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Advanced Servo Control Research at Philips CFT: Status and Future Challenges

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Outline

- Introduction
- Relation control groups TU Delft – Philips
- Servo control research @ CFT
- Closing remarks

Introduction: myself

- TU Delft, Mechanical Engineering :
  - **Student**: systems & control group (prof. Bosgra) [1984-1991]
  - **PhD student**: systems & control group (prof. Bosgra) [1991-1996]
- Philips:
  - **Research**: control engineer in ASML research projects (group Sastra) [1996-1998]
  - **CFT**:
    - Control engineer in ASML research projects (department van Eijk) [1998-2002]
    - Project leader EUV alpha tool [2002-..]
    - Competence group leader Acoustics & Control [aug2004-..]

The challenge is there and so is the solution

Philips in general

Philips CFT
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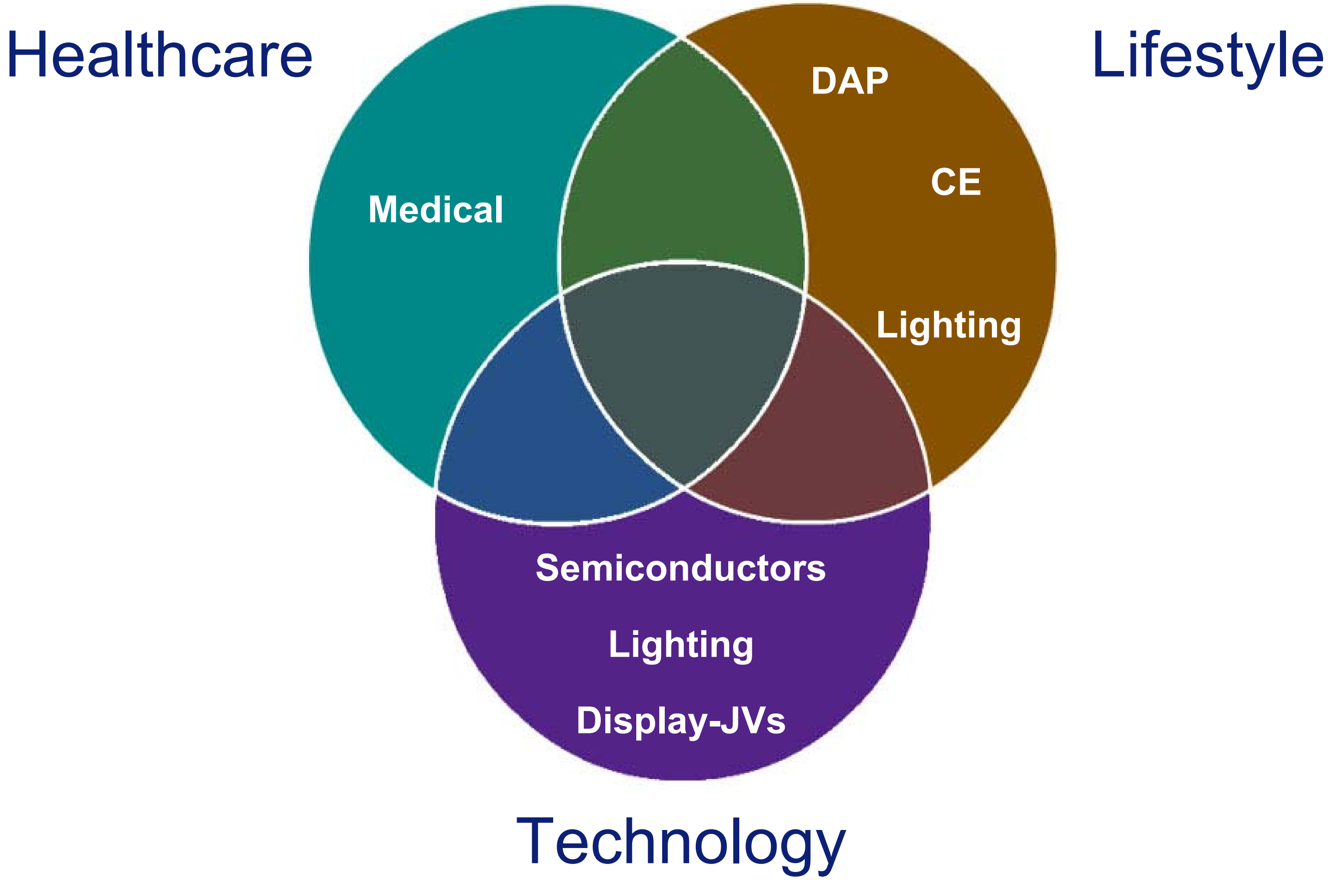
Royal Philips Electronics

Headquarters:

Amsterdam, The Netherlands

- Multinational workforce of 164,438 employees
- Active in:consumer electronics, medical systems, lighting, semiconductors, domestic appliances and personal care
- Sales 2003:
  EUR 29,037 mln
- 60 different businesses
- Sales and service in 150 countries
- R&D expenditures 2003 EUR 2,6 billion

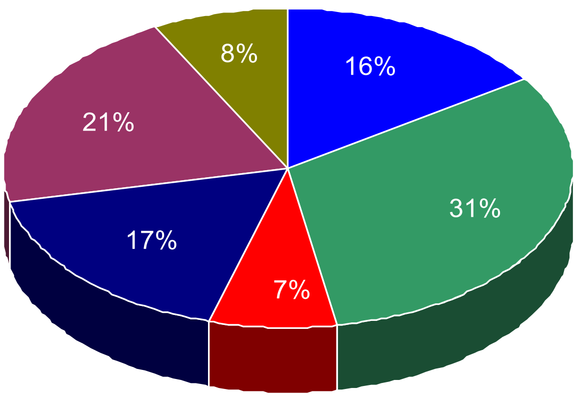
Areas of Philips activities



Philips today (2003 numbers)

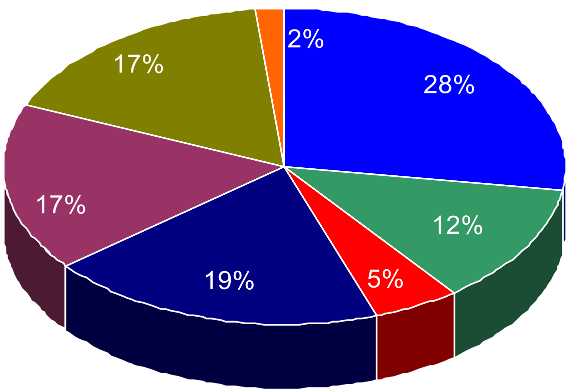
Sales per sector, *as % of total*

100%= EUR 29.0 B



Employment per sector, *as % of total*

100%= 164,400



Lighting **CE** **DAP** **Semiconductors** **Medical** **Misc.** **Unallocated**

The challenge is there and so is the solution

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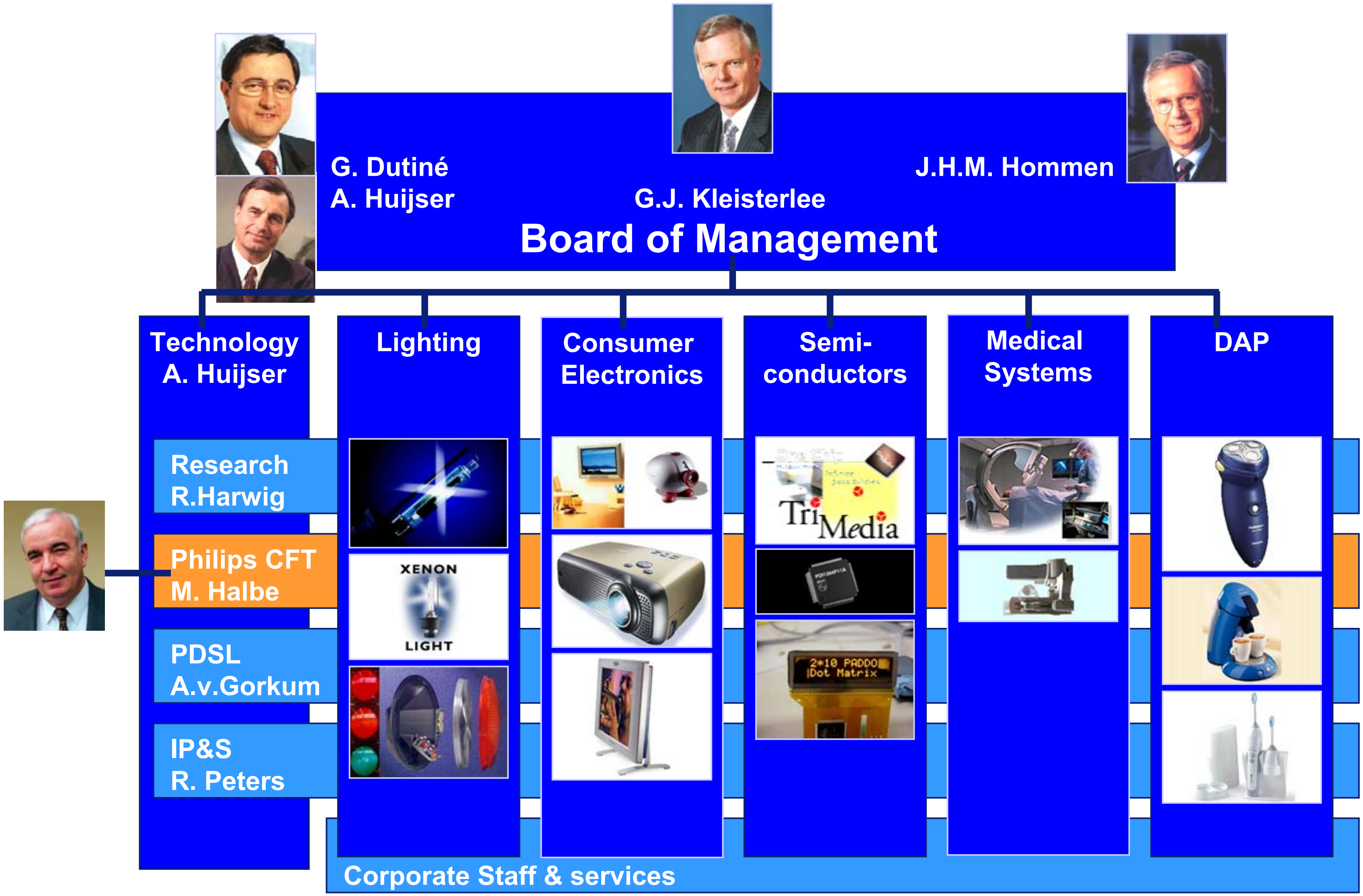
Philips CFT within Philips



Philips CFT mission

- To create value for Philips by providing Philips, its suppliers and partners, and selected non-Philips customers with world-class global solutions in industrial development, technology and consultancy

Particularly in the areas of :

- Mechatronics
- Process technology
- Assembly
- Innovation & Industrial support
- Environmental support

