Introduction to TEMPO Summer School on Numerical Optimal Control

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Overview

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

University of Freiburg

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

- today, 24 000 students (52% female, 14% international), all faculties (humanities, sciences, medicine, *engineering*)

Technical Faculty Freiburg

Opened in 1995, next to Freiburg's airfield. So far, two departments:
- Department of Computer Science - 23 professors
- *Department of Microsystems Engineering (IMTEK) - 22 professors*

The Systems, Control and Optimization Laboratory

- professor: Moritz Diehl
- secretary: Christine Paasch + Savannah Cook
- PhD students: Greg Horn, Mario Zanon, Rien Quirynen, Joris Gillis, Adeleh Mohammadi, Milan Vukov, Kurt Geebelen (last 4 in Leuven)
- current guests: Joel Andersson, Boris Houska

Research Topics

- Optimization Algorithms and Software, often for real-time optimization on embedded platforms
- Nonlinear Model Predictive Control and Moving Horizon Estimation
- Modelling Tools for Optimization and Parameter Identification
- Quadratic Programming (QP) solvers
- Airborne Wind Energy Modelling and Optimization

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 summer school

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Time-Optimal Point-To-Point Motions [PhD Vandenbrouck 2012]

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

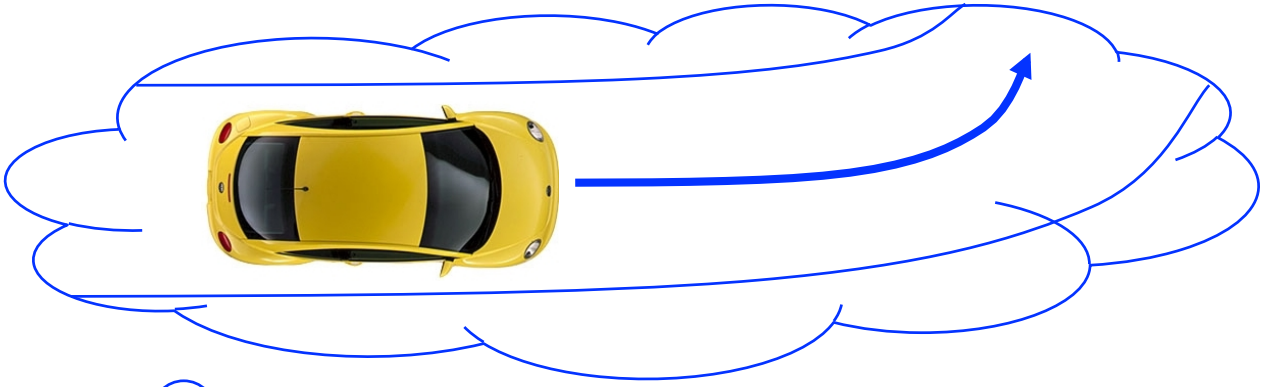
Control aims:

- 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)

