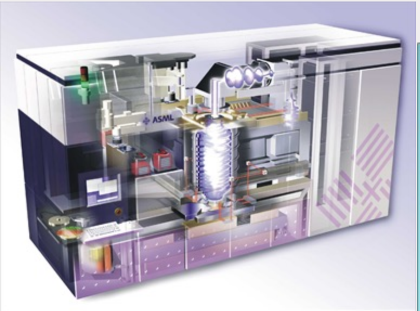
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

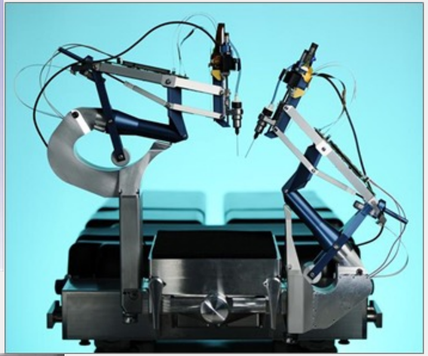
Control Systems Technology

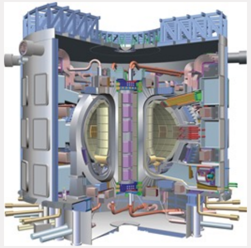
DSD info 2022

Maarten Steinbuch *Maurice Heemels*

Control Systems Technology







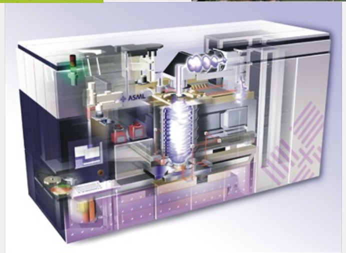
<u>Disciplines</u>

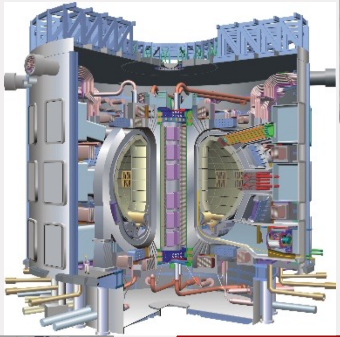
- systems and control theory
- mechanical design / mechatronics
- optimization
- systems engineering

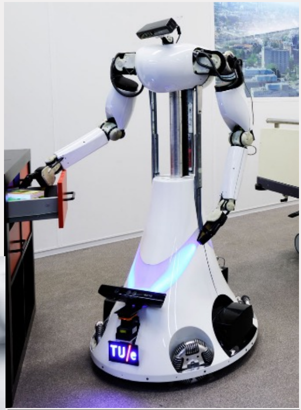
Our research focuses on understanding the fundamental system properties that determine the performance of engineering systems, and exploiting this knowledge for the design of the high-tech systems of the future in a broad range of applications.

KPIs:
50 PhDs
85 MSc/year

Application Domains







Energy Systems

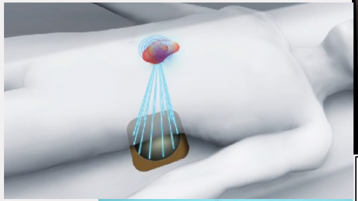
Advanced Motion Systems & Mechatronics

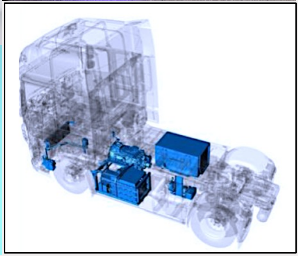
Automated Driving & Powertrains

Medical systems

Infra: Waterlocks, Bridges, Tunnels

Robotics & Drones





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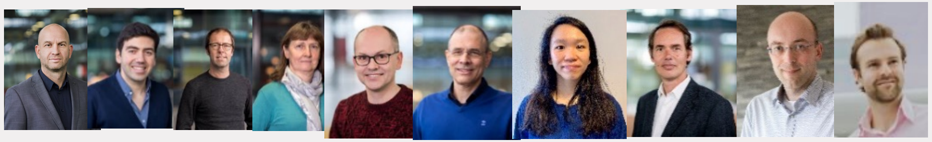
CST People and subprogrammes

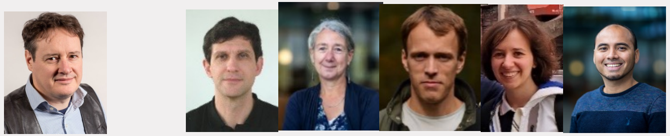
Steinbuch, Oomen, *Heertjes, Witvoet,* Tiels, *Vermeulen, Blancken,* Vrancken, *Sperling, Kappelhof, Cacace*

Model-based Control, Learning Control, Identification and Design of Motion Systems



Heemels,Antunes,Reniers,vd Mortel,Etman, v Beek, Chong, *Fokkink, van Eekelen, Wilschut*

Cyber-Physical Systems of Systems



vd Molengraft, *Bruyninckx,* Kappers, *Elfring,* Torta, *Lopez Martinez*

Robotics for Care, Cure & Agro-food

Hofman, Salazar, *Silvas, Willems, v Keulen, Huisman, Katriniok*

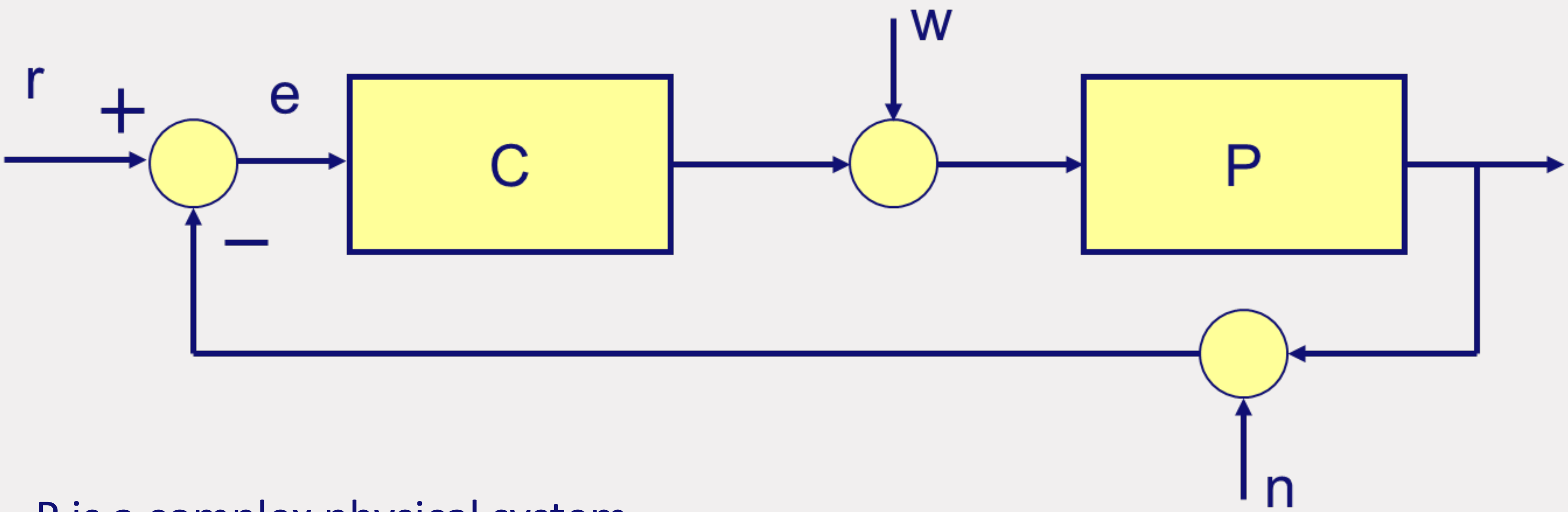
Automotive Powertrains & Smart Mobility

De Baar, Krishnamoorthy (from 1st of September)

