



Collaborative Project
Small-medium-scale focused research project (STREP)

Grant Agreement n. 224117

FP7-ICT-2007-2

WIDE

Decentralized Wireless Control of Large-Scale Systems

Starting date: 01 September 2008

Duration: 3 years

Deliverable number	D6.7
Title	Handbook on Networked Control Systems
Work package	WP6 - Dissemination and exploitation of results (RTD)
Due date	M24
Actual submission date	01/09/2010
Lead contractor for this deliverable	KTH
Author(s)	D. Barcelli barcelli@dii.unisi.it A. Bemporad bemporad@ing.unitn.it W.P.M.H. Heemels W.P.M.H.Heemels@tue.nl Mikael Johansson mikaelj@ee.kth.se
With the help of	
Revision	v1.0 (September 27, 2010)

Dissemination Level

PU	Public
PP	Restricted to other programme participants (including the Commission Services)
RE	Restricted to a group specified by the consortium (including the Commission Services)
→ CO	Confidential, only for members of the consortium (including the Commission Services)

Executive summary

Report describing the status of the Networked Control Systems handbook.

1 Handbook

The handbook is currently in the final stages of the production phase, the galley proofs were corrected during a few iterations in September 2010. Figure 1 shows the book cover. A printed copy of the book will be available within the next two months, and will be advertised at the Springer stand during the Conference on Decision and Control, December 2010, Atlanta (GA).

A final draft of the book in PDF will be available at the review meeting. It cannot be included here due to copyright issues.

