Control Systems Technology (CST) Section

DSD information meeting, March 27, 2023

Tom Oomen

Control Systems Technology

We aim to develop new methodologies for high-tech systems of the future in a broad range of applications that our essential for our society.

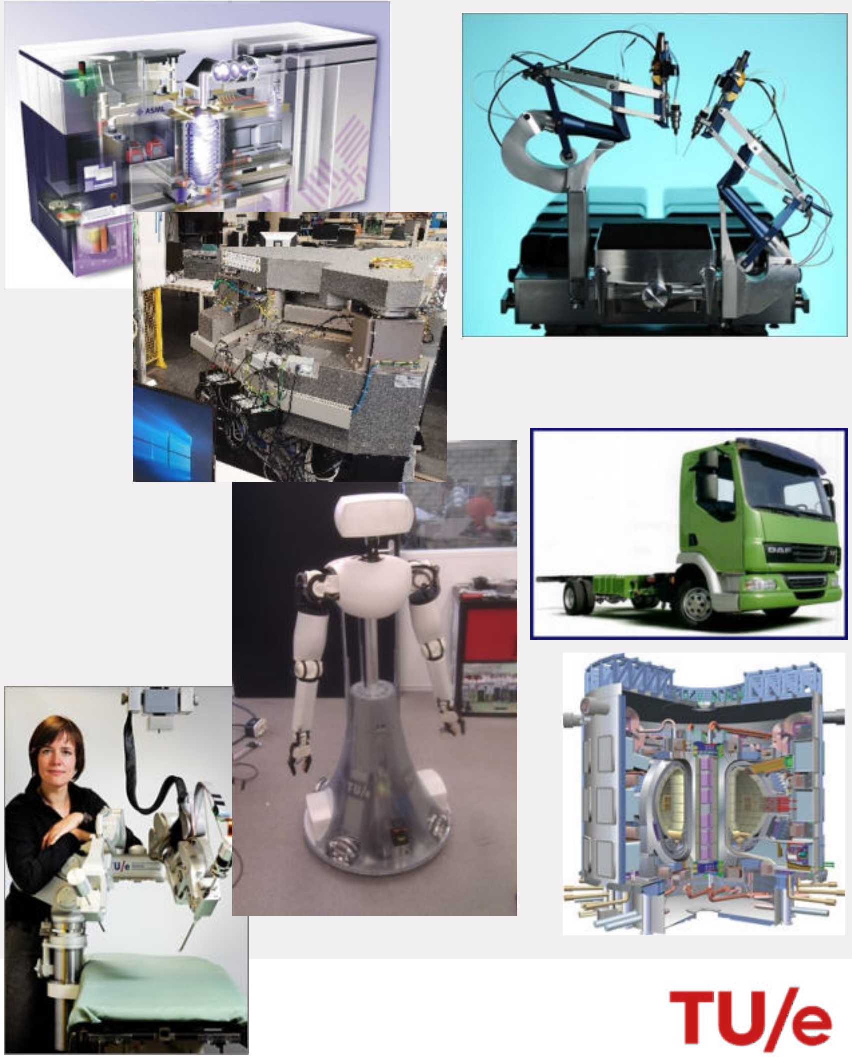
To achieve this, our research spans both

- world-leading applications and fundamental research
- uniquely interconnected and equally important

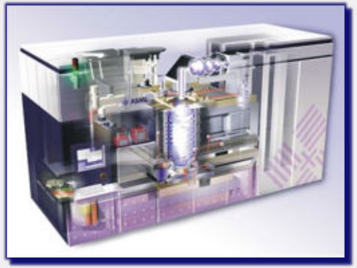
Our disciplines

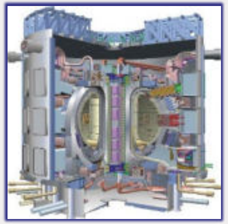
- systems and control theory
- mechanical design / mechatronics
- optimization
- systems engineering