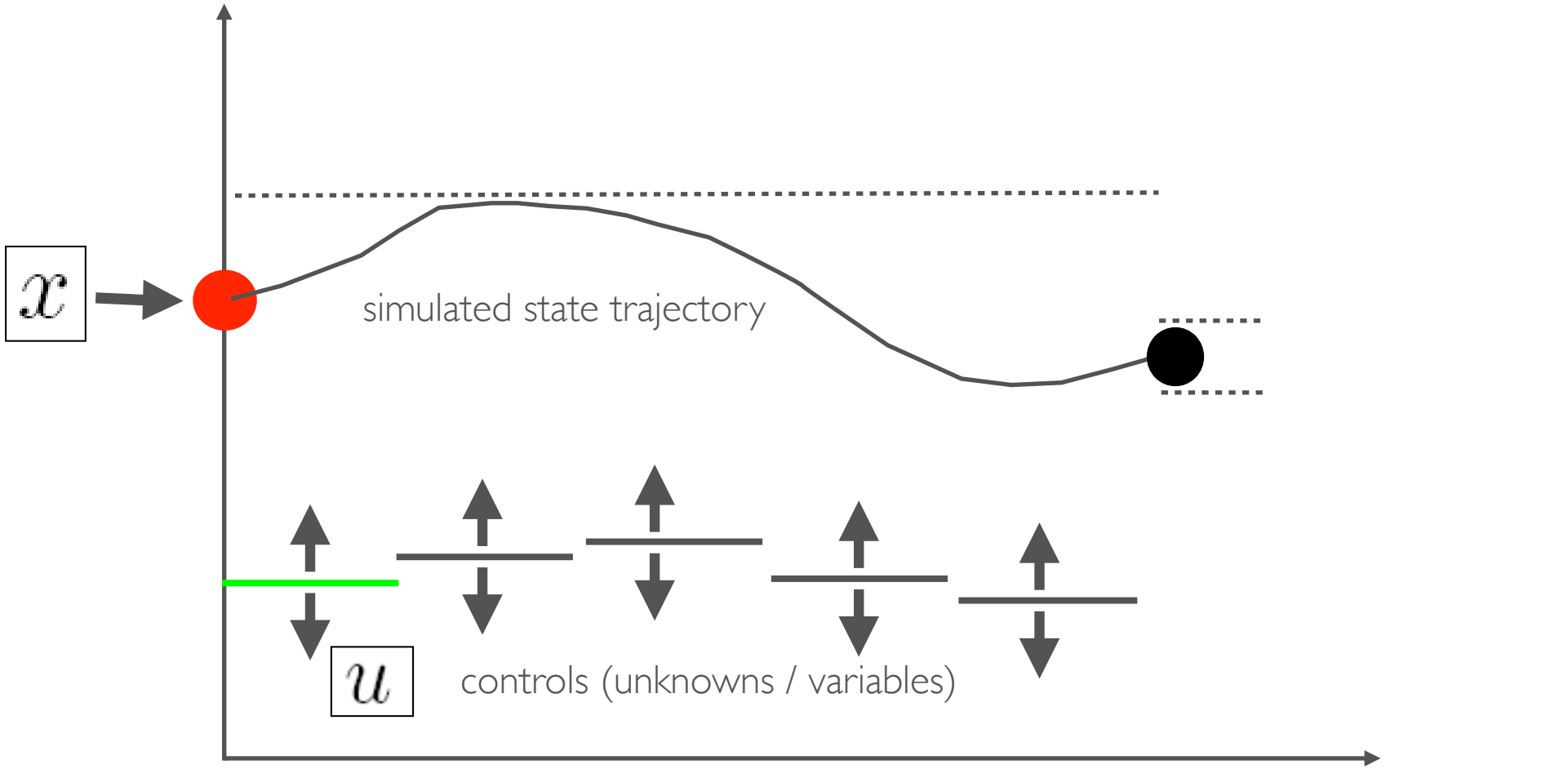
Always look a bit into the future



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 ?



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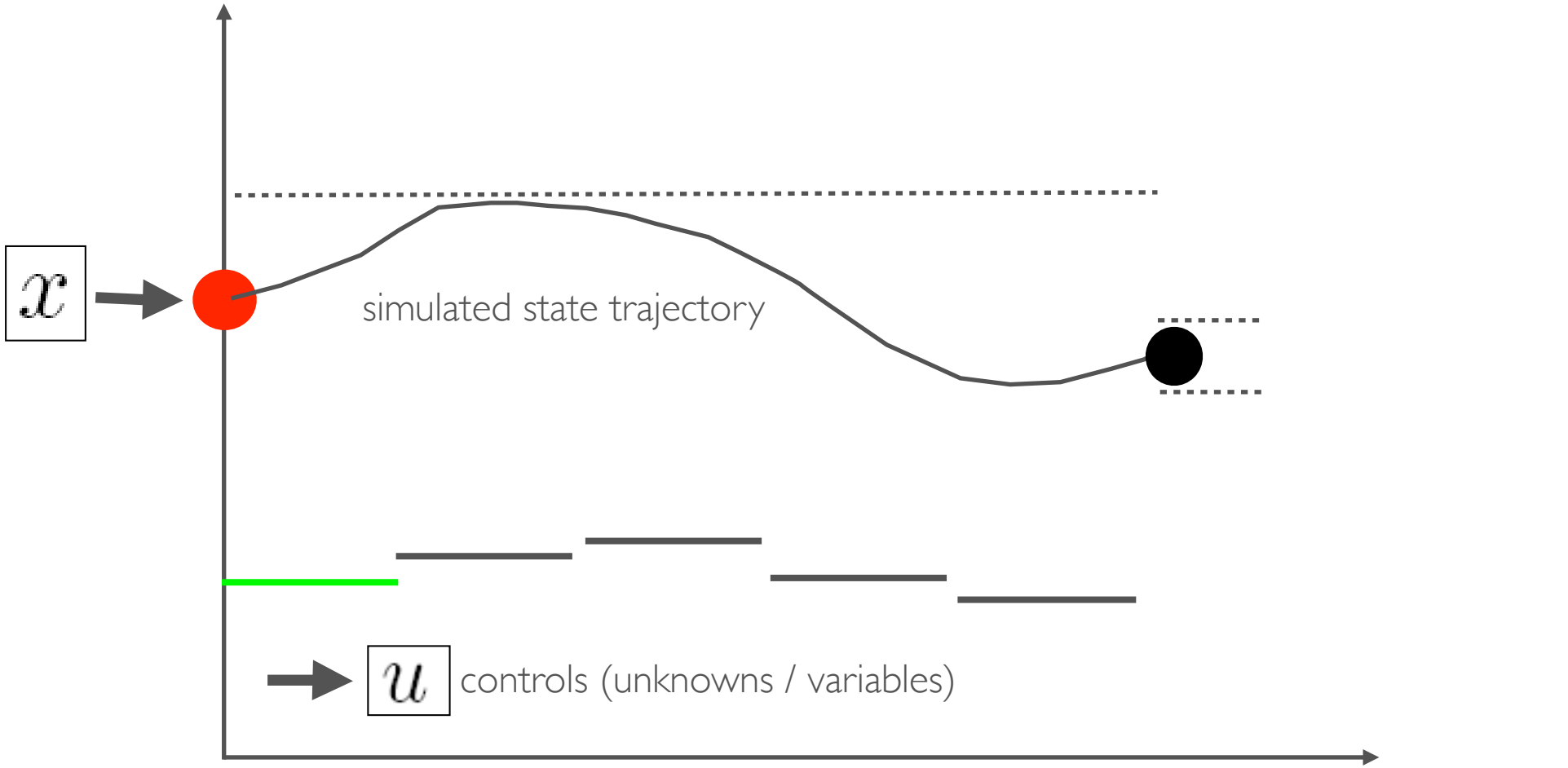