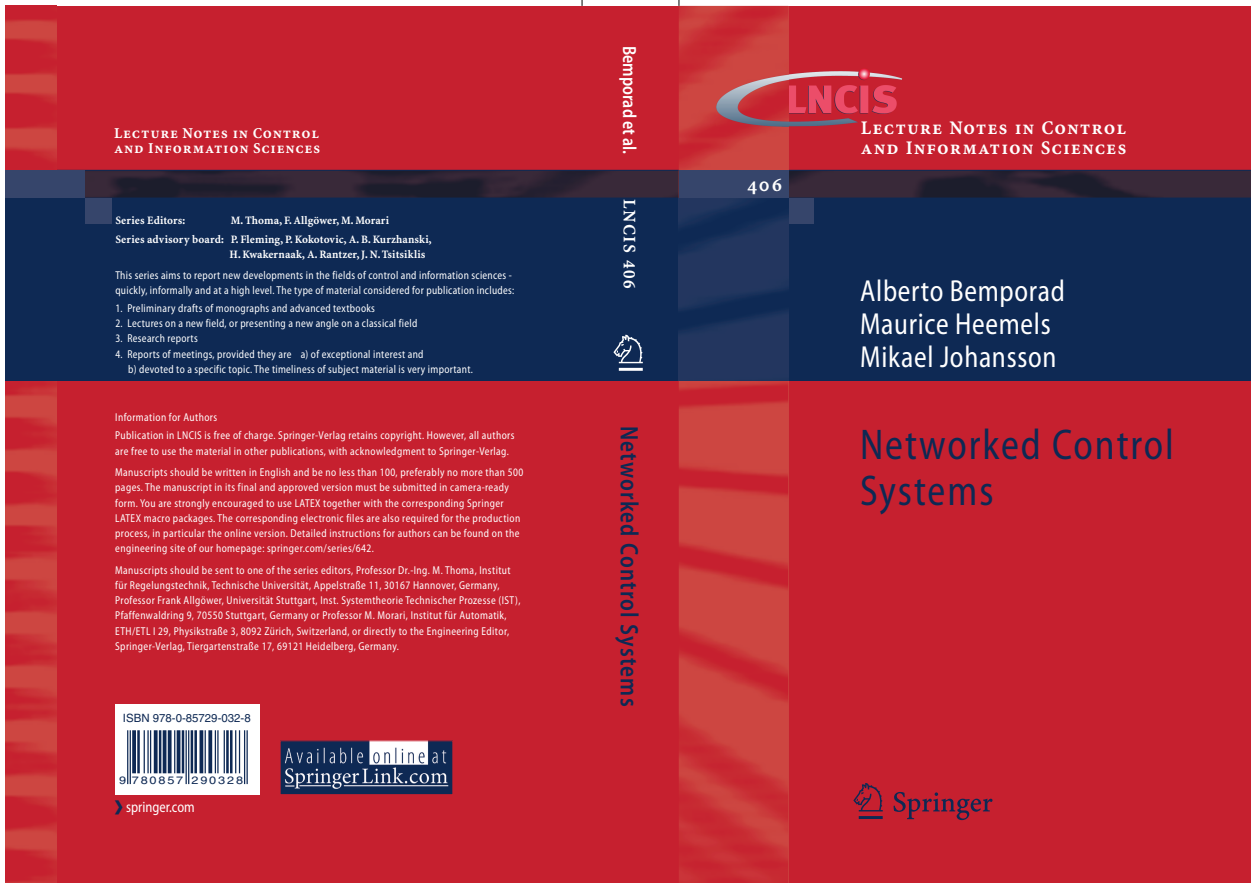


Figure 1: Cover of the Handbook on Networked Control Systems

Foreword

This book finds its origin in the WIDE PhD School on Networked Control Systems, which we organized in July 2009 in Siena, Italy. Having gathered experts on all the aspects of networked control systems, it was a small step to go from the summer school to the book, certainly given the enthusiasm of the lecturers at the school. We felt that a book collecting overviews on the important developments and open problems in the field of networked control systems could stimulate and support future research in this appealing area. Given the tremendous current interests in distributed control exploiting wired and wireless communication networks, the time seemed to be right for the book that lies now in front of you.

The goal of the book is to set out the core techniques and tools that are available for the modeling, analysis and design of networked control systems. Roughly speaking, the book consists of three parts. The first part presents architectures for distributed control systems and models of wired and wireless communication networks. In particular, in the first chapter important technological and architectural aspects on distributed control systems are discussed. The second chapter provides insight in the behavior of communication channels in terms of delays, packet loss and information constraints leading to suitable modeling paradigms for communication networks.

The second part focuses on decentralized and distributed control, estimation and optimization. The network aspect is here that not all information is available in one central controller, estimator or optimizer, but local agents have only limited information of the overall control, estimation or optimization problem and still aim at solving the central problem in an appropriate manner. Although the information might be limited for each individual agent, it is assumed that communication is ideal and imperfections such as communication delays, possible loss of information and quantization effects are ignored. Chapter 3 discusses distributed estimation and consensus problems and the fourth chapter surveys distributed optimization techniques. Chapter 5 and 6 provide overviews on decentralized and distributed control. The emphasis in chapter 5 is on decentralized and distributed model predictive control techniques.

While communication imperfections induced by the presence of a non-ideal and uncertain network channel are ignored in the second part of the book, they form the main topic of the third part. Methods for stability analysis and controller synthesis of control loops closed over communication channels are treated in chapter 7. Using appropriate models of networked control systems it is investigated how network-induced phenomena such as varying delays, varying sampling intervals, data loss and communication constraints influence the stability and performance of control loops. Chapter 8 studies the effects of the limited capacity of channels, *e.g.* limited bandwidth, on feedback control. Fundamental limitations in control using quantized information are discussed in detail in this chapter. Finally, chapter 9 treats control systems that do not use the conventional periodic sampling, but update their information based on specific discrete events. The resulting event-triggered feedback controllers have the potential to reduce the amount of communication required in networked systems while preserving the overall system's stability and performance. This last chapter provides in-depth analysis techniques for event-triggered control, estimation and optimization.

In summary, this book provides overviews on many facets of networked control systems. The writing of the book would have been impossible without the enormous efforts of the lecturers of the school and we are certainly indebted to them. We are also grateful to Davide Barcelli, who was responsible for the technical assembly of the separate contributions of the authors into one book. Finally, the support by the European Commission through the FP7-ICT-2007-2 thematic programme under project WIDE "Decentralized and wireless control of large-scale systems" (project no. 224168) for writing this book is greatly acknowledged.

We hope that you will enjoy reading this book and that it will be of assistance in your own research endeavors in the area of networked control systems.

April 2010

Alberto Bemporad, Trento, Italy
Maurice Heemels, Eindhoven, The Netherlands
Mikael Johansson, Stockholm, Sweden

Contents

1	The Importance, Design and Implementation of a Middleware for Networked Control Systems	1
	<i>Kyoung-Dae Kim, P.R. Kumar</i>	
1.1	Introduction	1
1.2	Networked Control Systems	2
1.2.1	Domain Characteristics	2
1.2.2	Domain Requirements	4
1.3	Middleware for Networked Control Systems	5
1.3.1	Middleware Fundamentals	5
1.3.2	Etherware	7
1.4	Real-Time Operation of Networked Control Systems	10
1.4.1	Real-Time System Fundamentals	10
1.4.2	Real-Time Support in Etherware	14
1.5	Reliability for Networked Control Systems	17
1.5.1	Fundamentals of Reliable System	17
1.5.2	Reliability Support in Etherware	20
1.6	Case Study: Networked Inverted Pendulum Control System	22
1.6.1	Inverted Pendulum Control System	22
1.6.2	Periodic Control under Stress	23
1.6.3	Runtime System Management	25
1.7	Conclusion	27
	References	28
2	Wireless Networking for Control: Technologies and Models	31
	<i>Mikael Johansson, Riku Jäntti</i>	
2.1	Introduction	31
2.2	Understanding the Single Link	32
2.2.1	Wireless Propagation and Outage	32