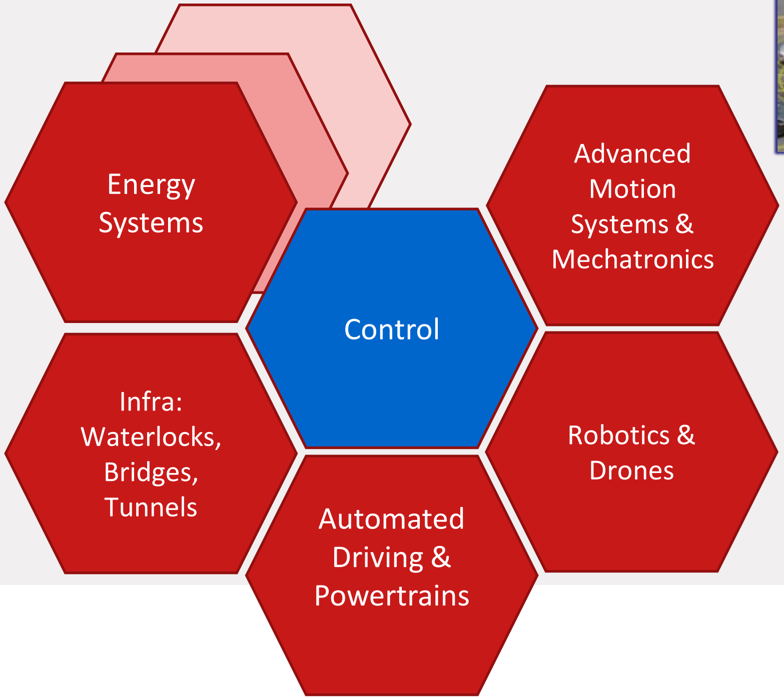
KPIs:
50 PhDs
85 MSc/year

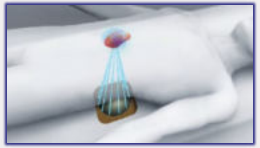


Control is the central technology in the subprogrammes

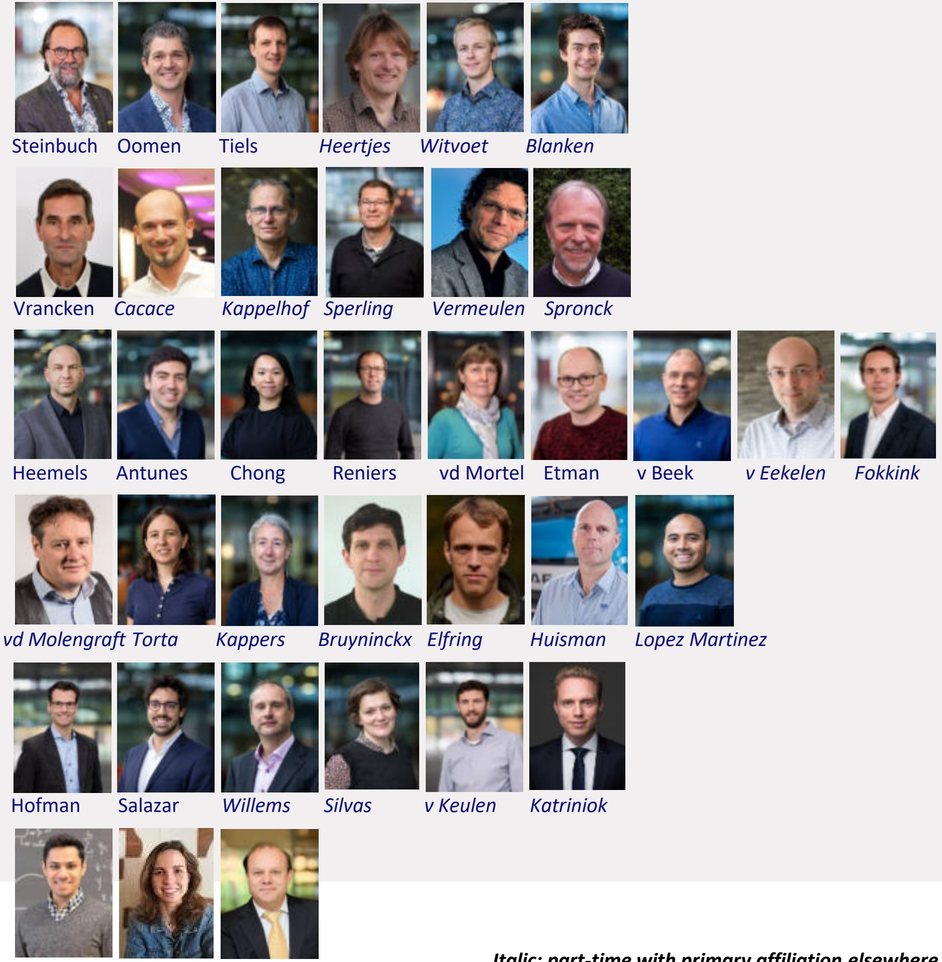








CST People and Research lines



Steinbuch, Oomen, Tiels, *Heertjes*, *Witvoet*, *Blanken*

Vrancken, *Cacace*, *Kappelhof*, *Sperling*, *Vermeulen*, *Spronck*

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

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

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

Krishnamoorthy, Chanfreut, *de Baar*

Learning, Identification, and Control for High-Tech Systems

Design for Precision Engineering

Cyber-Physical Systems

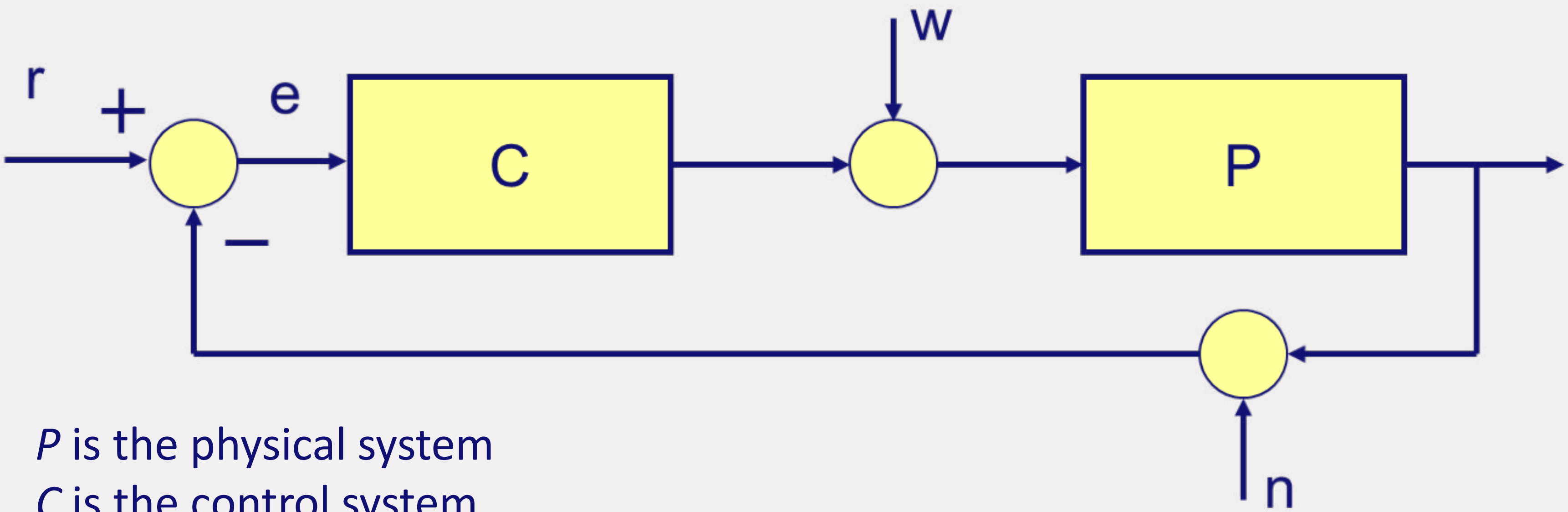
Robotics for Care, Cure & Agro-food

Automotive Powertrains & Smart Mobility

Process Control of Energy Systems

Italic: part-time with primary affiliation elsewhere

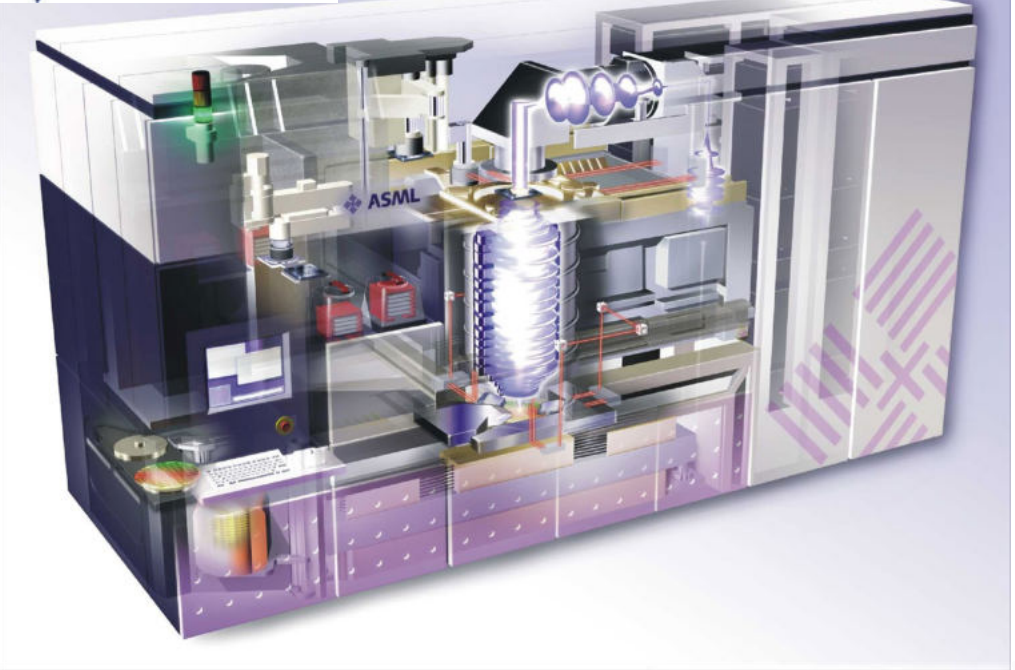
Control Systems & System Thinking

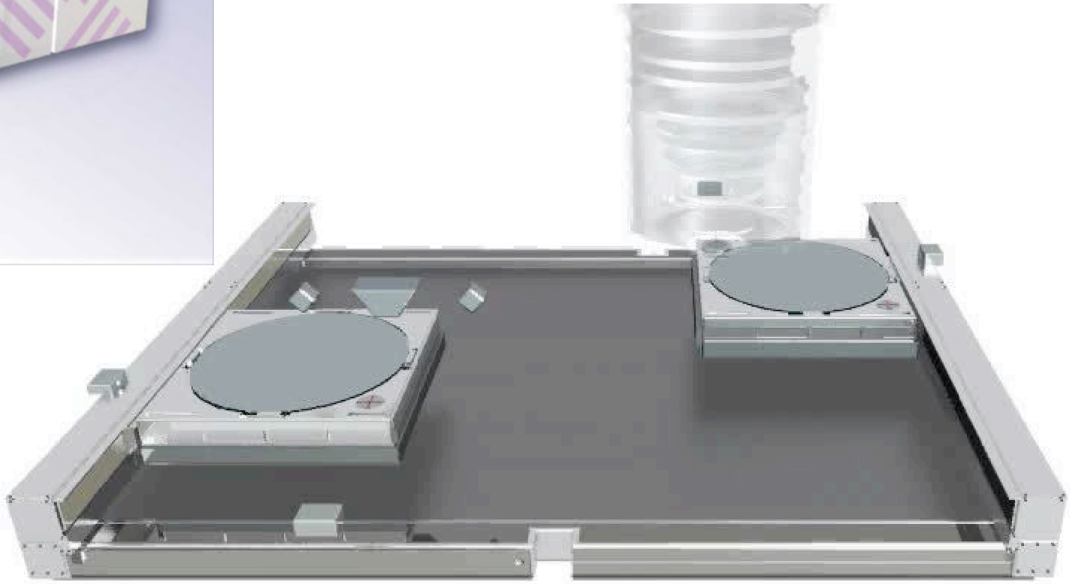


- *P* is the physical system
- *C* is the control system

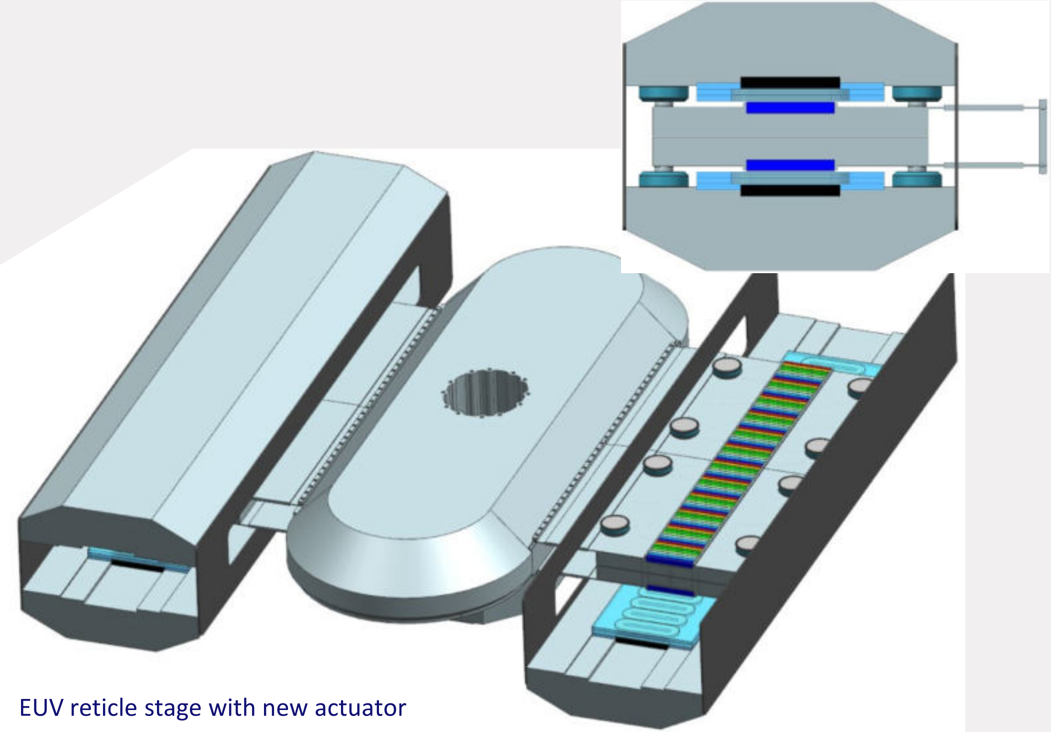
CST: both designing the physical system and the control system!

