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

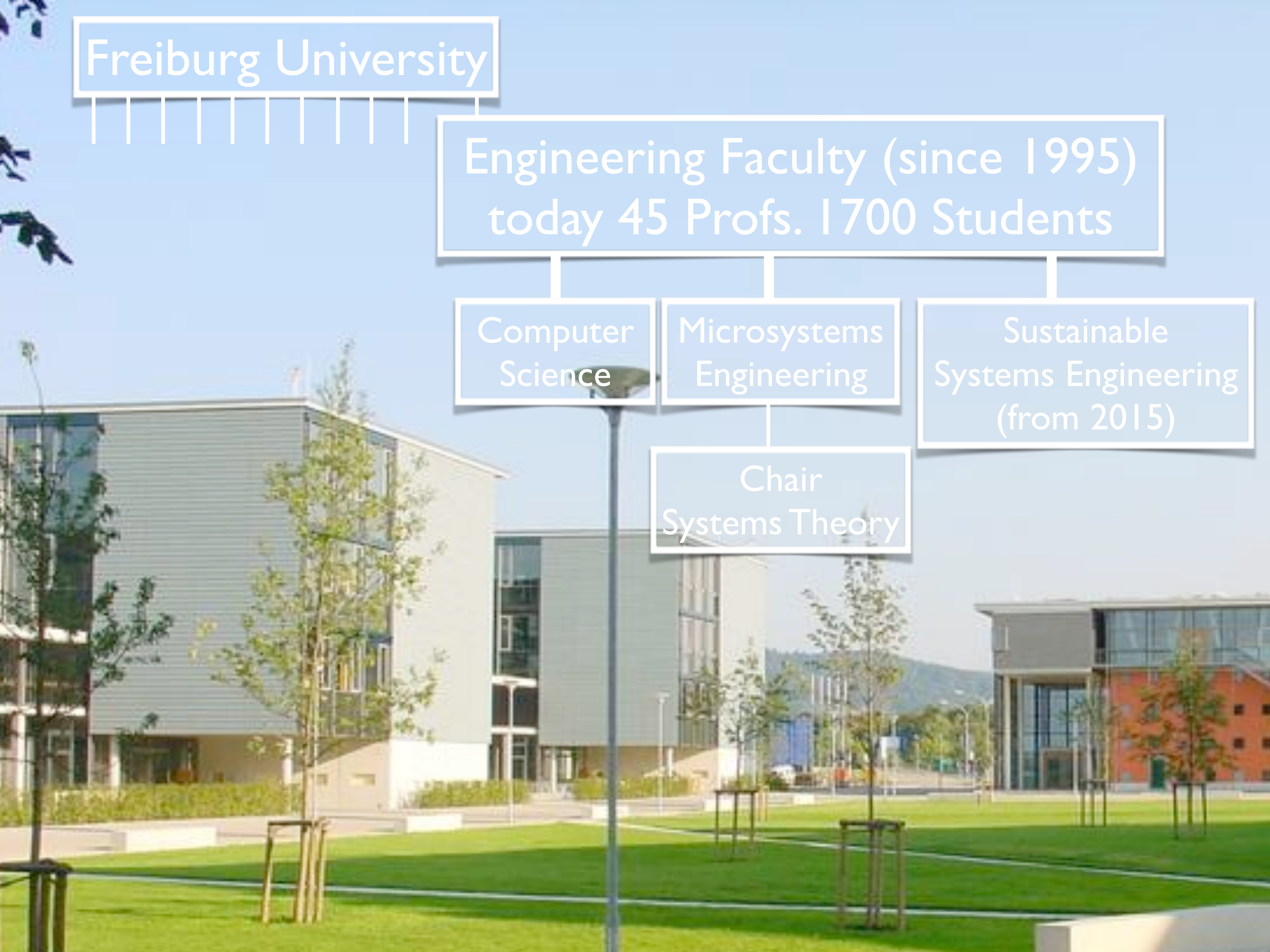
Overview

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

University of Freiburg

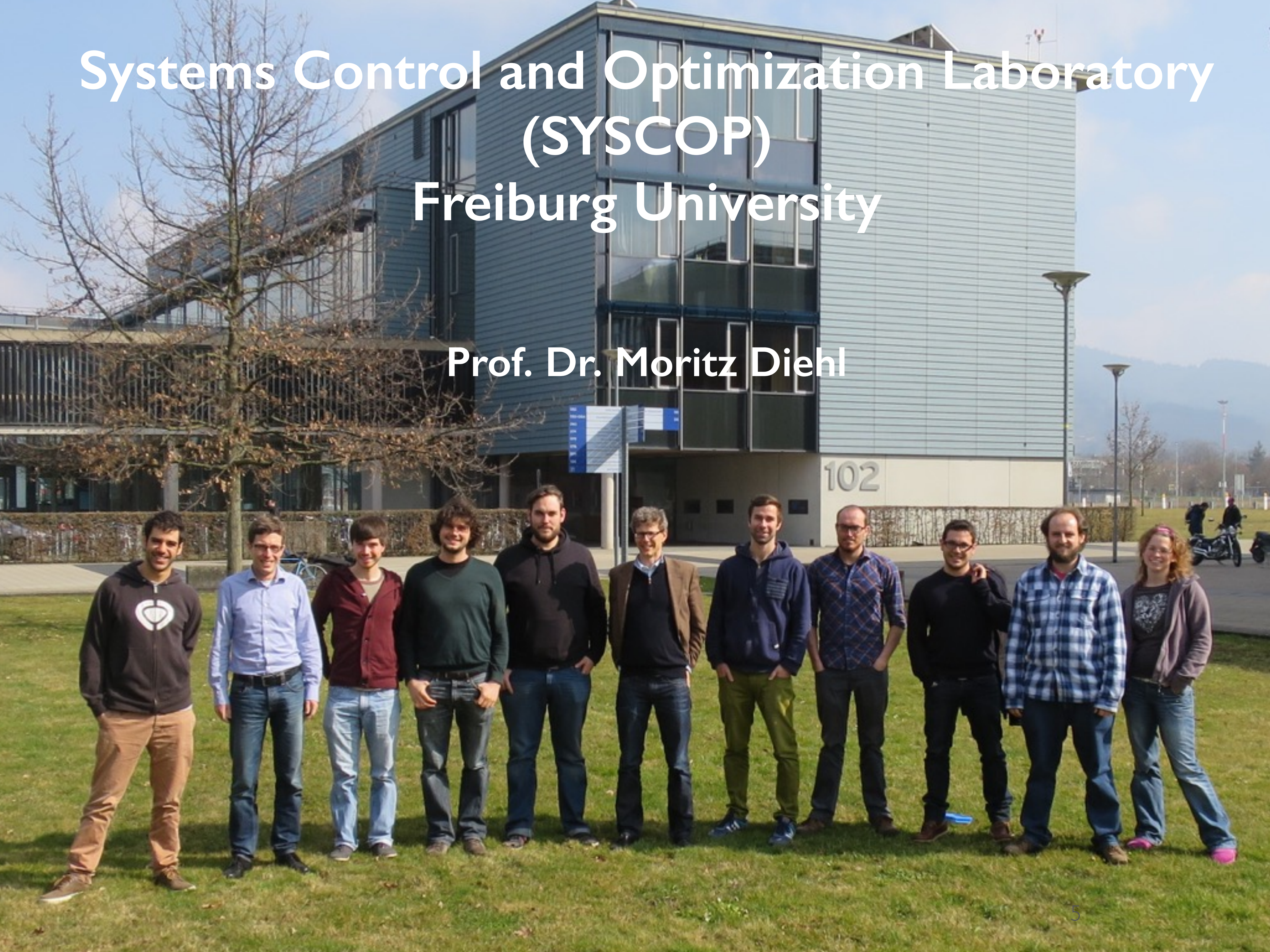
- founded in 1457 by Archduke Albert VI of Western Austria, as a comprehensive university

