Control Theory of Digitally Networked Dynamic Systems

Jan Lunze
Editor

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Editor
Jan Lunze
Lehrstuhl für Automatisierungstechnik und
Prozessinformatik
Fakultät für Elektrotechnik und
Informationstechnik
Ruhr-Universität Bochum
Bochum
Germany

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Preface

Modern means of communication make it easy to connect system components whenever information links may contribute to improving the overall system performance. Actuators, sensors and controllers can now exchange information from nearly any place within a technological system, and wireless connections allow to implement advanced control technology for mobile objects. Due to this flexibility, a new challenge for control theory is to elaborate systematic ways for the selection of information structures that are suitable for a given control task.

This new freedom in choosing the information topology of control systems is associated with some nondeterminism of the behavior of digital networks. As many networks used for control purposes act simultaneously as communication medium for other tasks, time delays in the delivery of the information or packet loss regularly occur and the controllers have to be made tolerant with respect to such imperfections.

Both, the flexibility of the communication structure and the imperfection of the communication links pose new challenges for the design and the implementation of control systems and have brought about *networked control systems* as a new area of control theory. This book gives a concise introduction to this area and describes new modelling paradigms, analysis methods for digitally networked dynamic systems, and design methods for distributed controllers. It provides an overview of the problems, methods and application areas that have been tackled in the recent past and which will initiate new development directions in industry in the near future.

Networked control systems cannot be handled with traditional methods for two reasons. First, the *event-driven mode of operation* of networked systems violates the precondition of discrete-time control theory that data is processed and transmitted with a constant sampling rate. Several chapters of this book are concerned with control problems in which event generators rather than clocks initiate the next communication, computation and control steps.

Second, the structure of the communication network is usually not predefined but the subject of control design. The data links may even adjust themselves to the needs and the technological constraints during operation. Under these circumstances, the question "*Which information is necessary to solve a control task?*" has stimulated the second leading research line of this book.

The tight combination of communication and control has direct consequences for the development of advanced control systems in industry. Networked systems open the way towards novel application areas like multi-agent systems that are controlled over wireless communication networks or smart grids of intelligent components that are supervised remotely. It broadens the importance of control in intelligent transportation systems, health care services, smart buildings, or telerobotics, just to name a few. Some of these applications are discussed in this book.

Structure and readership. The book is structured into seven chapters, each of which is devoted to one of the research problems that are currently discussed in the international literature and at all major control conferences:

1. **Introduction to networked control systems**
   describes the motivation and surveys the main problems to be solved by the control theory of networked systems.

2. **Analysis of networked systems**
   presents important properties of dynamic systems that are controlled over digital communication networks.

3. **Distributed estimation and control**
   describes methods for state estimation and optimization of systems that are composed of subsystems with local control stations, which communicate over a data network.

4. **Distributed and networked model predictive control**
   develops methods for distributed control algorithms that tolerate time delays and packet loss.

5. **Event-based control**
   surveys six different approaches to replace the traditional periodic sampling by event-based triggering schemes.

6. **Multi-agent systems**
   proposes new methods for controlling systems that have to satisfy a common control goal.

7. **Wireless networking for control**
   investigates the requirements on the digital communication network, which is used for control purposes, and describes methods for the cross-design of control and communication.

The book is written as a **survey of recent results** on networked control systems with references to numerous journal papers and conference presentations, in which the ideas have been originally presented together with the formal proofs. Emphasis is laid on the presentation of the main results and the illustration of these results by examples. Each chapter starts with an introduction to the problems considered, which includes a statement on how the chapter extends the current knowledge about networked control systems.

The results are presented in a uniform style, notation and terminology. Many cross-references show how the different lines of research belong together. The references are organized as a comprehensive list at the end of the book.

The intended readers of the book are graduate students, PhD students and researchers in control, communication, or mathematics, as well as practicing engineers with knowledge in systems theory who want to get an introduction to the main problems of networked control together with an up-to-date survey of recent results. Interesting practical examples illustrate the applicability of the methods and **extensive bibliographical notes** point to the origins of the presented ideas and the current research lines. The evaluation of the methods and the application results should help the reader to assess the available methods and the limits of the present knowledge about networked control with respect to their particular field of interest.