- To contribute to the position of Philips as a high-growth technology company

Philips CFT: global sites

Eindhoven Headquarters
Location: The Netherlands
Employees: 830

Budapest
Location: Hungary
Employees: 10

Sunnyvale
Location: USA
Employees: 33

Singapore
Employees: 29

The challenge is there and so is the solution

Philips CFT: Mechtronics

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Mechatronics Competences

Machine Dynamics & **Control**

Precision Engineering

Software Architecture & Design

Manufacturing Test

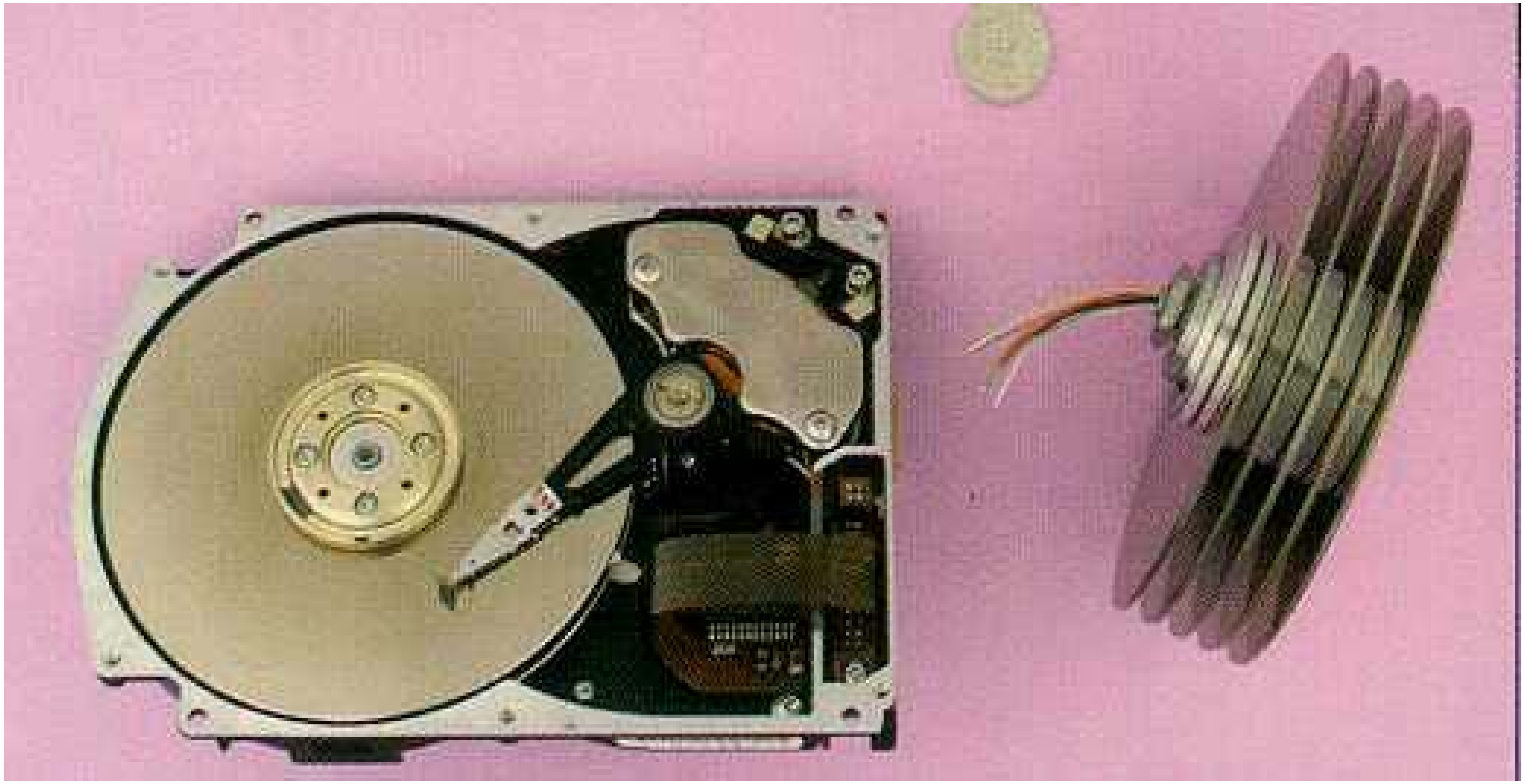
Machine Vision

Optics and analog electronics

Mechatronics: Synergy between disciplines to provide better solutions

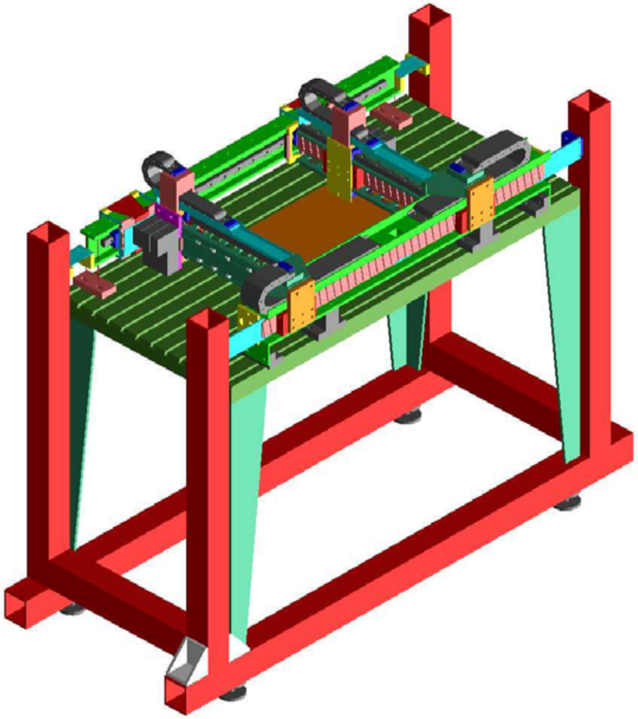
- Mechanics
- Electronics
- Software/Information
- **Control**