Maarten Steinbuch, Tom Oomen, and Hans Vermeulen, "Motion control, mechatronics design, and Moore's law", *IEEJ Journal of Industry Applications*, 11(2):245-255, 2022

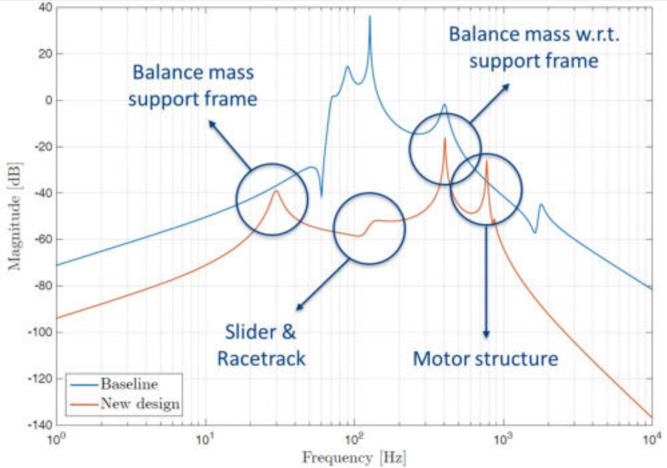

ASML



Long stroke actuator design for EUV reticle stage



Lightweight design (20% mass reduction)
with reduced force transmissibility (~50 DB)

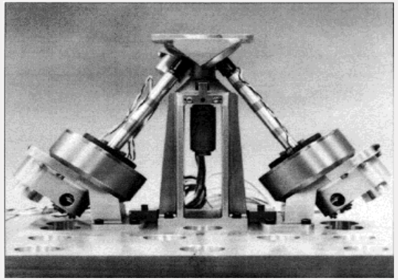


Duijsens, P.J.H., Design of a long stroke actuator unit for the EUV reticle stage, Master's thesis report, Eindhoven University of Technology, 2016

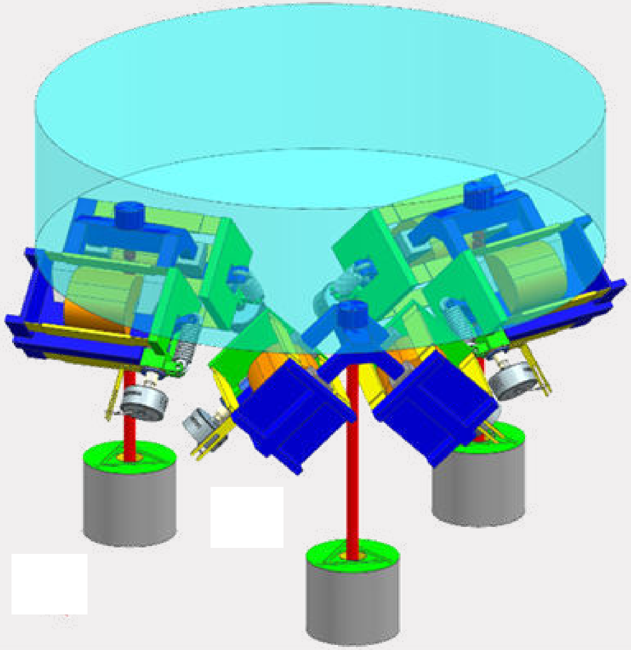
TU/e

EUV mirror actuator with high steepness to mass ratio

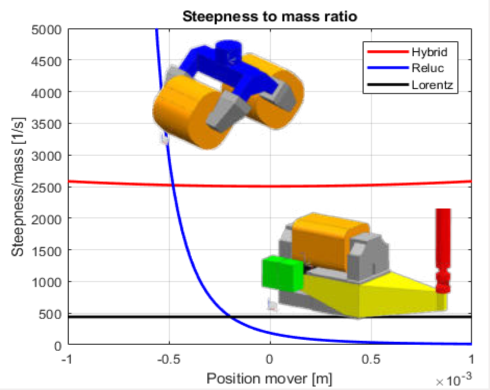
Compact lightweight alternative based on non-contact reluctance actuators with significantly improved dynamics

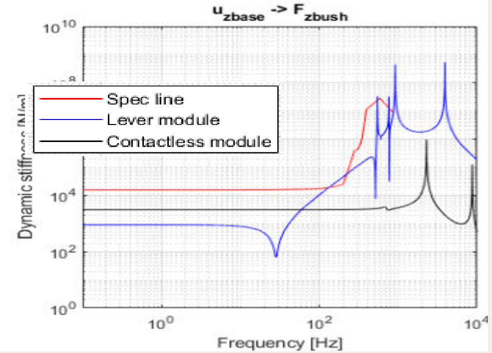


Traditional mirror actuation system with mechanical coupling between Lorentz actuator frame and mirror



New design proposal based on contactless reluctance actuation





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

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, 2019

Opto-mechatronics

Mechatronics for optical systems

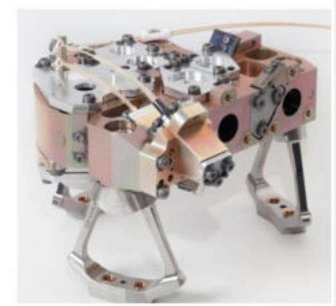
- Nanometer wavefront at forefront of precision
- System design, Design principles
- Understanding of optics