Priority Program 1305 of the German Research Foundation. The book presents, in a concise way, the results obtained by the participants of the Priority Program 1305 on *Control Theory of Digitally Networked Dynamic Systems* of the German Research Foundation (DFG). In this program, 17 PhD students have been working between 2007 and 2013 in 13 different research groups situated in control, mathematics, or communication departments at German universities. The book describes the research interests, the results, and the common expertise of 42 authors. All sections are co-authored by several researchers who have contributed to the corresponding topic. The authors are mentioned in alphabetic order with the responsible author first.

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Contents

List of Contributors

Frank Allgöwer
University of Stuttgart,
Institute for Systems Theory and Automatic Control,
Pfaffenwaldring 9,
70550 Stuttgart, Germany
frank.allgower@ist.uni-stuttgart.de
(Sections 4.1, 4.2, 4.3, 6.4, 7.3)

Rainer Blind
University of Stuttgart,
Institute for Systems Theory and Automatic Control,
Pfaffenwaldring 9,
70550 Stuttgart, Germany
rainer.blind@ist.uni-stuttgart.de
(Section 7.3)

Mathias Bürger
University of Stuttgart,
Institute for Systems Theory and Automatic Control,
Pfaffenwaldring 9,
70550 Stuttgart, Germany
mathias.buerger@ist.uni-stuttgart.de
(Section 6.4)

Alain Chamaken
University of Kaiserslautern,
Institute of Automatic Control,
Erwin Schrödinger Str. 12,
67653 Kaiserslautern, Germany
chamaken@eit.uni-kl.de
(Section 7.2)

Fritz Colonius
University of Augsburg,
Department of Mathematics,
Universitätsstr. 14,
86159 Augsburg, Germany
fritz.colonius@math.uni-augsburg.de
(Sections 2.1, 2.3)

Ozan Demir
Ruhr-Universität Bochum,
Institute of Automation and Computer Control,
Universitätsstr. 150,
44780 Bochum, Germany
demir@atp.rub.de
(Section 6.5)

Frederik Deroo
TU München,
Institute of Information-oriented Control,
Arcisstr. 21,
80333 München, Germany
fred.deroo@tum.de
(Section 3.3)

Rolf Findeisen
Otto-von-Guericke University Magdeburg,
Institute for Systems Theory and Automatic Control,
Universitätsplatz 2,
39106 Magdeburg, Germany
rolf.findeisen@ovgu.de
(Sections 4.1, 4.2, 4.3)

Jörg Fischer
Karlsruhe Institute of Technology,
Institute for Anthropomatics,
Intelligent Sensor-Actuator-Systems Laboratory,
Adenauerring 2,
76131 Karlsruhe, Germany
joerg.fischer@kit.edu
(Section 4.5)

Reinhard Gotzhein
University of Kaiserslautern,
Department of Computer Science,
Postfach 3049,
67653 Kaiserslautern, Germany
gotzhein@informatik.uni-kl.de
(Sections 7.1, 7.2)

Dominic Groß
University of Kassel,
Control and System Theory,
Wilhelmshöher Allee 73,
34121 Kassel, Germany
dgross@uni-kassel.de
(Section 4.4)

Lars Grüne
University of Bayreuth,
Chair of Applied Mathematics,
Universitätsstr. 30,
95440 Bayreuth, Germany
lars.gruene@uni-bayreuth.de
(Sections 1.3, 4.1, 4.2, 4.3, 5.1, 5.4, 5.6)

Uwe D. Hanebeck
Karlsruhe Institute of Technology,
Institute for Anthropomatics,
Chair of Intelligent Sensor-Actuator-Systems,
Adenauerring 2,
76131 Karlsruhe, Germany
uwe.hanebeck@kit.edu
(Sections 4.1, 4.5)

Andreas Haupt
University of Kaiserslautern,
Institute of Automatic Control,
Erwin Schrödinger Str. 12,
67653 Kaiserslautern, Germany
haupt@eit.uni-kl.de
(Section 7.2)