Hard-disk drive

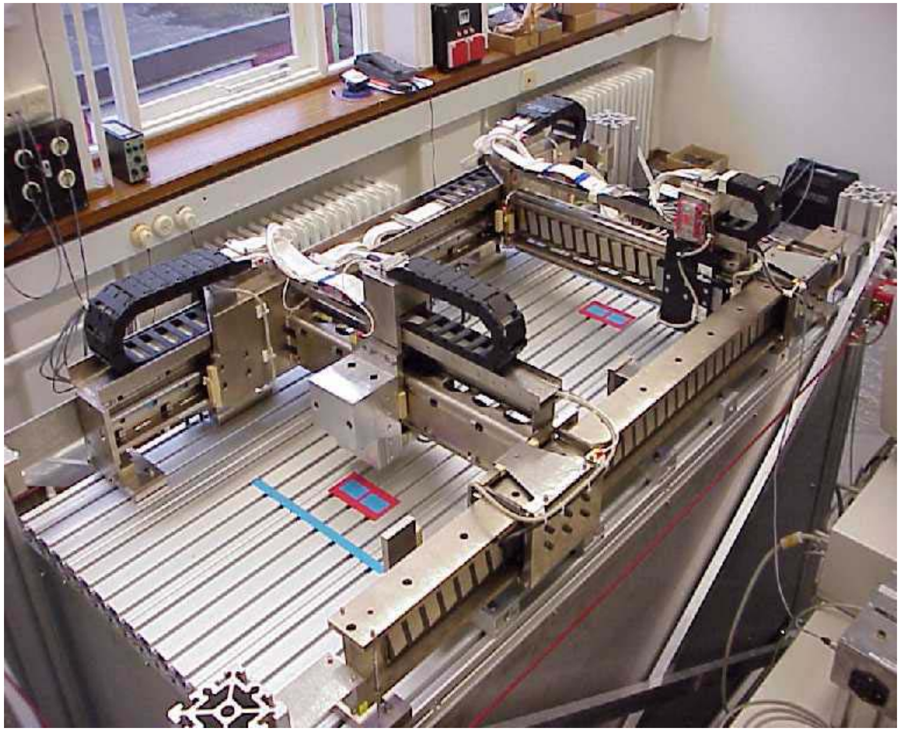


Component mounter

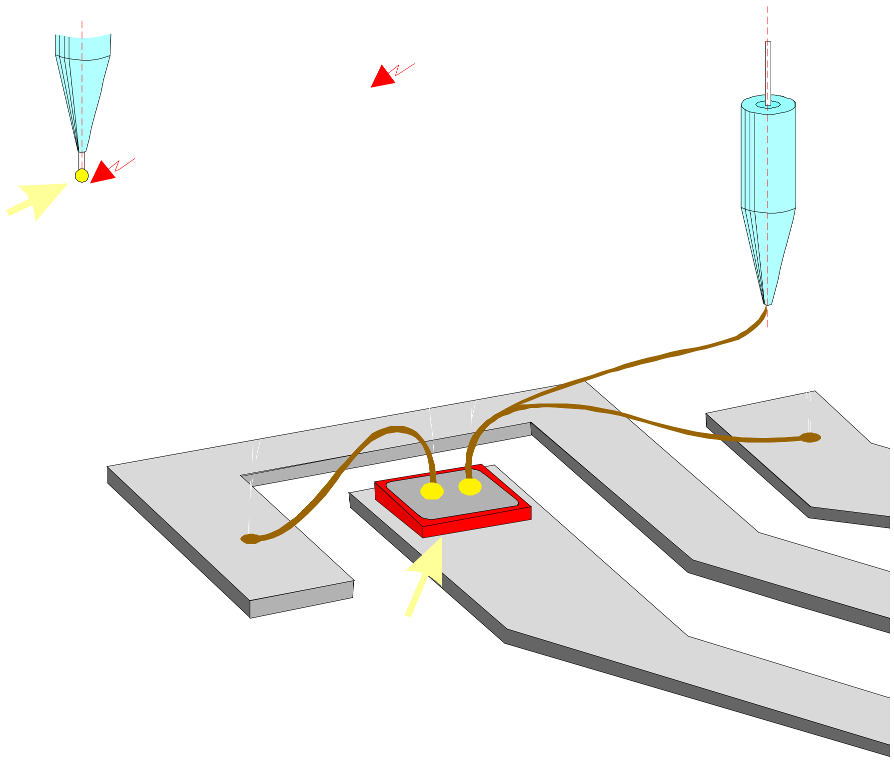
CAD-representation

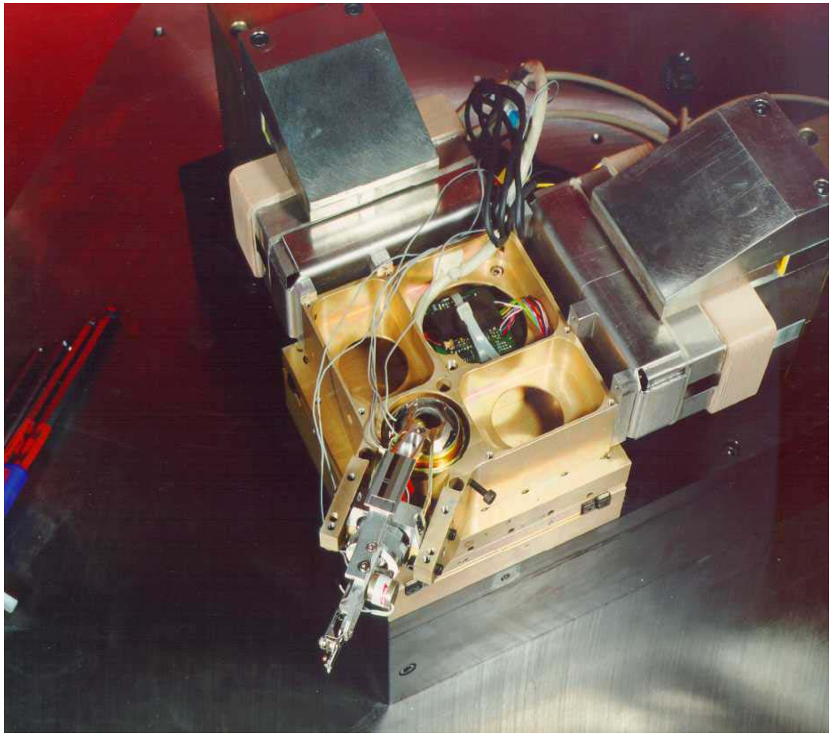


Functional model



Phicom 3, wirebonder ITEC

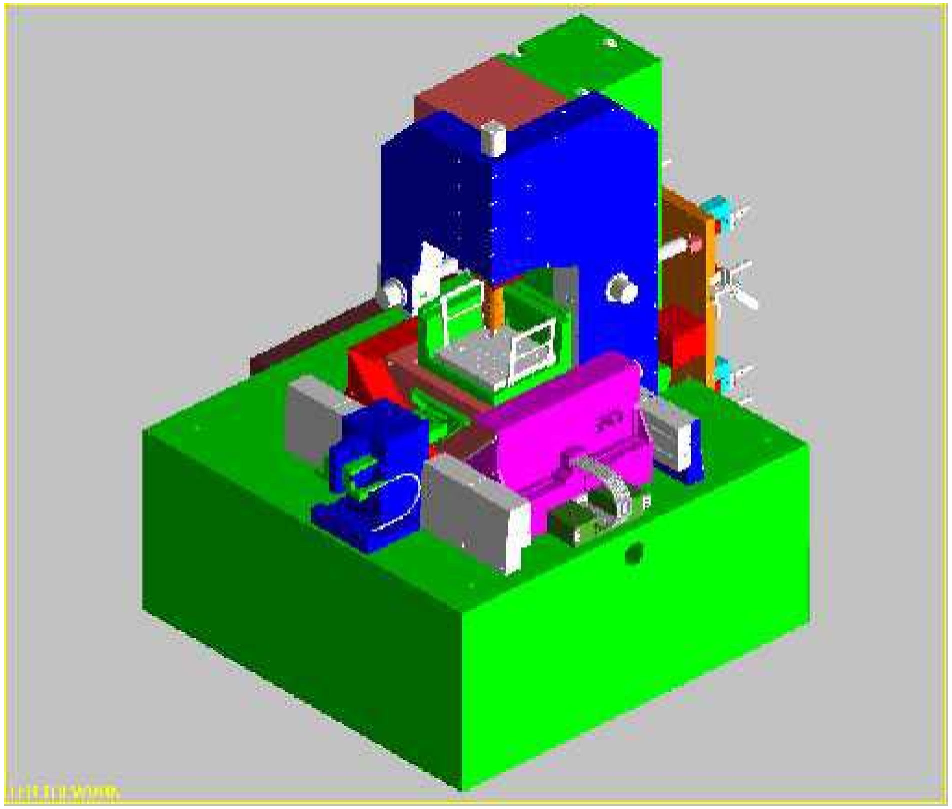




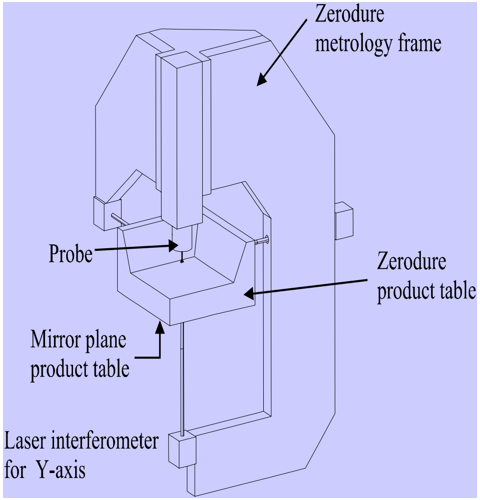
- 14k4 components/hour
- capillary movement

- Lorentz force actuators
- Two-stage principle
  - z-position
  - z-force

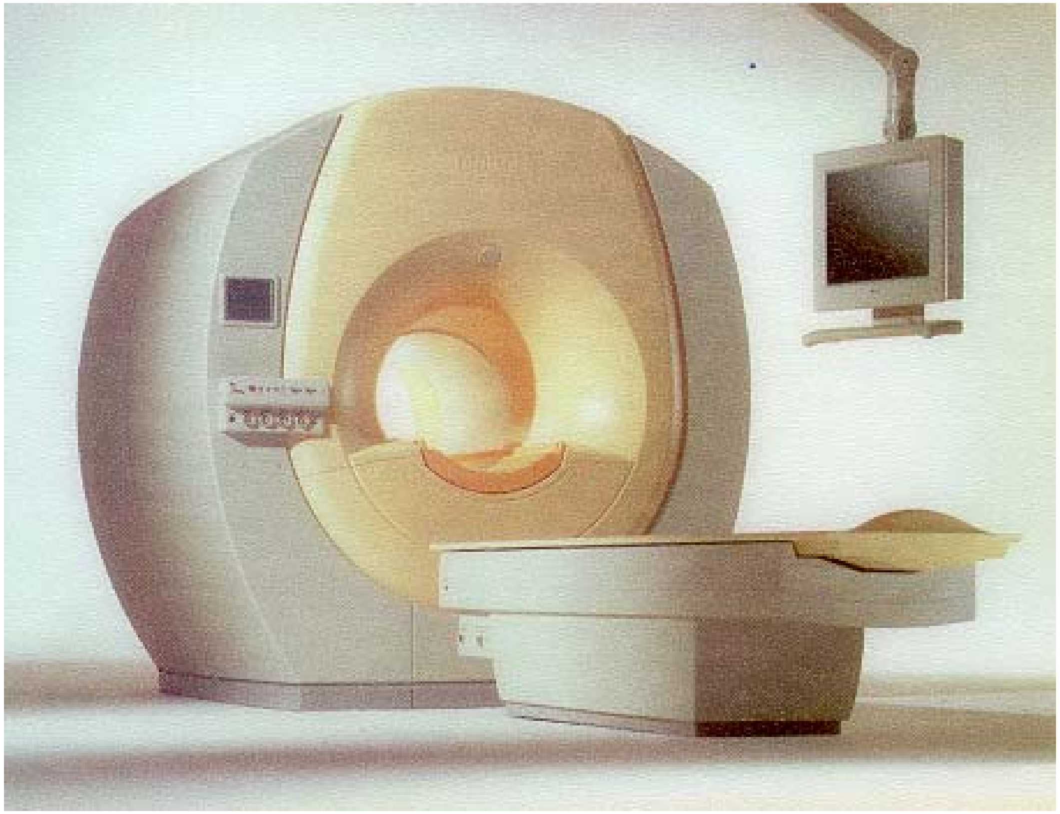
Metrology for accurate manufacturing control



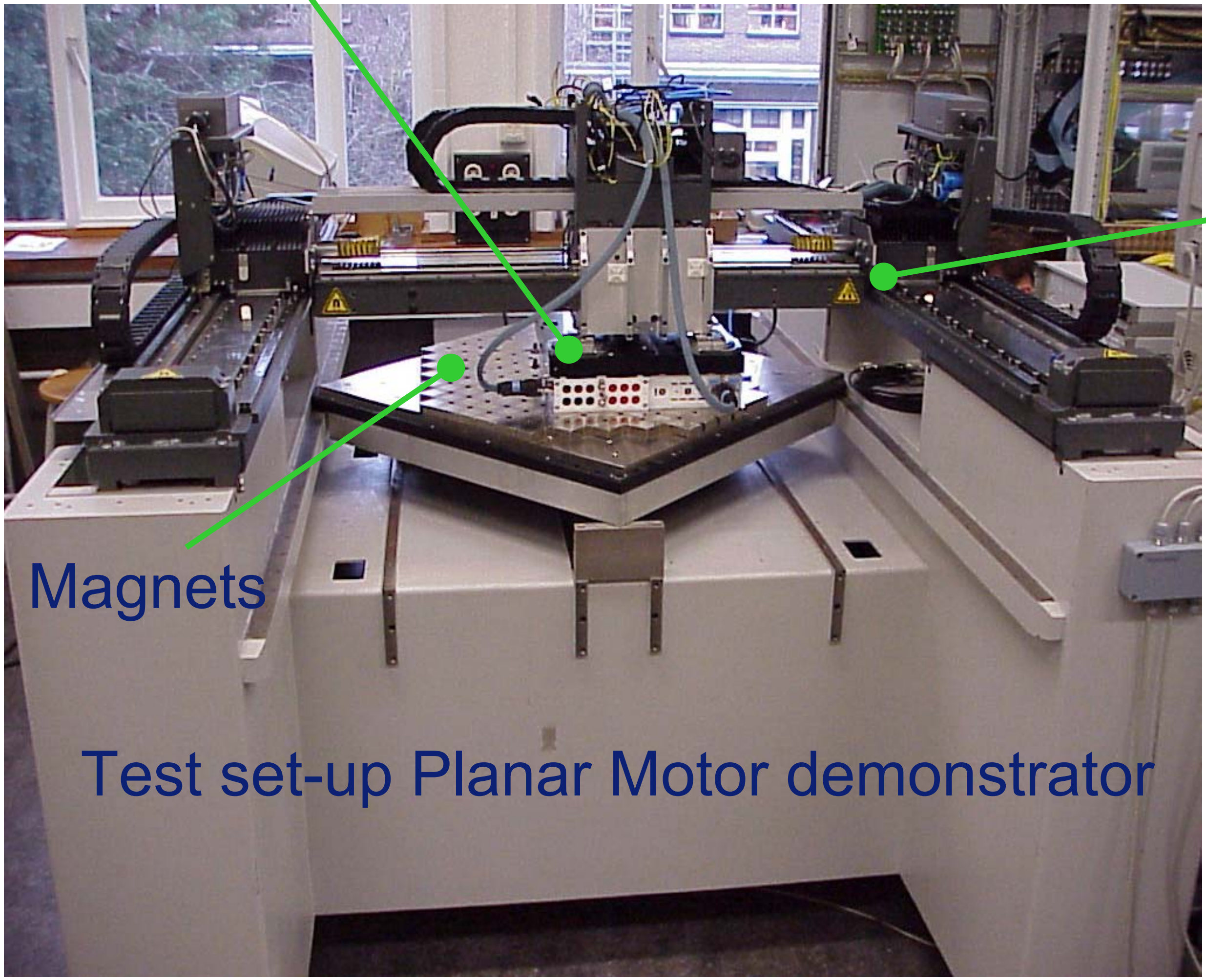
Zero Abbe offset's
Thermally insensitive
0.1 μm accuracy target
rapid sampling



MRI scanner: PMS



- Noise reduction
- Active vibration isolation
- Controller design


Planar motor
H-bridge
Magnets
Test set-up Planar Motor demonstrator

ASML research : SIRE-T5 300 mm stage

x-y stroke	300 mm
velocity	1000 mm/s
acceleration	10 m/s^2
jerk	1000 m/s^3
movement noise (1σ)	<7.5 nm
mov.average (slit 10 mm)	<2.5 nm
mov.st.dev.	8 nm

The challenge is there and so is the solution

Relation control groups TU Delft – Philips

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The early years : 80-ties – ‘98

Bosgra

Mech Eng.
Systems&Control

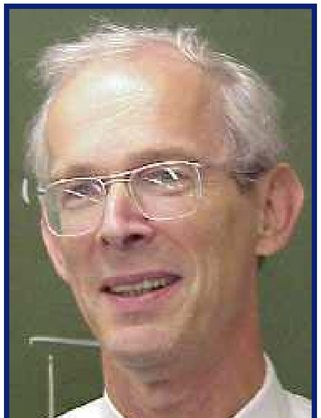
Technische Universiteit Delft

Sastra

(Mechanics
Research)

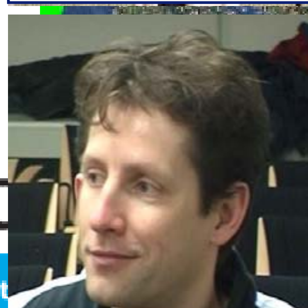
Philips research recruits heavy control artillery

Steinbuch



Bosgra

Sperling



Wortelboer

Sastra

TU Delft
Technische Universiteit Delft

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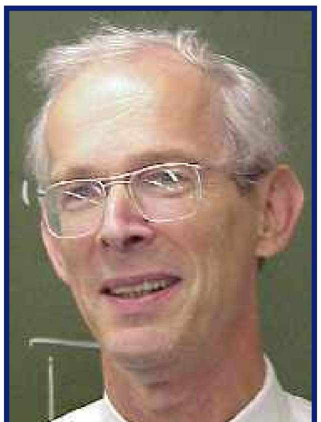
Send in a whole bunch of students for MsC assignment @ Philips



Bosgra

Sastra

List of MsC assignments at Philips

STUDENTS (incomplete..)