Education

- Opto-mechatronics (4CM90)
- Technical Optics
- Optics for Mechanical Engineers

Master Assignments

- Realize hardware
- Half in Industry & Science



Satcom

Aerospace, Space Ground

Airbus, TNO, VDL, Demcon

Semicon

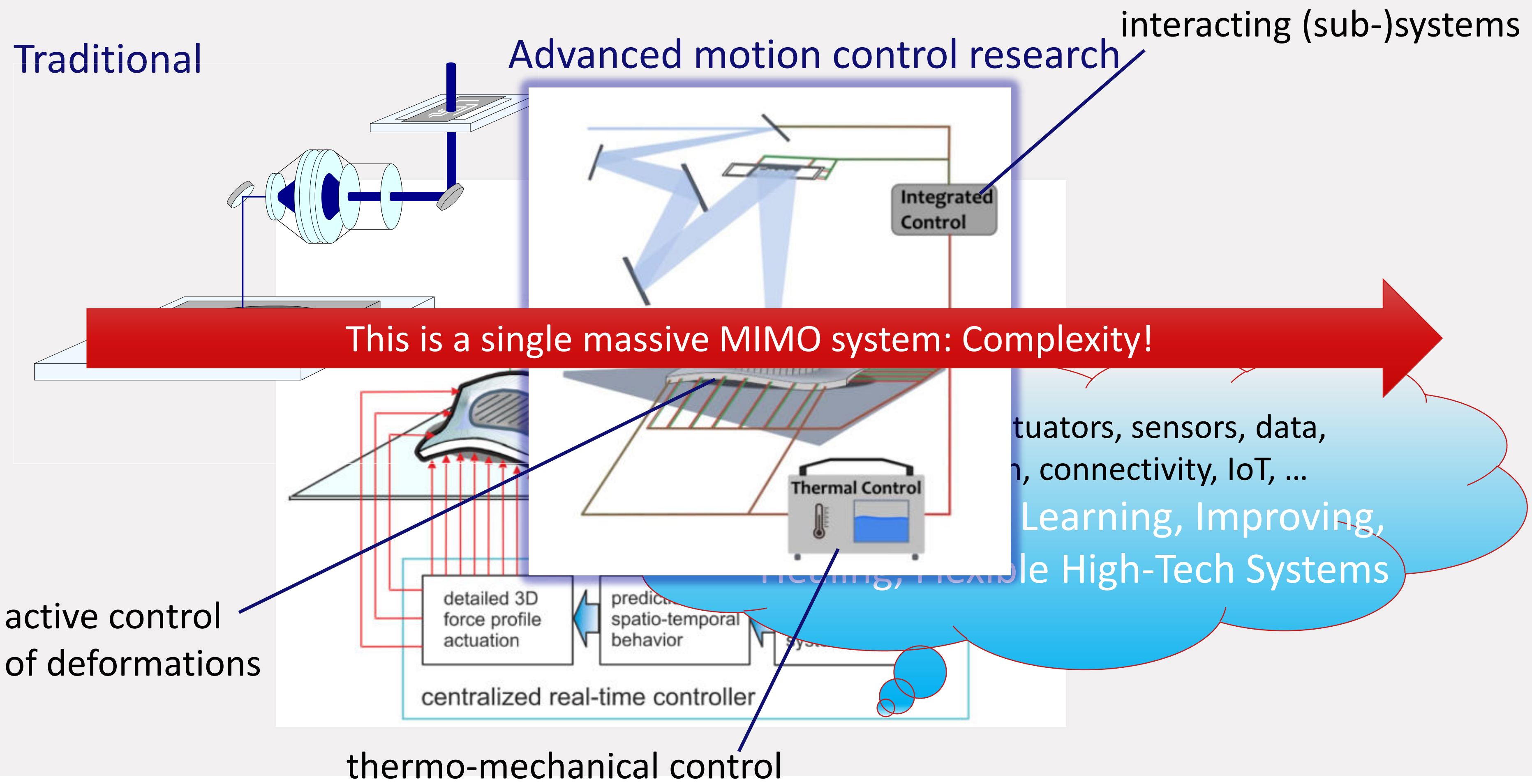
Sensing & stages

ASML, Liteq, K&S

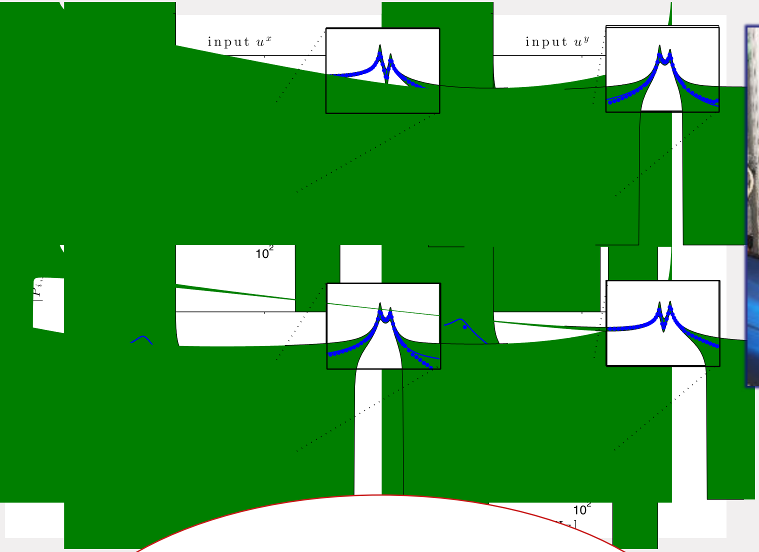
Astronomy

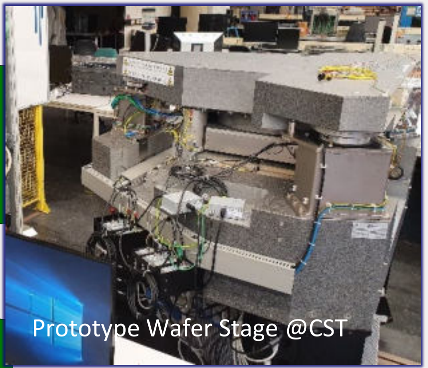
Adaptive optics, Sensing

TNO, VDL

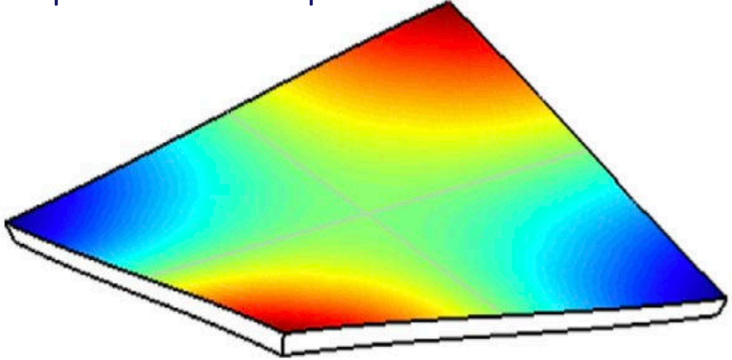

Traditional
Advanced motion control research
interacting (sub-)systems
Integrated Control
This is a single massive MIMO system: Complexity!
tuators, sensors, data,
, connectivity, IoT, …
Learning, Improving,
le High-Tech Systems
Thermal Control
detailed 3D force profile actuation
spatio-temporal behavior
centralized real-time controller
active control of deformations
thermo-mechanical control

Where physical system design and control meet: virtual stiffness and damping





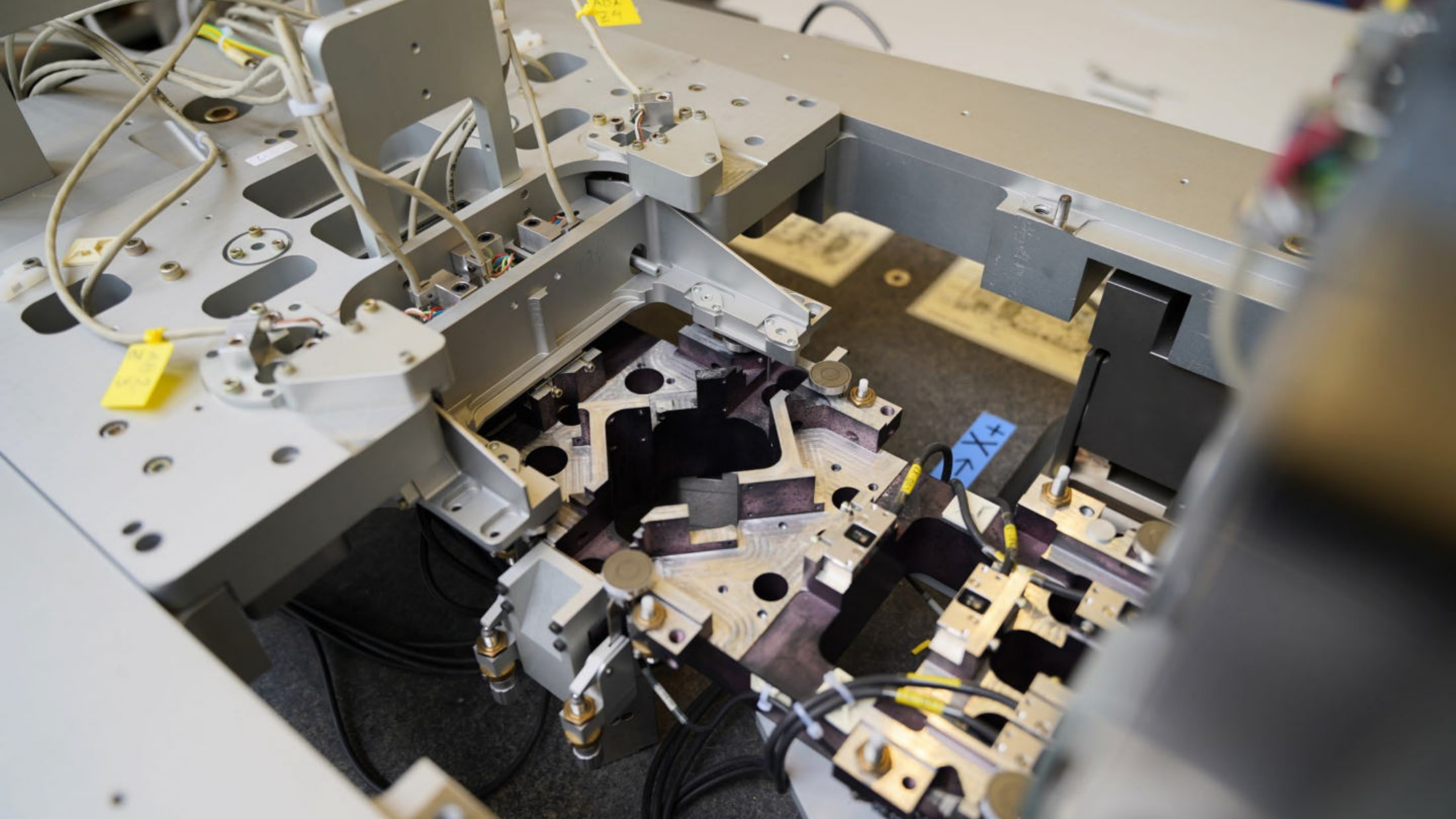
Create virtual stiffness through control:
Compensate torsion: performance +100%



Identify models for control!

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

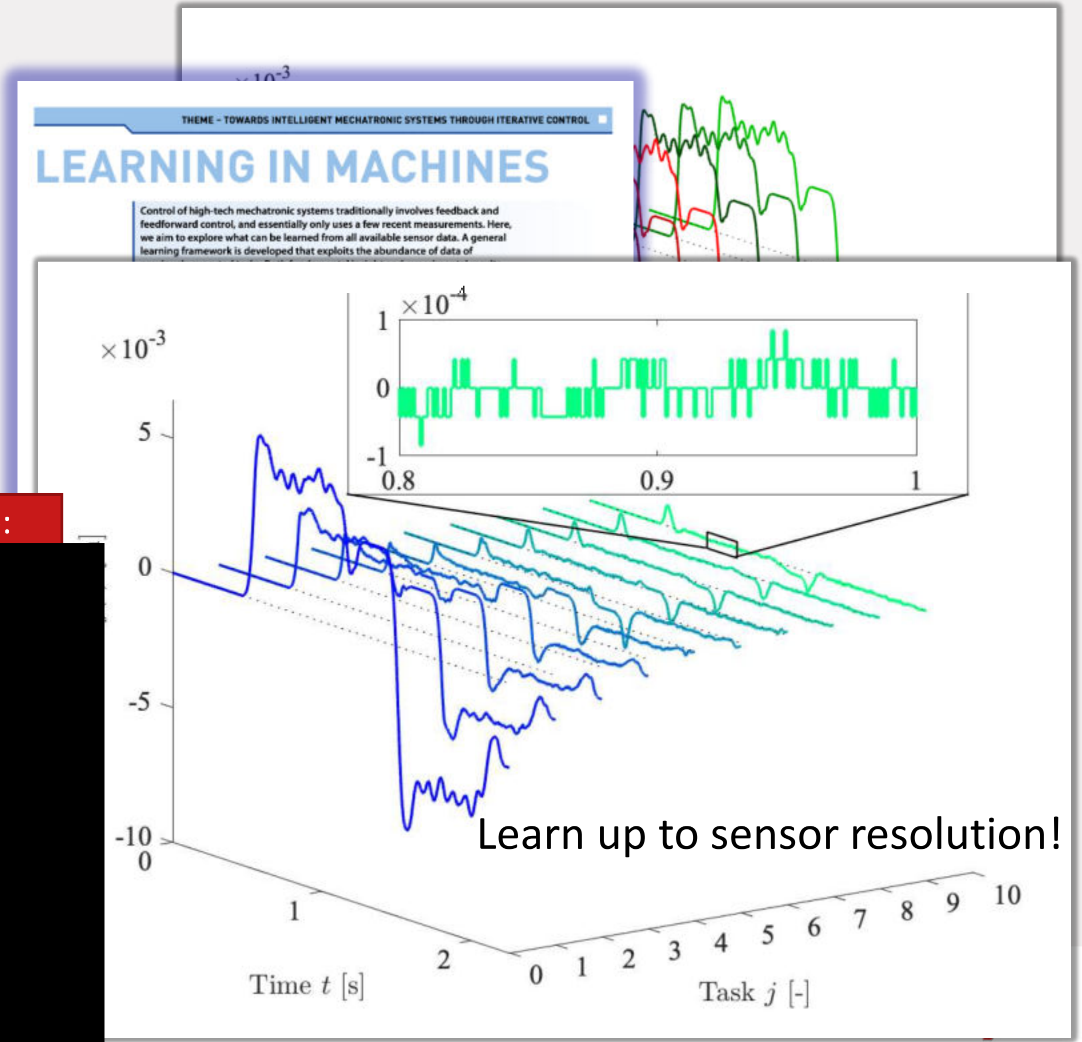
Tom Oomen, “Advanced Motion Control for Precision Mechatronics: Control, Identification, and Learning of Complex Systems”, *IEEJ Journal of Industry Applications*, 7(2), 1-14, 2018


