Introduction to TEMPO Spring School on Nonlinear Model Predictive Control

Mario Zanon (on behalf of Moritz Diehl)

Systems Control and Optimization Laboratory (SYSCOP)
IMTEK, Faculty of Engineering, and Department of Mathematics
University of Freiburg
and
Electrical Engineering Department, University of Leuven

Freiburg, August 4, 2014
Overview

- The University of Freiburg and TEMPO
- Optimal Control Applications and Software
- Overview of the Course
University of Freiburg

- founded in 1457 by Archduke Albert VI of Western Austria, as a comprehensive university

- today, 24,000 students (14% international), all faculties (humanities, sciences, medicine, engineering)
Freiburg University

Engineering Faculty (since 1995) today 45 Profs. 1700 Students

- Computer Science
- Microsystems Engineering
- Chair Systems Theory
- Sustainable Systems Engineering (from 2015)
SYSCOP Team History

2006 - 2013
KU Leuven

2013 -
Freiburg University
Research

Embedded Optimization

\[ u = \arg \min_u \begin{bmatrix} x^T & u^T \end{bmatrix} \begin{bmatrix} Q & S^T \\ S & R \end{bmatrix} \begin{bmatrix} x \\ u \end{bmatrix} + \begin{bmatrix} g^T \\ h^T \end{bmatrix} \text{ s.t. } Au + Bx \leq b \]

Methods for
- Model Predictive Control (kHz NMPC)
- State and Parameter Estimation
- Nonlinear Optimal Control

Open-Source Software: qpOASES, ACADO, CasADi, qpDUNES, …

Applications in
- Mechatronics and Robotics
- Renewable Energy and Airborne Wind Energy
Education

Bachelor
• Systems and Control Theory

Master
• Optimal Control and Estimation
• Modelling and System Identification
• Model Predictive Control
• Numerical Optimal Control
• Numerical Optimization
Team Structure

1 Professor, 1 Secretary, 1 Postdoc
6 Freiburg PhD students
3 Leuven PhD students
5 external PhD students (Industrie, Fraunhofer, HAW, Max-Planck)

1 open Postdoc positions (airborne wind energy)
2 open PhD positions (Marie Curie, airborne wind energy)
1 open PhD position at Xsens (Netherlands) on Motion Tracking
The TEMPO Project

- TEMPO - Training in Embedded Model Predictive Control and Optimization
- Marie Curie Initial Training Network,
- NTNU Norway (coordinator), Freiburg, Leuven, Oxford / ETH Zurich, EPF Lausanne, Supelec Paris, Imperial College London,…
- 14 PhD scholarships for 3 years from 2014-2018
- organises and funds intensive training activities… among other, this spring school
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Time-Optimal Point-To-Point Motions [PhD Vandenbrouck 2012]

Fast oscillating systems (cranes, plotters, wafer steppers, …)

Control aims:
• reach end point as fast as possible
• do not violate constraints
• no residual vibrations

Idea: formulate as embedded optimization problem in form of Model Predictive Control (MPC)
Model Predictive Control (MPC)

Always look a bit into the future

Example: driver predicts and optimizes, and therefore slows down before a curve
Optimal Control Problem in MPC

For given system state $x$, which controls $u$ lead to the best objective value without violation of constraints?
Optimal Control Problem in MPC

For given system state $x$, which controls $u$ lead to the best objective value without violation of constraints?

controls (unknowns / variables)

predicted state trajectory

prediction horizon (length also unknown for time optimal MPC)
Time Optimal MPC of a Crane

**SENSORS**
- line angle
- cart position

**MPC**

**ACTUATOR**
- cart motor

Hardware: xPC Target. Software: qpOASES [Ferreau, D., Bock, 2008]
Time Optimal MPC of a Crane

Univ. Leuven [Vandenbrouck, Swevers, D.]
Optimal Solutions in qpOASES Varying in Time

Time Optimal MPC in Industry: 25cm step, 100nm accuracy

TOMPC at 250 Hz (+PID with 12 kHz)

Lieboud’s results after 1 week at ETEL:
- 25 cm step in 300 ms
- 100 nm accuracy

equivalent to: „fly 2,5 km with MACH15, stop with 1 mm position accuracy“
Open Source Software Tools from the Systems, Control and Optimization Laboratory

under industry friendly LGPL license

- **qpOASES**: dense parametric quadratic programming
  [Joachim Ferreau, …]

- **qpDUNES**: sparse online quadratic programming
  [Janick Frasch, …]

- **ACADO**: nonlinear MPC
  [Boris Houska, Joachim Ferreau, Milan Vukov, Rien Quirynen, Robin Verschueren, …]

- **CasADi**: modelling environment for dynamic optimization
  [Joel Andersson, Joris Gillis, Greg Horn, …]
Time Optimal “drawing” by crane

Univ. Leuven [Wannes Van Loock et al.,] (CasADi)
Time-optimal “hand writing” by robot