- Schrama, Draaijer, Smit, van Groos, Ceton, Bruinsma, van der Laan, van der Vlugt, Rietjens, Terlouw, la Bastide, Koekebakker, Chang, de Callafon, Tousain, van Duin, van der Slikke, van der Meche,…
- Rambaratsingh, Groot-Wassink, de Gelder,…

TOPICS / APPLICATIONS

- Optical disk drives
- Hard disk drives
- Lithographic stages
- Closed-loop model reduction
- Optimal control
- H_inf, mu
- Repetitive/learning control
- Input shaping
- ……

Start Philips-funded PhD program in Delft

Bosgra

TU Delft
Technische Universiteit Delft

Sastra

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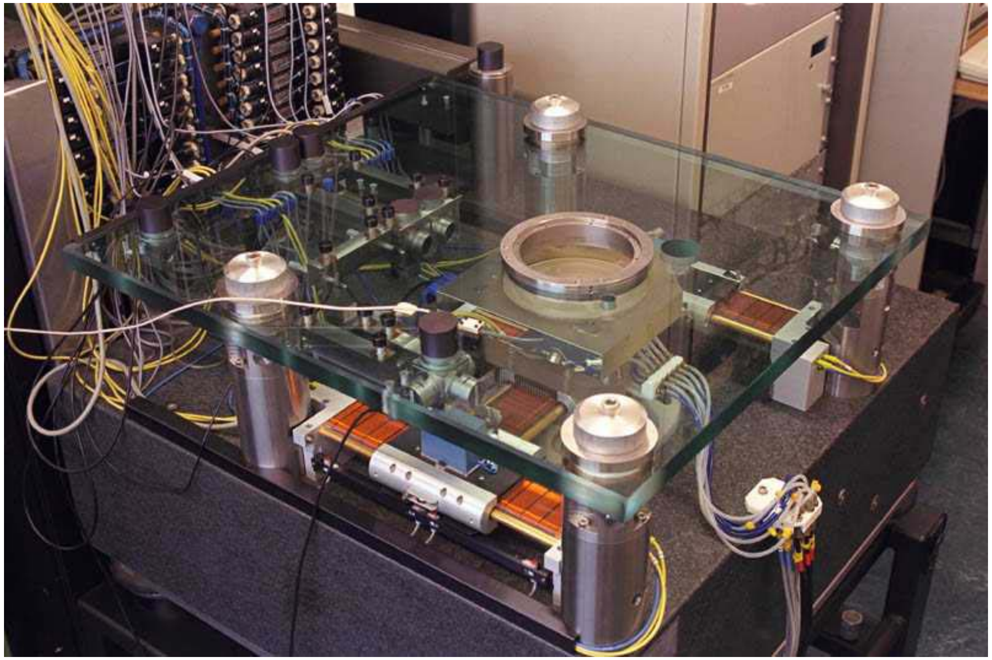
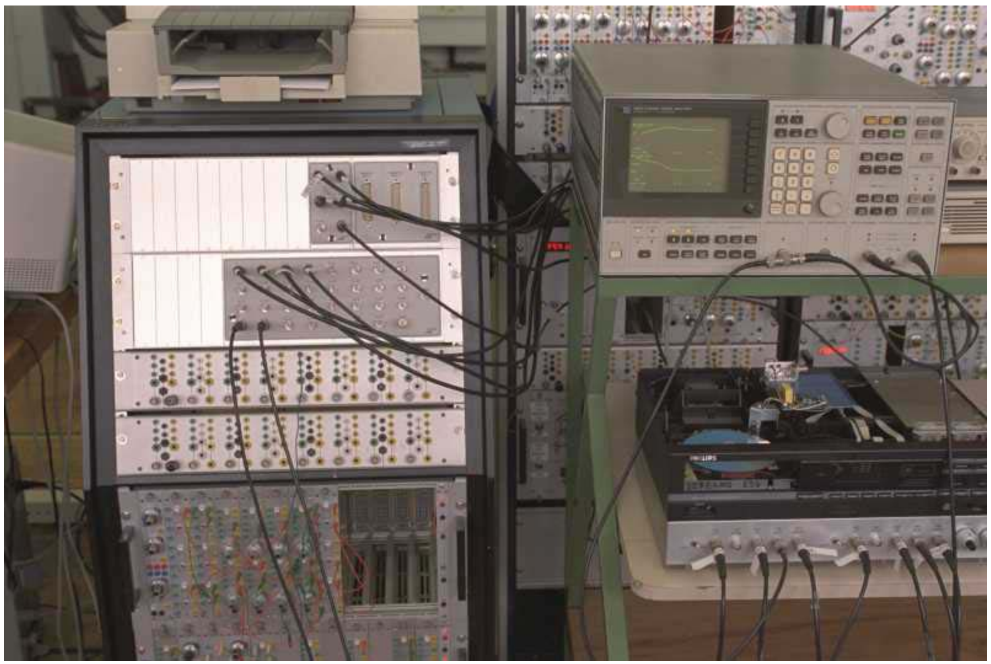
Philips-funded PhD's: Wafer stepper



De Roover

Dijkstra

Philips-funded PhD's : CD-player



Dotsch

Dettori

Philips-funded PhD: ongoing

Hol

Fixed order /structured H_∞ controller synthesis

- Fixed-order H_∞-controller design
  - Studied as part of a PhD project at Delft Univ. Tech.
  - The aim is to design H_∞-controllers with *a priori* specified
    - order (number of states),
    - controller configuration (such as multi-loop SISO controllers),
    - controller stability requirements (besides closed-loop stability requirements).
  - And much more….

v.d. Meche

MIMO FRF/LPV model identification

Given $\hat{G} \in \mathbb{C}^{p\times m}$ in ω_o, weighting matrices $W \in \mathbb{C}^{p\times p}$, $V \in \mathbb{C}^{m\times m}$ and system $G(s) \in \mathcal{RH}_\infty$ with realization

$$G(s) := C(sI - A)^{-1}B + D$$

then the following two statements are equivalent:

(i) $$\begin{bmatrix} Z & W(G(j\omega_o) - \hat{G})V \\ * & -I \end{bmatrix} < 0$$

(ii) $\exists L \in \mathbb{C}^{p\times n}, Y \in \mathcal{S}^n$ s.t.

$$\begin{bmatrix} Z & L(A - j\omega_o I) + WC & LB + W(D - \hat{G})V \\ * & YA + A^T Y & YBV \\ * & V^H B^T Y & -I \end{bmatrix} < 0, \quad Y > 0$$

Research group implanted @ CFT after departure Sastra ('98)

Bosgra

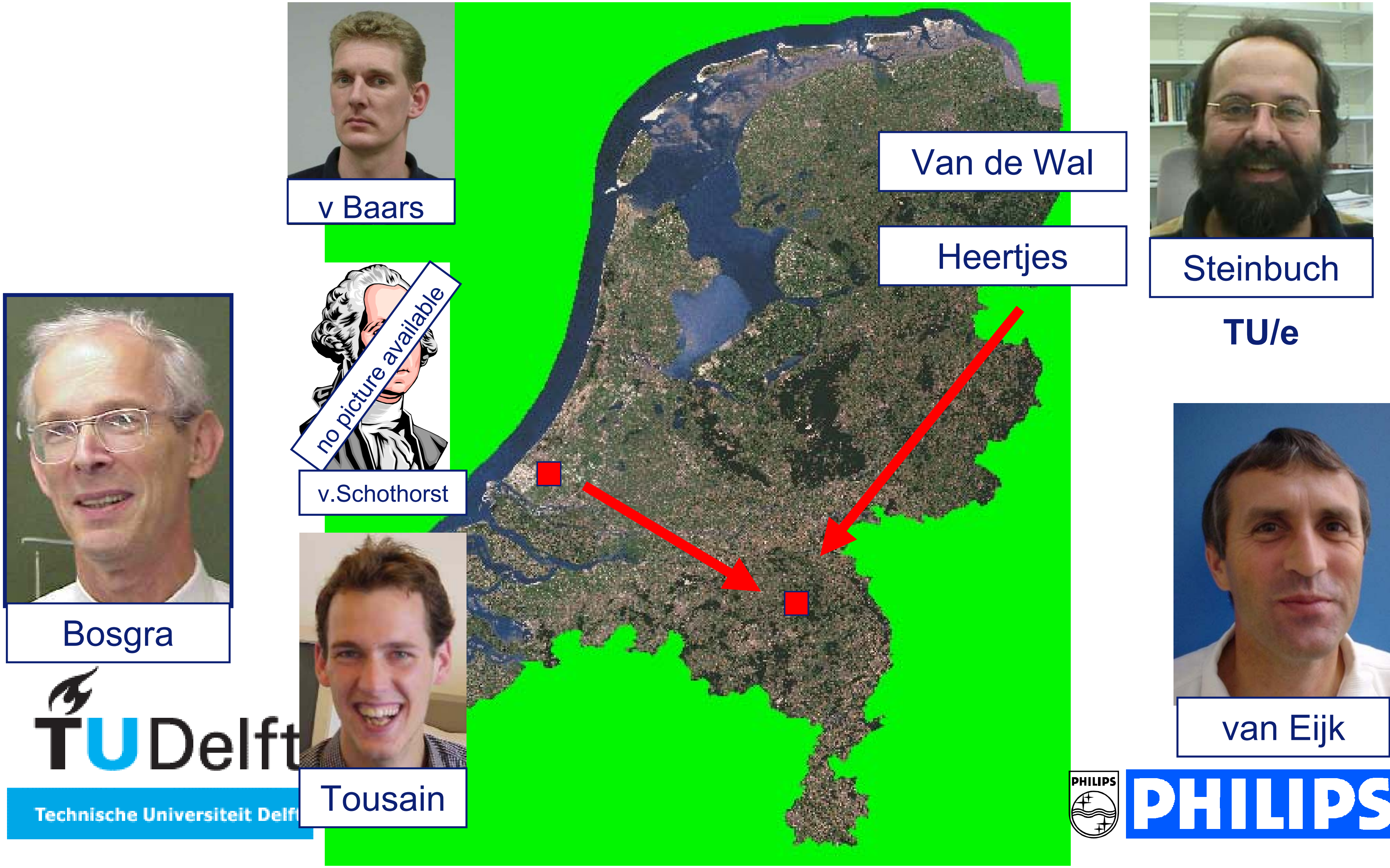
Mech Eng.
Systems&Control

Sastra

van Eijk

CFT Mechatronics

Philips recruits fresh horses and continues control research



The challenge is there and so is the solution

Servo control research @ CFT

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Current examples of advanced servo control research

