Lecture Notes in Control and Information Sciences 433

For further volumes:
http://www.springer.com/series/642

Carla Seatzu, Manuel Silva,
and Jan H. van Schuppen (Eds.)

Control of Discrete-Event Systems

Automata and Petri Net Perspectives

Springer

Editors
Carla Seatzu
Department of Electrical
and Electronic Engineering
University of Cagliari
Cagliari
Italy

Jan H. van Schuppen
Centrum Wiskunde & Informatica
Amsterdam
The Netherlands

Manuel Silva
Department of Computer Science
and Systems Engineering
University of Zaragoza
Zaragoza
Spain

ISSN 0170-8643
e-ISSN 1610-7411
ISBN 978-1-4471-4275-1
e-ISBN 978-1-4471-4276-8
DOI 10.1007/978-1-4471-4276-8
Springer London Heidelberg New York Dordrecht

Library of Congress Control Number: 2012941741

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Control of discrete-event dynamic systems is the topic of this book. The aim is to provide an introduction to the field, starting at an elementary level and going to close to the current research front. The reader will find concepts, theorems, algorithms, and examples. Particularly addressed to Ph.D. students and junior researchers working on control of discrete-event dynamic systems (DEDS) and, more generally, on control theory, this monograph only presumes a little background of elementary topics of control theory. The chapters are almost all based on lectures of a summer school for Ph.D. students held in June 2011 in Cagliari, Sardinia, Italy.

Three related modeling formalisms of DEDS are covered: *automata*, *Petri nets*, and *systems in dioids*. The first focus of the book is on control of *decentralized* and of *distributed* DEDS, informally speaking composed by the interconnection of two or more subsystems. Most engineering systems are currently of this type. The second focus of the book deals with heavily loaded or populated DEDS, eventually distributed, for which the so called *state explosion* problem becomes particularly acute. Therefore it becomes important to consider 'coarse views' obtained through fluidization of the discrete event model. Those fluid or continuous over-approximated views of DEDS lead to special classes of hybrid systems.

Control theory for DEDS is motivated by the ordering of events or actions. Problems of control of DEDS arise in control engineering, computer engineering, and sciences. Areas in which DEDS control problems arise include manufacturing systems, automated guided vehicles, logistics, aerial vehicles, underwater vehicles, communication networks, mobile phones or chemical engineering systems, but also software systems on computers, laptops, and readers. The research into control of DEDS, heavily loaded or not, is thus well motivated by engineering but also theoretically quite deep.

A brief description of the book by parts and by chapters follows. The first part (nine chapters) concerns control of *automata*. After a chapter on modeling of engineering systems by automata (Chapter 1) there follows one with the concepts of automata, decidability, and complexity (Chapter 2). Supervisory control of automata is summarized first with respect to complete observations and subsequently with respect to partial observations (Chapters 3 and 4, respectively). Observers and diagnosers for automata, in particular distributed observers, are covered in Chapter 5. Supervisory control of distributed DEDS is introduced by three special cases in Chapter 6. That chapter is followed by one on distributed control with communication (Chapter 7) and one on coordination control (Chapter 8). Finally, Chapter 9 deals with timed automata.

The second part of the book addresses the control of *Petri nets*. It includes eleven chapters and can be seen as structured into two main parts: the first one, including eight chapters, dealing with discrete Petri nets; the second part, including three chapters, dealing with fluid relaxations. The former eight chapters can be divided into two blocks: the first six are devoted to *untimed* models, while the remaining two are related to *timed* models. In particular, Chapters 10 and 11 introduce basic concepts and structural analysis techniques. Chapters 12 and 13 are related to control. After considering supervisory control with languages specifications (Chapter 12), structural methods tailored for resource allocation problems are studied in the following one. Chapters 14 and 15 deals with diagnosis problems, the second one using net unfolding. Petri nets enriched with different temporal metrics and semantics are introduced in Chapter 16 and used in Chapter 17 for fault diagnosis, now on-line over timed models.