X+

(Machine) learning for control

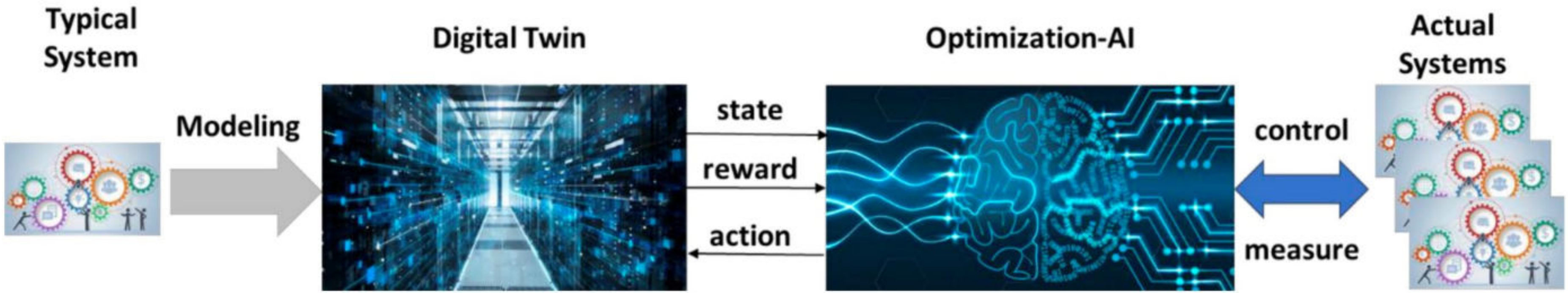
What does learning have to offer?

Corresponding youtube video:



Learn up to sensor resolution!

More Learning: Digital Twins and Reinforcement Learning



ThermoFisher SCIENTIFIC

CCM

TNO

Digital twins also being developed for

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

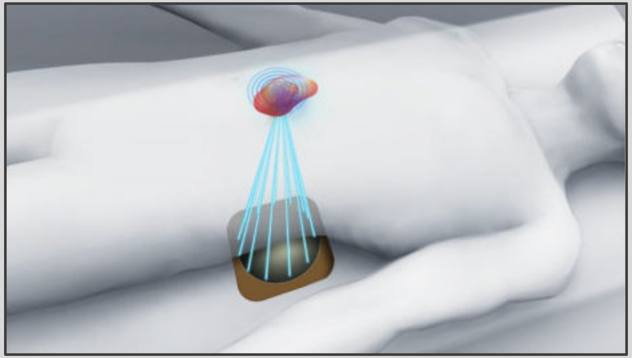
Koen Classens, Maurice Heemels, and Tom Oomen, “Digital Twins in Mechatronics: From Model-based Control to Predictive Maintenance”, In *2021 IEEE International Conference on Digital Twins and Parallel Intelligence*, Beijing, China, 2021

TU/e

Feedback in hyperthermia

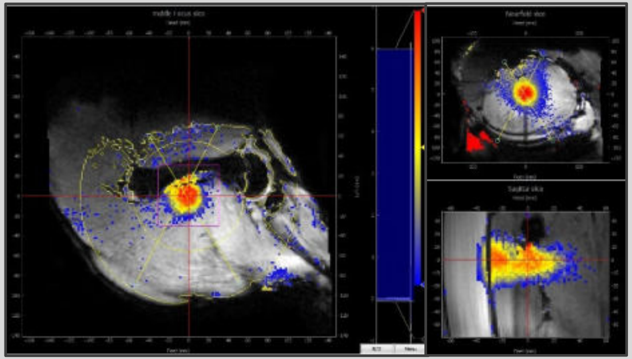
HIFU/RF

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

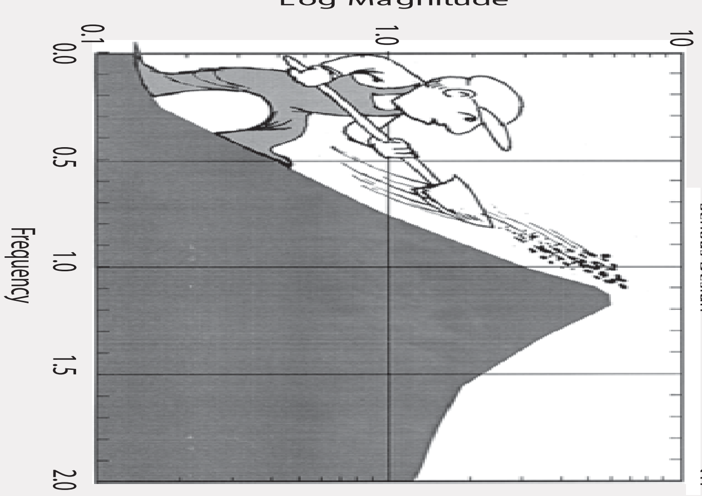
Linear motion systems are controlled by linear strategies:

performance limitations such as Bode integral

Can we improve controllers using nonlinear

and hybrid control strategies?

Avoid Bode's waterbed effect!



Wafer Scanners

Pick and place machines

Electron microscopes

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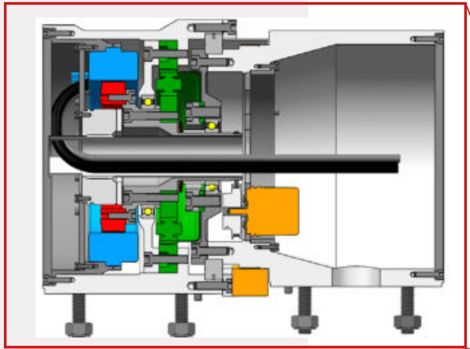
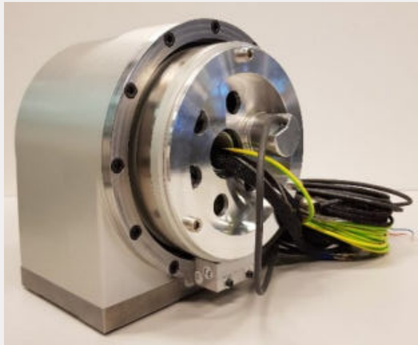
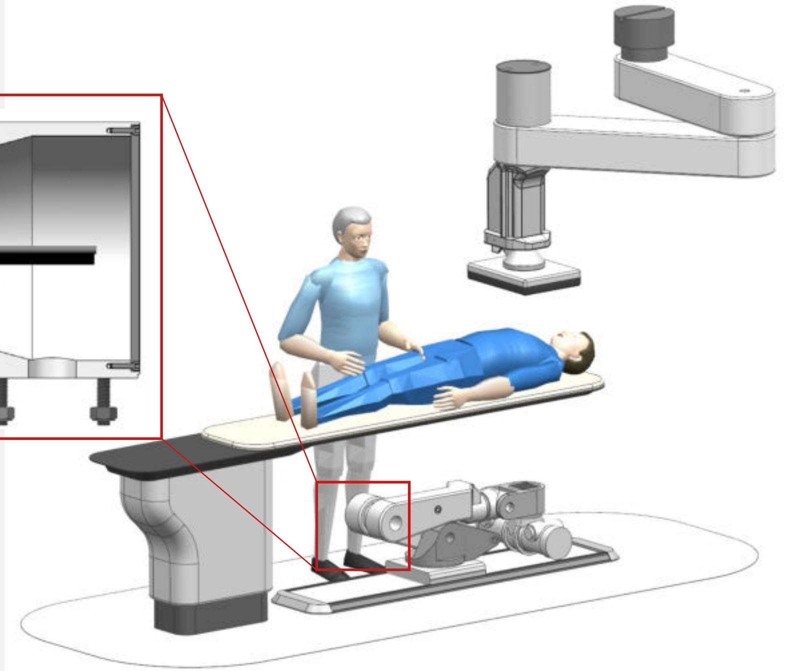
Novel mechatronic concepts for X-ray imaging systems

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





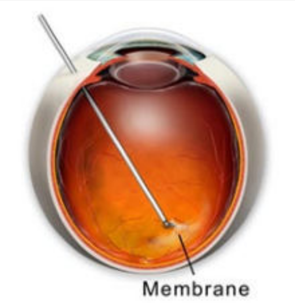


Significantly improved positioning performance at reduced clinical obstruction to medical treatment

(patent applied 2018PF00583, 2018PF00737)