- APM Wetzlar: automotive CD/DVD drives
  - Nonlinear control
- Airmounts : vibration isolation
  - Modal control
- Medical Systems: MRI scanners
  - Noise control
    - Vibration cancellation, piezo actuation
    - Distributed sensors/actuators
- ASML: lithographic stages positioning
  - Four research topics (see later slides)
- …

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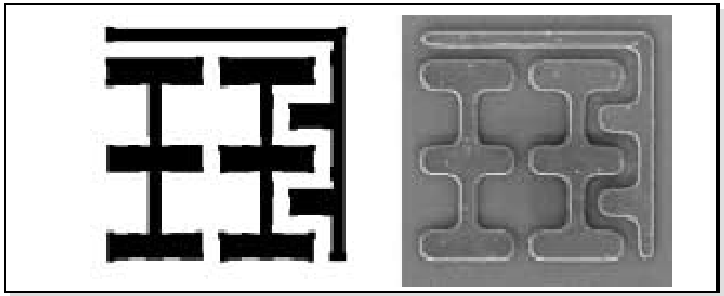
Case: Lithographic stages positioning
- Four control research topics

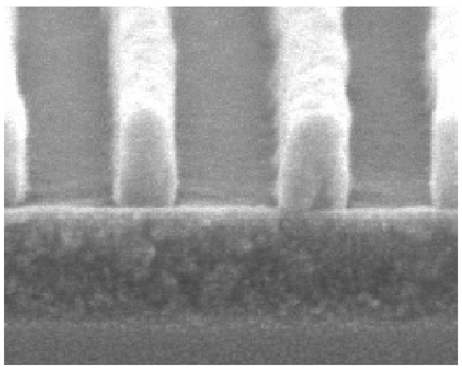
Typical lithographic stage research project setting

- First-of-a-kind prototype (feasibility study for next generation equipment)
- On-the-edge stage motion systems
  - High throughput (80/140 wafers/hour, 80-200 ICs/wafer) : aggressive setpoint trajectory (few g, 0.5-1m/s)
  - Extremely high positioning accuracy (nm) during scan
- Accuracy requirements in 6 DOF
- Servo control involved from the start in multi-disciplinary team during mechatronic process: concept, design, realization, test, optimization

Expose a desired pattern in resist

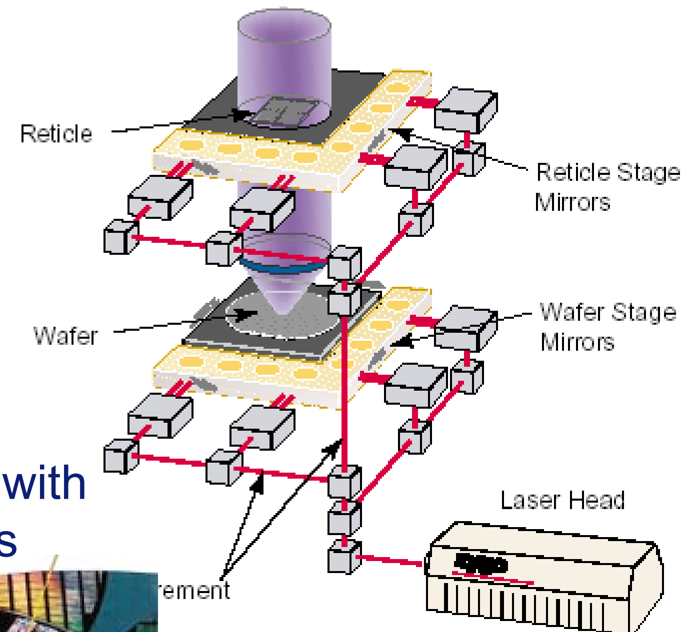


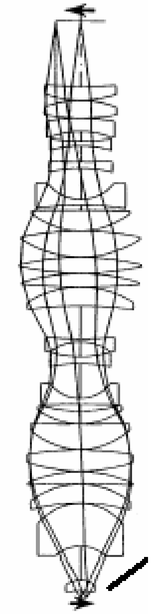
Develop and etch exposed pattern



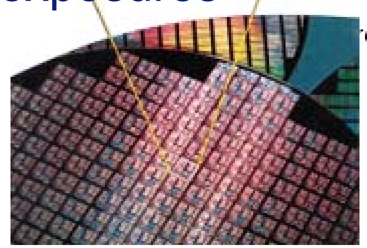
Build up IC by stacking layers of patterns (repeat previous steps)

Lithographic scanner is exposure tool (optics/imaging + scanning stages)





Fill wafer with exposures

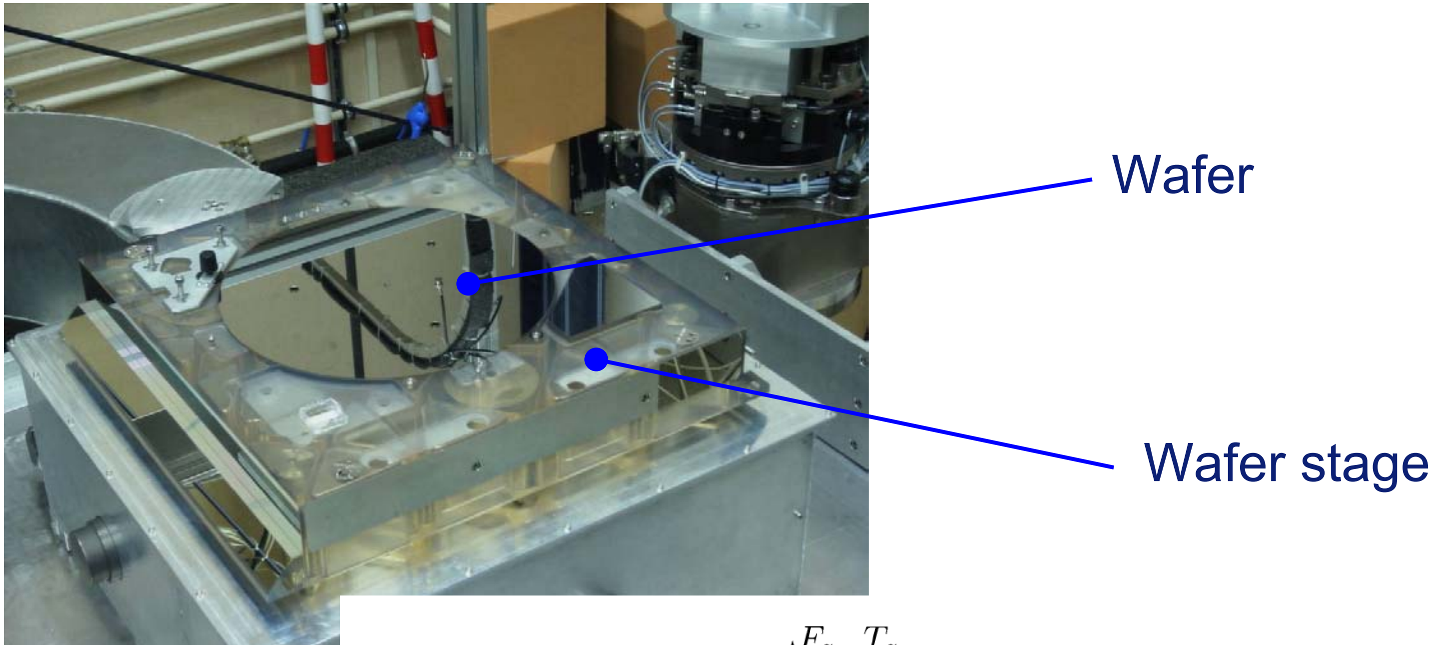


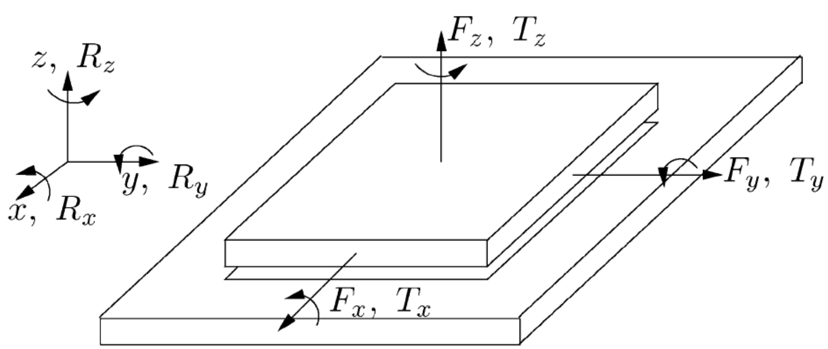
Pattern dimensions (CD) keep decreasing (Moore's Law), i.e. faster chip, higher capacity

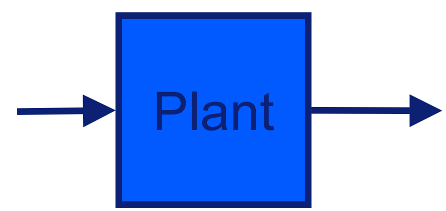
YEAR	1999	2000	2001	2002	2003	2004	2005	2007	2010	2013
CD (nm)	180	150	130	115	100	90	80	65	45	33
OVERLAY (nm, mean +3 sigma)	65	52	45	40	35	31	28	26	18	13

Required stage accuracy keeps increasing (e.g. overlay)