- 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
Sustainable Systems Engineering (from 2015)
Chair Systems Theory

Systems Control and Optimization Laboratory (SYSCOP) Freiburg University

Prof. Dr. Moritz Diehl



SYSCOP Team History

2013 -
Freiburg University

Research

$\ldots, y_{i-1}, y_i, y_{i+1}, \ldots$ $\rightarrow$

Embedded Optimization

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

$\rightarrow$ $\ldots, u_{i-1}, u_i, u_{i+1}, \ldots$

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

European Research Council erc

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, …)

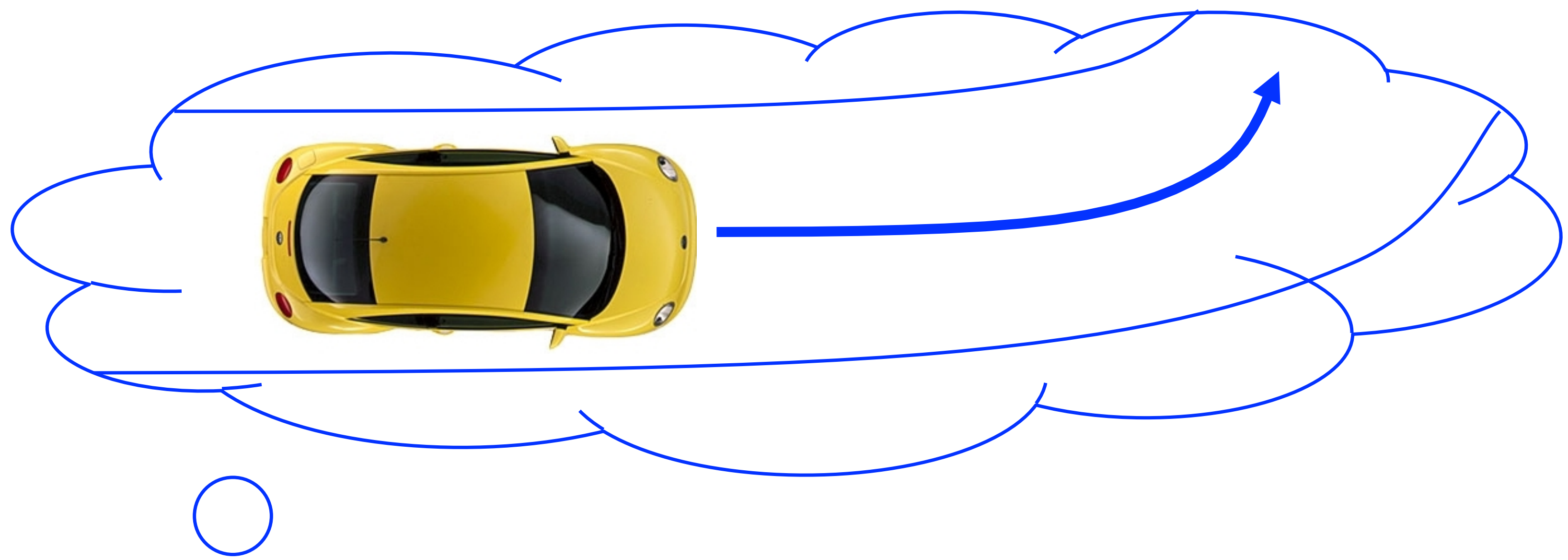
Control aims:

- 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)