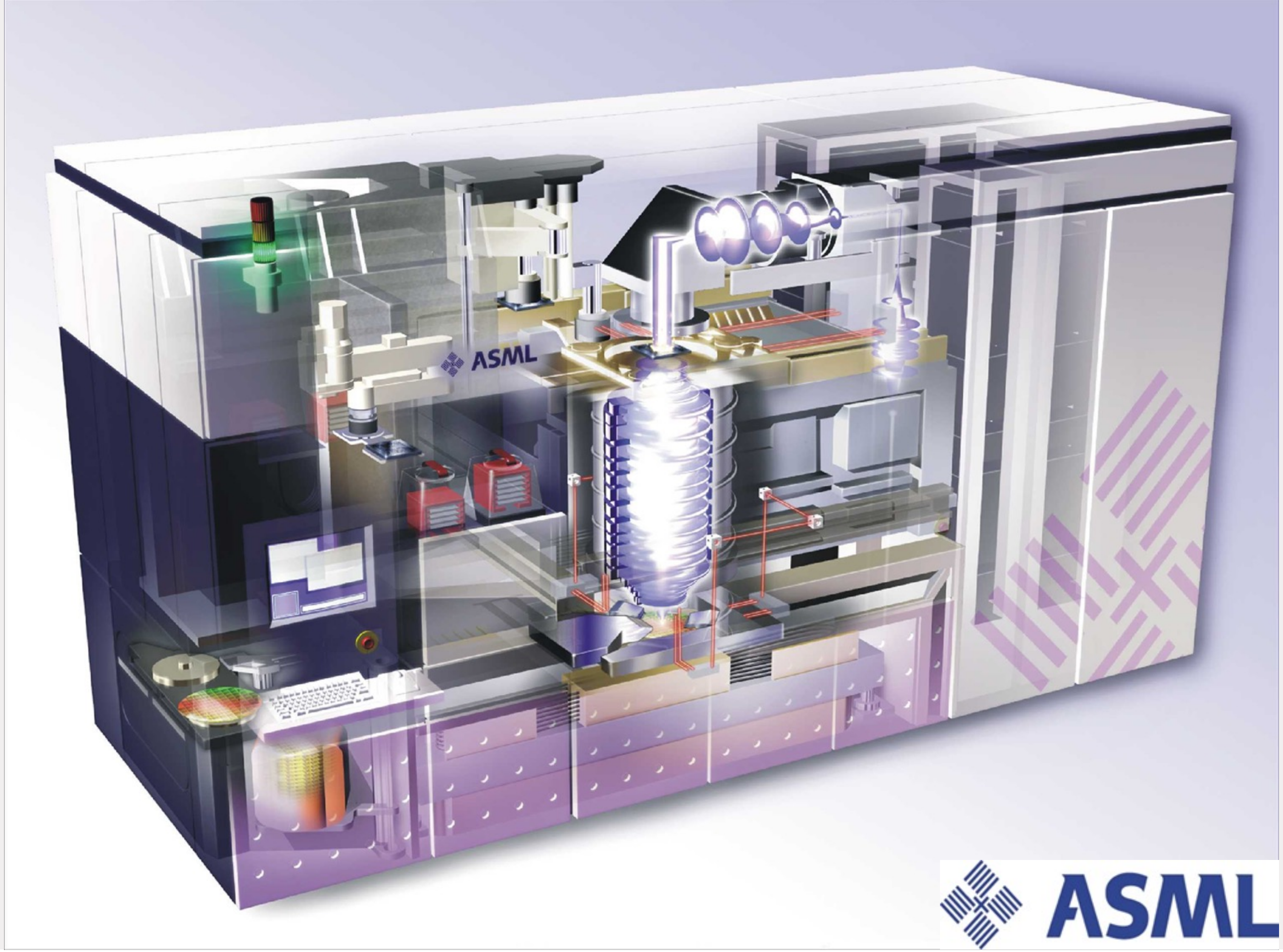
Process Control of Energy Systems

DIFFER
Dutch Institute for Fundamental Energy Research

Control Systems & System Thinking

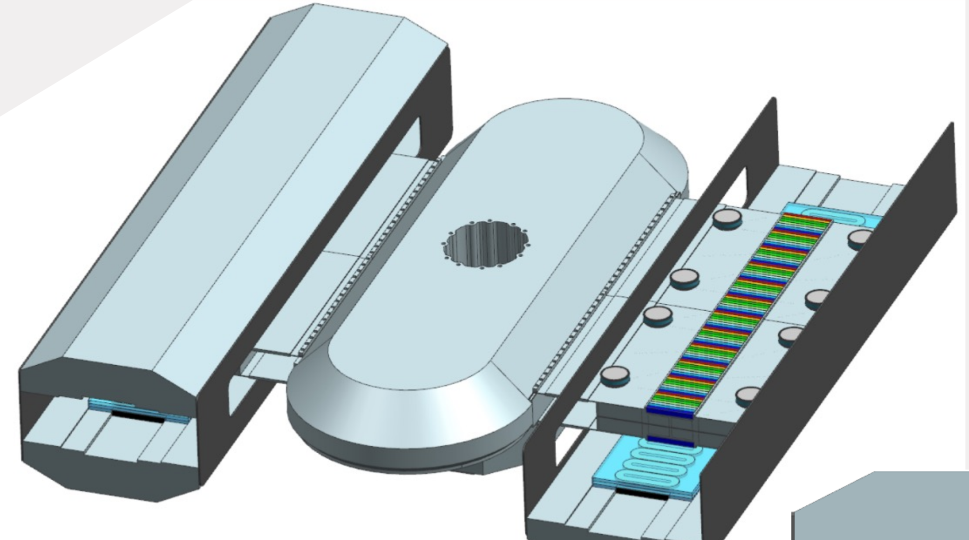


- P is a complex physical system
- C is a (distributed, adaptable, reconfigurable) control system

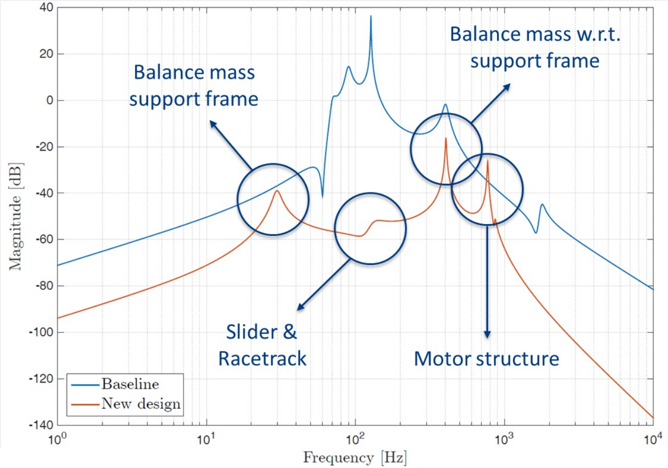

ASML
ASML

Long stroke actuator unit for an EUV reticle stage

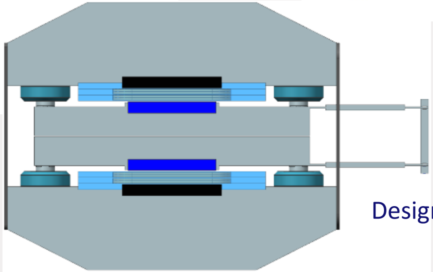
Lightweight design (20% mass reduction) with reduced force transmissibility (~50 DB) – MSc Pim Duijsens (2016)



Design of EUV reticle stage with new long stroke actuator unit



Disturbance force transmissibility in vertical direction, baseline vs. new design

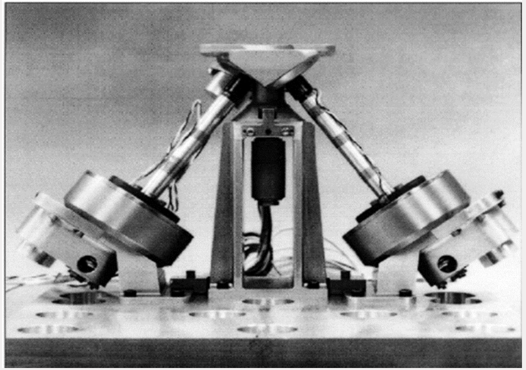


Design of the long stroke actuator unit

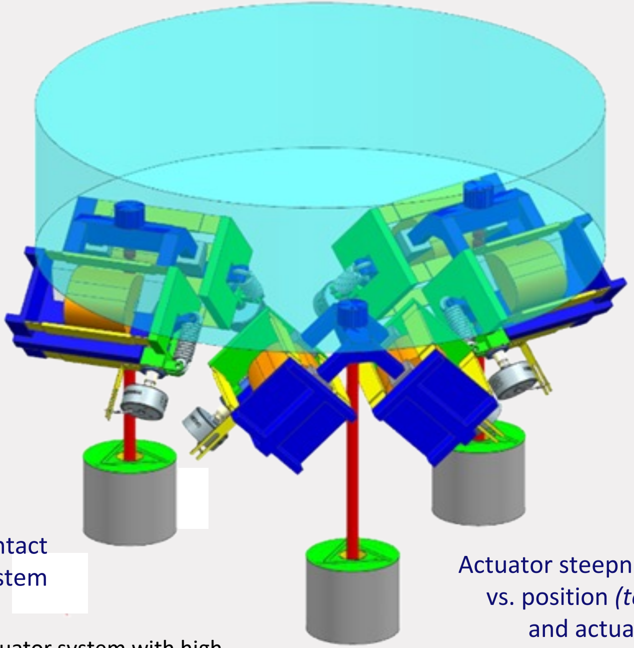
Ref: Duijsens, P.J.H., Design of a long stroke actuator unit for the EUV reticle stage, Master's thesis report, Eindhoven University of Technology, September 17, 2016

EUV mirror actuator with high steepness to mass ratio

Compact light-weight alternative based on non-contact reluctance actuators with significantly improved dynamics – MSc Rene v/d Meulen (2019)