Time Optimal MPC of a Crane

SENSORS

- line angle
- cart position

MPC

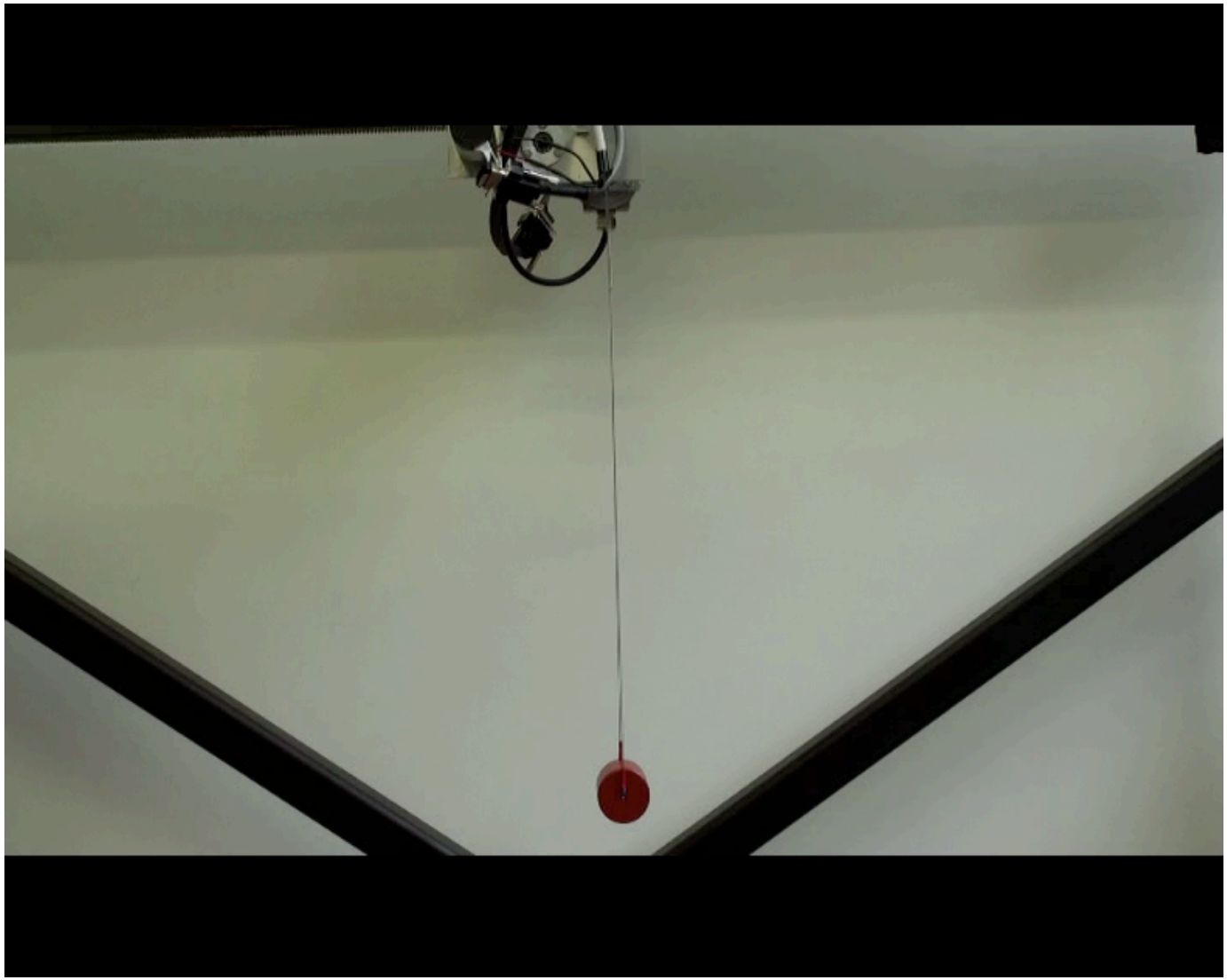
ACTUATOR

- cart motor