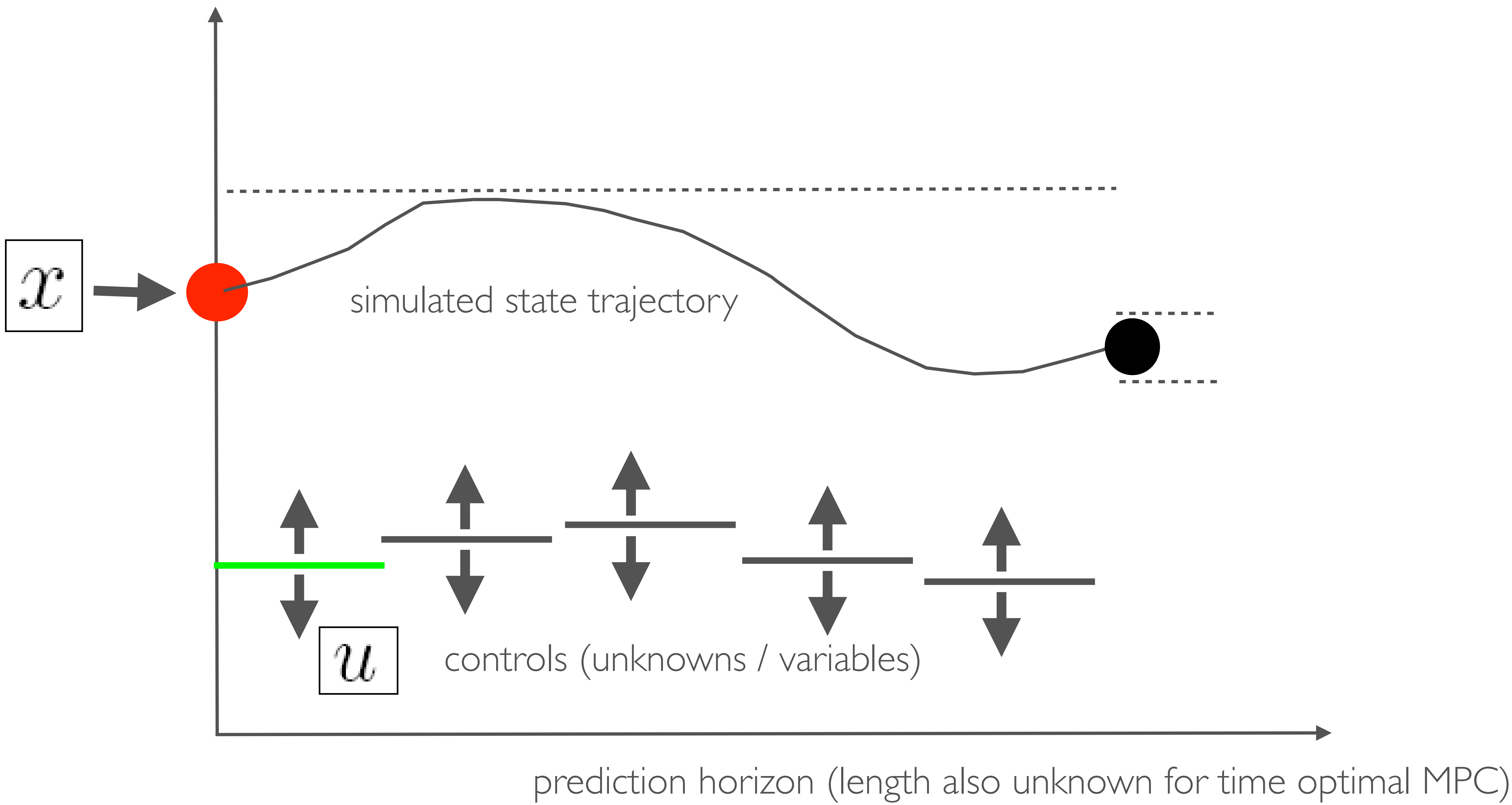
Always look a bit into the future



Example: driver predicts and optimizes, and therefore slows down before a curve

Optimal Control Problem in MPC

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



Optimal Control Problem in MPC

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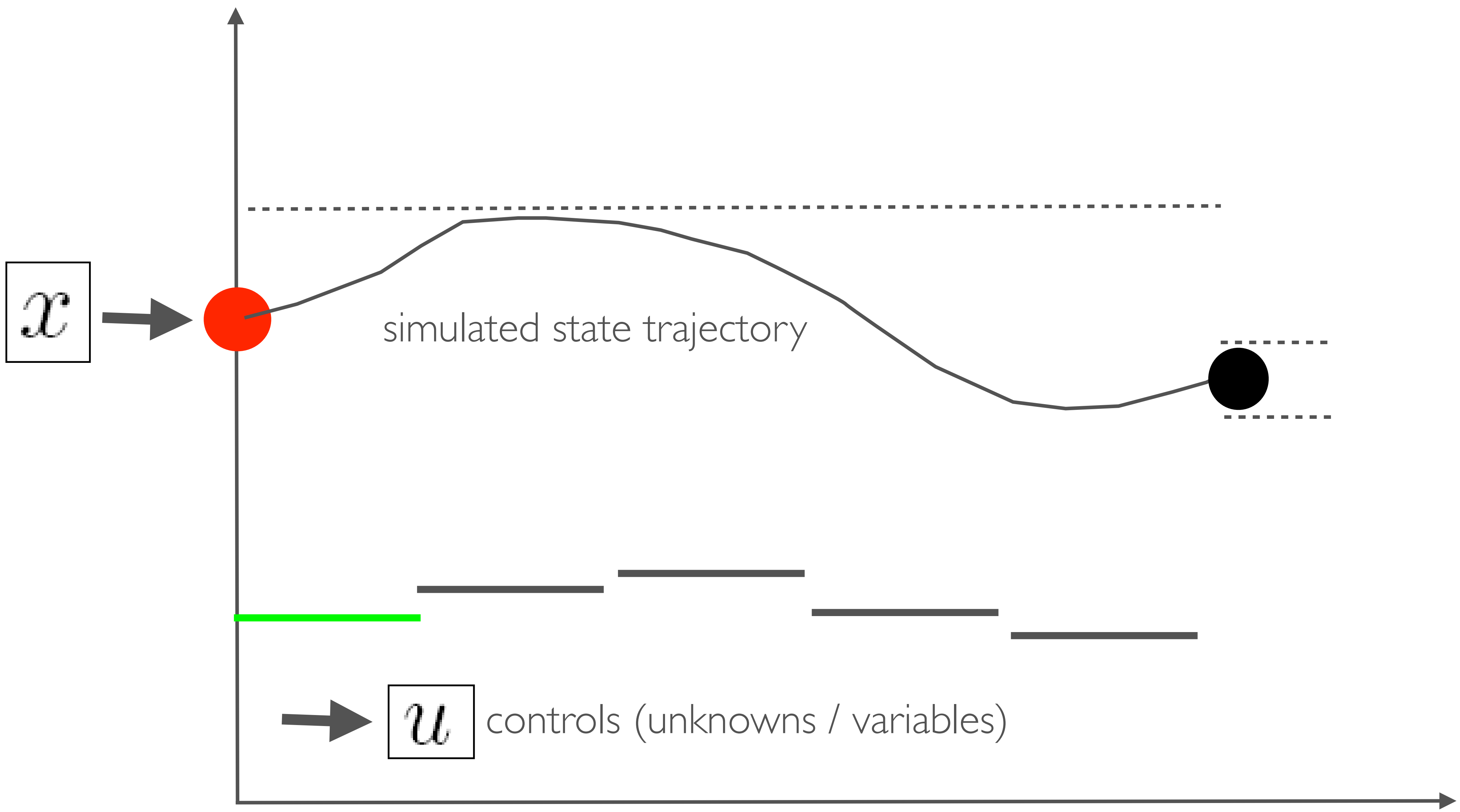


prediction horizon (length also unknown for time optimal MPC)