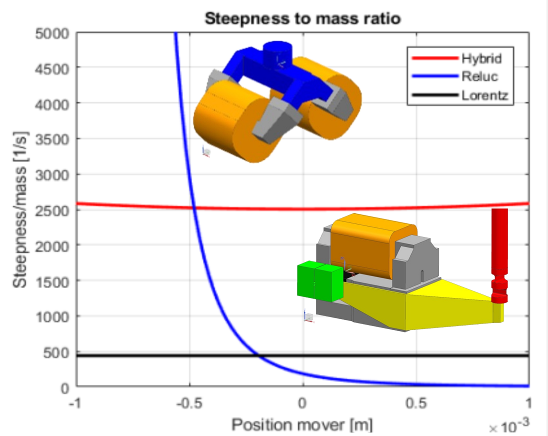


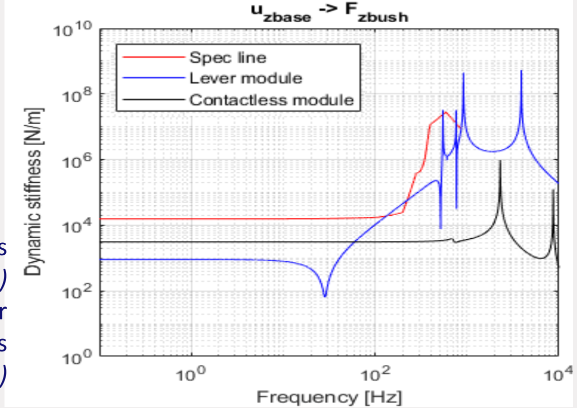
Traditional mirror actuation system with mechanical coupling between (Lorentz) actuator frame and mirror



New design proposal based on non-contact (reluctance) actuation system

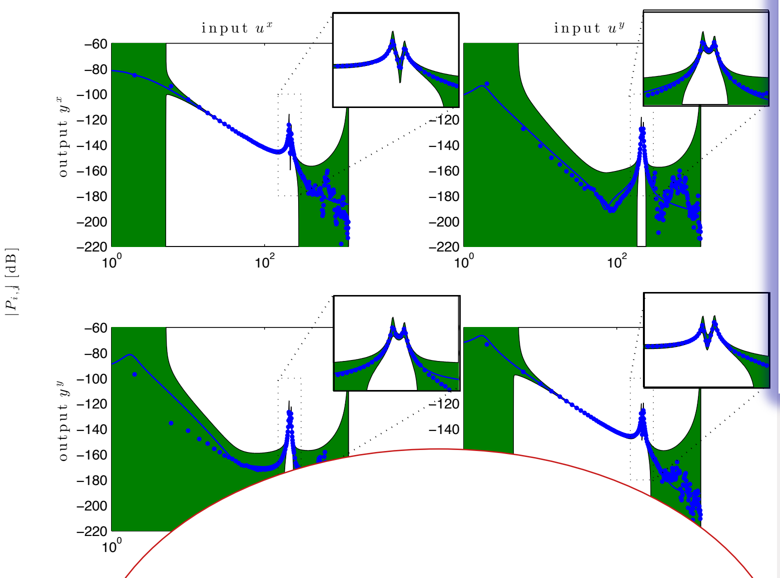
Ref*:* Meulen, R.J.J. van der, Design of an EUV mirror actuator system with high steepness and low mirror deformation, Master's thesis report, Eindhoven University of Technology, August 13, 2019 (patent pending)





Actuator steepness vs. position *(top)* and actuator dynamic stiffness *(bottom, black)*

Control for virtual stiffness and damping



Contents lists available at ScienceDirect

Mechatronics

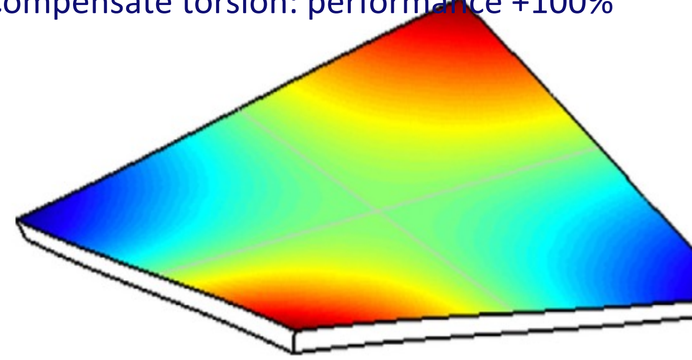
journal homepage: www.elsevier.com/locate/mechatronics

ELSEVIER

Exploiting additional actuators and sensors for nano-positioning robust motion control

Robbert van Herpen [a,*], Tom Oomen
Maarten Steinbuch [a]

Create virtual stiffness through control:
Compensate torsion: performance +100%



Identify models for control!

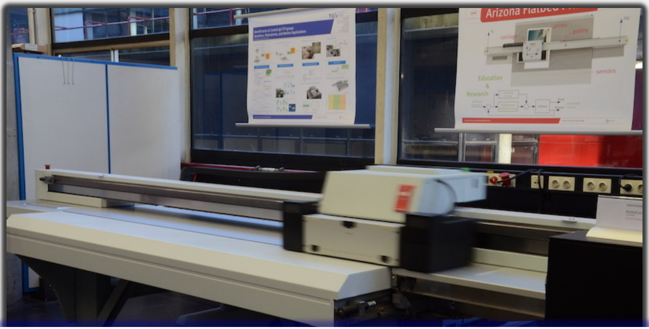
$$d^Y(\hat{P}_s, P_{0,s}) = \left\|T(P_{0,s}, C_s^{\mathrm{exp}}) - T(\hat{P}_s, C_s^{\mathrm{exp}})\right\|_\infty$$

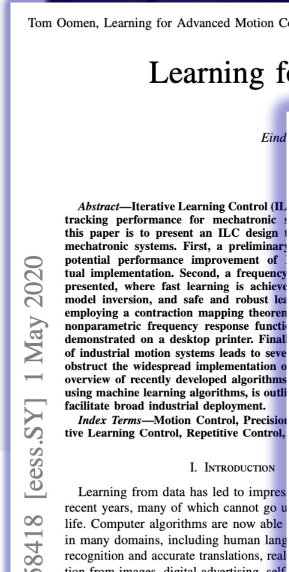
Advanced Motion Control for Precision Mechatronics: Control, Identification, and Learning of Complex Systems, Tom Oomen, IEEJ Journal of Industry Applications, 7(2), 1-14, 2018

TU/e

(Machine) learning for control

What does learning have to offer?




Tom Oomen, Learning for Advanced Motion Control, In *IEEE International Workshop on Advanced Motion Control*, Agder, Norway, 202

Learning for Advanced Motion Control

Eind

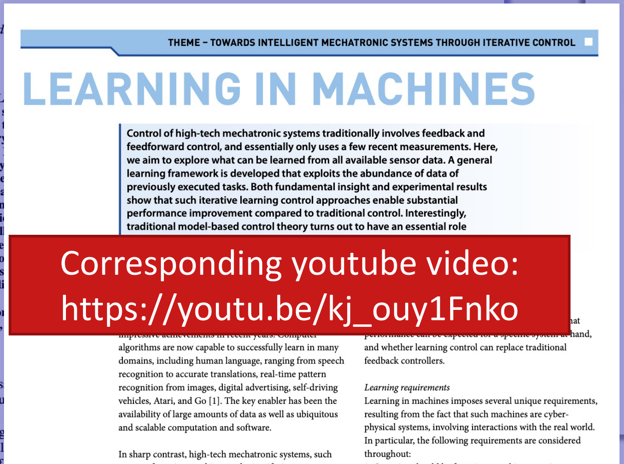
Abstract—Iterative Learning Control (IL
tracking performance for mechatronic
this paper is to present an ILC design
mechatronic systems. First, a preliminary
potential performance improvement of
tual implementation. Second, a frequency
presented, where fast learning is achieve
model inversion, and safe and robust lea
employing a contraction mapping theorem
nonparametric frequency response functi
demonstrated on a desktop printer. Final
of industrial motion systems leads to seve
obstruct the widespread implementation o
overview of recently developed algorithms
using machine learning algorithms, is outli
facilitate broad industrial deployment.

Index Terms—Motion Control, Precision
tive Learning Control, Repetitive Control,

I. Introduction

Learning from data has led to impres
recent years, many of which cannot go u
life. Computer algorithms are now able
in many domains, including human lang
recognition and accurate translations, real

58418 [eess.SY] 1 May 2020


THEME – TOWARDS INTELLIGENT MECHATRONIC SYSTEMS THROUGH ITERATIVE CONTROL

LEARNING IN MACHINES

Control of high-tech mechatronic systems traditionally involves feedback and feedforward control, and essentially only uses a few recent measurements. Here, we aim to explore what can be learned from all available sensor data. A general learning framework is developed that exploits the abundance of data of previously executed tasks. Both fundamental insight and experimental results show that such iterative learning control approaches enable substantial performance improvement compared to traditional control. Interestingly, traditional model-based control theory turns out to have an essential role

algorithms are now capable to successfully learn in many domains, including human language, ranging from speech recognition to accurate translations, real-time pattern recognition from images, digital advertising, self-driving vehicles, Atari, and Go [1]. The key enabler has been the availability of large amounts of data as well as ubiquitous and scalable computation and software.