Chapters 18, 19 and 20 are based on fluid relaxation of DEDS. In particular, the fluid or continuous views of Petri nets are introduced in Chapter 18 on both untimed and timed models, dealing even with improvements of the relaxation with respect to the underlying discrete case. Finally, Chapters 19 and 20 are devoted to observability and diagnosis, and controllability and control, respectively.

The third and last part deals with the modeling and control of DEDS in dioids. A *dioid* is a mathematical structure with two operations, usually referred to as addition and multiplication, where the former, unlike in standard algebra, is idempotent. The most well known example for a dioid is the so-called max-plus algebra. Restricted classes of timed DEDS, in particular timed event graphs, become linear in a suitable dioid framework. For such systems, control does not involve logical decisions, only choices regarding the timing of events. They frequently appear in the context of manufacturing systems, but also arise in other engineering areas. Chapter 21 shows how to model timed event graphs in dioid frameworks and provides a detailed example from the area of high-throughput screening. Chapter 22 summarizes and illustrates control synthesis for systems in dioids.

Cagliari, Italy — *Carla Seatzu*
Zaragoza, Spain — *Manuel Silva*
Amsterdam, Netherlands — *Jan H. van Schuppen*
April 2012 — Editors

Acknowledgements

The editors thank the authors of the chapters of this book for their dedicated efforts to produce well readable chapters for the intended audience. They also thank the reviewers of the book for their efforts to provide comments to the authors on the chapters. A list of the reviewers is provided elsewhere in the book. They thank the Guest Editor Christoforos N. Hadjicostis for handling the review process of several chapters co-authored by one of the editors.

The European Commission is thanked for its financial support in part by the European Community's Seventh Framework Programme for the DISC Project under Grant Agreement number INFSO-ICT-224498. They also thank Alessandro Giua as the coordinator of the DISC project for his stimulation of the editors for this book.

The authors of Chapters 2, 3, 4, 6, and 8 acknowledge the financial support by the GAČR grants P103/11/0517 and P202/11/P028, and by RVO: 67985840.

The authors of Chapters 13, 18, 19 and 20 acknowledge the financial support by the Spanish CICYT under grant: DPI2010-20413.

Contents

Part I: Automata

List of Contributors

Béatrice Bérard
LIP6, Université Pierre & Marie Curie and CNRS UMR 7606
BC 169, 4 place Jussieu, 75005 Paris, France
e-mail: `Beatrice.Berard@lip6.fr`

René K. Boel
EESA SYSTeMS Research Group, Ghent University
Technologiepark 914, Zwijnaarde 9052, Belgium
e-mail: `rene.boel@ugent.be`

Olivier Boutin
Calle Santiago 2 – 4ºC, 11005 Cadiz, Spain
e-mail: `olivier.research@gmail.com`

Thomas Brunsch
Fachgebiet Regelungssysteme, TU Berlin, Sekr. EN11, Einsteinufer 17, 10587 Berlin, Germany.
Also: Laboratoire d'Ingénierie des Systèmes Automatisés, Université d'Angers, 62 Avenue Notre-Dame du Lac, 49000 Angers, France
e-mail: `brunsch@control.tu-berlin.de`

Maria Paola Cabasino
Department of Electrical and Electronic Engineering, University of Cagliari
Piazza D'Armi, 09123 Cagliari, Italy
e-mail: `cabasino@diee.unica.it`

José-Manuel Colom
Instituto de Investigación en Ingeniería de Aragón (I3A), University of Zaragoza
María de Luna 1, E-50018, Zaragoza, Spain
e-mail: `jm@unizar.es`

Bertrand Cottenceau
LUNAM, University of Angers, LISA, ISTIA
62 Av. Notre-Dame du Lac, 49000 Angers, France
e-mail: bertrand.cottenceau@univ-angers.fr

Angela Di Febbraro
Department of Mechanical Engineering, Energetics, Production, Transportation and Mathematical Models, University of Genova
Via Montallegro 1, 16145 Genova, Italy
e-mail: angela.difebbraro@unige.it

Eric Fabre
INRIA Rennes Bretagne Atlantique
Campus de Beaulieu, 35042 Rennes Cedex, France
e-mail: eric.fabre@inria.fr