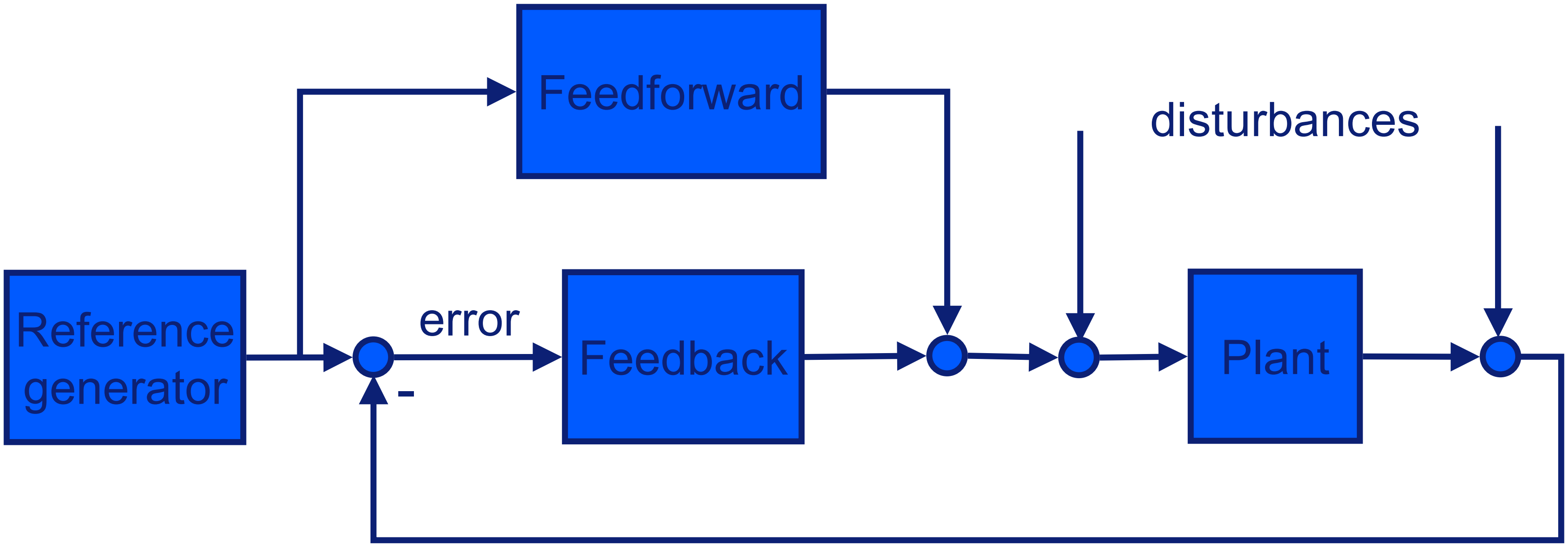
Wafer stage 6 DoF servo control





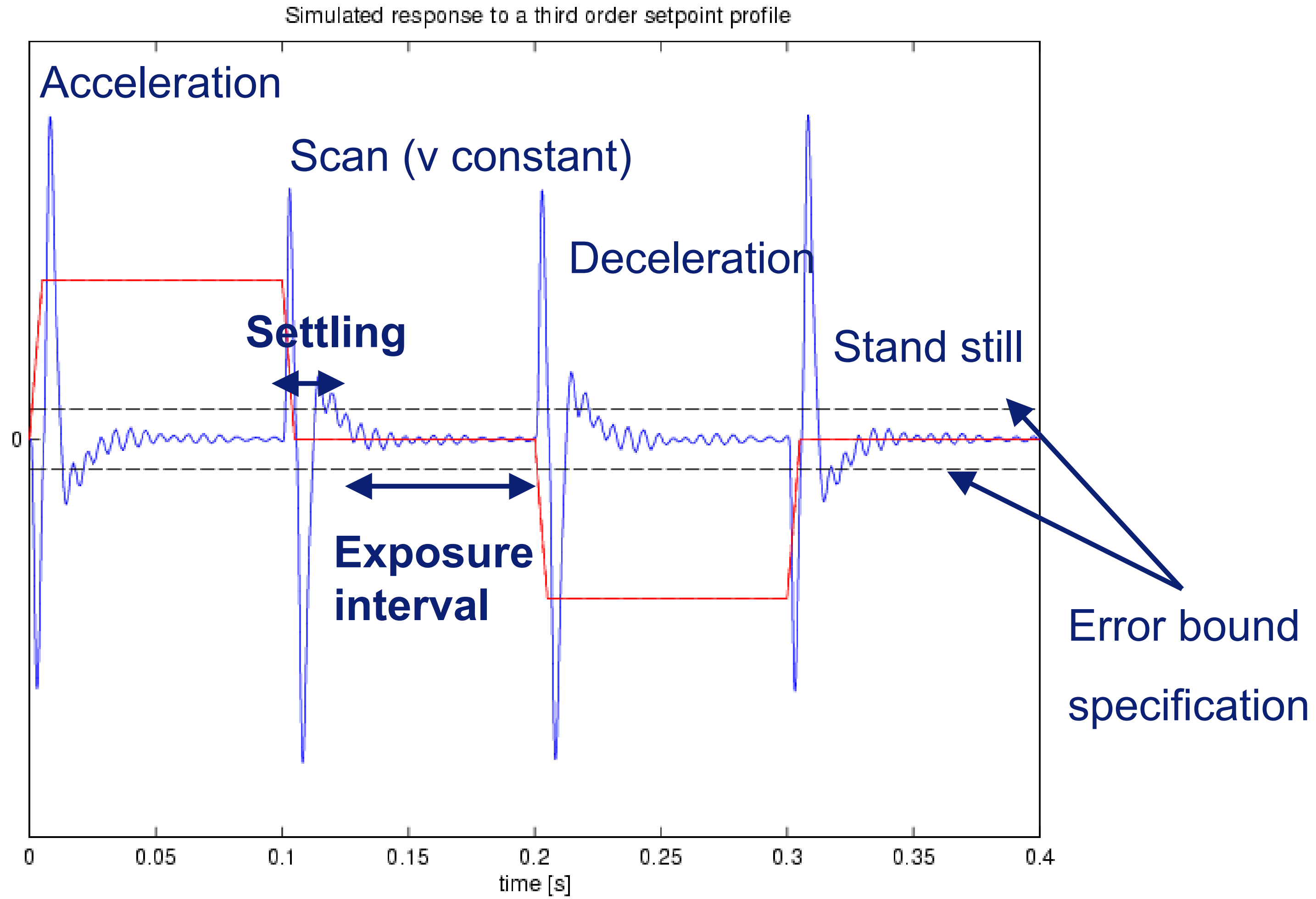


Servo Control: basic setting (motion systems)



- Plant: stage mechanics, actuators, sensors
- Feedback control: disturbance suppression, closed-loop stability and robustness
- Feedforward control: reference following, settling

Scanning trajectory: performance requirement and typical servo error

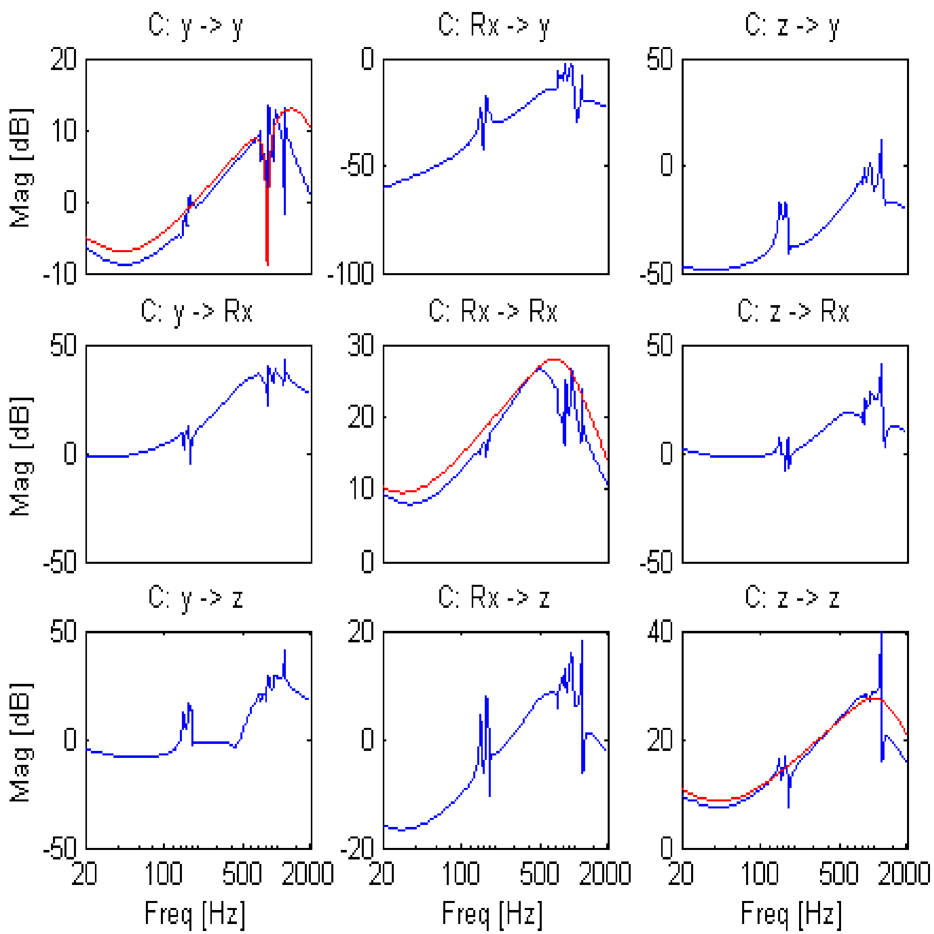


Four control research topics:
expected servo performance limits (1999/2000)

- Interactions between DOF's (limited scope of rigid body decoupling)
  - ➢ Explore **multivariable** control (MIMO H_∞, μ synthesis)
- A fixed servo controller for the whole operational range (inherent design conservatism : dynamic behaviour of the system changes with position)
  - ➢ Explore **position-dependent** control (gain scheduling, LPV control)
- Settling time limits throughput (vibrations must settle to start exposure)
  - ➢ Explore options to achieve **0-settling** (input shaping, model-based ff, ILC)
- Disturbances limit performance (difficult to characterize and to find source)
  - ➢ Explore **disturbance-based** control

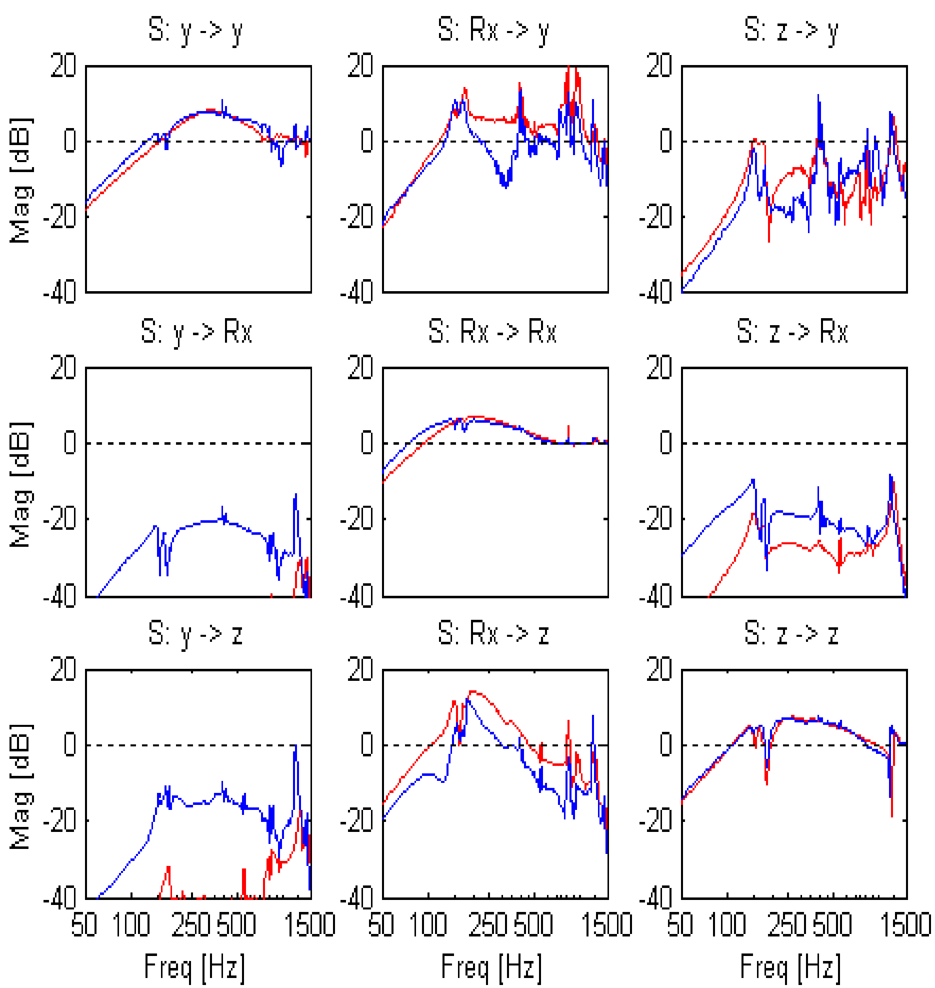
Multivariable control (MIMO)