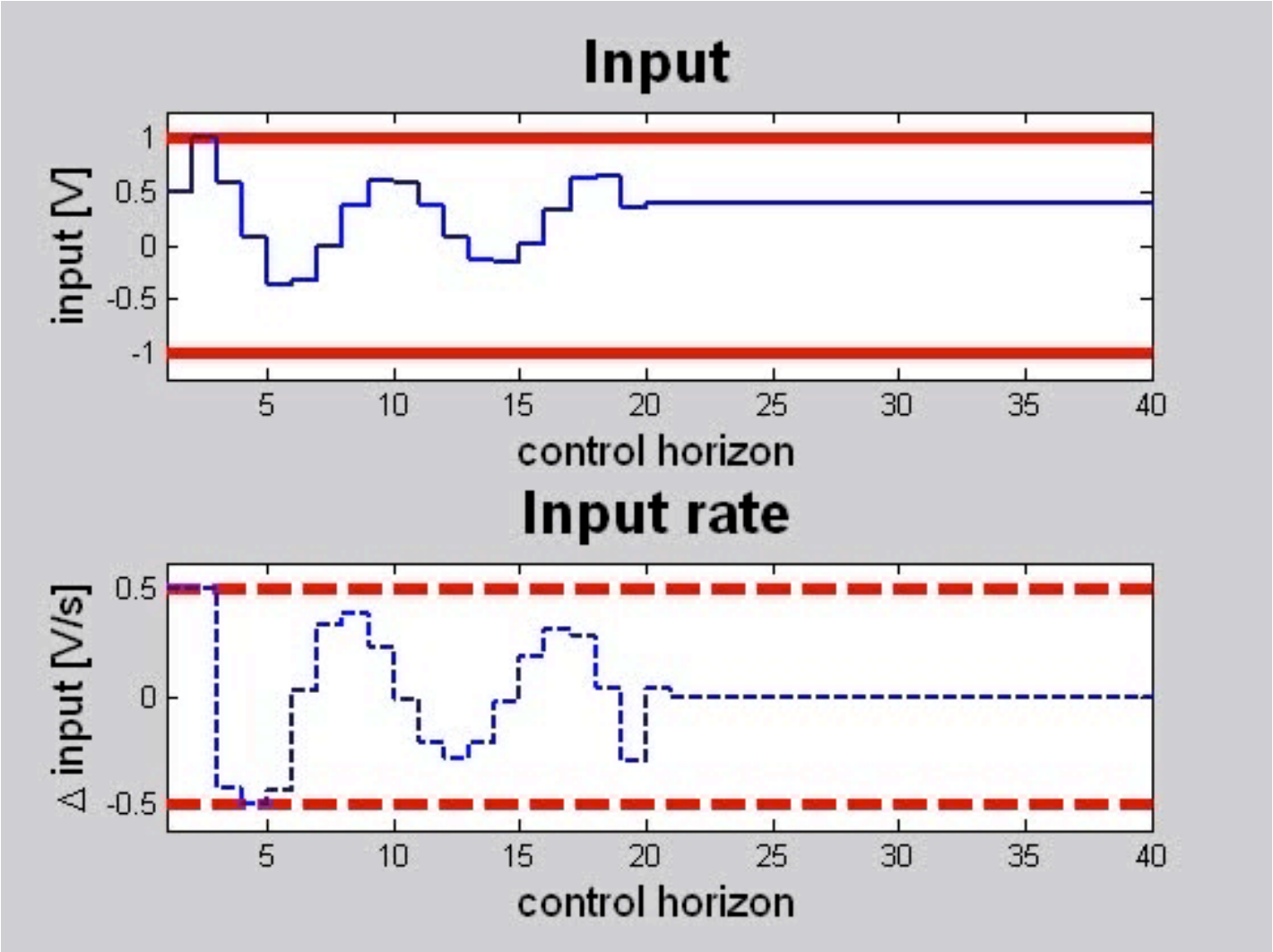
Hardware: xPC Target. Software: qpOASES [Ferreau, D., Bock, 2008]

Time Optimal MPC of a Crane

Univ. Leuven [Vandenbrouck, Swevers, D.]