Alessandro Giua
Department of Electrical and Electronic Engineering, University of Cagliari
Piazza D'Armi, 09123 Cagliari, Italy
e-mail: giua@diee.unica.it

Stefan Haar
INRIA/LSV, CNRS & ENS de Cachan
61, avenue du Président Wilson, 94235 CACHAN Cedex, France
e-mail: Stefan.Haar@inria.fr

Laurent Hardouin
Laboratoire d'Ingénierie des Systèmes Automatisés, Université d'Angers
62 Avenue Notre-Dame du Lac, 49000 Angers, France
e-mail: laurent.hardouin@istia.univ-angers.fr

George Jiroveanu
Transelectrica SA - Romanian National Power Grid Company
Brestei 5, 200581, Craiova, Romania
e-mail: george.jiroveanu@transelectrica.ro

Jorge Júlvez
Instituto de Investigación en Ingeniería de Aragón (I3A), University of Zaragoza
María de Luna 1, E-50018, Zaragoza, Spain
e-mail: julvez@unizar.es

Juan-Pablo López-Grao
Department of Computer Science and Systems Engineering, University of Zaragoza
María de Luna 1, E-50018, Zaragoza, Spain
e-mail: jpablo@unizar.es

Jan Komenda
Institute of Mathematics, Academy of Sciences of the Czech Republic
Žižkova 22, 616 62 Brno, Czech Republic
e-mail: komenda@math.cas.cz

Cristian Mahulea
Instituto de Investigación en Ingeniería de Aragón (I3A), University of Zaragoza
María de Luna 1, E-50018, Zaragoza, Spain
e-mail: cmahulea@unizar.es

Tomáš Masopust
Institute of Mathematics, Academy of Sciences of the Czech Republic
Žižkova 22, 616 62 Brno, Czech Republic
e-mail: masopust@math.cas.cz

Jörg Raisch
Fachgebiet Regelungssysteme, TU Berlin, Sekr. EN11, Einsteinufer 17, 10587 Berlin, Germany.
Also: Fachgruppe System-und Regelungstheorie, Max-Planck-Institut für Dynamik komplexer technischer Systeme, Magdeburg
e-mail: raisch@control.tu-berlin.de

S. Laurie Ricker
Department of Mathematics & Computer Science, Mount Allison University
67 York St. Sackville, NB Canada E4L 1E6
e-mail: lricker@mta.ca

Carla Seatzu
Department of Electrical and Electronic Engineering, University of Cagliari
Piazza D'Armi, 09123 Cagliari, Italy
e-mail: seatzu@diee.unica.it

Manuel Silva
Instituto de Investigación en Ingeniería de Aragón (I3A), University of Zaragoza
María de Luna 1, E-50018, Zaragoza, Spain
e-mail: silva@unizar.es

Jan H. van Schuppen
CWI, P.O. Box 94079, 1090 GB Amsterdam, Netherlands
e-mail: J.H.van.Schuppen@cwi.nl

C. Renato Vázquez
Instituto de Investigación en Ingeniería de Aragón (I3A), University of Zaragoza
María de Luna 1, E-50018, Zaragoza, Spain
e-mail: cvazquez@unizar.es

