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University of Stuttgart
Institute for Systems Theory in Engineering

European Control Training Site

One Day Mini Course
Introduction to and Current Issues in Nonlinear Model Predictive Control

Tuesday August 31st, 2004

directly prior to Nolcos 2004 at the IST, University of Stuttgart, Germany

Content and objective:

Linear model predictive control is popular since the 70s of the past century and by now widely employed in practice. The 90s have witnessed a steadily increasing attention from control theoreticians as well as control practitioners in the area of nonlinear model predictive control (NMPC) and over the past decade significant theoretical as well as implementational advances in the area of NMPC have been achieved. The focus of this mini course is twofold. Besides an in depth introduction to the basic ideas and principles of (nonlinear) predictive control current application and research issues in NMPC spanning from stability and robustness, output-feedback, efficient numerical solution as well as implementation aspects are discussed. For this purpose the course is split up in six parts. The first part provides an introduction as well as a historical review of (nonlinear) predictive control, often also referred to as receding horizon control or moving horizon control. Part two focuses on how to achieve nominal stability of the closed-loop using NMPC. In part three the robustness as well as the robust design of NMPC are discusses. Part four provides an overview on output-feedback in conjunction with NMPC. The efficient numerical solution and implementation of NMPC is discussed in depth in part five. Part six discusses existing applications as well as application aspects of NMPC. The mini course is concluded by a short wrap up, summary and outlook.

Major parts of the lecture will focus on NMPC for continuous time systems, either with or without sampling. Most of the presented results, however, possess discrete time counterparts.

The course is given in English. It starts with an elementary level before moving to the more advanced topics. It is accompanied by copies of the slides and suplementary material provided by the lecturers.

You can find the announcement as pdf here or as postscript here. A one page announcment can be found as html here, as pdf here, or as postscript here.

Who should attend?

Graduate students, engineers, mathematicians and researchers, who are interested in becoming familiar with nonlinear model predictive control or who want to improve their understanding of nonlinear model predictive control.

Lecturers (alphabetical order):

- Frank Allgöwer (IST, University of Stuttgart, Germany)
- Moritz Diehl (IWR, University of Heidelberg, Germany)
- Rolf Findeisen, organizer (IST, University of Stuttgart, Germany)
- Lalo Magni (SISDIN, University of Pavia, Italy)
- Zoltan Nagy (IST, University of Stuttgart, Germany)

Details about the lecturers can be found following the links.

Date and location:

The one day mini course will be held on Tuesday August 31st 2004 at the IST at the University of Stuttgart (see also note on how to find the IST) starting at 8:30am.

Detailed program:

Time	Lecture Content	Lecturer	Lecture Details
08:30-09:30	Introduction and history of predictive control	Frank Allgöwer	The main focus in this lecture is laid on an introduction and historical perspective of (nonlinear) predictive control. Specifically we outline the basic principle of predictive control, reasons for the huge success of linear model predictive control and the key advantages, disadvantages and challenges inherent in NMPC.
09:30-10:30	Basic theory and stability of NMPC	Rolf Findeisen	Nonlinear model predictive control is based on the repeated solution of a (finite) horizon open-loop optimal control problem subject to system dynamics and input and state constraints. However, as is well known by now, optimality does not automatically imply stability in the case of finite prediction horizons. Different approaches to achieve closed-loop stability using finite horizon lengths exist. The main purpose of this lecture is to review the underlying main ideas and theoretical foundations for these approaches and to provide a unified view on nominally stabilizing NMPC schemes.
10:30-11:00	Coffee Break		
11:00-12:00	Robustness and robust design of NMPC	Lalo Magni	The introduction of uncertainty in the system description raises the question of robustness. In this lecture we present several approaches to the study of robustness. The first is concerned with the robustness analysis of closed-loop systems, designed using a nominal model. The second attempts to achieve robustness in the context of conventional model predictive control by consideration of a min-max open-loop model predictive control. The third one addresses the robustness problem by introducing feedback in the min-max optimal control problem solved on-line.
12:00-13:30	Lunch break		
13:30-14:30	Output feedback and NMPC	Rolf Findeisen	Nonlinear model predictive control is inherently a state feedback control scheme. Often, however, the full state information is not available and a suitable state observer must be used for state estimation. Since the well known separation principle does not apply for nonlinear systems, it is not guaranteed that a combination of a stabilizing NMPC state feedback controller with a stable state estimator does lead to a stabilizing output-feedback control scheme. In this lecture we review results and conditions on output-feedback NMPC schemes that guarantee stability of the closed loop.
14:30-15:30	Efficient numerical implementation of NMPC	Moritz Diehl	This lecture presents state-of-the-art methods for numerical solution of the optimal control problems arising in NMPC. After first giving a brief overview of different solution approaches to optimal control we focus on direct shooting methods and collocation, in conjunction with nonlinear programming techniques. In particular, we discuss the direct multiple shooting method, an algorithm suitable for nonlinear problems with complex constraints that is often used in NMPC applications, and show ways to deal with limited time for on line computation.
15:30-16:00	Coffee break		
16:00-17:00	Applications and application aspects of NMPC	Zoltan K. Nagy	This lecture provides an introduction in the development of practical model-based control approaches that can be supported in an industrial environment. The importance of the judicious compromise between, modeling, sensors, estimation and optimization are assessed. Academic NMPC approaches are confronted with industrial methods through several example processes with contouring current trends toward potential applications in biotechnology, polymer, pharmaceutical and microelectronics industry.
17:00-17:30	Wrap up, summary and outlook		

Provided material:

A binder containing the copies of the slides and supplementary material will be provided to the registered participants.