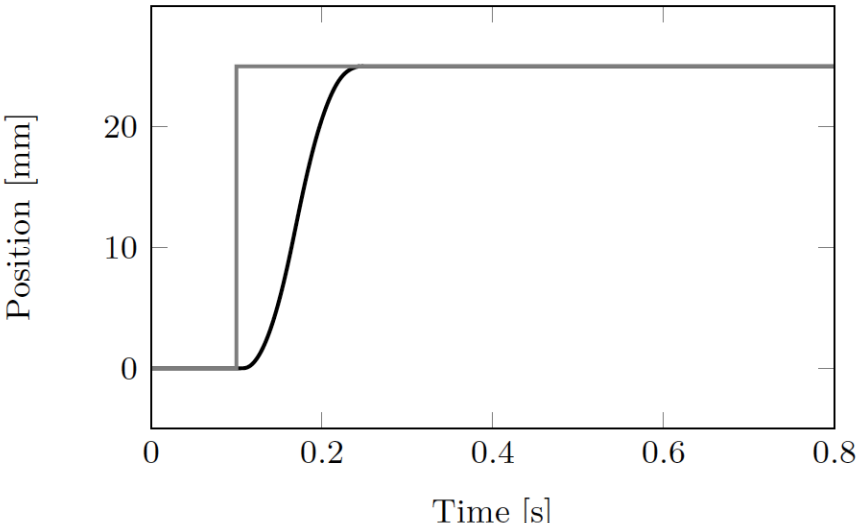


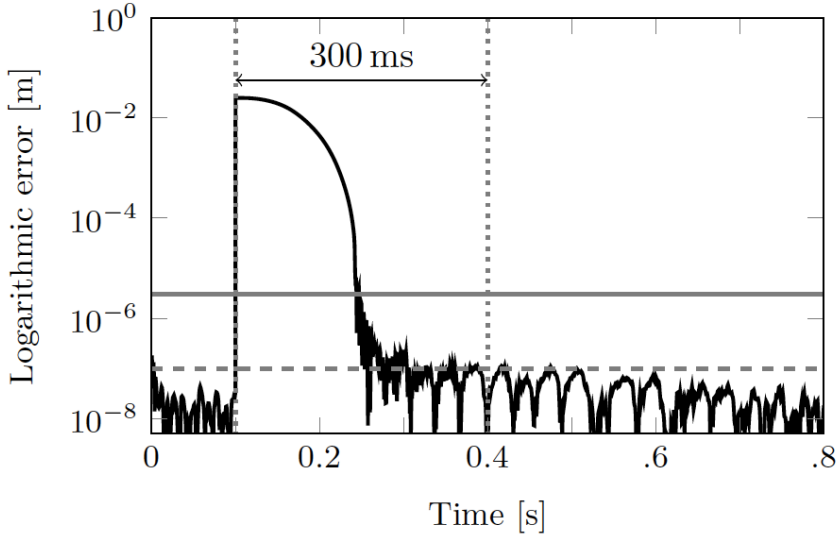
Optimal Solutions in qpOASES Varying in Time



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"

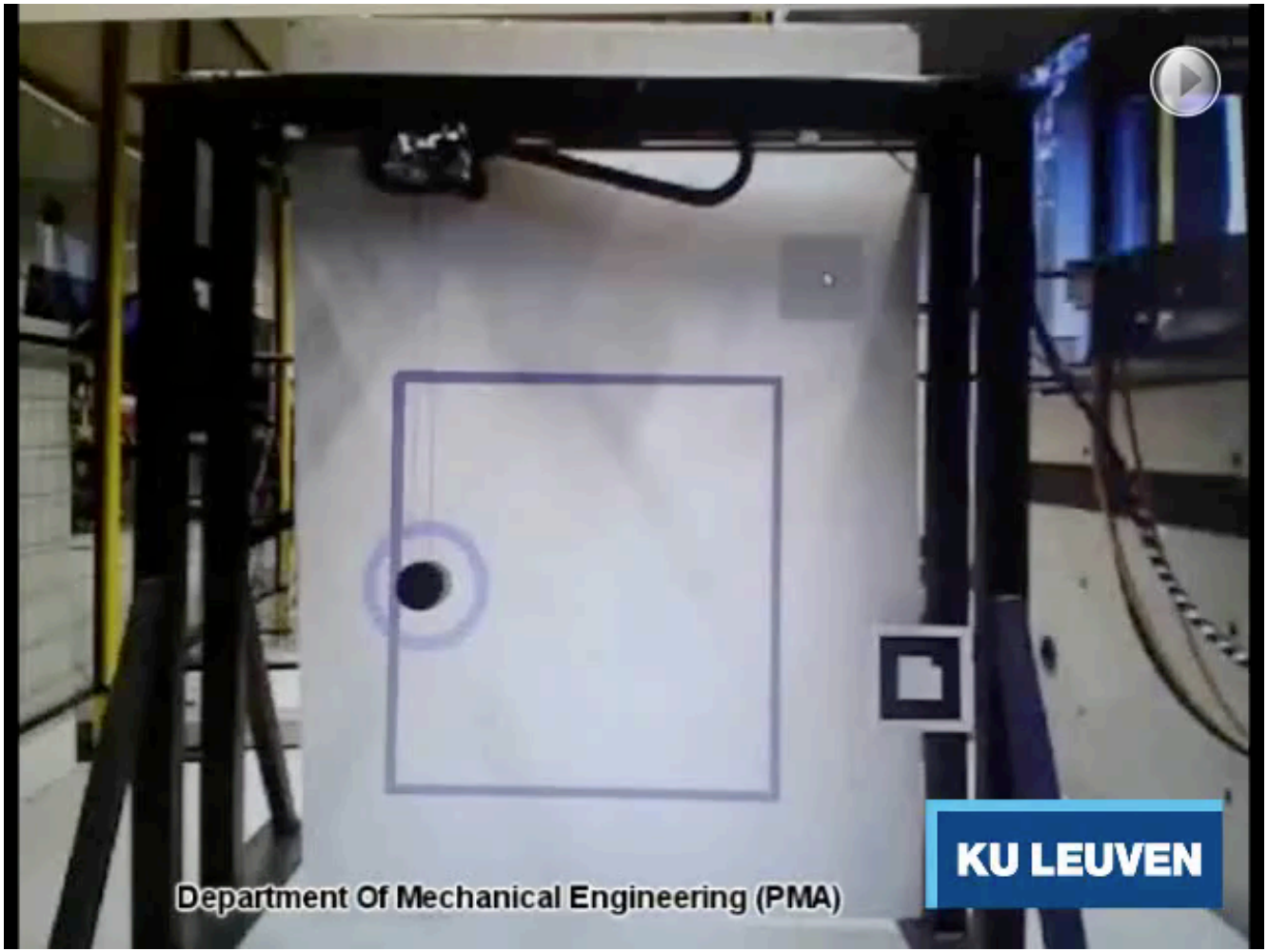
Open Source Software Tools from the Systems, Control and Optimization Laboratory