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

Eye surgery robots



PRECEYES

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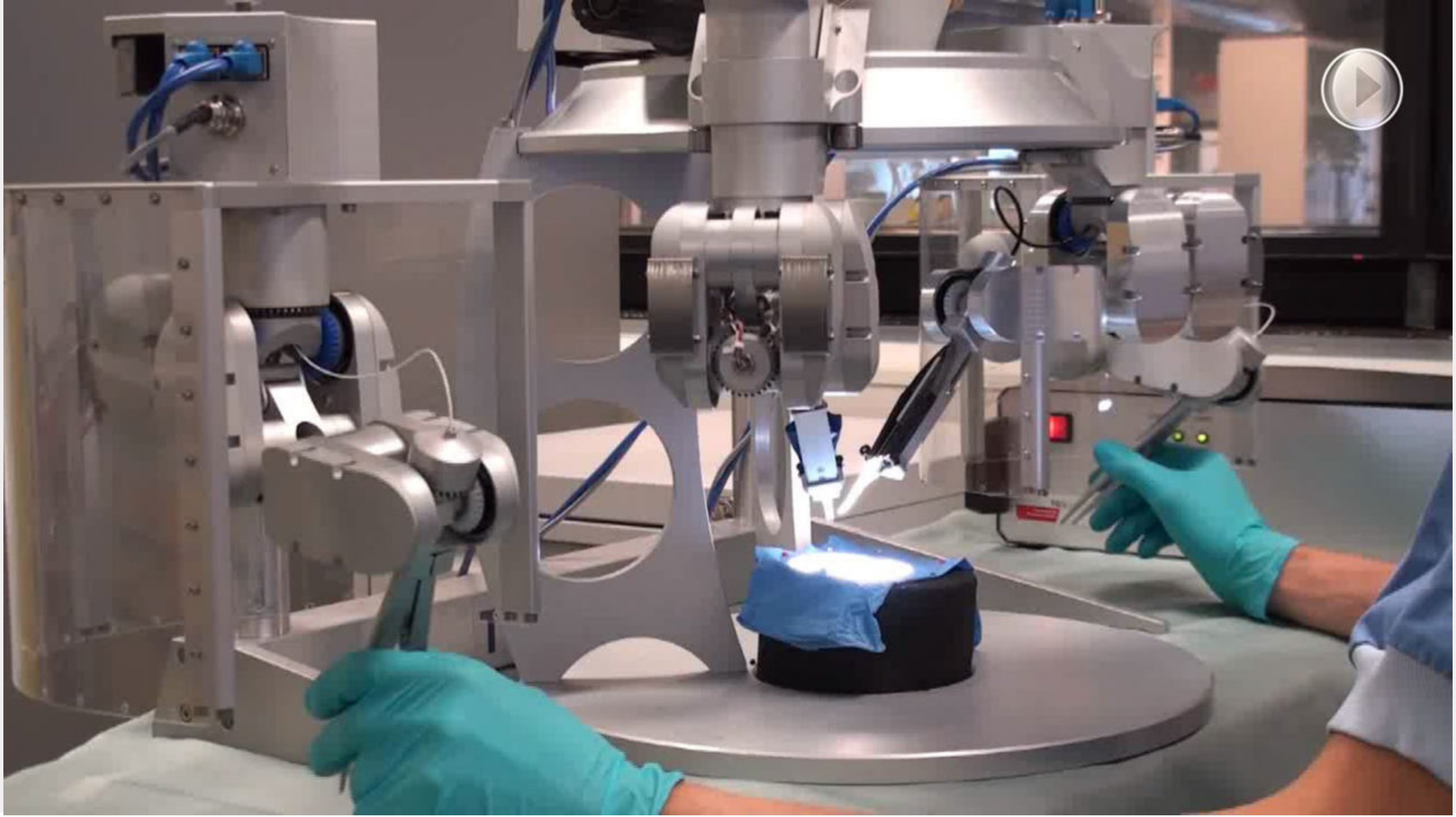
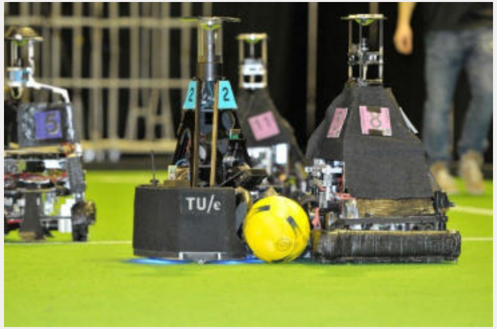


Home robotics (robotics for care)

RoboEarth

TechUnited: Soccer robots and beyond….



Five times and reigning champion of the world …

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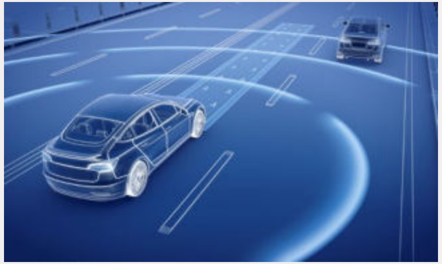
Automated driving (world modelling, AI, sensor fusion, MPC)