SISO versus MIMO: controllers



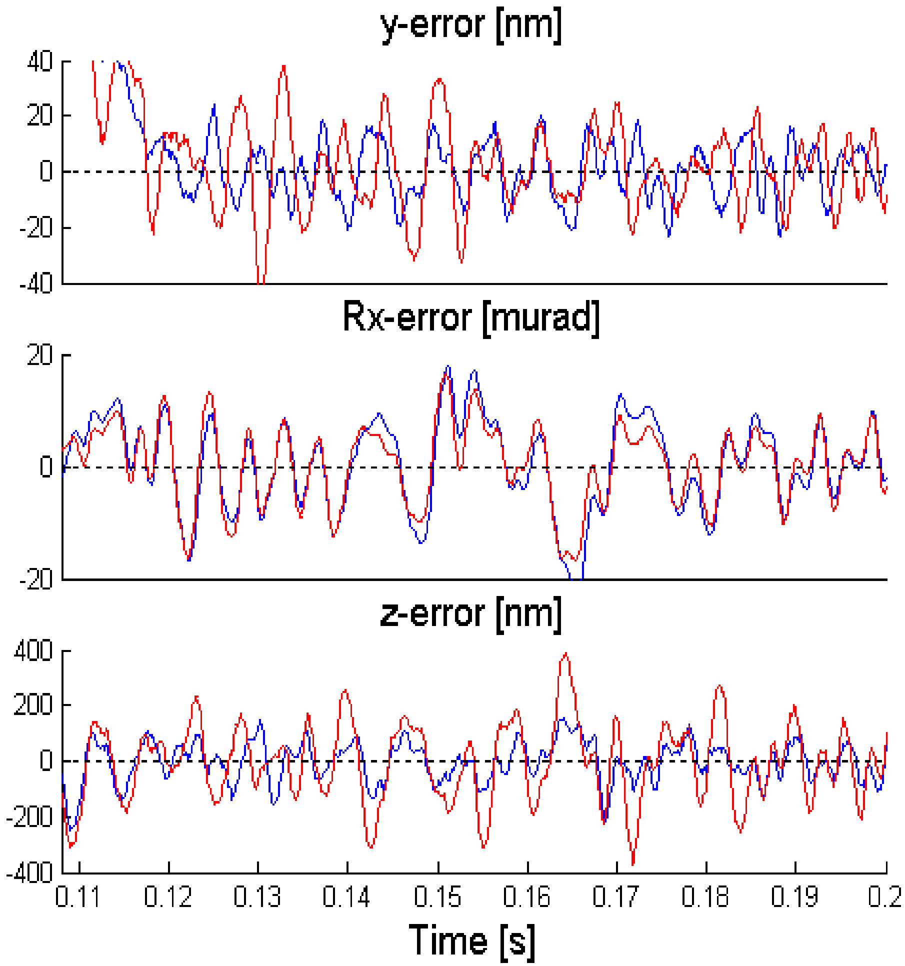
- MIMO exploits freedom to deal with interaction.
- Diagonal entries SISO and MIMO controller same basic shape.

SISO versus MIMO: sensitivity



- MIMO better for $R_x \to y$, $R_x \to z$, and $z \to y$.
- MIMO worse for $y \to R_x$, $z \to R_x$, and $y \to z$ …
- … but still $|S| < 0$ [dB]
- MIMO control improves performance where it is necessary.

SISO versus MIMO : servo errors



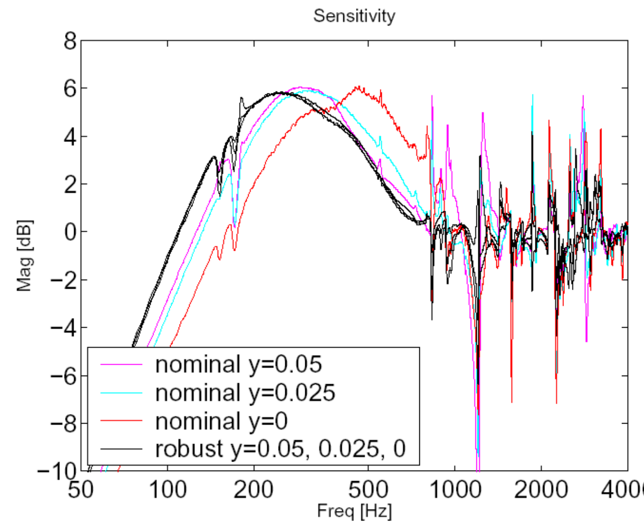
- MIMO better for *y* and *z*, due to better suppression of R_x disturbance.
- MIMO/SISO equally good for R_x.
- MIMO control improves performance due to effectively accounting for interaction.

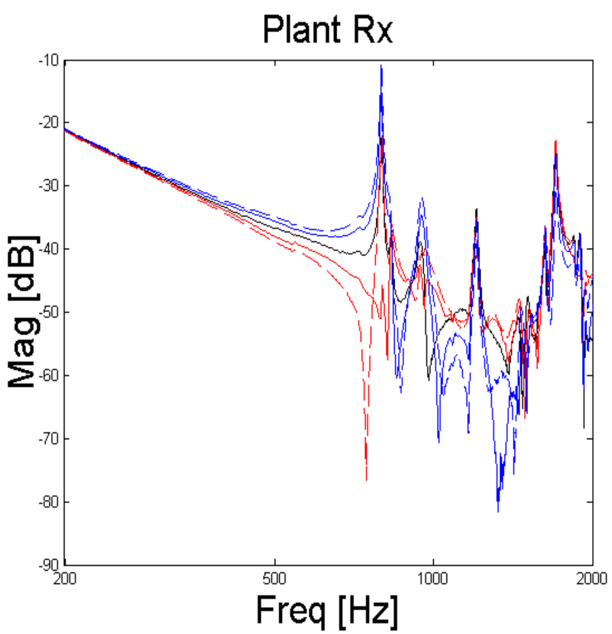
Position-dependent control

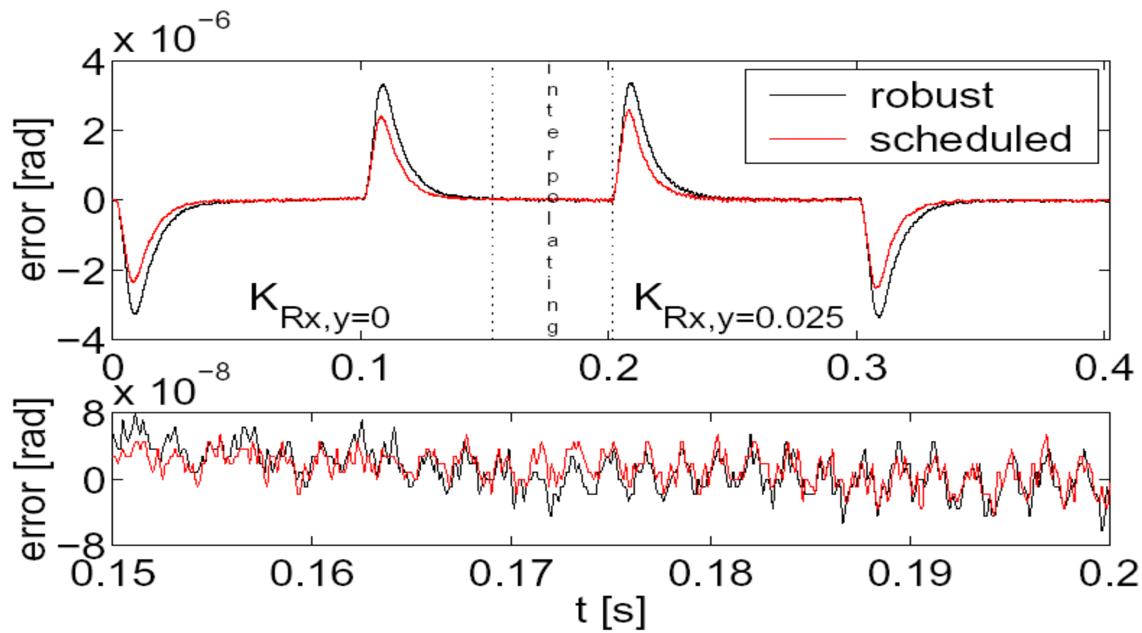
Position-dependent control

- Account for position-dependent dynamics.
- Reduce possible conservatism of robust controller design …
- … by modifying controller dynamics according to plant dynamics.
- Increase performance over complete stroke.
- Two approaches:
  - Conventional gain scheduling
  - Linear Parameter Varying (LPV) control

Implementation of gain-scheduled control (SIRE-T5)