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 Verscheuren, …]
- **CasADi:** modelling environment for dynamic optimization [Joel Andersson, Joris Gillis, Greg Horn, …]

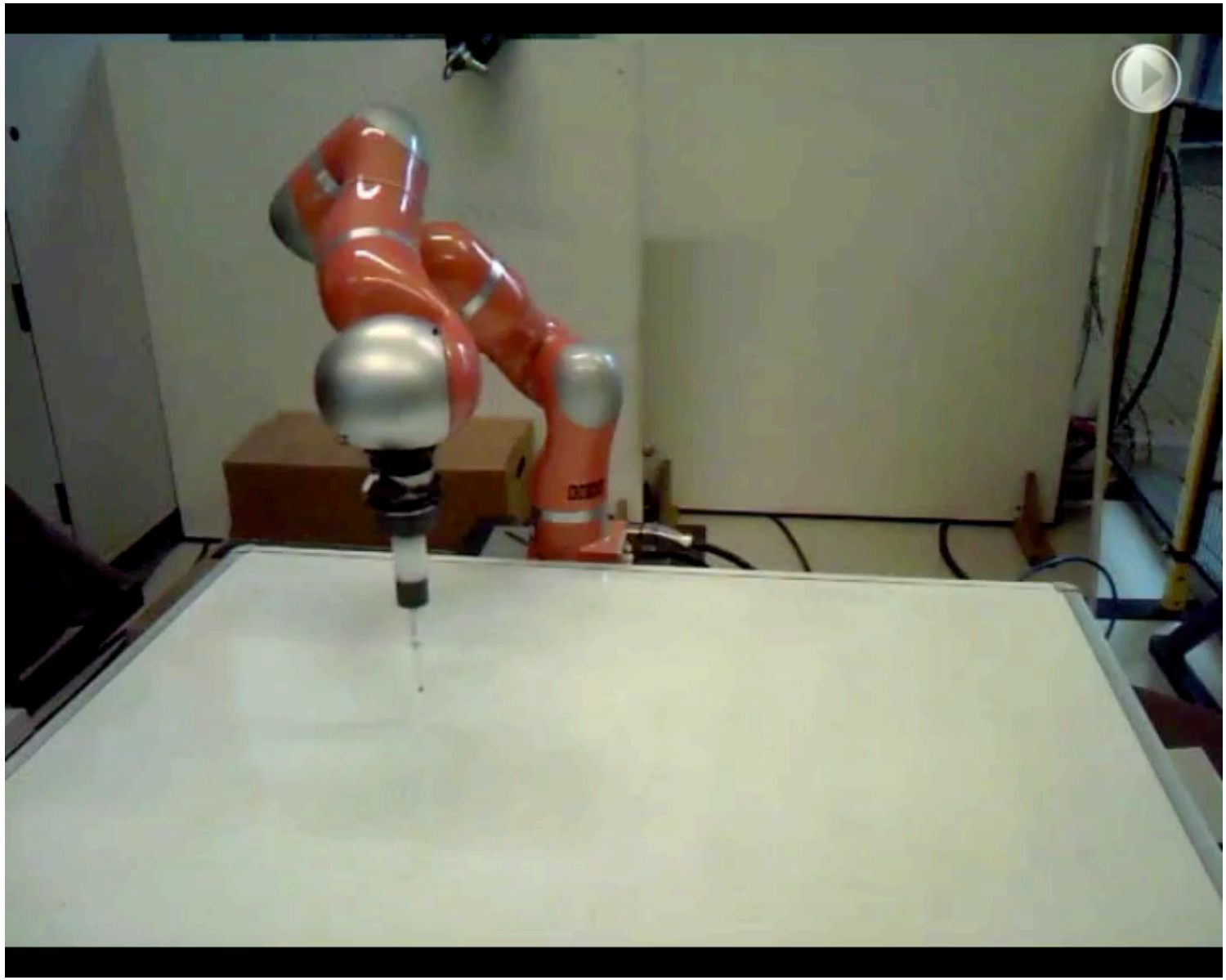
Time Optimal “drawing” by crane

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



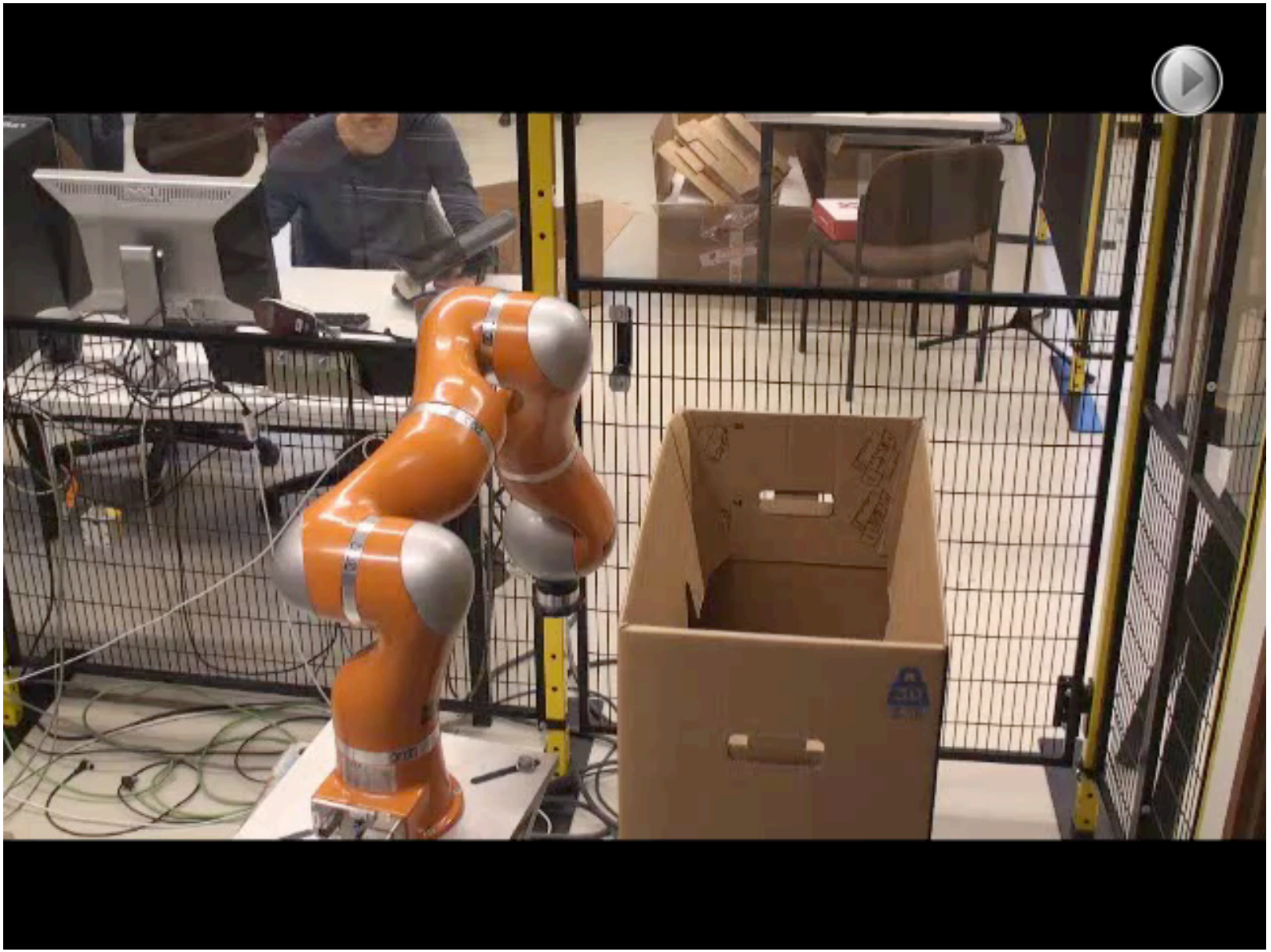
Time-optimal “hand writing” by robot

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



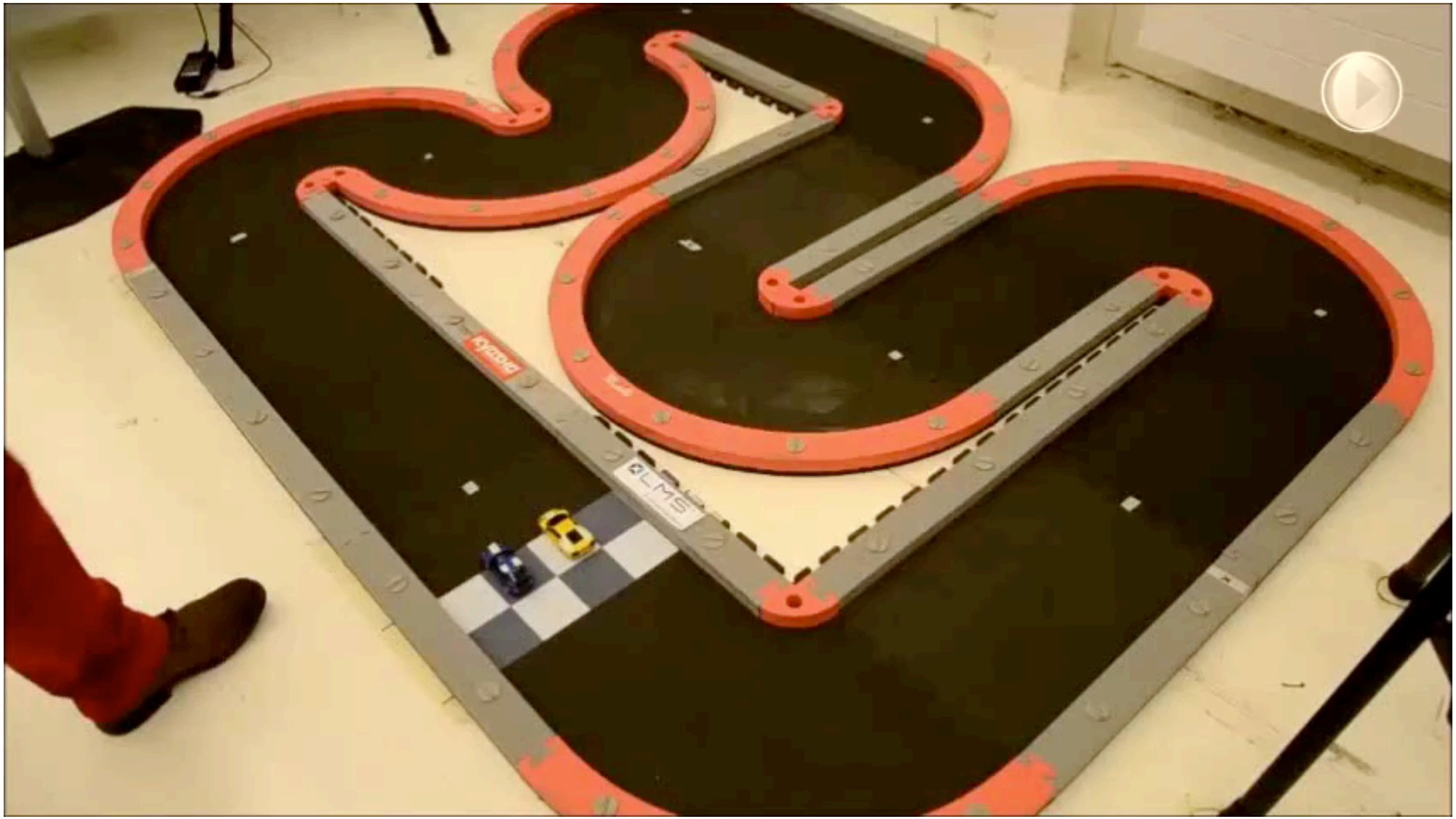
Robot avoiding a box while moving time optimally

Univ. Leuven [Swevers et al.]



Time-optimal “racing” of model cars

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



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Overview of the course

- Monday: Optimization (Python)
- Tuesday: Simulation and Derivatives (CasADi)
- Wednesday: Optimal Control
