Model Predictive Control for Nonlinear Networked Control Systems

A Model-based Compensation Approach for Nondeterministic Communication Networks

Dissertation
zur Erlangung des akademischen Grades
Doktoringenieur (Dr.-Ing.)

von
Paolo Varutti
geboren am 27. September 1982
in Motta di Livenza (TV), Italien

genehmigt durch die Fakultät für Elektrotechnik und Informationstechnik der
Otto-von-Guericke-Universität Magdeburg

Gutachter:
Prof. Dr.-Ing. Rolf Findeisen
Prof. Dr.-Ing. Sandra Hirche

eingereicht am 28. Februar 2013
Promotionskolloquium am 11. Februar 2014

Contributions in Systems Theory and Automatic Control
Otto-von-Guericke-Universität Magdeburg

Band 5

Paolo Varutti

Model Predictive Control for Nonlinear Networked Control Systems

A Model-based Compensation Approach for Nondeterministic Communication Networks

Shaker Verlag
Aachen 2014

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Magdeburg, Univ., Diss., 2014

Copyright Shaker Verlag 2014
All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-2801-0
ISSN 2192-2799

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

Acknowledgements

This thesis is the result of the work done as a PhD and research assistant at the Systems Theory and Control group of Prof. Rolf Findeisen, Otto-von-Guericke University. During this period I was also a PhD student at the International Max Plank Research School for Advanced Methods in Process and Systems Engineering in Magdeburg.

This work would have not been possible without the support of the many people that accompanied me through these years. Without mentioning all of them in detail, a special thank you goes to Prof. Findeisen for his supervision; to my family for their love and support; and to all my colleagues from the institute for the beautiful time we spent together.

Magdeburg, April 2014 Paolo Varutti

Contents

Abstract **IX**

Deutsche Kurzfassung **XI**

List of Symbols and Abbreviations **XIII**

1 Introduction **1**
1.1 Networked Control Systems 1
1.2 Contribution 2
1.3 Thesis Outline 5

2 Sampled-data Nonlinear Model Predictive Control **7**
2.1 Review on Model Predictive Control 7
2.2 Sampled-data NMPC 8
2.2.1 Nominal Stability 11
2.2.2 Robustness of NMPC 13
2.3 Event-based Sampled-data NMPC 14
2.3.1 Event-based Control 14
2.3.2 Event-based Predictive Control 17
2.3.3 Simulation Example: a CSTR 20
2.4 Summary and Discussion 26

3 Networked Control Systems **27**
3.1 Introduction on NCSs 27
3.1.1 Problems in NCSs 29
3.1.2 State of the Art and Motivations 30
3.2 Problem Formulation 31
3.3 Motivational Examples 34
3.3.1 Example 1: CSTR 34
3.3.2 Example 2: PVTOL Aircraft 36
3.3.3 Example 3: Inverted Pendulum on a Cart 37
3.4 Summary and Discussion 40

4 Model-based Compensation **42**
4.1 Basic Idea 43

4.2 Compensation of Random Delays 44
4.2.1 Random Measurement Delays 44
4.2.2 Random Computational and Input Delays 48
4.2.2.1 UDP-like Communication: Worst-case Compensation . 49
4.2.2.2 TCP-like Communication 52
4.2.3 Simulation Example: PVTOL Aircraft 55
4.3 Compensation of Nondeterministic Information Losses 56
4.3.1 Random Measurement Dropouts 56
4.3.2 Random Input Dropouts 58
4.3.2.1 TCP-like Communication 59
4.3.2.2 UDP-like Communication 67
4.3.3 Simulation Example: CSTR 70
4.4 Model-based Compensation without Clock-synchronization 73
4.4.1 Random Delay Compensation 74
4.4.2 Random Dropout Compensation 76
4.4.3 Simulation Examples: CSTR and Inverted Pendulum 77
4.5 Summary and Conclusions 78

5 Asymptotic Stability for "Tree-like" Interconnected Systems with Distributed Dissipativity-based NMPC 81
5.1 Introduction and State-of-the-art 82
5.2 Distributed Dissipativity-based NMPC 83
5.2.1 Problem Formulation 86
5.2.2 Simple Case: Cascade of Interconnected Systems 87
5.2.2.1 Simulation Example: Two-tank System 94
5.2.3 "Tree-like" Interconnecting Structures 96
5.2.3.1 Simulation Example: Four-tank System 98
5.3 Summary and Discussion 101

6 Conclusions and Future Work 102
6.1 Event-based Nonlinear Predictive Control 102
6.2 Delays and Information Losses Compensation 103
6.3 Dissipativity-based Predictive Control for "Tree-like" Interconnected Systems 104
6.4 Final Remarks 105

Bibliography 107

A Stability of Nonlinear Continuous-time Systems 117
A.1 Stability 117
A.2 Barbalat's Lemma 118
A.3 Quasi-dominant Matrices and Hurwitz Stability 118

B Values and Meanings of Parameters **120**