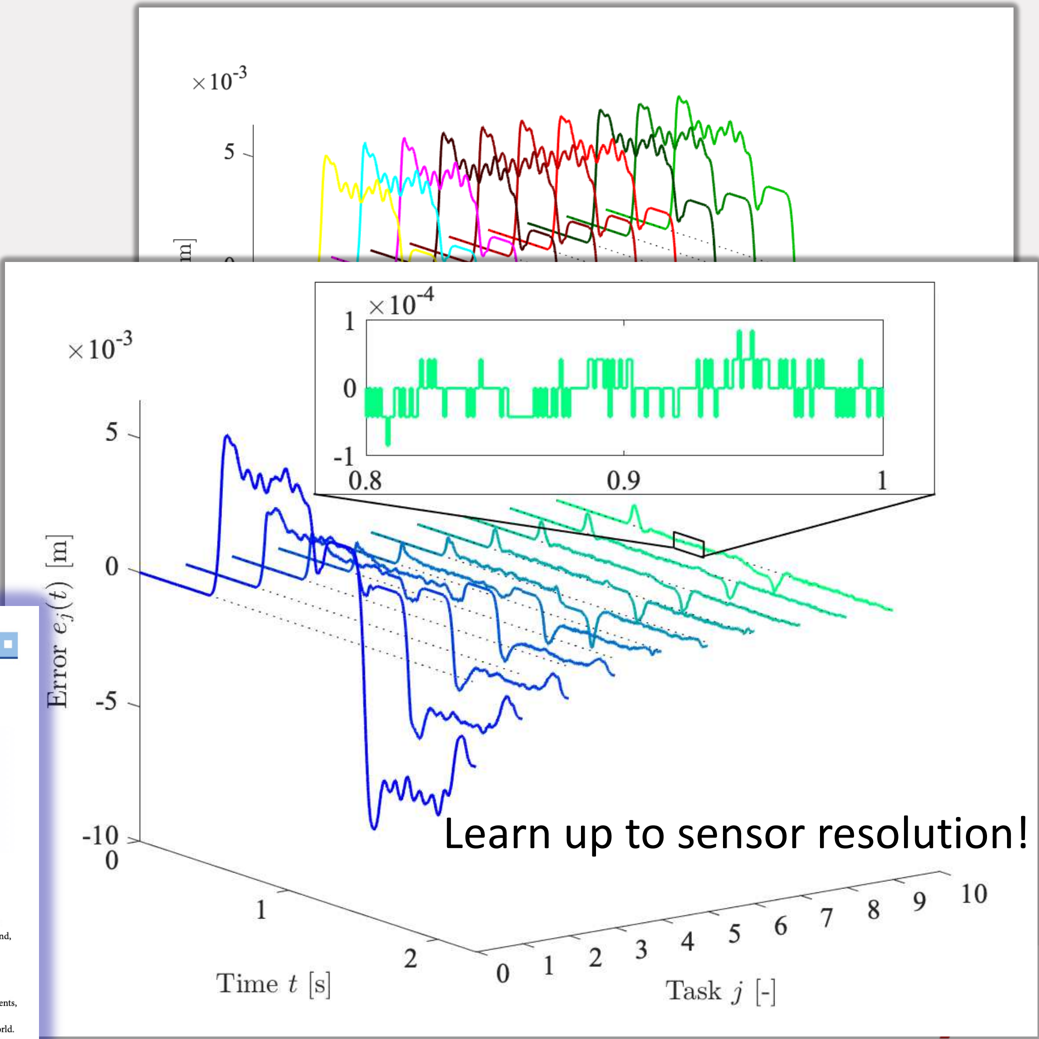
In sharp contrast, high-tech mechatronic systems, such

and whether learning control can replace traditional feedback controllers.

Learning requirements

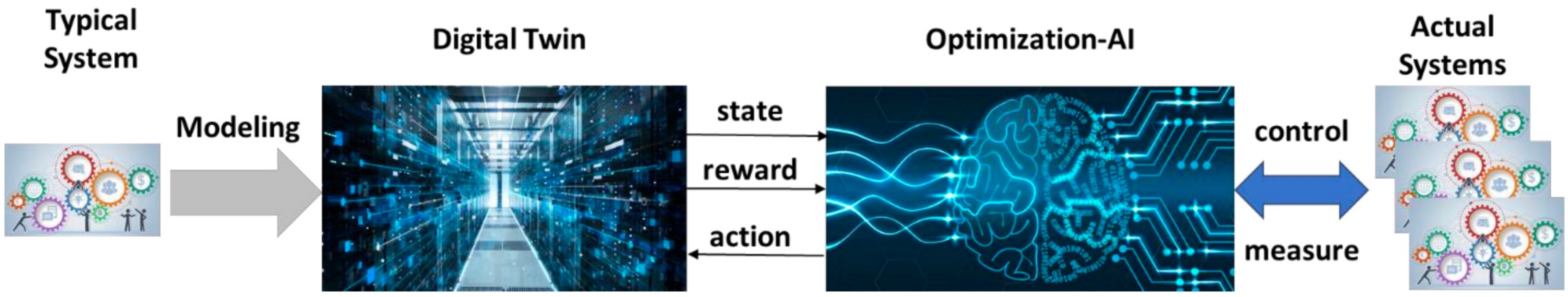
Learning in machines imposes several unique requirements, resulting from the fact that such machines are cyber-physical systems, involving interactions with the real world. In particular, the following requirements are considered throughout:

Corresponding youtube video:
https://youtu.be/kj_ouy1Fnko



Learn up to sensor resolution!

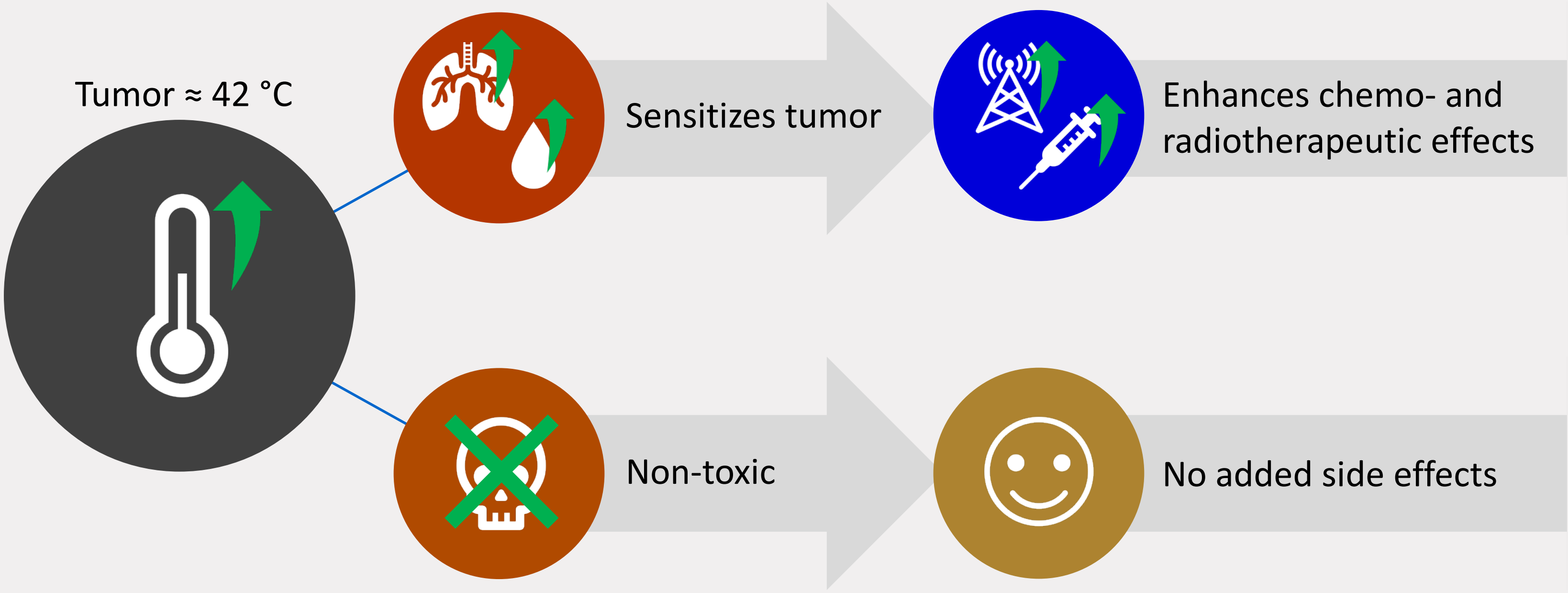
Digital Twinning and Reinforcement Learning



Other (ASML):

- Predictive maintenance for mechatronic systems
- Thermal-mechanical systems -- optimisation-based control (MPC)

Hyperthermia therapy in cancer treatment



MR-based hyperthermia

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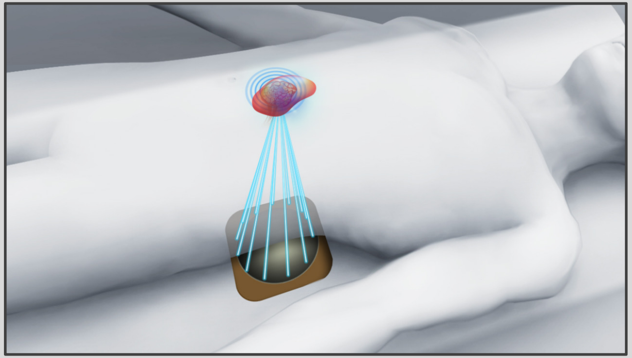
MR-RF: Magnetic-Resonance-guided Radio Frequencies (RF)

MR-HIFU: Magnetic-Resonance-guided High-Intensity Focused Ultrasound

Feedback in hyperthermia

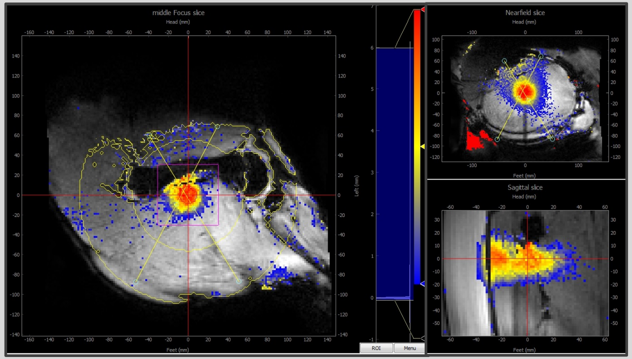
HIFU/RF

Non-invasive Heating



MR

Real-time thermometry by MRI



How to optimize tumor temperature
by controlling HIFU/RF based on MR thermometry?