Uwe Helmke
University of Würzburg,
Department of Mathematics,
Emil-Fischer-Str. 40,
97074 Würzburg, Germany
helmke@mathematik.uni-wuerzburg.de
(Sections 2.1, 2.2, 6.1, 6.3)

Anna von Heusinger
University of Würzburg,
Department of Mathematics,
Emil-Fischer-Str. 40,
97074 Würzburg, Germany
heusinger@mathematik.uni-wuerzburg.de
(Section 6.3)

Sandra Hirche
TU München,
Institute of Information-oriented Control,
Arcisstr. 21,
80333 München, Germany
hirche@tum.de
(Sections 3.3, 5.1, 5.7)

Jens Jordan
University of Würzburg,
Department of Mathematics,
Emil-Fischer-Str. 40,
97074 Würzburg, Germany
jordan@mathematik.uni-wuerzburg.de
(Section 2.2)

Oliver Junge
TU München,
Department of Mathematics,
Boltzmannstr. 3,
85748 Garching b. München, Germany
oj@tum.de
(Sections 5.1, 5.4, 5.6)

Christoph Kawan
University of Augsburg,
Department of Mathematics,
Universitätsstr. 14,
86159 Augsburg, Germany
christoph.kawan@math.uni-augsburg.de
(Section 2.3)

Benjamin Kern
Otto-von-Guericke University Magdeburg,
Institute for Systems Theory and Automatic Control,
Universitätsplatz 2,
39106 Magdeburg, Germany
benjamin.kern@ovgu.de
(Sections 4.1, 4.2, 4.3)

Péter Koltai
TU München,
Department of Mathematics,
Boltzmannstr. 3,
85748 Garching b. München, Germany
koltai@ma.tum.de
(Section 5.6)

Marc Krämer
University of Kaiserslautern,
Department of Computer Science,
Postfach 3049,
67653 Kaiserslautern, Germany
kraemer@informatik.uni-kl.de
(Section 7.2)

Daniel Lehmann
KTH Royal Institute of Technology,
Automatic Control,
Osquldas väg 10,
100 44 Stockholm, Sweden
dlehmann@kth.se
(Section 5.2)

Lothar Litz
University of Kaiserslautern,
Institute of Automatic Control,
Erwin Schrödinger Str. 12,
67653 Kaiserslautern, Germany
litz@eit.uni-kl.de
(Sections 7.1, 7.2)

Boris Lohmann
TU München,
Institute of Automatic Control,
Boltzmannstr. 15,
85748 Garching b. München, Germany
lohmann@tum.de
(Section 3.2)

Jan Lunze
Ruhr-Universität Bochum,
Institute of Automation and Computer Control,
Universitätsstr. 150,
44780 Bochum, Germany
lunze@atp.rub.de
(Sections 1.1, 1.2, 3.1, 5.1, 5.2, 5.3, 6.1, 6.2, 6.5)

Martin Meinel
TU München,
Department of Mathematics,
Boltzmannstr. 3,
85748 Garching b. München, Germany
meinel@ma.tum.de
(Section 3.3)

Adam Molin
TU München,
Institute of Information-oriented Control,
Barer Str. 21,
80333 München, Germany
adam.molin@tum.de
(Section 5.7)

Matthias A. Müller
University of Stuttgart,
Institute for Systems Theory and Automatic Control,
Pfaffenwaldring 9,
70550 Stuttgart, Germany
matthias.mueller@ist.uni-stuttgart.de
(Section 4.3)

Jürgen Pannek
Universität der Bundeswehr München,
Institut für Mathematik und Rechneranwendung,
Werner-Heisenberg-Weg 39,
85577 Neubiberg b. München, Germany
juergen.pannek@unibw.de
(Sections 4.2, 4.3)

Peter Philipp
TU München,
Institute of Automatic Control,
Boltzmannstr. 15,
85748 Garching b. München, Germany
peter.philipp@tum.de
(Section 3.2)

Marcus Reble
University of Stuttgart,
Institute for Systems Theory and Automatic Control,
Pfaffenwaldring 9,
70550 Stuttgart, Germany
reble@ist.uni-stuttgart.de
(Sections 4.1, 4.2)

