications and networking (Chapter 5), big data (Chapter 6), computation (Chapter 7), decision-making (Chapter 8), CPS security and privacy (Chapter 9).

Part 2 is composed of 11 chapters. This part presents various engineering principles of CPS, including human-CPS interaction (Chapter 10), signal processing (Chapter 11), system design and verification (Chapters 12 and 19), CPS autonomy (Chapter 13), localization (Chapter 14), green communications and networking (Chapter 15), wireless charging (Chapter 16), game theory (Chapter 17), machine learning (Chapter 18), and smart and connected communities (Chapter 20).

Part 3 is composed of seven chapters. This part presents various CPS applications, spanning agriculture (Chapter 25), energy (Chapters 24 and 27), transportation (Chapters 22 and 23), and manufacturing (Chapters 21 and 26).

This book would not have been possible without the help of many people. First, we would like to thank all the contributors and reviewers of the book from all over the world. Second, we would like to thank our editorial assistants, Ruth Hausmann, Denis Özdemir, Alicia Dröge, all at RWTH Aachen University, who provided indispensable support at all stages of the editorial process of the book. Also we would like to thank our Editorial Project Manager, Amy Invernizzi at Morgan Kaufmann, Imprint of Elsevier, and our Senior Acquisitions Editor, Brian Romer at Elsevier, who helped shepherd us through the book-editing process. Third, we would like to acknowledge the German Research Foundation (DFG) for funding the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" of the RWTH Aachen University within the German Excellence Initiative. Further, we

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