• Hybrid Control of Motion Systems

Linear motion systems (wafer scanners, pick-and-place machines, electron microscopes) are controlled by linear strategies. **How to achieve improved performance at lower cost using innovative hybrid control strategies?** – beating Bode's waterbed effect

Wafer Scanners

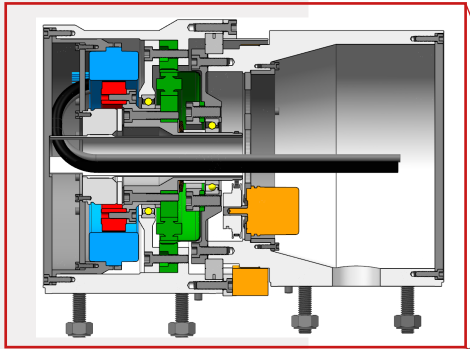
Pick and place machines

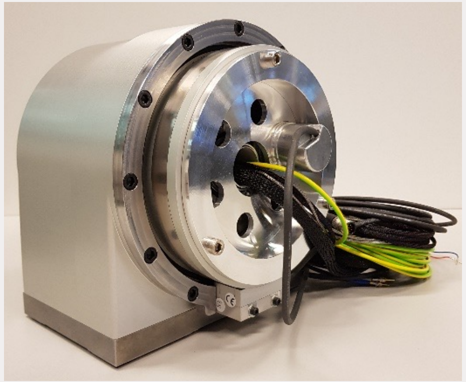
Electron microscopes

Novel mechatronic concepts for X-ray imaging systems

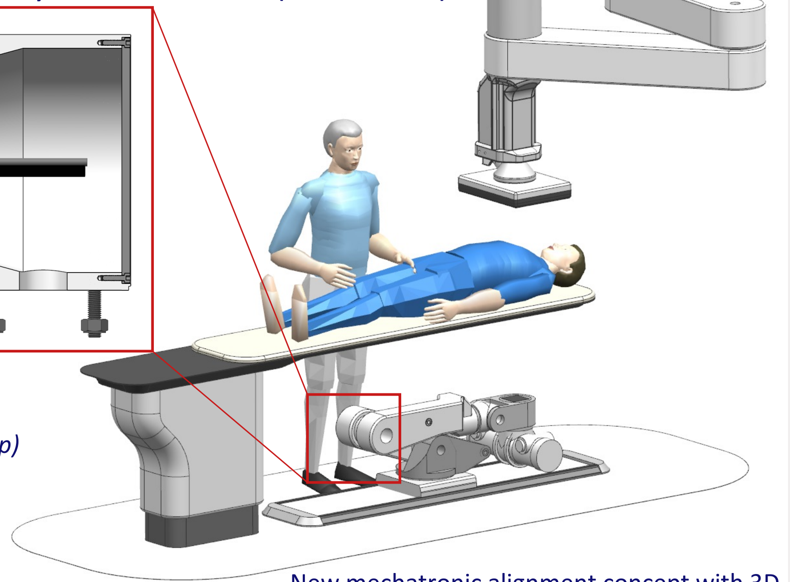
Significantly improved positioning performance at reduced clinical obstruction to medical treatment – PhD Jeffrey van Pinxteren (2016-now)

State of the art interventional X-ray imaging (Philips)





New compact high-stiffness rotary joint for maximum bandwidth, cross-section *(top)* and hardware realization *(bottom left)*



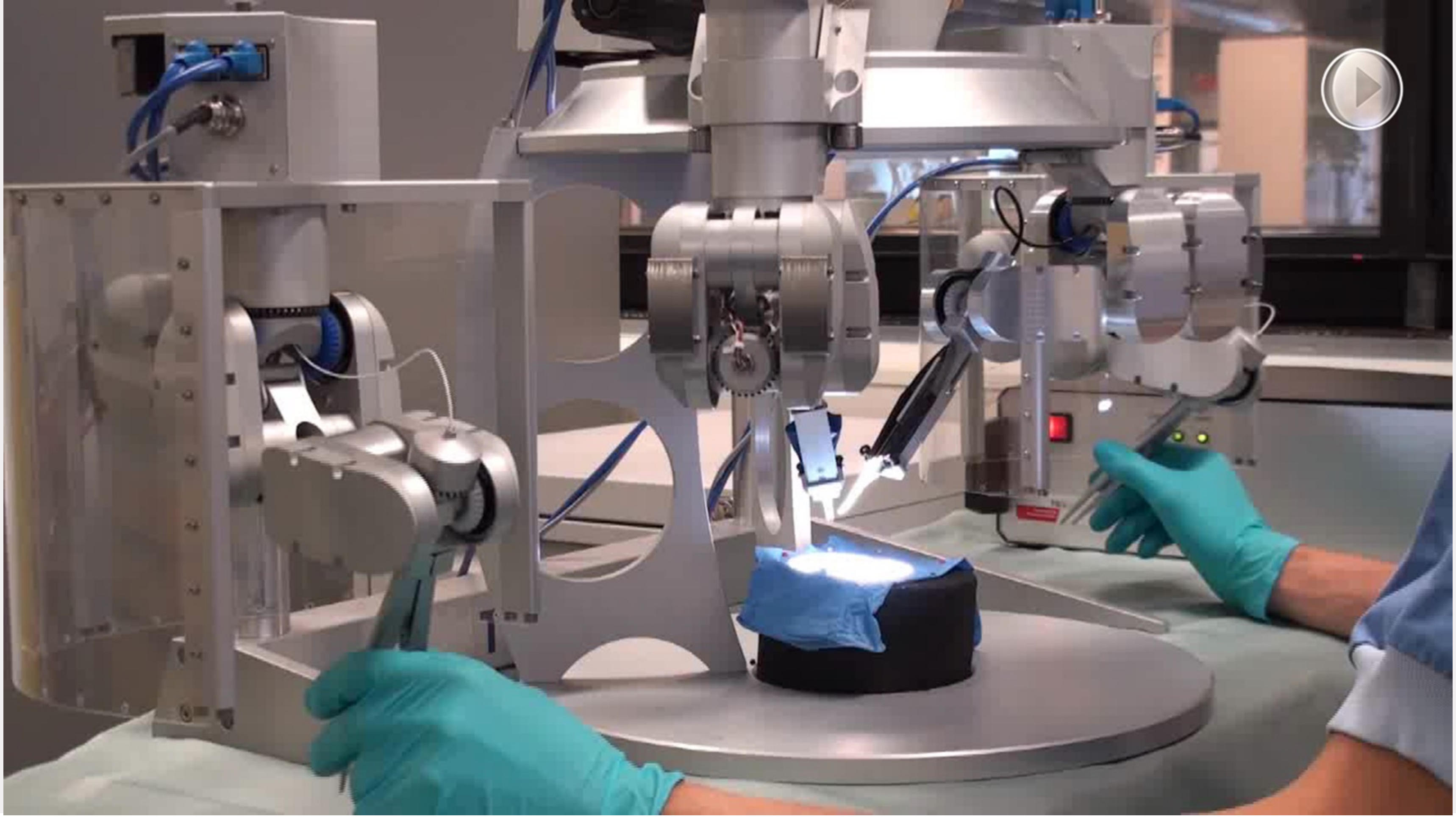
New mechatronic alignment concept with 3D motion capability in upper and lower robot allow

Ref*:* Pinxteren, J.A.W. van, Vermeulen, J.P.M.B. Loon, R. van, (R)evolutionairy improvements in the design of interventional X-ray imaging systems, Proc. of the 19th euspen international conference, Bilbao, Spain, June 3-7, 2019

(patent applied 2018PF00583, 2018PF00737)

Eye surgery robots

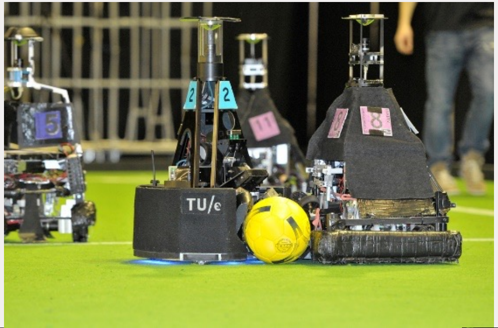
PRECEYES



Home robotics (robotics for care)

RoboEarth

TechUnited: Soccer robots and beyond….