Time Optimal MPC of a Crane

SENSORS

- line angle
- cart position

→

MPC

→

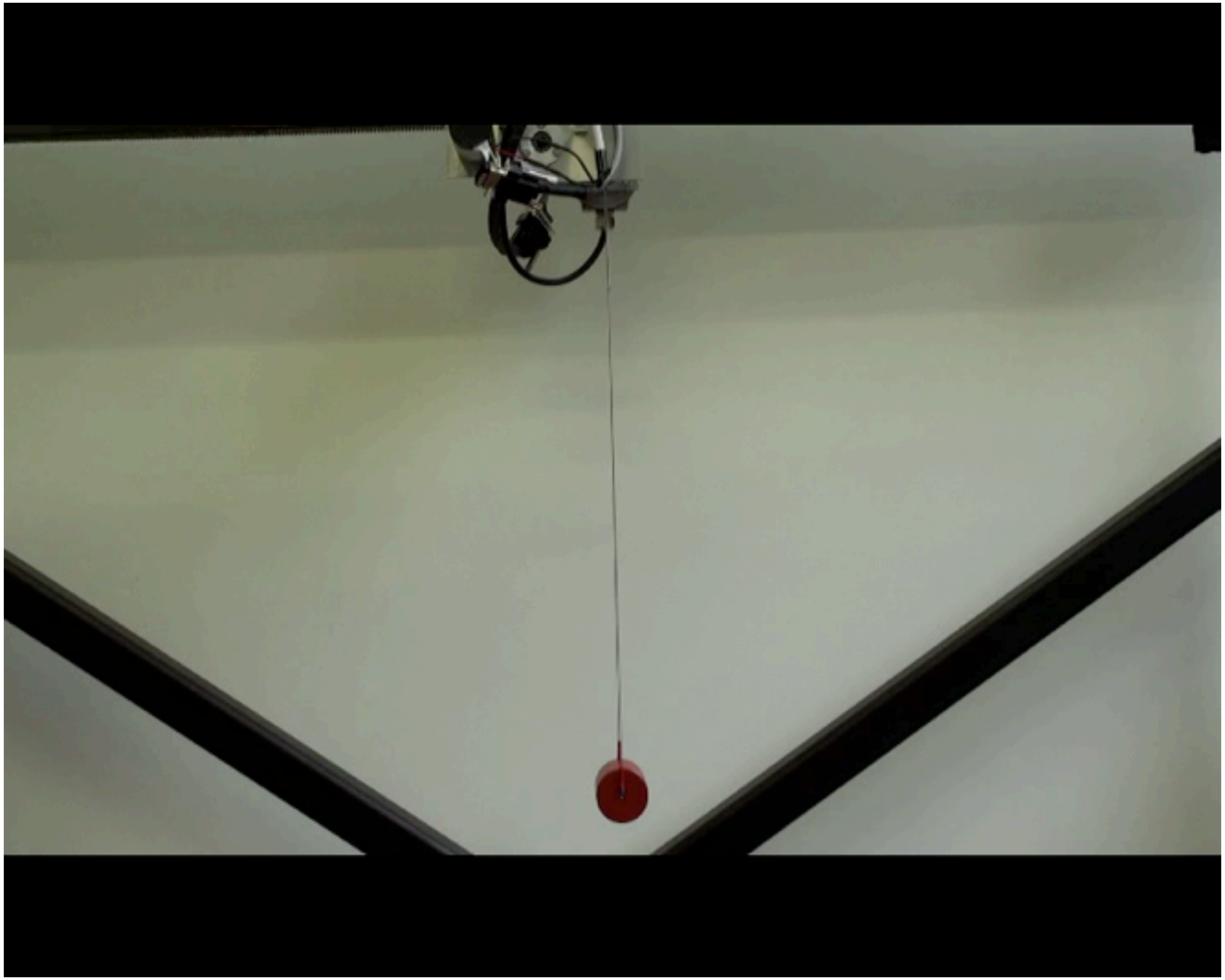
ACTUATOR

- cart motor

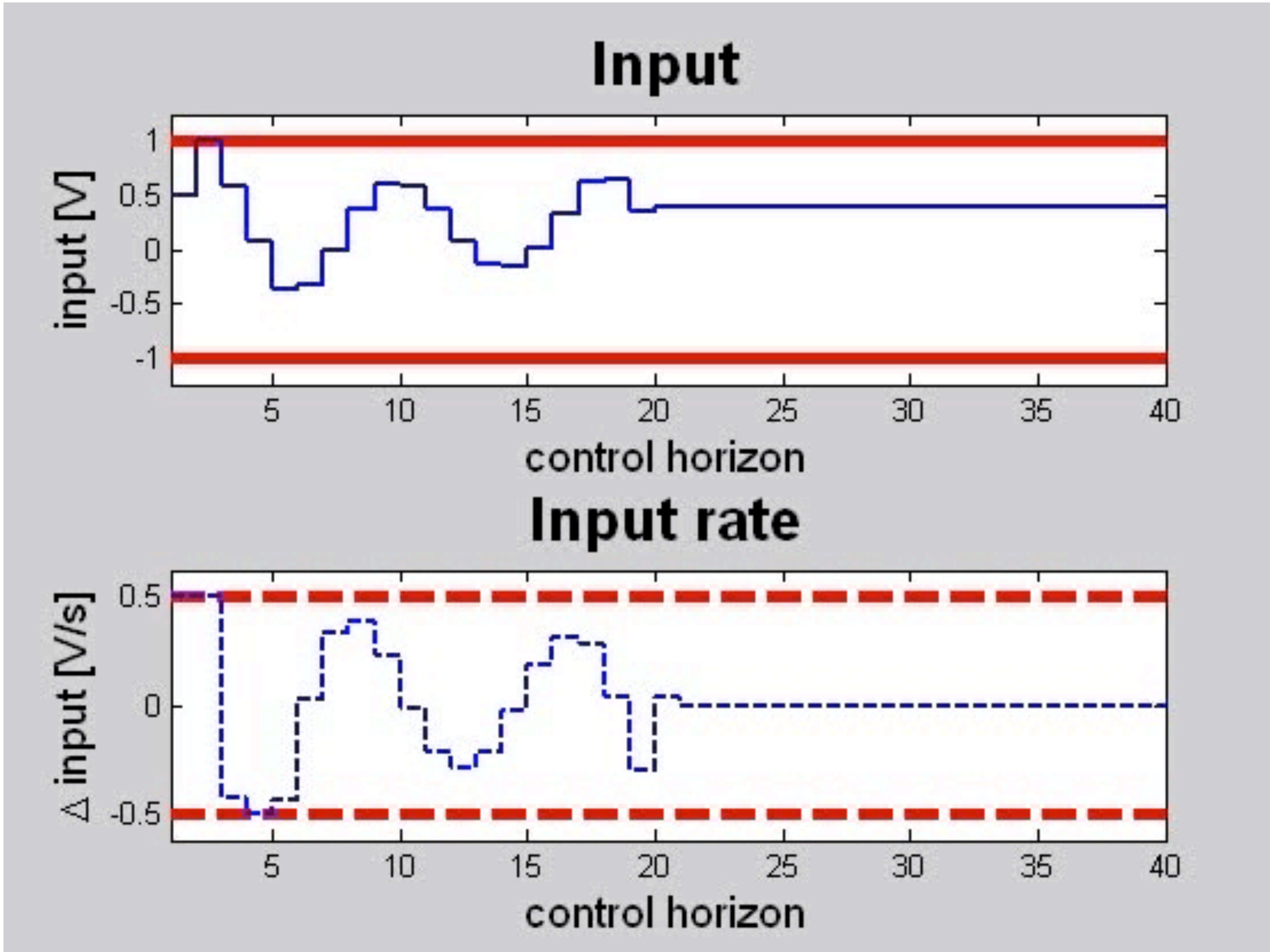
Hardware: xPC Target. Software: qpOASES [Ferreau, D., Bock, 2008]