Course Web Page:

http://www.ist.uni-stuttgart.de/nmpccourse/

Organization fee and registration:

Please note that the total number of participants is limited to 40. For this reason the registration is performed on a first-come-first-serve basis. The organization fee/contribution towards expenses of 100 € includes:

- binder containing copies of the slides and supplementary material
- coffee and refreshments
- lunch

For registration please fill out the registration form and sent it to Rolf Findeisen via e-mail (please add NMPC mini course as subject) or fax it to +49 711 6857735. The organization fee of 100 € will be collected during the workshop. You will receive an official receipt from the IST for the organization fee, so that you can claim the expenses at your company/university. If you require a written invitation, please indicate this clearly on the registration form.

Accommodation:

If you need an accommodation in Stuttgart you might consider one of the following hotels:

- Telekom Hotel - located close to the IST (map), but frequently booked out:
  Universitätsstrasse 34, 70569 Stuttgart; phone: +49-711-68633; Fax: +49-711-68 634898;
  e-mail rezeption.bz.suedwest@suedwest.telekom.de
- Hotel am Dachswald - located approx. 2km from the University, convenient if you have a car or if you willing to ride a bus:
  Dachswaldweg 120, 70569 Stuttgart; phone +49-711-67833 Telefax +49-711-6783500;
  e-mail: hotel.dachswald@t-online.de
- Hotel am Feuersee - nice location between the campus in Vaihingen and the city center, easy campus access via public transport:
  Johannessstrasse 2, 70176 Stuttgart; Phone: +49-711-619 54-0; Fax: +49-711-619 54-160; e-mail: hotel-am-feuersee@t-online.de
- further hotels are listed here
- cheap alternative to hotels - Stuttgart youth hostel:
  Haussmannstr. 27, 70188 Stuttgart; Phone: +49-711-241583, Fax: +49-711-2361041;
  e-mail: info@jugendherberge-stuttgart.de

Please book your hotel early! since the course is directly prior to the **Nolcos 2004**.

Questions:

In case of additional questions or requests please feel free to contact:

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Details about the lecturers (alphabetical order)

- **Frank Allgöwer (IST, University of Stuttgart, Germany)**

Frank Allgöwer is professor in the mechanical engineering department of the University of Stuttgart and director of the Institute for Systems Theory in Engineering. Besides his interests in predictive control, he is active in the areas of nonlinear and robust control, identification of nonlinear systems and application of modern systems and control theoretical methods in engineering and biology. He is Editor for the journal Automatica, Associate Editor of the Journal of Process Control and the European Journal of Control and is on the editorial board of several further journals. He is organizer or co-organizer of several international conferences and has published over 100 scientific articles.

Selected publications relevant to the mini course:

- F. Allgöwer and A.Z. Zheng. Nonlinear Model Predictive Control: Assessment and Future Directions for Research. Progress in Systems and Control Series, Birkhäuser Verlag, Basel. 2000.
- F. Allgöwer, R. Findeisen, and C. Ebenbauer. Nonlinear model predictive control. Encyclopedia for Life Support Systems (EOLSS) article contribution 6.43.16.2, 2003.
- H. Chen and F. Allgöwer. A quasi-infinite horizon nonlinear model predictive control scheme with guaranteed stability. Automatica. Vol. 34, issue. 10, S. 1205-1218, 1998.

- **Moritz Diehl (IWR, University of Heidelberg, Germany)**

Moritz Diehl is mathematics lecturer at the Interdisciplinary Center for Scientific Computing (IWR) of the University of Heidelberg. His main research interests are: algorithms for dynamic optimization, nonlinear model predictive control, parameter- and state estimation; applications e.g. in chemical engineering, medicine, robotics, power engineering. He serves as reviewer for "Automatica", "Automatisierungstechnik", "Computational Optimization and Applications", "Computers and Chemical Engineering", "Optimization and Engineering", "Journal of Process Control".