2.2.2	Markov Models for the Wireless Channel	39
2.2.3	The ISM Band, Co-existence and Interference	40
2.2.4	Means for Increasing Reliability	42
2.3	Multiple Links: Medium Access Control	45
2.3.1	Scheduled Medium Access: TDMA and FDMA	47
2.3.2	Contention-Based Medium Access: Aloha, CSMA and Beyond	48
2.3.3	Dynamic Access Scheduling via Polling and Reservation	52
2.3.4	Energy-Efficient Medium Access Control	53
2.4	From Single Links to Network: The Upper Networking Layers	54
2.4.1	Topologies and Multi-hop Communications	54
2.4.2	Routing	58
2.4.3	Transport Layer Protocols and Traffic Patterns	61
2.4.4	Standards and Specifications for Industrial Wireless Networking	62
2.5	Control Relevant Models of Latency and Loss	66
2.6	Conclusions	69
	References	70
3	A Survey on Distributed Estimation and Control Applications Using Linear Consensus Algorithms	75
	<i>Federica Garin, Luca Schenato</i>	
3.1	Introduction	75
3.2	Linear Consensus Algorithms: Definitions and Main Results	77
3.2.1	Analysis	78
3.2.2	Design	82
3.3	Estimation and Control Problems as Average Consensus	89
3.3.1	Parameter Estimation with Heterogeneous Sensors	89
3.3.2	Node Counting in a Network	90
3.3.3	Generalized Averages	90
3.3.4	Vehicle Rendezvous	91
3.3.5	Least Squares Data Regression	91
3.3.6	Sensor Calibration	92
3.3.7	Kalman Filtering	93
3.4	Control-Based Performance Metrics for Consensus Algorithms	95
3.4.1	Performance Indices	95
3.4.2	Evaluation and Optimization of Performance Indices	100
3.5	Conclusion	104
	References	104

4	Distributed Optimization and Games: A Tutorial Overview	109
	<i>Bo Yang, Mikael Johansson</i>	
4.1	Introduction	109
4.2	Convex Optimization Using First-Order Methods	110
4.2.1	Gradient Methods for Smooth Problems	111
4.2.2	Subgradient Methods for Non-smooth Problems	114
4.2.3	Incremental Subgradient Methods	115
4.3	Decomposition Techniques	117
4.3.1	Dual Decomposition	118
4.3.2	Augmented Lagrangian and Proximal Point Methods	122
4.3.3	Primal Decomposition	124
4.4	Networked Optimization	126
4.4.1	Networked Optimization via Dual Decomposition	127
4.4.2	Consensus-Subgradient Schemes	129
4.4.3	Networked Incremental Subgradient Methods	132
4.5	Game Theory in Distributed Optimization	133
4.5.1	Basics of Game Theory	133
4.5.2	Properties of Nash Equilibria	134
4.6	Dynamics of Gradient Algorithms	139
4.6.1	Connection between Lyapunov Functions and Objective Functions	140
4.6.2	Krasovskii's Method	142
4.6.3	Non-strictly Convex Problem	143
4.7	Conclusions	144
	References	145
5	Decentralized Model Predictive Control	149
	<i>Alberto Bemporad, Davide Barcelli</i>	
5.1	Introduction	149
5.2	Model Predictive Control	152
5.3	Existing Approaches to DMPC	153
5.3.1	DMPC Approach of Alessio, Barcelli, and Bemporad	154
5.3.2	DMPC Approach of Jia and Krogh	161
5.3.3	DMPC Approach of Venkat, Rawlings, and Wright	162
5.3.4	DMPC Approach of Dunbar and Murray	163
5.3.5	DMPC Approach of Keviczky, Borrelli, and Balas	164
5.3.6	DMPC Approach of Mercangöz and Doyle	165
5.3.7	DMPC Approach of Magni and Scattolini	166
5.4	Example of Decentralized Temperature Control in a Railcar	166
5.4.1	Example Description	166
5.4.2	Simulation Results	168