  - Evening out at "Feierling"
- Thursday: Direct Methods for Optimal Control
- Friday: Model Predictive Control
- Saturday: optional excursion to Black Forest

2nd week:

- Monday: Exam and start of own projects
- Tuesday: Work on own projects
- Wednesday: Presentations of own projects

Detailed Schedule of First Week

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
9:00 - 10:30	L1: Introduction to optimization	L3: Initial-value problems	L5: Optimal control overview	L7: Direct shooting methods	L9: Nonlinear model predictive control
10:30 - 11:00	Coffee break	Coffee break	Coffee break	Coffee break	Coffee break
11:00 - 13:00	E1: Python + Quadratic programming	E3: Integrators	E5: Dynamic programming	E7: Direct single and multiple shooting	E9: NMPC + RTI
13:00 - 14:00	Lunch break	Lunch break	Lunch break	Lunch break	Lunch break
14:00 - 15:30	L2: Nonlinear programming	L4: Derivatives and BVP	L6/E6: Indirect methods + exercise	L8: Direct collocation	L10: Summary
15:30 - 16:00	Coffee break	Coffee break	Coffee break	Coffee break	Coffee break
16:00 - 18:00	E2: CasADi + Nonlinear programming	E4: Newton's method	Introduction to projects	E8: Direct collocation	End of first week
19:30-			Drinks etc. at Feierling		

Introduction of Teachers and Organizers

Moritz Diehl (German, PhD Heidelberg 2001) - Lectures

Joel Andersson (Swedish, PhD Leuven 2013) - Exercises and Lectures

Joris Gillis (Belgian, MSc Leuven) - Exercises and Lectures

Rien Quirynen (Belgian, MSc Leuven) - Excursion, Lectures, and Exercise Tutor

Mario Zanon (Italian, MSc Trento) - Exercise Tutor

Greg Horn (American, MSc Stanford) - Exercise Tutor

Christine Paasch (German, MA Konstanz) - Secretary

Savannah Cook (American, MA Leuven) - Secretary