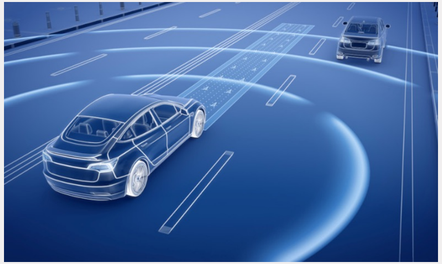


Five times and reigning champion of the world …

TU/e

Automated driving

(world modelling, AI, sensor fusion, MPC)

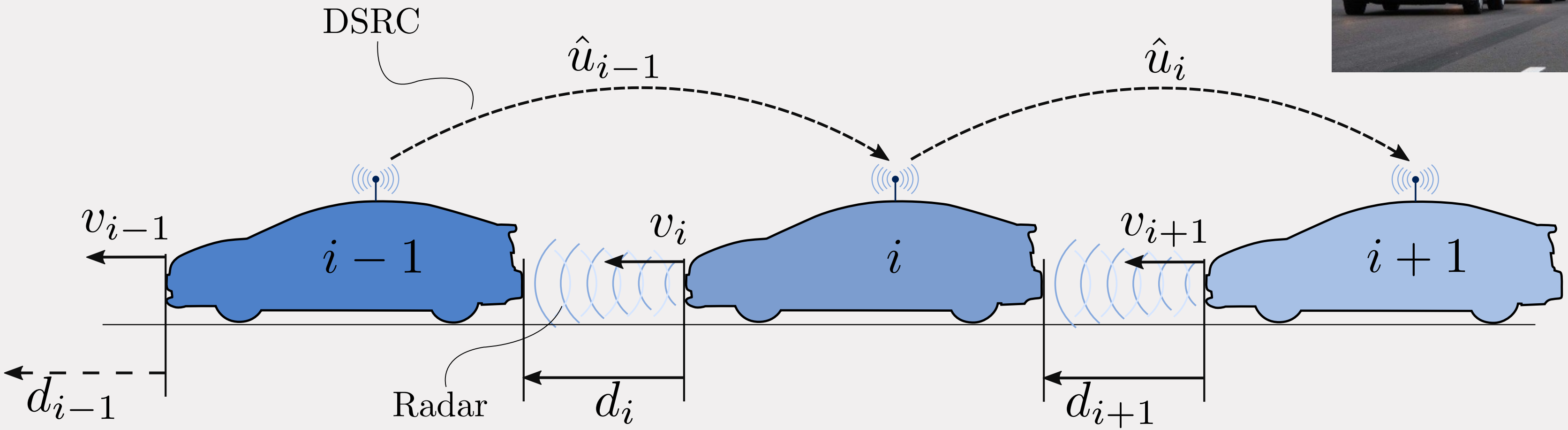


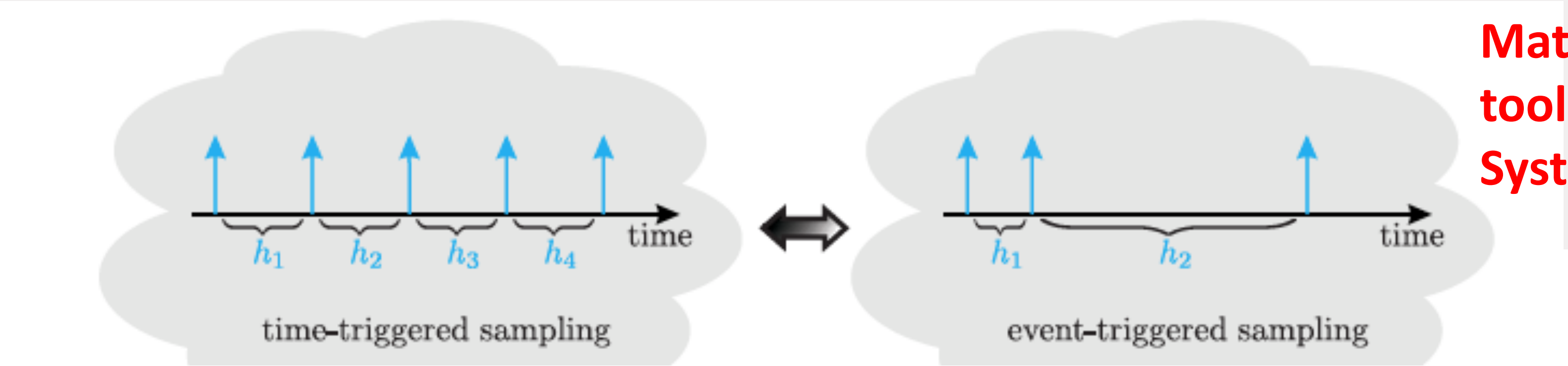
Mobile and cooperative robotics

Jumbo distribution centre Veghel

TruckLab inside AES-lab TU/e

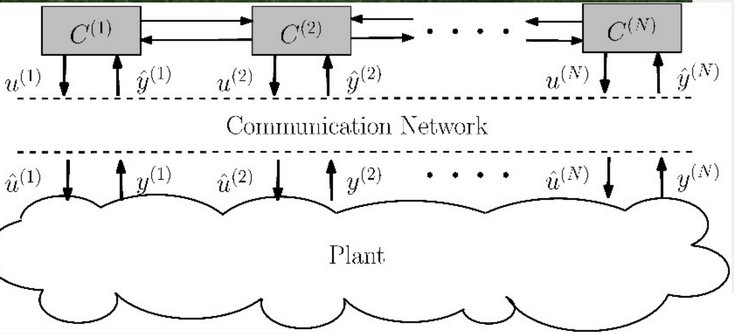
Networked control systems (CPSoS)



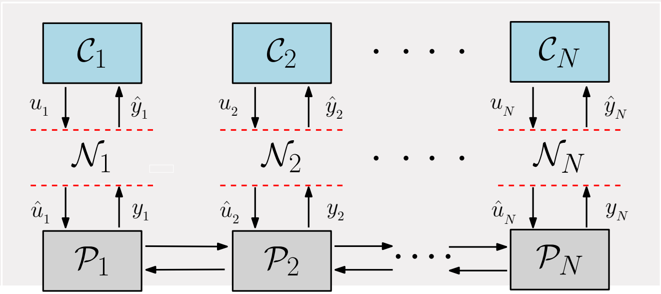


Mathematical tools: Hybrid Systems

From 2D to 3D: soccer robots to drones
…all cyber-physical systems of systems…



avular



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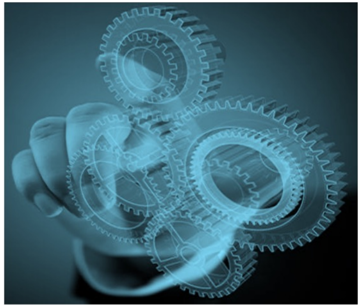
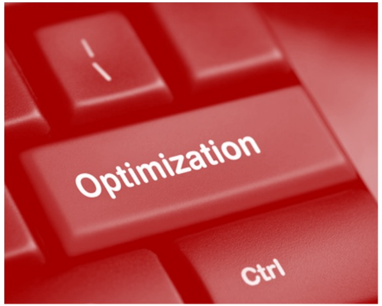
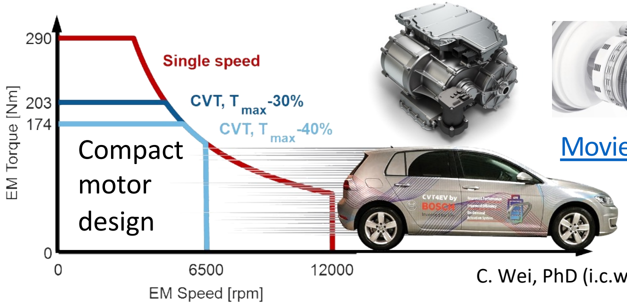
Vision of farming in the future: Multi-agent systems

Powertrain system design: electrified vehicles – an integrated approach





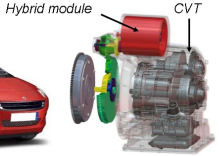
CVT design for Electric Vehicle: battery, E-drive, CVT



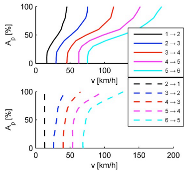
Movie CVT4EV

C. Wei, PhD (i.c.w. Bosch)

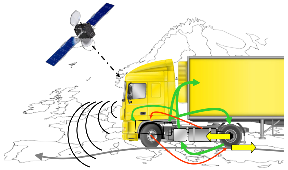
...cars, ships, machinery equipment, trucks, buses, ...



K. Van Berkel, PhD

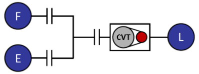


N. Dac Viet, PhD

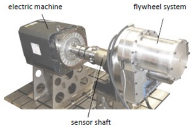


V. Van Reeven, PhD

Component specification
Storage (kWh), conversion (kW) and transmission technology (%)



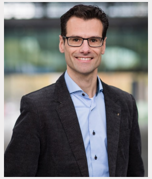
Control design
Low/high level



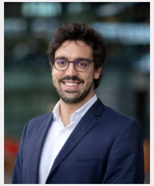
Validation and verification
System performances

...low cost (€), energy (kWh/km), CO_2 (g)...