Selected publications relevant to the mini course:

- M. Diehl, H.G. Bock, J.P. Schlöder, R. Findeisen, Z. Nagy, and F. Allgöwer: Real-time optimization and nonlinear model predictive control of processes governed by differential-algebraic equations . Journal of Process Control 12, pp. 577-585, 2002.
- M. Diehl, R. Findeisen, S. Schwarzkopf, Ilknur Uslu, F. Allgöwer, H.G. Bock, E. D. Gilles, J.P. Schröder: An Efficient Algorithm for Optimization in Nonlinear Model Predictive Control of Large-Scale Systems. Automatisierungstechnik 12/2002 and 1/2003.
- M. Diehl, I. Uslu, S. Schwarzkopf, F. Allgöwer, H.G. Bock, R. Findeisen, E.D. Gilles, A. Kienle, J.P. Schlöder, and E. Stein: Real-Time Optimization for Large Scale Processes: Nonlinear Model Predictive Control of a High Purity Distillation Column In Groetschel, Krumke, Rambau (eds.): Online Optimization of Large Scale Systems: State of the Art, Springer, 2001.

- **Rolf Findeisen (IST, University of Stuttgart, Germany)**

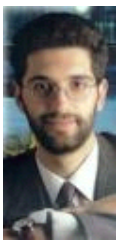
Rolf Findeisen is researcher and lecturer at the Institute for Systems Theory in Engineering at the University of Stuttgart. His main research areas are: nonlinear model predictive control, output feedback control, optimization based control and state estimation, differential algebraic systems, nonlinear control, system theoretical methods in biomedical engineering and biological systems; and the application of these methods in chemical, biological and mechanical systems. He serves as reviewer for various journals and conferences including Automatica, IEEE Transaction on Automatic Control, SIAM Journal on Control and Optimization, Computers and Chemical Engineering, System and Control Letters, Journal of Process Control.

Selected publications relevant to the mini course:

- R. Findeisen, L. Imsland, F. Allgöwer, and B.A. Foss. Output feedback

stabilization for constrained systems with nonlinear model predictive control. Int. J. of Robust and Nonlinear Control, 13(3-4):211-227, 2003.
- R. Findeisen, L. Imsland, F. Allgöwer, and B.A. Foss. State and output feedback nonlinear model predictive control: An overview. Europ. J. Contr., 9(2-3):190-207, 2003.
- R. Findeisen, L. Imsland, F. Allgöwer, and B.A. Foss. Towards a sampled-data theory for nonlinear model predictive control. In C. Kang, M. Xiao, and W. Borges, editors, New Trends in Nonlinear Dynamics and Control, and their Applications, Lecture Notes in Control and Information Sciences, 295, pages 295-313, New York, 2003. Springer-Verlag.

- **Lalo Magni (SISDIN, University of Pavia, Italy):**



Lalo Magni got his PhD in Electronic and Computer Engineering in 1998 with the dissertation :"Nonlinear Receding Horizon Control: Theory and Application". Currently he is Assistant Professor at the University of Pavia, Italy. His research in model predictive control is witnessed by 20 papers appeared in the main international journals of the field. He has been Guest Editor of the Special Issue "Control of nonlinear systems with Model Predictive Control" in the International Journal of Robust and Nonlinear Control. He serves as an Associate Editor of the IEEE Transactions on Automatic Control.

Selected publications relevant to the mini course:

- Fontes F.A.C.C. and L. Magni, Min-max Model Predictive Control of Nonlinear Systems using Discontinuous Feedbacks, IEEE Transactions on Automatic Control,48,pp. 1750-1755, 2003.
- Magni L., G. De Nicolao, R. Scattolini and F. Allgöwer, Robust Model predictive Control of nonlinear discrete-time systems, International Journal of Robust and nonlinear control, 13, Issue 3-4, pp. 229-246, 2003.
- Magni L., H. Nijmeijer and A.J. Van Der Schaft, A receding-horizon approach to the nonlinear H Inf. Control problem, Automatica, 37(3), pag. 429-435, 2001.

- **Zoltan Nagy (IST, University of Stuttgart, Germany):**

Zoltan K. Nagy received his Ph.D. in chemical engineering, from the "Babes-Bolyai" University of Cluj, Romania in 2001, where he holds a lecturer position. In 2001-2003 he was a research associate and lecturer at the University of Illinois at Urbana-Champaign, USA. He is currently with the University of Stuttgart, working on an industrial project with BASF and ABB related to a feasibility study of industrial NMPC. His research interests include: nonlinear model predictive control, batch process control, uncertainty analysis, robust optimal control, mathematical modeling of chemical processes. He received the outstanding reviewer award for Automatica in 2003, and serves as reviewer for McGraw-Hill and for several journals and conferences including, Journal of Process Control, IEE Proceedings on Control Theory and Applications, Chemical Engineering Communications.

Selected publications relevant to the mini course:

- Z. K. Nagy and R. D. Braatz, Robust nonlinear model predictive control of batch processes, AIChE J., 49 (7), 1776-1786, 2003.
- Z. K. Nagy, R. D. Braatz, Worst-case and Distributional Robustness Analysis of Finite-time Control Trajectories for Nonlinear Distributed Parameter Systems, IEEE Transaction on Control Systems Technology, 11 (5), 694-704, 2003.
- Z. K. Nagy and R. D. Braatz, Open-loop and closed-loop robust optimal control of batch processes using distributional and worst-case analysis, Journal of Process Control, 14, 411-422, 2004.