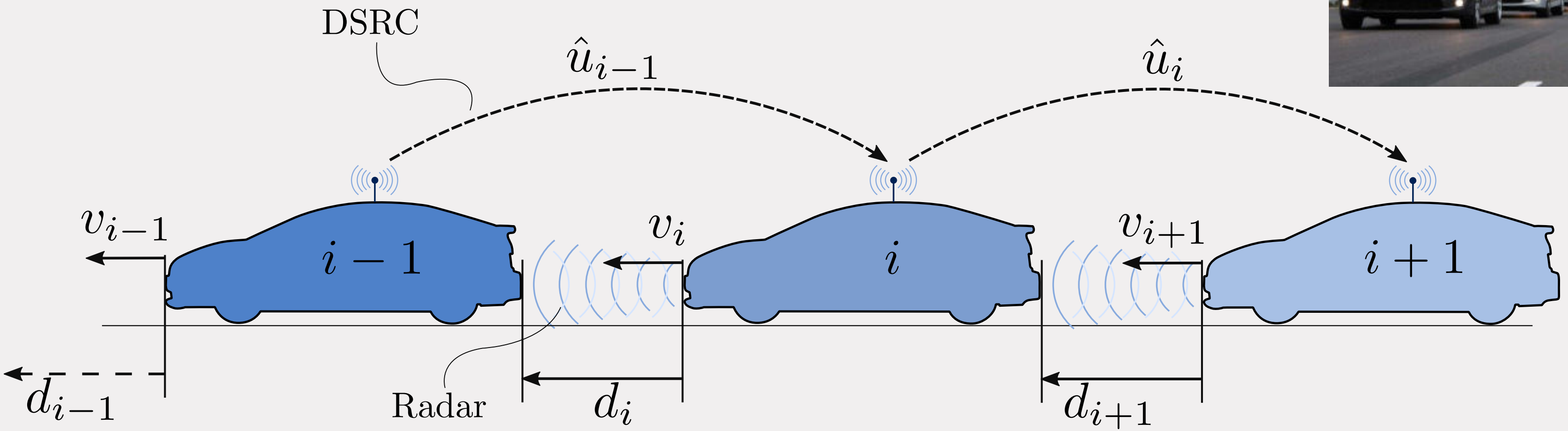


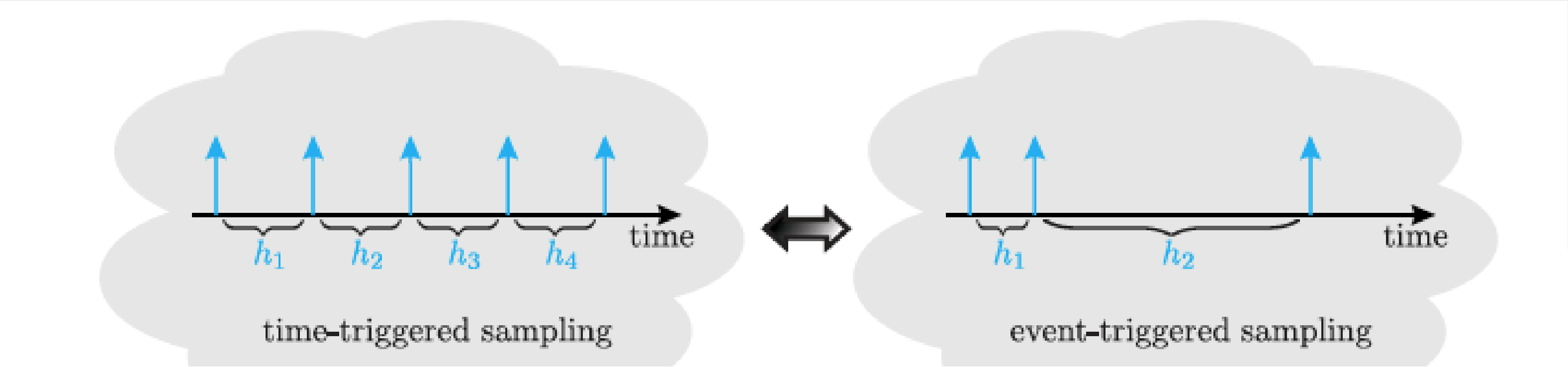
Mobile and cooperative robotics

Jumbo distribution centre Veghel

TruckLab inside AES-lab TU/e

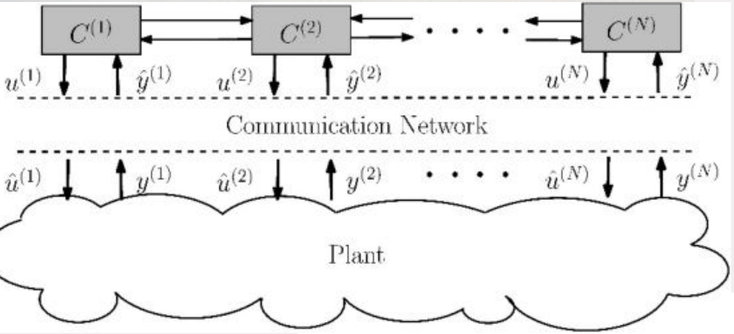
Networked control systems

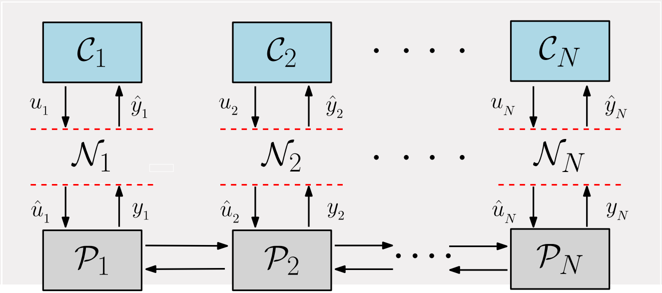




Mathematical tools: Hybrid Systems

From soccer robots to swarms of drones: cyber-physical systems of systems





avular

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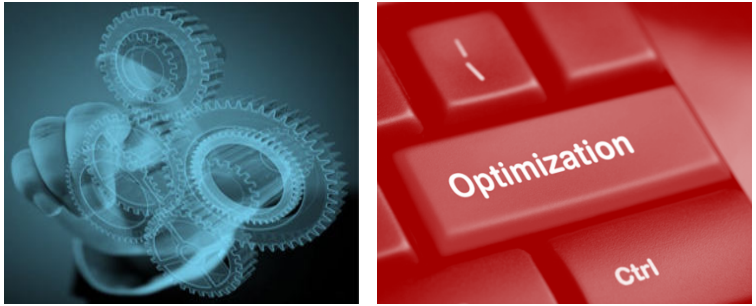
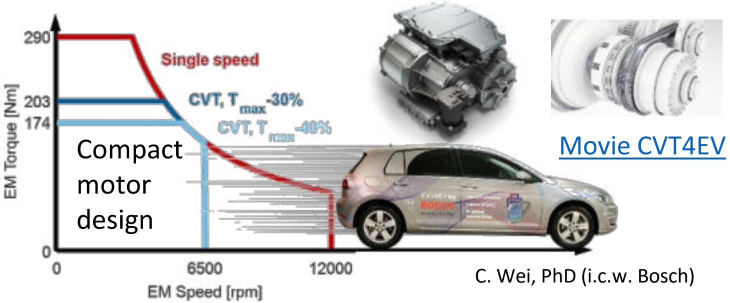
Vision of farming in the future: Multi-agent systems

Powertrain system design: electrified vehicles – an integrated approach



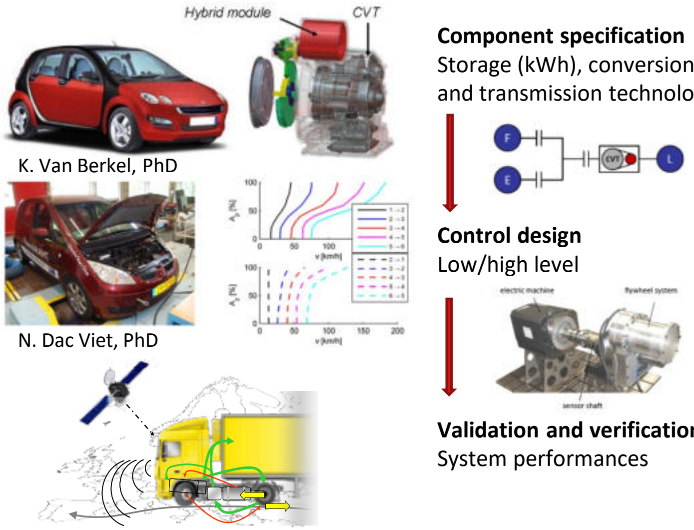
CVT design for Electric Vehicle: battery, E-drive, CVT



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

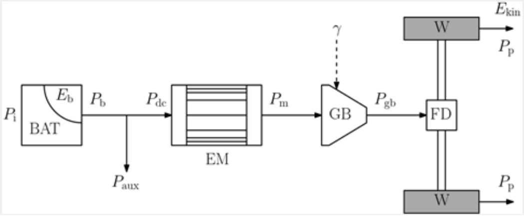
…low cost (€), energy (kWh/km), CO_2 (g)…

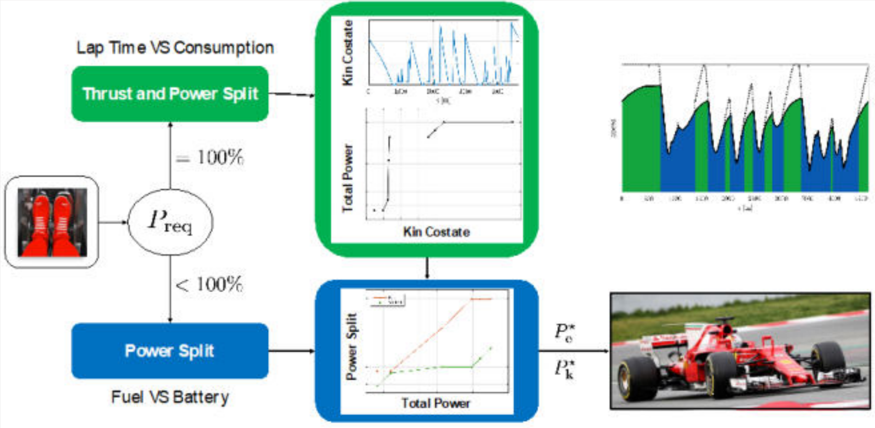
…new system engineering methods & tools…

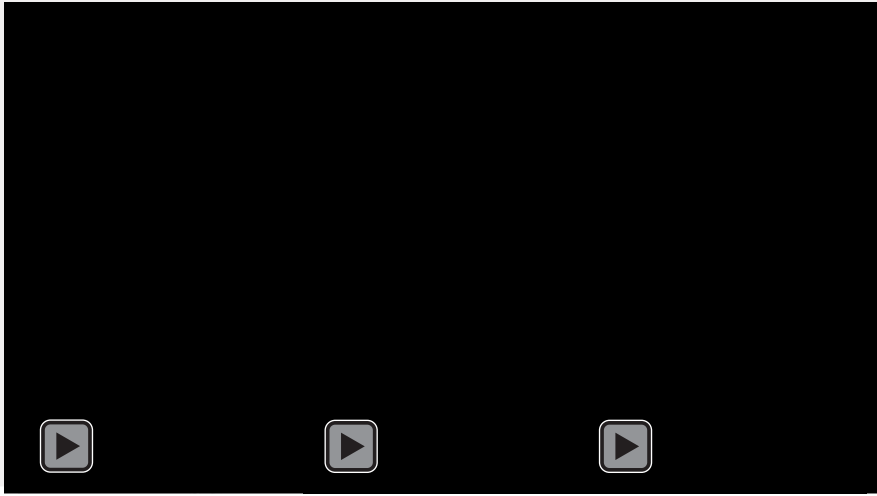
TU/e

(Hybrid) Electric Powertrain Design and Control for Racing

Optimal control for real-world racing applications



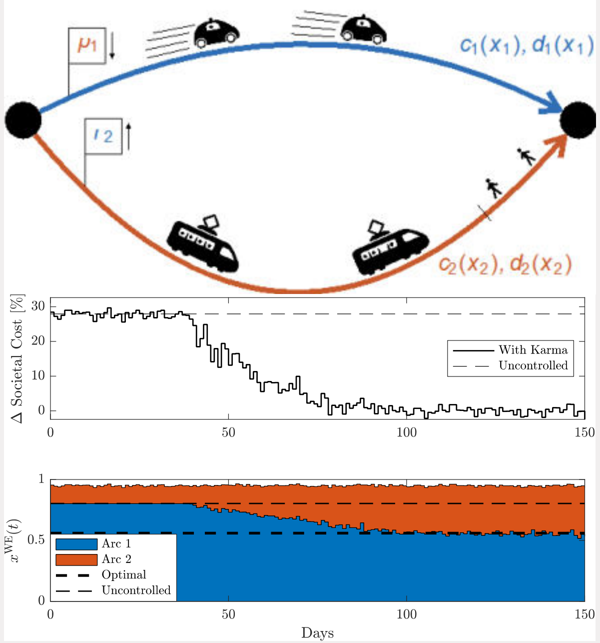


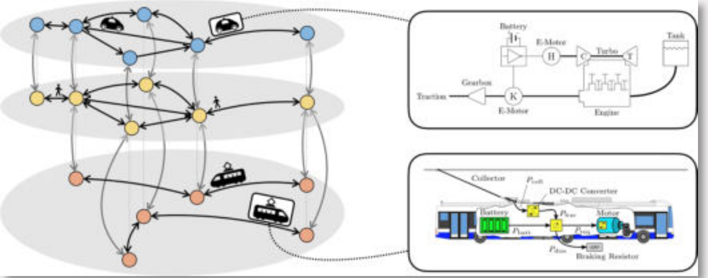


Salazar, Elbert, Ebbesen, Bussi, Onder, “Time-optimal Control Policy for a Hybrid Electric Race Car”, IEEE Transactions on Control Systems Technology, 2017

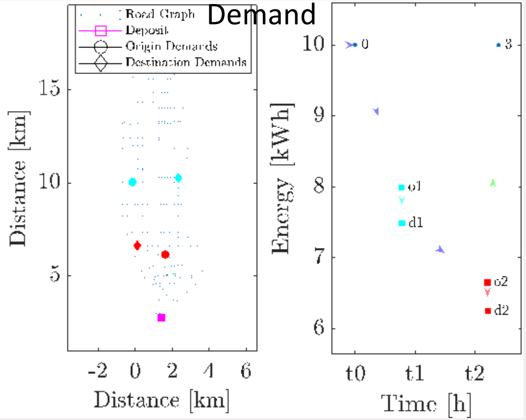
Multi-scale Design and Operation of Sustainable Mobility Systems