...new system engineering methods & tools...



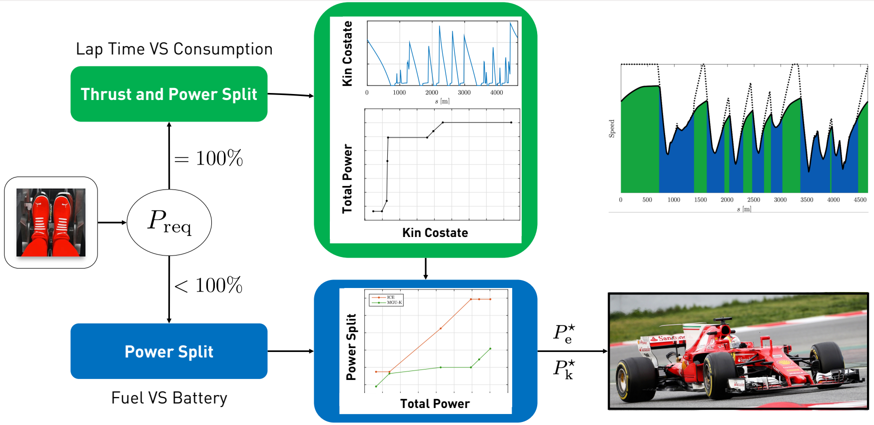
Theo Hofman



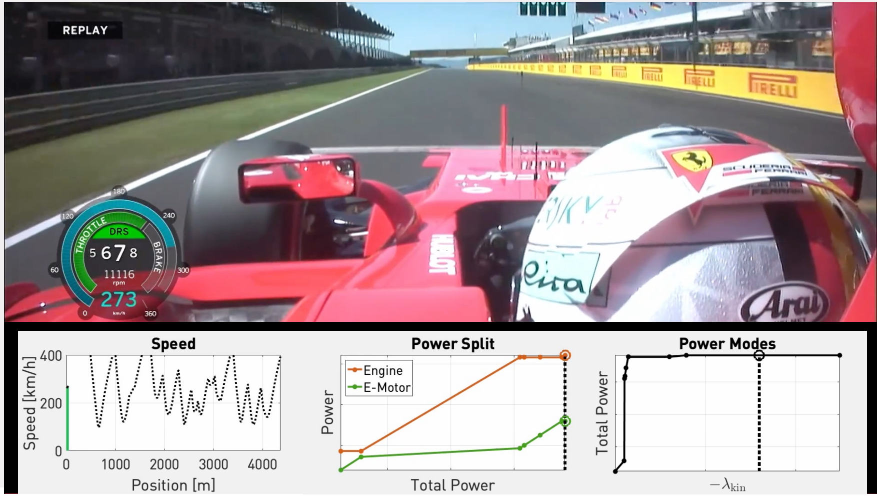
Mauro Salazar

(Hybrid) Electric Powertrain Design and Control for Racing

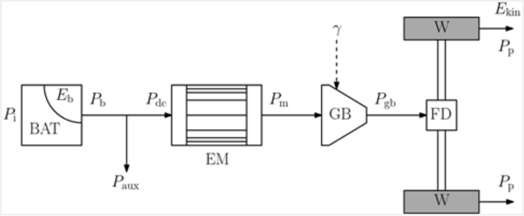
Leverage theoretical **optimal control** methods and **optimization** algorithms for real-world racing applications



Salazar, Elbert, Ebbesen, Bussi and Onder: "Time-optimal Control Policy for a Hybrid Electric Race Car", IEEE TCST, 2017

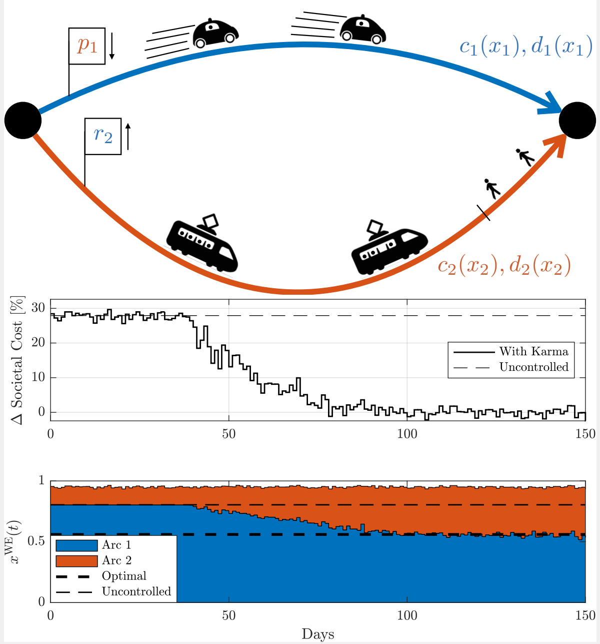


Mauro Salazar



Multi-scale Design and Operation of Sustainable Mobility Systems

Artificial currencies for urgency-aware and human-centered system-optimal routing

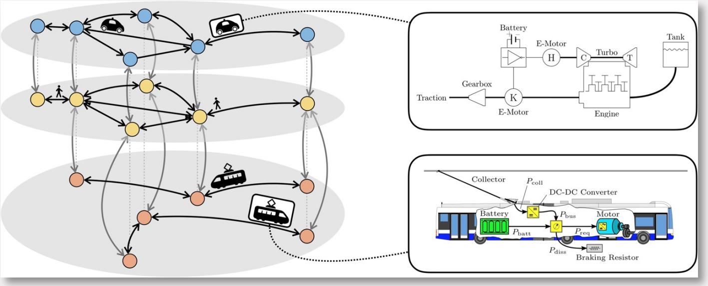


Salazar, Paccagnan, Agazzi, Heemels, *Urgency-aware Optimal Routing in Repeated Games through Artificial Currencies*, EJC, 2021

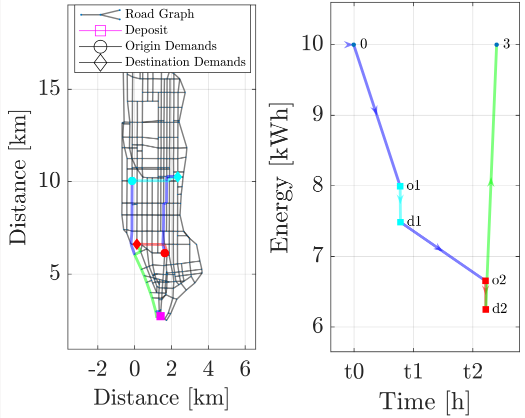
Mauro Salazar

Maurice Heemels

Theo Hofman



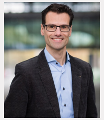
Joint Design and Operation of Electric (Intermodal) Autonomous Mobility-on-Demand