Time Optimal MPC of a Crane

Univ. Leuven [Vandenbrouck, Swevers, D.]

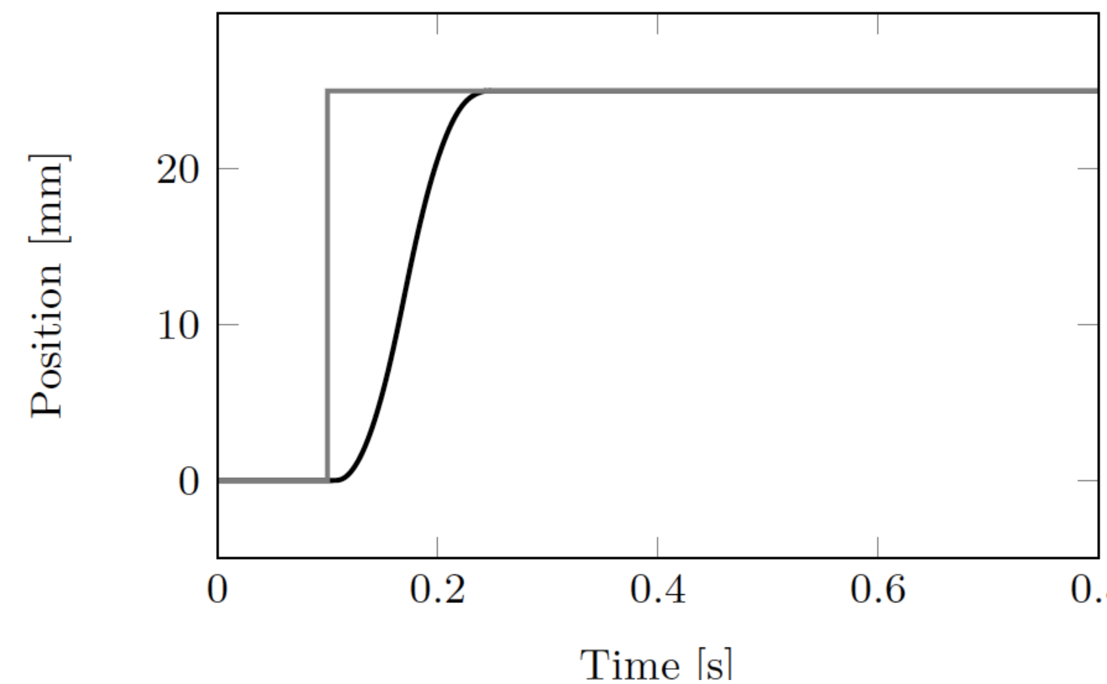


Optimal Solutions in qpOASES Varying in Time



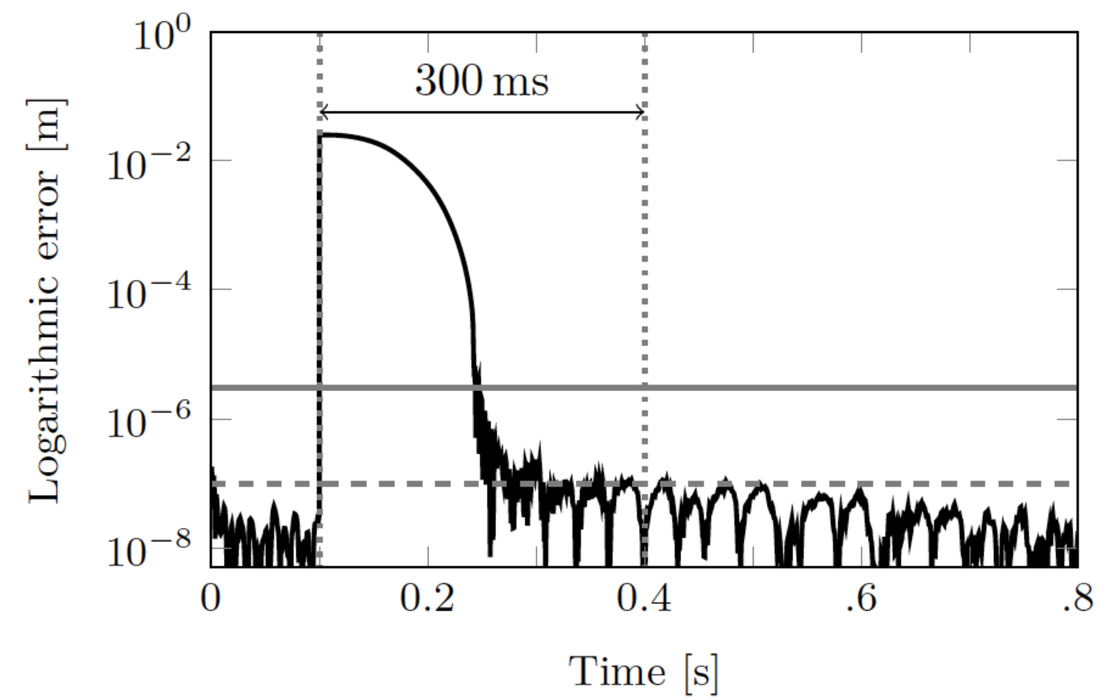
Solver qpOASES [PhD H.J. Ferreau, 2011], [Ferreau, Kirches, Potschka, Bock, D. , A parametric active-set algorithm for quadratic programming, Mathematical Programming Computation, 2014]