5.5	Hierarchical MPC	172
5.5.1	Problem Description	172
5.5.2	Illustrative Example	173
5.6	Conclusions	175
	References	176
6	Decentralized Control	179
	<i>John Swigart, Sanjay Lal</i>	
6.1	Motivating Examples	179
6.1.1	Vehicle Spacing	180
6.1.2	Witsenhausen's Counterexample	181
6.2	Static Problems	182
6.2.1	Solution of the Multi-vehicle Problem	184
6.2.2	Nonlinear Policies	185
6.3	Dynamic Problems	188
6.3.1	Quadratic Invariance	190
6.3.2	Skyline Information Structures	191
6.3.3	Control of Networks	193
6.3.4	Non-convex Systems	195
6.3.5	Unstable Plants	196
6.4	Solving the Optimization Problem	196
6.4.1	Spectral Factorization	197
6.4.2	Solution of the Two-Player Problem	198
6.5	Summary	199
	References	200
7	Stability and Stabilization of Networked Control Systems	203
	<i>W.P.M.H. Heemels, N. van de Wouw</i>	
7.1	Introduction	203
7.2	Overview of Existing Approaches	205
7.2.1	The Types of Network-Induced Phenomena	205
7.2.2	Different Approaches in Modeling/Analysis of NCS	206
7.3	NCS with Delays, Varying Sampling Intervals and Packet Loss ...	209
7.3.1	Description of the NCS	209
7.3.2	Discrete-Time Modeling Approaches	211
7.3.3	Sampled-Data Modeling Approaches	223
7.4	NCS Including Communication Constraints	228
7.4.1	Continuous-Time (Emulation) Approaches	228
7.4.2	Discrete-Time Approach	238
7.4.3	Comparison of Discrete-Time and Continuous-Time Approaches	245
7.5	Conclusions	246
	References	248

8	Feedback Control over Limited Capacity Channels	255
	<i>Hideaki Ishii</i>	
8.1	Introduction	255
8.2	Control under Capacity Constraints: System Setup and Background	258
8.3	The Minimum Data Rate for Stabilization	261
8.3.1	Problem Formulation and Initial Results	261
8.3.2	Dynamic Quantizers	263
8.3.3	The Solution to the Minimum Data Rate Problem	265
8.4	The Coarsest Quantization for Stabilization	267
8.4.1	The Coarsest Quantizers	268
8.4.2	The Coarsest Quantizer for Stabilization over Lossy Channels	272
8.4.3	Quantized Adaptive Control for Uncertain Systems	276
8.5	Information Theoretic Approach to Bode's Integral Formula	282
8.5.1	Bode's Integral Formula for Complementary Sensitivity Functions	283
8.5.2	Entropy and Mutual Information	284
8.5.3	Characterization of Complementary Sensitivity Properties	285
8.6	Conclusion	288
	References	289
9	Event-Triggered Feedback in Control, Estimation, and Optimization	293
	<i>Michael Lemmon</i>	
9.1	Introduction	293
9.2	Mathematical Preliminaries	297
9.3	Event-Triggered Feedback in Embedded Control Systems	302
9.4	Event-Triggered Feedback in Networked Control Systems	320
9.5	Event-Triggered Estimation	330
9.6	Event-Triggered Approaches to Optimization	340
9.7	Research Issues	350
	References	353
	Index	359

List of Contributors

Davide Barcelli

Department of Information
Engineering, University of Siena, Italy
barcelli@dii.unisi.it

Alberto Bemporad

Department of Mechanical and Structural Engineering,
University of Trento, Italy
bemporad@ing.unitn.it

Federica Garin

INRIA Grenoble Rhône-Alpes, France
federica.garin@inrialpes.fr

W.P.M.H. Heemels

Eindhoven University of Technology,
Department of Mechanical
Engineering, P.O. Box 513, 5600 MB
Eindhoven, The Netherlands
M.Heemels@tue.nl

Hideaki Ishii

Department of Computational Intelligence and Systems Science,
Tokyo Institute of Technology, 4259
Nagatsuta-cho, Midori-ku, Yokohama
226-8502, Japan
ishii@dis.titech.ac.jp

Riku Jäntti

Department of Communications and
Networking Comnet Helsinki University
of Technology TKK, Finland
riku.jantti@tkk.fi

Mikael Johansson

School of Electrical Engineering and
ACCESS Linnaeus Center, Sweden
mikaelj@ee.kth.se

Kyoung-Dae Kim

Department of Electrical and Computer
Engineering, University of Illinois at
Urbana-Champaign, USA
kkim50@illinois.edu

P. R. Kumar

Department of Electrical and Computer
Engineering, University of Illinois at
Urbana-Champaign, USA
prkumar@illinois.edu

Sanjay Lall

Department of Electrical Engineering
and Department of Aeronautics and
Astronautics, Stanford University,
Stanford, CA 94305, USA
lall@stanford.edu

Michael Lemmon

University of Notre Dame,
Notre Dame, Indiana, USA
lemmon@nd.edu

Luca Schenato

Department of Information
Engineering, University of Padova,
Italy
schenato@dei.unipd.it

John Swigart

Department of Aeronautics and Astro-
nautics, Stanford University, Stanford,
CA 94305, USA
jswigart@stanford.edu

Bo Yang

Department of Automation,
Shanghai Jiao Tong University,
China
bo.yang@sjtu.edu.cn

N. van de Wouw

Eindhoven University of Technology,
Department of Mechanical
Engineering,
P.O. Box 513,
5600 MB Eindhoven,
The Netherlands
N.v.d.Wouw@tue.nl