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





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



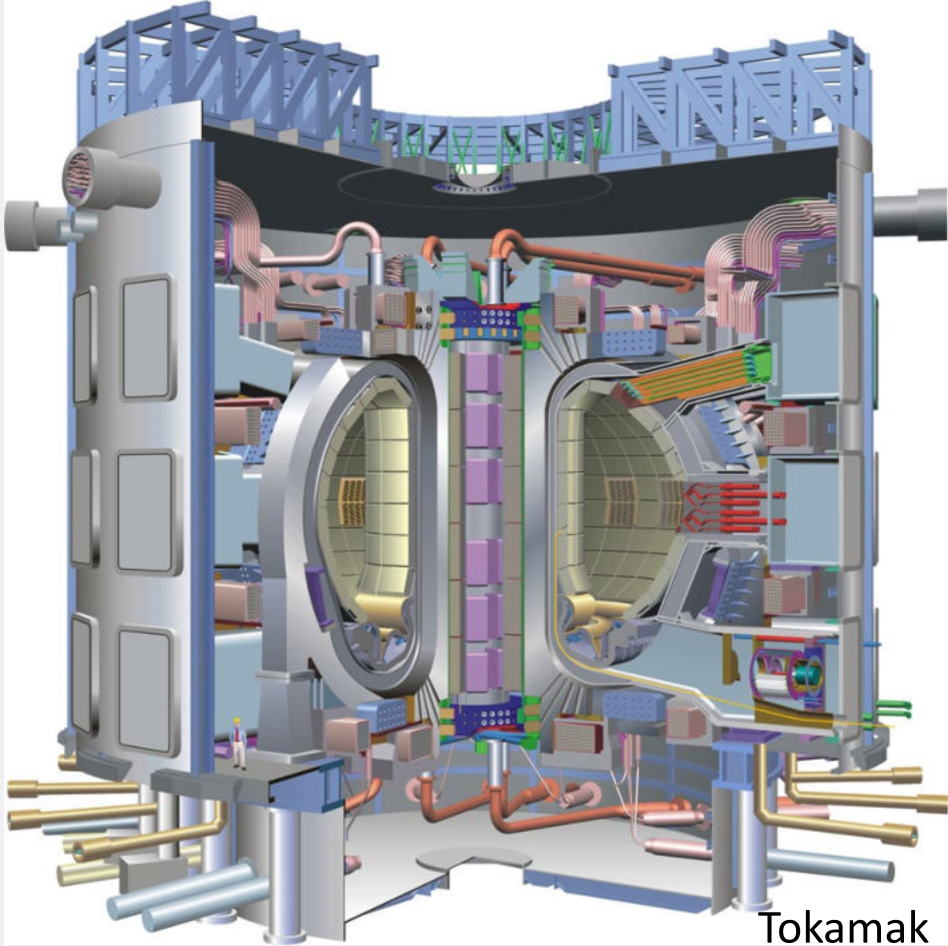
Salazar, Paccagnan, Agazzi, Heemels, *Urgency-aware Optimal Routing in Repeated Games through Artificial Currencies*, European Journal of Control, 2021

Energy Systems

- Plasma control
  (nuclear fusion & CO_2 dissociation)
- Solar fuels
- Energy transition/charging
  infrastructures / electrification
  (ZenMO)

Strong collaboration with DIFFER (TU/e campus)

DIFFER
Dutch Institute for Fundamental Energy Research



Tokamak

TU/e

CST Master Courses

Code	Title	Responsible lecturer
4CM10	System theory for control	W.P.M.H. Heemels
4CM00	Control engineering	G. Witvoet
4CM60	Advanced motion control	T.A.E. Oomen
4SC010	Control and operation of tokamaks	M.R. de Baar
4CM70	Integrated system design	L.F.P. Etman
4SC000	Optimal control and reinforcement learning	D.J. G. Tomé Antunes
4DM20	Engineering optimization	M.R.U. Salazar
4CM80	Extremum seeking control for data-based perf. optimization	T.A.C. van Keulen
4CM90	Opto-mechatronics	L.A. Cacace
4CM40	Physical and data-driven modelling	K. Tiels
4CM30	Supervisory control	M.A. Reniers
4AT070	Advanced control for future HD powertrains	F.P.T. Willems
4AT030	Advanced full-electric and hybrid powertrain design	T. Hofman
4CM50	Applications of design principles	P.J.E.M. Vrancken
4SC030	Control of magnetic instabilities in fusion plasmas	M.R. de Baar
4SC040	Haptics - perception and technology	A.M.L. Kappers
4CM20	Hybrid systems and control	W.P.M.H. Heemels
4SC070	Learning control	T.A.E. Oomen
4SC020	Mobile robot control	M.J.G. van de Molengraft

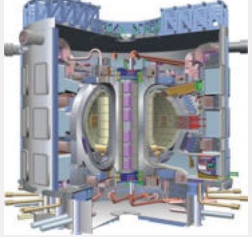
MSc degrees:

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:

- Informations meetings @ start in CST (year 1, Q1)
- Individual mentoring program (choose a mentor)
- Projects: Guidance by project supervisors, regular meetings (permanent) faculty

Summarizing



CST group unites

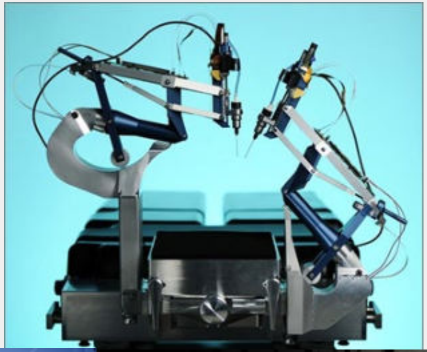
- Science and fundamental (control) theory
- Applied research & design
- Society / Spin-offs / Impact

Combine Highest quality standards & Fun

Eindhoven Medical Robotics

DTI

avular



PRECEYES

microsure
robot assisted microsurgery

TU/e

Links CST

https://www.tue.nl/cst (check the personal pages of our researchers!)

Movie iterative learning control:
https://youtu.be/kj_ouy1Fnko

Program

Monday March 27, 2023

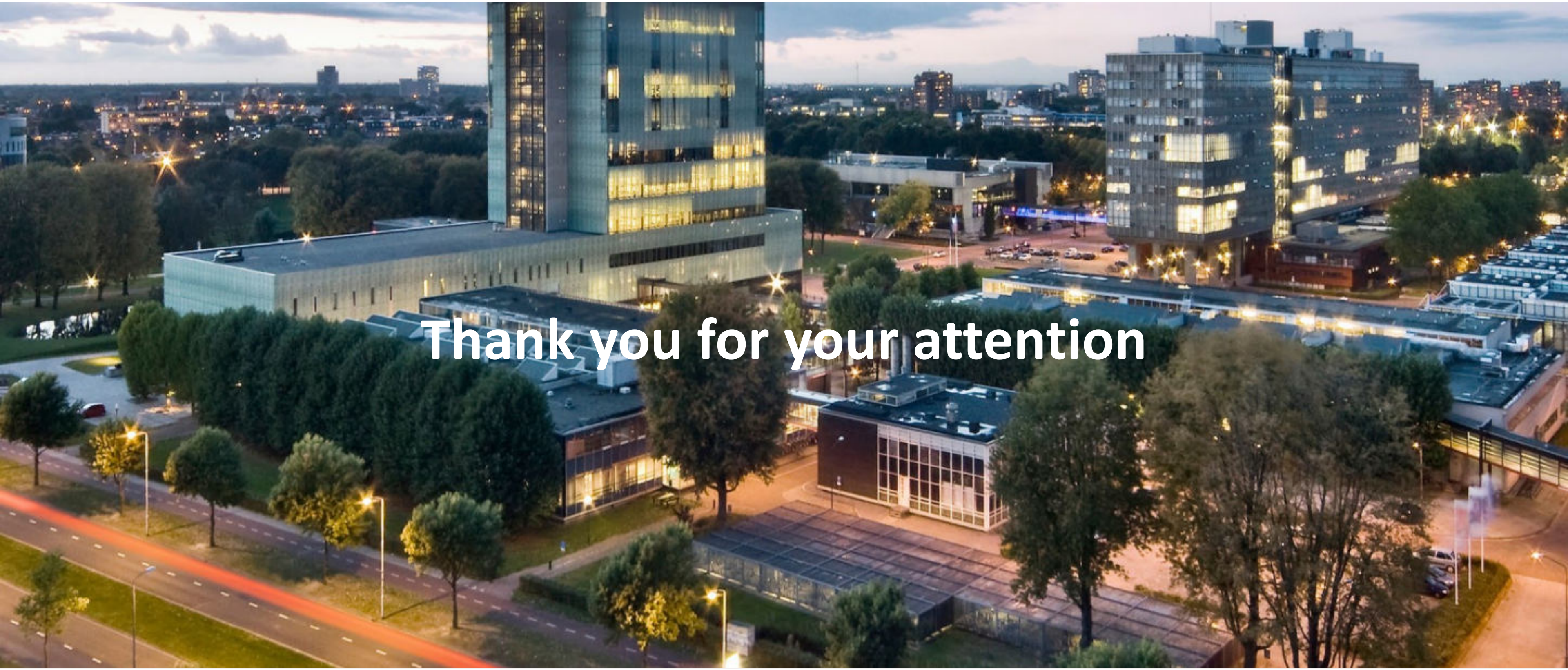
General Master information session – Gemini-Zuid

13:30 – 13:50 Division DSD general introduction by Prof.dr.ir. Nathan van de Wouw / Prof.dr.ir. T.A.E. Oomen
13:50 – 14:10 Section: Dynamics and Control (D&C) by Prof.dr.ir. Nathan van de Wouw
14:10 – 14:30 Section: Control Systems Technology (CST) by Prof.dr.ir. Tom Oomen

14:30 – 15:15 lab visits DSD

15:15 – 15:30 run-out lab visits

15:15 – 16:00 Drinks Coffee corner GEM-Z 0.143



Thank you for your attention