Robot avoiding a box while moving time optimally

Univ. Leuven [Swevers et al.]
Time-optimal “racing” of model cars

Univ. Leuven/ETH & LMS [Robin Verschueren] (ACADO qpOASES)
Overview

• The University of Freiburg and TEMPO

• Optimal Control Applications and Software

• Overview of the Course
Introduction of Teachers and Organizers

Joel Andersson (Swedish, PhD Leuven 2013) - Exercises and Lectures
Moritz Diehl (German, PhD Heidelberg 2001) - Lectures
Greg Horn (American, MSc Stanford) - Exercise Tutor
Rien Quirynen (Belgian, MSc Leuven) - Excursion, Lectures, and Exercise Tutor
Jim Rawlings (American, PhD Wisconsin-Madison) - Lectures
Mario Zanon (Italian, MSc Trento) - Exercises and Lectures

Thilo Bronnenmeyer (German, BEng Freiburg) - Technical Coordinator and Secretary
Christine Paasch (German, MA Konstanz) - Secretary

[Joris Gillis (Belgian, MSc Leuven) - Python Course on Wednesday]
## Schedule of First Week

### TEMPO Spring School on Theory and Numerics of Nonlinear Model Predictive Control, 1st Week from March 25-27, 2015
(led by Moritz Diehl)

<table>
<thead>
<tr>
<th>Time</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday, 25.3.2015</th>
<th>Thursday, 26.3.2015</th>
<th>Friday, 27.3.2015</th>
<th>Saturday</th>
<th>Sunday, 29.3.2015</th>
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</thead>
<tbody>
<tr>
<td>08:30</td>
<td>Registration</td>
<td>2. Registration</td>
<td>Prometheus Hall, 1st floor, KG I</td>
<td>Prometheus Hall, 1st floor, KG I</td>
<td>Nonlinear Programming and Convex Optimization</td>
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<tr>
<td>09:00</td>
<td>Python course</td>
<td></td>
<td></td>
<td>Introduction to Optimization</td>
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<tr>
<td>10:30</td>
<td>Break</td>
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<tr>
<td>11:00</td>
<td>Python course</td>
<td></td>
<td>CasADi Introduction and Nonlinear Optimization Exercise</td>
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<td>Gauss-Newton Exercise</td>
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<tr>
<td>12:00</td>
<td>Lunch</td>
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<tr>
<td>13:00</td>
<td>Python course</td>
<td></td>
<td>Optimal Control Overview</td>
<td>Real-Time Optimization</td>
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<td>Sunday Hike (10:00-17:00)</td>
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<tr>
<td>14:30</td>
<td>Break</td>
<td></td>
<td>Break</td>
<td>Break</td>
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<tr>
<td>15:00</td>
<td>Python course</td>
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<td>Direct Multiple Shooting Exercise</td>
<td>Real-Time Optimization Exercise</td>
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<tr>
<td>16:00</td>
<td>Break</td>
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<td>Break</td>
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<tr>
<td>16:30</td>
<td>Python course</td>
<td></td>
<td>Dynamic System Models and Numerical Integration</td>
<td>ACADO Code Generation (Robin and Rien)</td>
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<td>18:00</td>
<td>End</td>
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*Welcome Reception* (18:00-19:00)
# Schedule of Second Week

## TEMPO Spring School on Theory and Numerics of Nonlinear Model Predictive Control, 2nd Week from March 30 to April 2, 2015 (led by Jim Rawlings)

<table>
<thead>
<tr>
<th>Time</th>
<th>Monday, 30.3.2015</th>
<th>Tuesday, 31.3.2015</th>
<th>Wednesday, 1.4.2015</th>
<th>Thursday, 2.4.2015</th>
<th>Friday</th>
<th>Saturday</th>
<th>Sunday</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00</td>
<td>Introductory Review: Linear Regulation and State Estimation (LQR and LQE)</td>
<td>Nonlinear Model Predictive Control - Regulation</td>
<td>Exam</td>
<td>Project Presentations</td>
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<tr>
<td>10:30</td>
<td>Break</td>
<td>Break</td>
<td>Break</td>
<td>Break</td>
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<tr>
<td>11:00</td>
<td>Exercise: LQR and LQE</td>
<td>Exercises</td>
<td>Project Work</td>
<td>Project Presentations</td>
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<tr>
<td>12:00</td>
<td>Lunch</td>
<td>Lunch</td>
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<td>Lunch</td>
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</tr>
<tr>
<td>13:00</td>
<td>Tracking, Disturbances and Zero -Offset</td>
<td>Nonlinear Moving Horizon Estimation</td>
<td>Project Work</td>
<td>Project Presentations</td>
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<tr>
<td>14:30</td>
<td>Break</td>
<td>Break</td>
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<tr>
<td>15:00</td>
<td>Exercise</td>
<td>Exercises</td>
<td>Nonlinear MPC Applications (Thomas Besselmann, ABB)</td>
<td>Closing Session and Handout of Certificates</td>
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<tr>
<td>16:00</td>
<td>Break</td>
<td>Break</td>
<td>Break</td>
<td>End at 16:00</td>
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<tr>
<td>16:30</td>
<td>Review and Exercises</td>
<td>Review and Exercises</td>
<td>Project Work</td>
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<tr>
<td>18:00</td>
<td>End</td>
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<td>End</td>
<td>End</td>
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Spring School Dinner**
(18:30-22:00)