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“

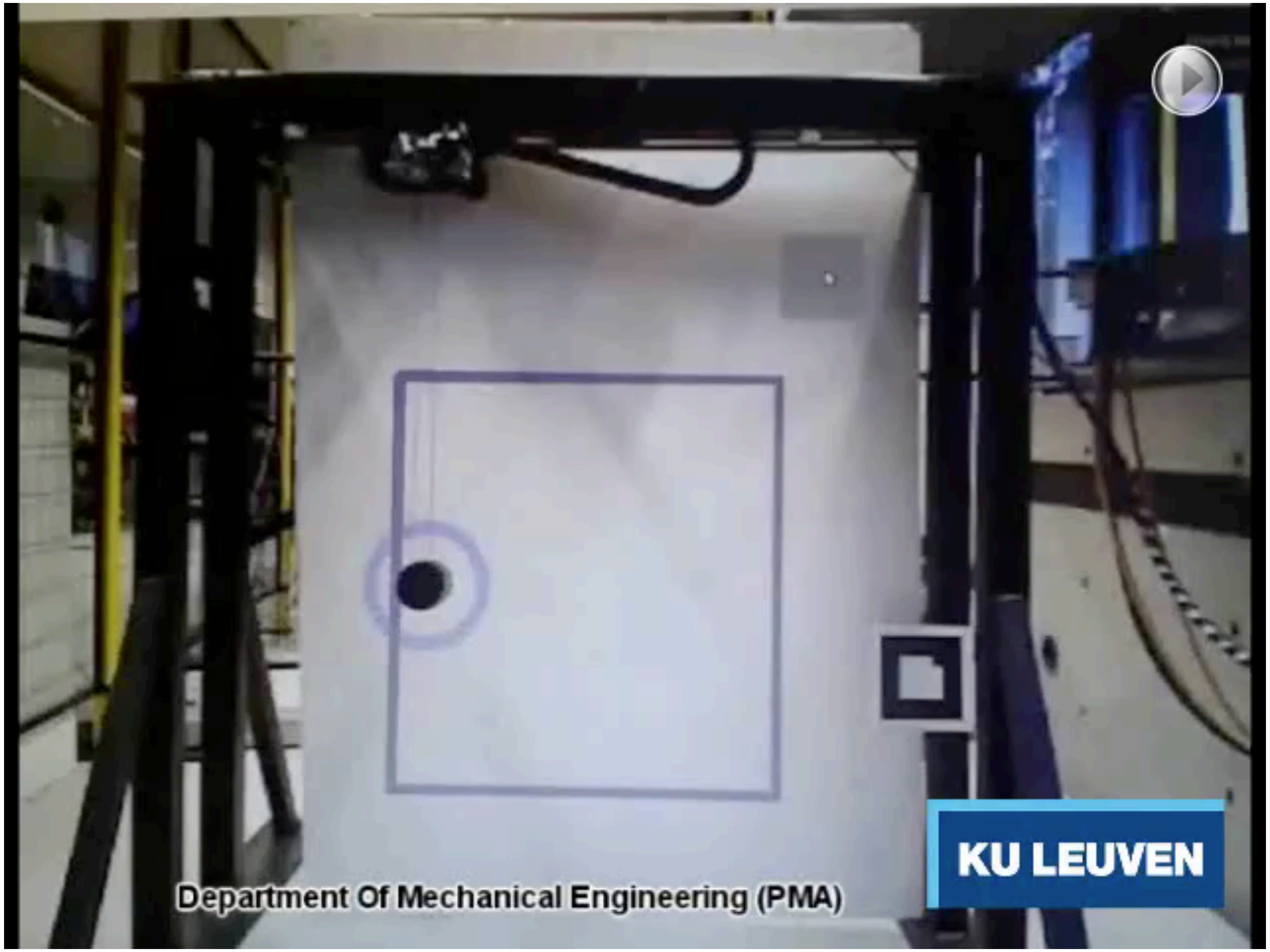
Open Source Software Tools from the Systems, Control and Optimization Laboratory

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, …]