Rudolf Sailer
University of Würzburg,
Department of Mathematics,
Emil-Fischer-Str. 40,
97074 Würzburg, Germany
sailer@mathematik.uni-wuerzburg.de
(Sections 2.4, 5.5)

Manuela Sigurani
University of Bayreuth,
Chair of Applied Mathematics,
Universitätsstr. 30,
95440 Bayreuth, Germany
manuela.sigurani@uni-bayreuth.de
(Section 5.6)

René Schuh
Ruhr-Universität Bochum,
Institute of Automation and Computer Control,
Universitätsstr. 150,
44780 Bochum, Germany
schuh@atp.rub.de
(Section 6.5)

Christian Stöcker
Ruhr-Universität Bochum,
Institute of Automation and Computer Control,
Universitätsstr. 150,
44780 Bochum, Germany
stoecker@atp.rub.de
(Sections 5.3, 5.8)

Olaf Stursberg
University of Kassel,
Control and System Theory,
Wilhelmshöher Allee 73,
34121 Kassel, Germany
stursberg@uni-kassel.de
(Sections 4.1, 4.4)

Michael Ulbrich
TU München
Chair of Mathematical Optimization,
Boltzmannstr. 3,
85748 Garching b. München, Germany
mulbrich@ma.tum.de
(Section 3.3)

Paolo Varutti
Otto-von-Guericke University Magdeburg,
Institute for Systems Theory and Automatic Control,
Universitätsplatz 2,
39106 Magdeburg, Germany
paolo.varutti@ovgu.de
(Sections 4.1, 4.2, 4.3)

Fabian Wirth
University of Würzburg,
Department for Mathematics
Emil-Fischer-Str. 40,
97074 Würzburg, Germany
wirth@mathematik.uni-wuerzburg.de
(Sections 2.1, 2.4, 5.1, 5.5)

Karl Worthmann
University of Bayreuth,
Chair of Applied Mathematics,
Universitätsstr. 30,
95440 Bayreuth, Germany
karl.worthmann@uni-bayreuth.de
(Sections 4.1, 4.2, 4.3)

Notation

The symbols are chosen according to the following conventions. Lower-case letters like x, a or t denote scalar values or signals, boldface letters like $\boldsymbol{x}$ or $\boldsymbol{y}$ vectors and boldface upper-case letters such as $\boldsymbol{A}$, $\boldsymbol{B}$ matrices. Accordingly, the elements x_1,...,x_n of a vector $\boldsymbol{x}$ or a_{11}, a_{12},..., a_{mn} of a matrix $\boldsymbol{A}$ are represented by italics. Sets are symbolized by calligraphic letters like $\mathcal{F}$ and $\mathcal{Z}$. $\boldsymbol{O}$ or $\mathbf{0}$ denotes a zero matrix or a zero vector of appropriate dimension, respectively. For a matrix $\boldsymbol{E}$, e_{ij} or $[\boldsymbol{E}]_{ij}$ denotes the ij-th element. $\mathbf{1}$ is the vector of appropriate size with unity elements:

$$\mathbf{1} = \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix}.$$

$\mathrm{diag}(a_1, ..., a_n)$ is a diagonal matrix with diagonal entries a_1,...,a_n. It is sometimes abbreviated as $\mathrm{diag}\, a_i$. In structured matrices, sometimes the vanishing blocks are suppressed for the clarity of notation.

The inequality $\boldsymbol{P} > 0$ is interpreted in two different ways, which is explicitly mentioned. In connection with optimal control or linear matrix inequalities, it states that the matrix $\boldsymbol{P}$ is positive definite. For this interpretation also the symbol $\boldsymbol{P} \succ 0$ is used. Alternatively, the sign $>$ has to be interpreted as an elementwise relation saying that all elements of the matrix $\boldsymbol{P}$ are positive ($p_{ij} > 0$ for all i, j).

Book Homepage. The book homepage at `www.atp.rub.de/buch/SPP` provides further information on the subject of this book.