Reviewers

René K. Boel	Ghent University, Belgium
José Manuel Colom	University of Zaragoza, Spain
Isabel Demngodin	University Aix-Marseille, France
Mariagrazia Dotoli	Polytechnique of Bari, Italy
Maria Pia Fanti	Polytechnique of Bari, Italy
Anne-Kathrin Hess	Technical University of Berlin, Germany
Richard Hill	University of Detroit Mercy, Michigan, USA
Jorge Júlvez	University of Zaragoza, Spain
Pia L. Kempker	VU University Amsterdam, Amsterdam, Netherlands
Jan Komenda	Academy of Sciences, Brno, Czech Republic
Xenofon Koutsoukos	Vanderbilt University, Nashville, Tennessee, USA
Dimitri Lefebvre	University Le Havre, Strasbourg, France
Feng Lin	Wayne State University, Detroit, Michigan, USA
Jan Lunze	University of Bochum, Germany
Kristian Lyngbaek	Palo Alto Research Center, Palo Alto, California, USA
Cristian Mahulea	University of Zaragoza, Spain
Tomáš Masopust	Academy of Sciences, Brno, Czech Republic
José Merseguer	University of Zaragoza, Spain
Behrang Monajemi Nejad	Technical University of Berlin, Germany
Geert Jan Olsder	Delft University of Technology, Delft, Netherlands
Laurie Ricker	Mount Allison University, Sackville, NB Canada
Karen Rudie	Queen's University, Kingston, Canada
Carla Seatzu	University of Cagliari, Italy
Manuel Silva	University of Zaragoza, Spain
Rong Su	Nanyang Technological University, Singapore
John Thistle	University of Waterloo, Ontario, Canada
Ton van den Boom	Delft University of Technology, Delft, Netherlands
Jan H. van Schuppen	CWI, Amsterdam, Netherlands
Renato Vázquez	University of Zaragoza, Spain
Tiziano Villa	University of Verona, Italy
Tae-Sic Yoo	Idaho National Laboratory, Idaho, USA
Liewei Wang	University of Zaragoza, Spain
Xu Wang	University of Zaragoza, Spain
Yorai Wardi	Georgia Institute of Technology, Atlanta, Georgia, USA
Thomas Wittmann	University of Erlangen, Germany

Acronyms

AGV	Automated Guided Vehicle
BIC	Bounded Input Controllable
BRG	Basis Reachability Graph
CDFG	Controlled Deterministic Finite Generator
CPN	Continuous Petri Net
CS	Controllability Space
CSS	Cooperating Sequential System
CTMC	Continuous Time Markov Chain
DcontPN	Distributed Continuous Petri Net
DEDS	Discrete Event Dynamic Systems
DES	Discrete Event System
DFA	Deterministic Finite Automaton
DFG	Deterministic Finite Generator
DFMeA	Deterministic Finite Mealy Automaton
DFMoA	Deterministic Finite Moore Automaton
DTPN	Deterministic Timed Petri Net
DuSCOP	Dual Supervisory Control and Observation
ELCP	Extended Linear Complementarity Problem
EQ	Equal Conflict
FMS	Flexible Manufacturing System
FSM	Finite State Machine
FSS	Finite Server Semantics
GTS	Graph Transformation System
HC	Hamiltonian Circuit
HTS	High-Throughput Screening
ILP	Integer Linear Programming
ILPP	Integer Linear Programming Problem
ISS	Infinite Server Semantics
JF	Join Free
LPP	Linear Programming Problem
L-S^3PR	Linear System of Simple Sequential Processes with Resources

MPC	Model Predictive Control
MPN	Markovian Petri Net
MRI	Magnetic Resonance Imaging
MTS	Mono-T-Semiflow
MVN	Modified Verifier Net
NDFG	Nondeterministic Finite Generator
NDFMeA	Nondeterministic Finite Mealy Automaton
NDFMoA	Nondeterministic Finite Moore Automaton
NFA	Nondeterministic Finite Automaton
NS-RAS	Non-Sequential Resource Allocation System
OCC	Output Control Consistent
PC^2R	Processes Competing for Conservative Resources
PDA	PushDown Automaton
PLC	Programmable Logic Controller
PN	Petri Net
QPP	Quadratic Programming Problem
RAP	Resource Allocation Problem
RAS	Resource Allocation System
SAT	Satisfiability
SB	Structurally Bounded
SCTdMG	Strongly Connected Timed Marked Graph
SL	Structurally Live
SPQR	System of Processes Quarrelling over Resources
S^3PR	System of Simple Sequential Processes with Resources
S-RAS	Sequential Resource Allocation System
STdPN	Stochastic Timed Petri Net
TCPN	Timed Continuous Petri Net
TdPN	Timed Petri Net
TEG	Timed Event Graph
TM	Turing Machines
TMG	Timed Marked Graph
TPN	Time Petri Net
VN	Verifier Net
WP	Weighted Path