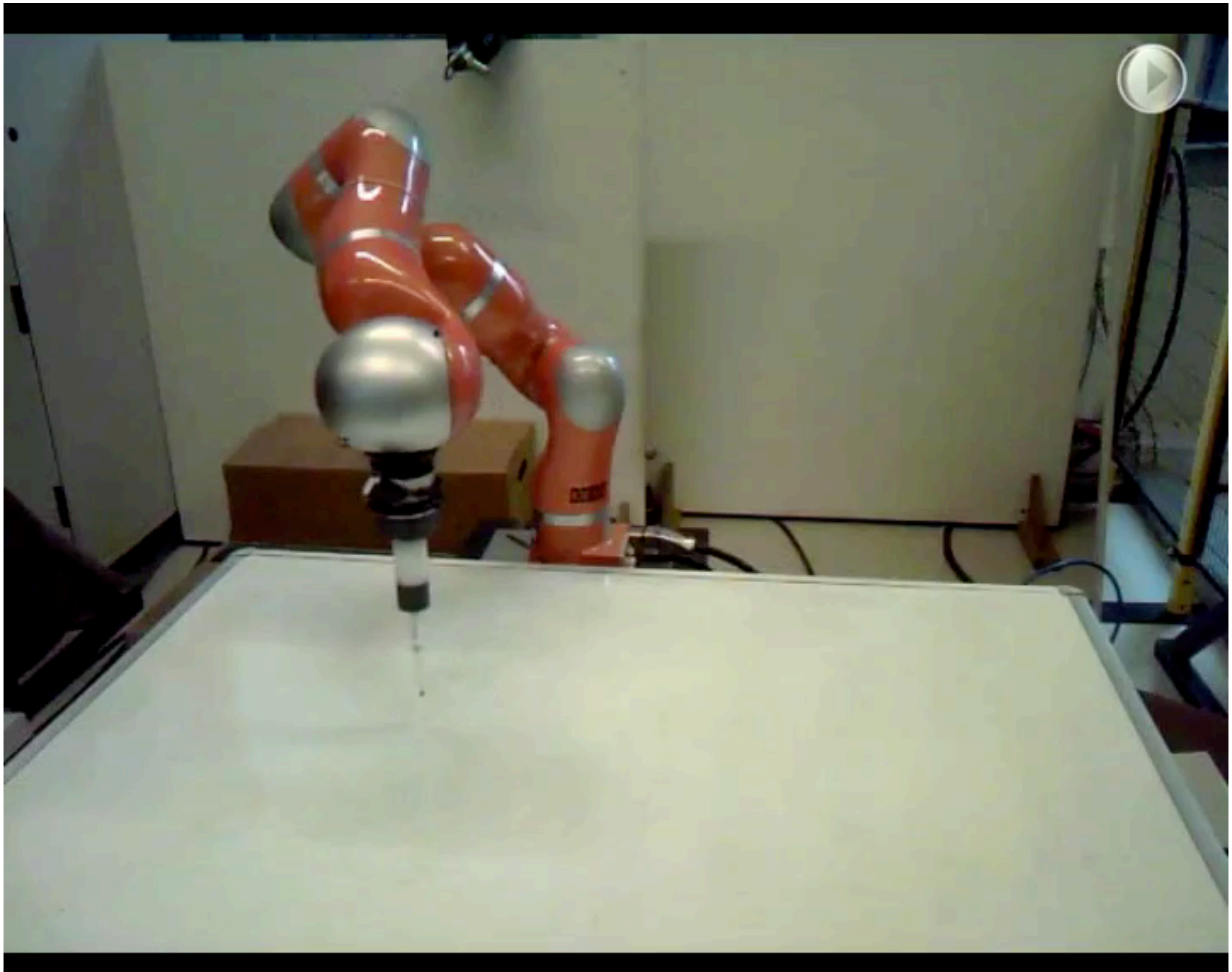
Time Optimal “drawing” by crane

Univ. Leuven [Wannes Van Loock et al.,] (CasADi)



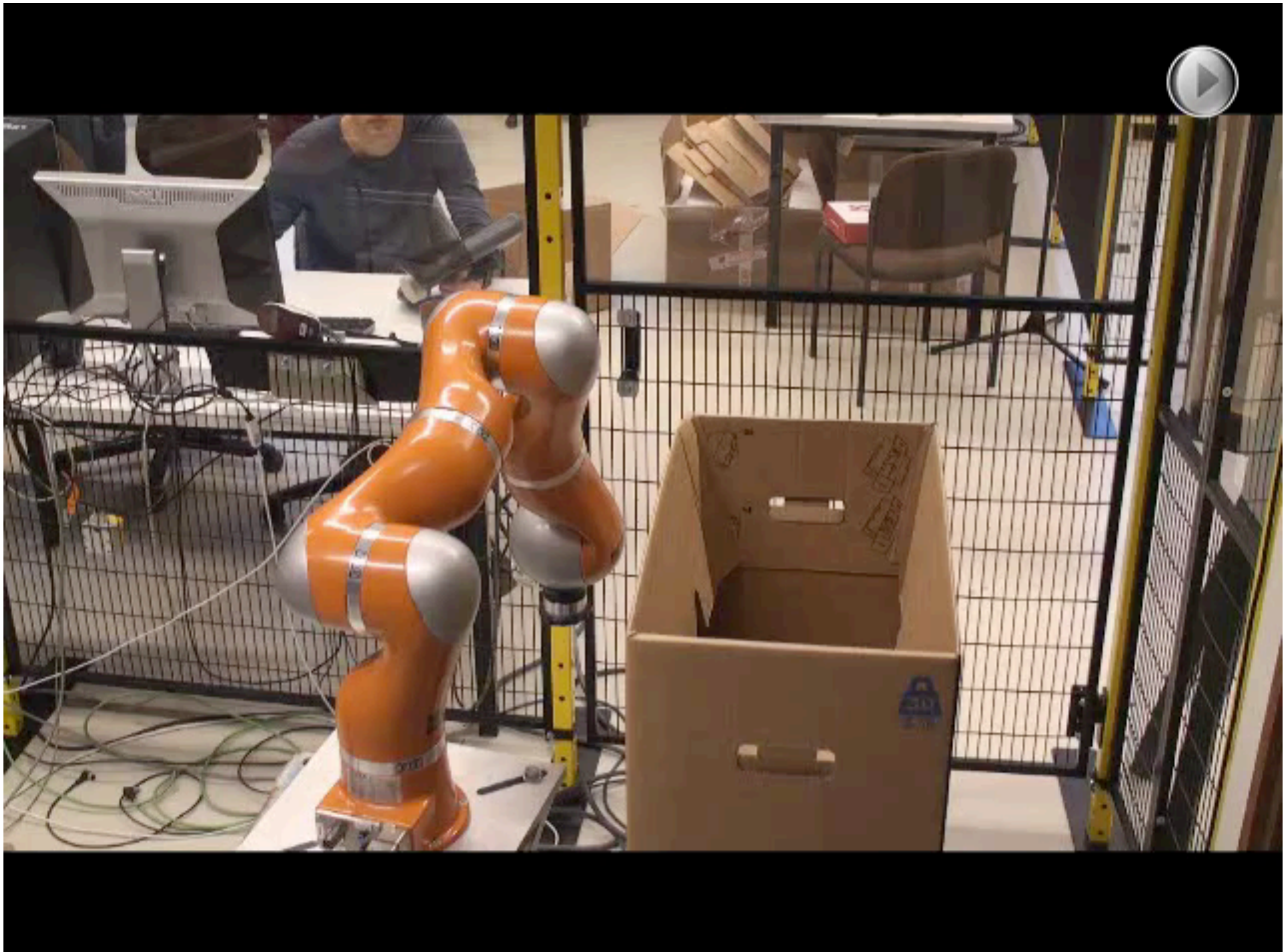
Time-optimal “hand writing” by robot

Univ. Leuven [Debrouwere, Swevers] using [Verscheure et al, IEEE TAC 2009]