Fabio Paparella, PhD Student

(NWO) NEON project: Electric Mobility concepts with Lightyear and TNO

CST team with



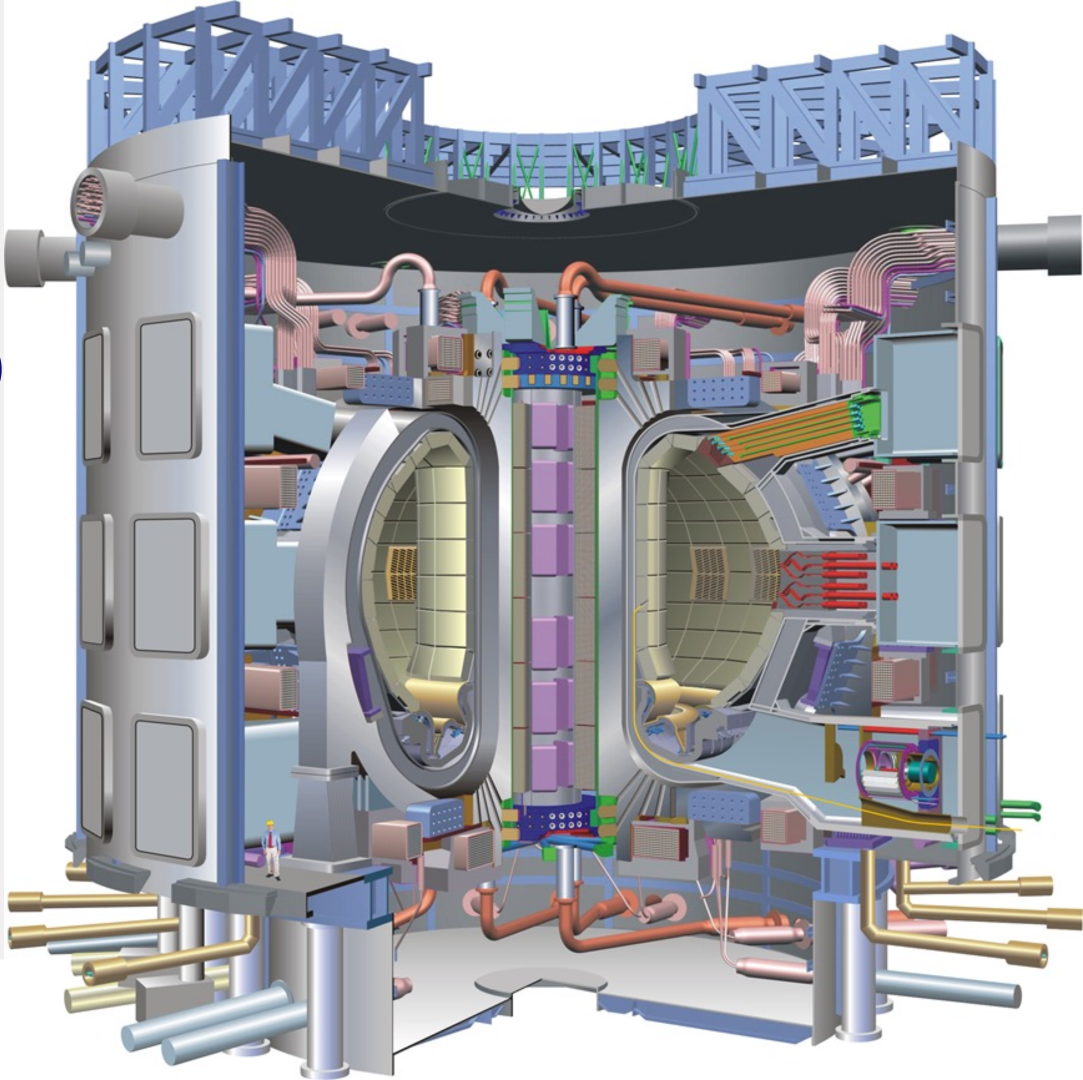
Theo Hofman

Mauro Salazar

Pascal Etman

Energy Systems

- Plasma control
  (nuclear fusion & CO2 dissociation)
- Solar fuels
- Energy transition/charging
  infrastructures / electrification
  (ZenMO)



Example of a tokamak

CST Master Courses

Course	Code
Control engineering	4CM00
System theory for control	4CM10
Engineering Optimization	4DM20
Hybrid systems and control	4CM20
Supervisory control	4CM30
Advanced motion control	4CM60
Mobile robot control	4SC020
Optimal control and reinforcement learning	4SC000
Haptics – perception and technology	4SC040

Course	Code
Physical and data-driven modelling	4CM40
Applications of Design principles	4CM50
Advanced full-electric & hybrid powertrain design	4AT030
Advanced control for future HD powertrains	4AT070
Control and operation of tokamaks	4SC010
Control of magnetic instabilities in fusion plasmas	4SC030
Integrated system design	4CM70
Learning Control	4SC070
Extremum seeking control for data-based performance optimization	4CM80

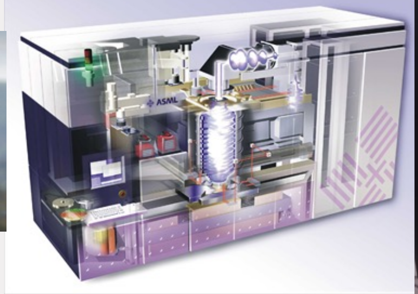
MSc degrees:

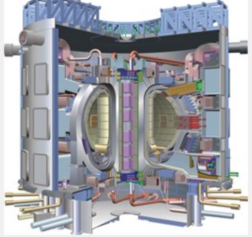
1. Master on **Mechanical Engineering (ME)**
2. Master on **Systems & Control (S&C)**
3. Master on **Automotive Technology (AT)**
4. Master on **Artificial Intelligence & Engineering Systems (AI&ES)**
5. Master on Science and Technology of **Nuclear Fusion (NF)**

Further practicalities:

- Info meetings @ start in CST
- Mentoring program
- Projects: Guidance by project coaches, regular meetings (permanent) staff employee

Summarizing





CST group unites

- Science and fundamental (control) theory
- Applied research & design
- Society / Spin-offs / Impact

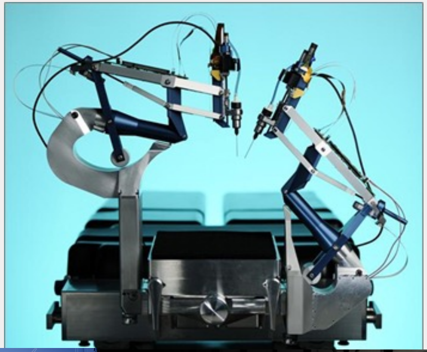
Combine Highest quality standards & Fun

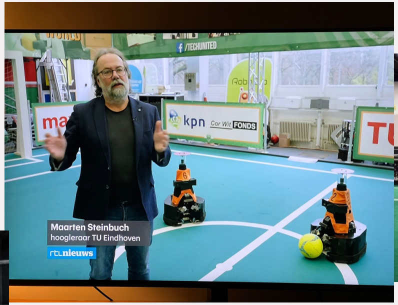
Eindhoven Medical Robotics

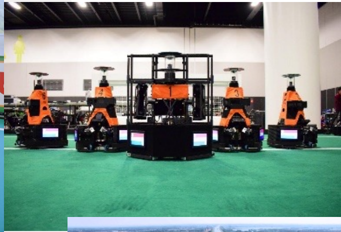
IEEE TRANSACTIONS ON AUTOMATIC CONTROL

DTI

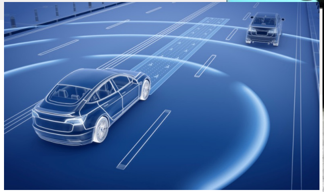
avular







PRECEYES



microsure
robot assisted microsurgery

Links CST

https://www.tue.nl/en/research/research-groups/control-systems-technology/
https://www.tue.nl/cst (also works and shorter)

Movie iterative learning control:

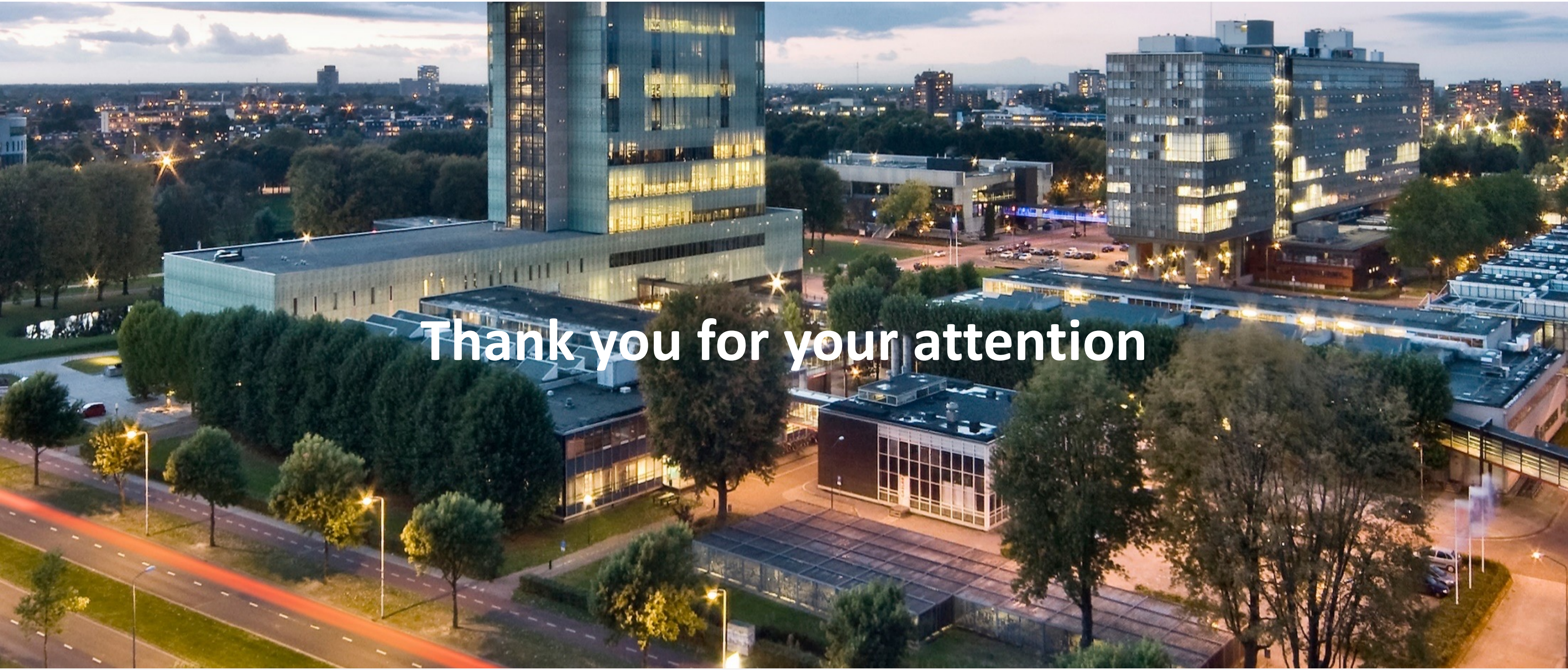
https://www.youtube.com/watch?v=kj_ouy1Fnko&feature=youtu.be

Program

10.00 – 10.20 General introduction division Dynamical Systems Design (DSD)

10.20 – 10.40 Dynamics and Control (D&C)	Prof.dr.ir. Nathan van de Wouw
10.40 – 11.00 Control Systems Technology (CST)	Prof.dr.ir. Maurice Heemels

11:00 – 12:30 lab visits DSD



Thank you for your attention