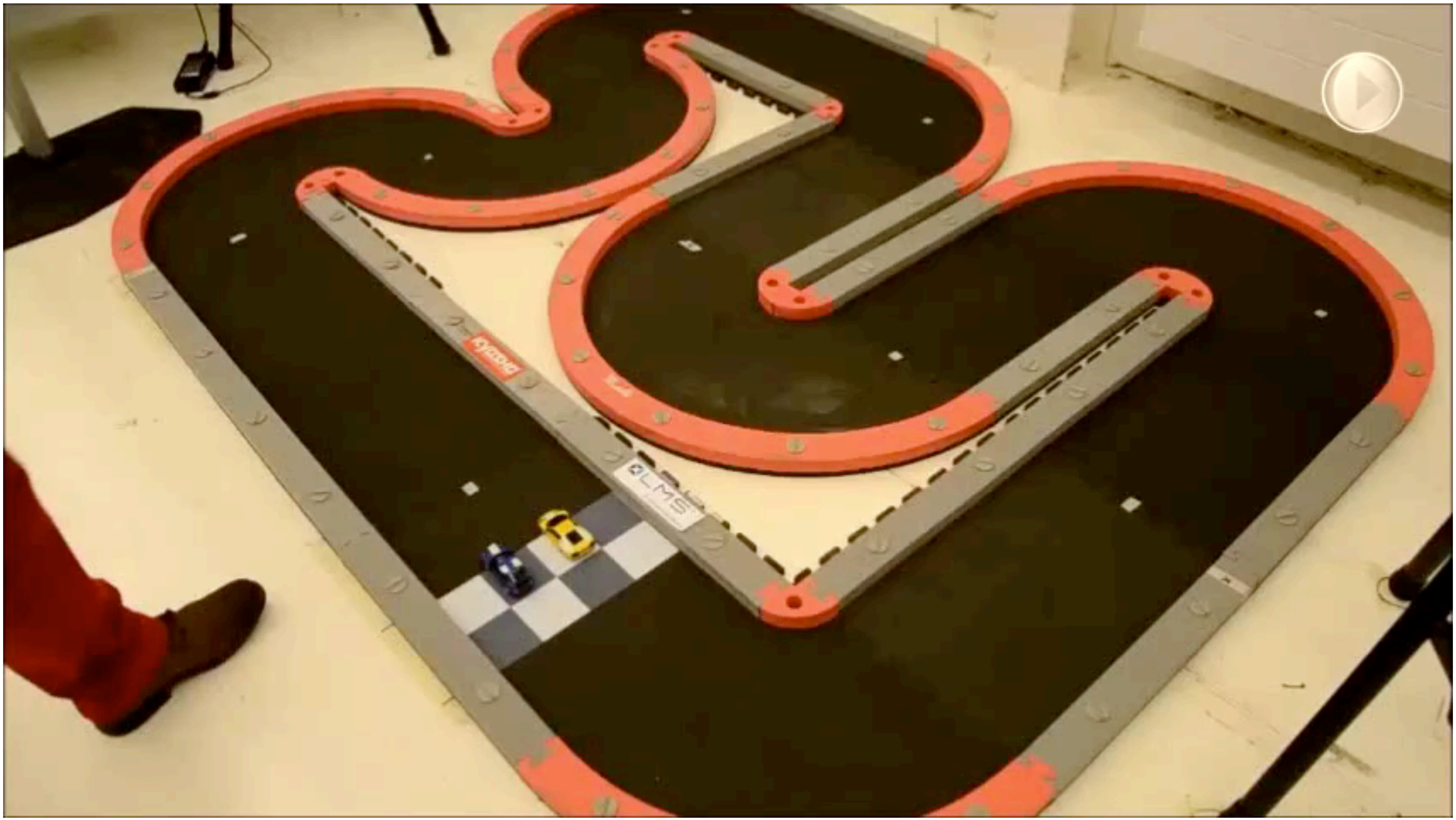
Robot avoiding a box while moving time optimally

Univ. Leuven [Swevers et al.]



Time-optimal “racing” of model cars

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



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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)							
	Monday	Tuesday	Wednesday, 25.3.2015	Thursday, 26.3.2015	Friday, 27.3.2015	Saturday	Sunday, 29.3.2015
08:30			Registration Prometheus Hall, 1st floor, KG I	2. Registration Prometheus Hall, 1st floor, KG I			
09:00			Python course	Introduction to Optimization	Nonlinear Programming and Convex Optimization		
10:30			Break	Break	Break		Sunday Hike (10:00-17:00)
11:00			Python course	CasADi Introduction and Nonlinear Optimization Exercise	Gauss-Newton Exercise		
12:00			Lunch	Lunch	Lunch		
13:00			Python course	Optimal Control Overview	Real-Time Optimization		
14:30			Break	Break	Break		
15:00			Python course	Direct Multiple Shooting Exercise	Real-Time Optimization Exercise		
16:00			Break	Break	Break		
16:30			Python course	Dynamic System Models and Numerical Integration	ACADO Code Generation (Robin and Rien)		
18:00			End	End	End		
				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)							
	Monday, 30.3.2015	Tuesday, 31.3.2015	Wednesday, 1.4.2015	Thursday, 2.4.2015	Friday	Saturday	Sunday
09:00	Introductory Review: Linear Regulation and State Estimation (LQR and LQE)	Nonlinear Model Predictive Control - Regulation	Exam	Project Presentations			
10:30	Break	Break	Break	Break			
11:00	Exercise: LQR and LQE	Exercises	Project Work	Project Presentations			
12:00	Lunch	Lunch	Lunch	Lunch			
13:00	Tracking, Disturbances and Zero -Offset	Nonlinear Moving Horizon Estimation	Project Work	Project Presentations			
14:30	Break	Break	Break	Break			
15:00	Exercise	Exercises	Nonlinear MPC Applications (Thomas Besselmann, ABB)	Closing Session and Handout of Certificates			
16:00	Break	Break	Break	End at 16:00			
16:30	Review and Exercises	Review and Exercises	Project Work				
18:00	End	End	End				
	Spring School Dinner** (18:30-22:00)						