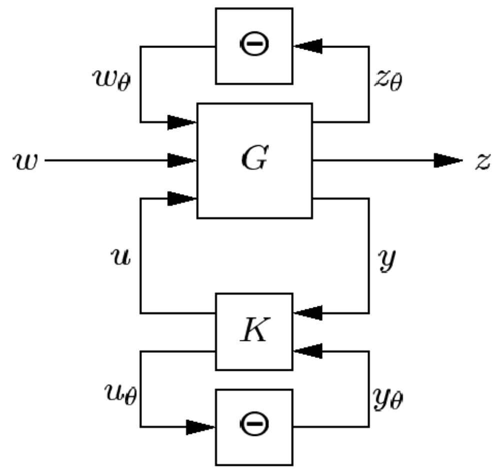


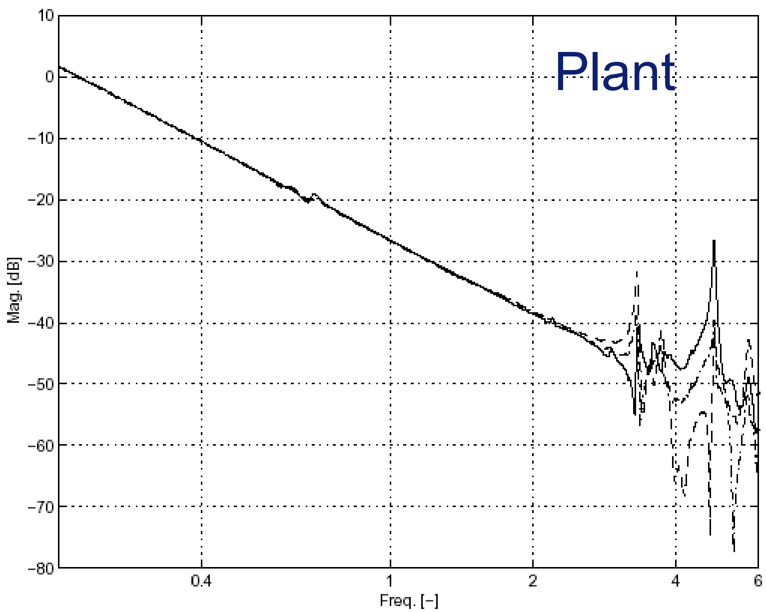


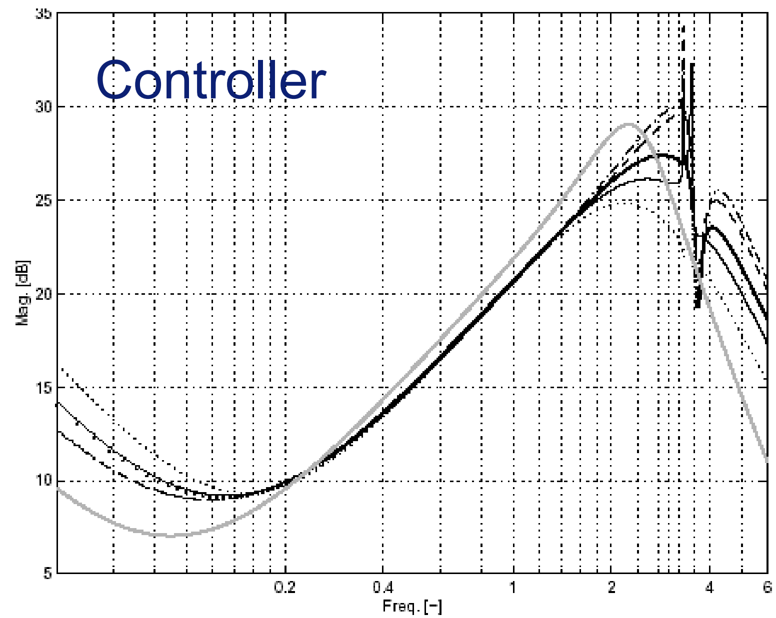


Implementation of LPV control (SIRE T5)

$$P: \begin{cases} \dot{x} = A(\theta)x + B(\theta)u \\ y = C(\theta)x + D(\theta)u \end{cases}$$







0-Settling control

Advanced control research: 0-settling

- **Input shaping**
  - Lots of solutions generated, no recent results pursued
- **Learning control**
  - Recent results addressed by previous speaker
  - Practical implementation challenges remain
- **Model-based feedforward control**
  - MSc project (among other efforts)
  - A method has been developed for advanced feedforward controller design minimizing settling time.
  - Using a (SISO or MIMO) plant model and linear programming algorithms to compute optimal controller.
  - Applied to the WS test-rig

Disturbance-based control

Disturbance based control & modeling

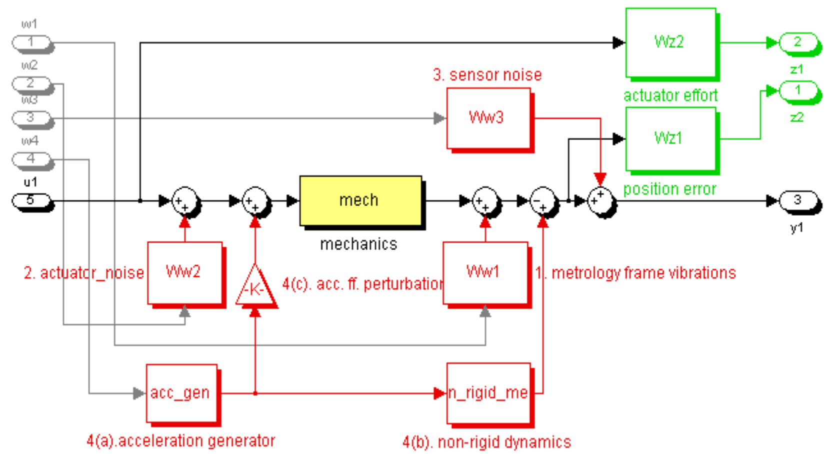
- For improved control of mechatronic systems in the presence of disturbances
  - Control design has so far been directed to system dynamics and not explicitly directed to disturbance suppression
- For improved mechatronic design (taking into account disturbances in an early stage)

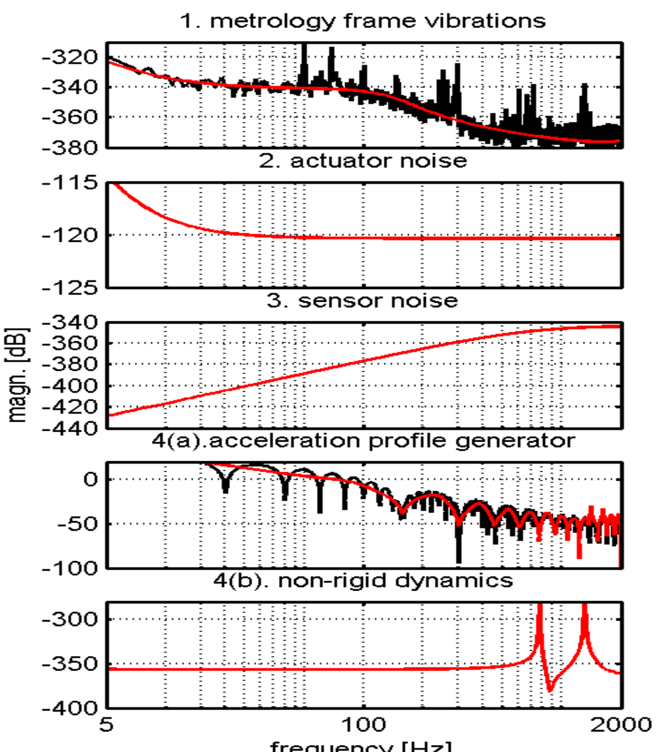
Advanced control research: dist-based

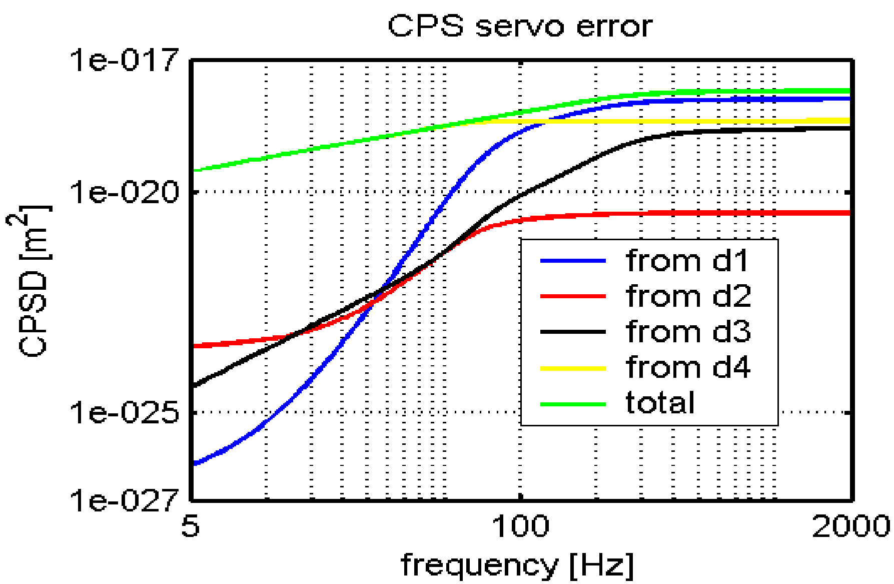
Disturbance modelling and H_2 optimal control: RSSS example

Disturbances:

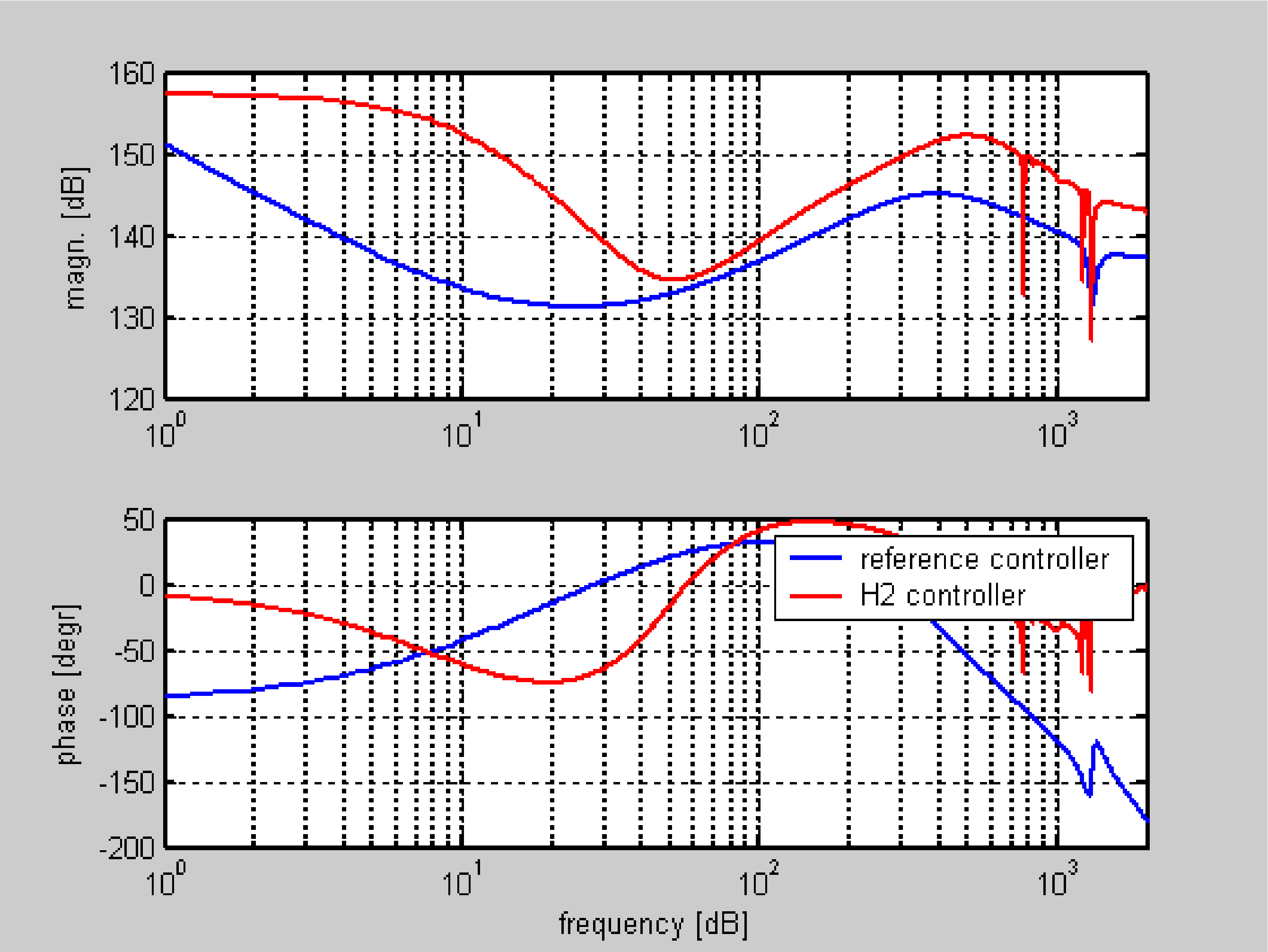
1. metrology frame vibrations,
2. actuator noise,
3. sensor noise,
4. setpoint-feedforward mismatch



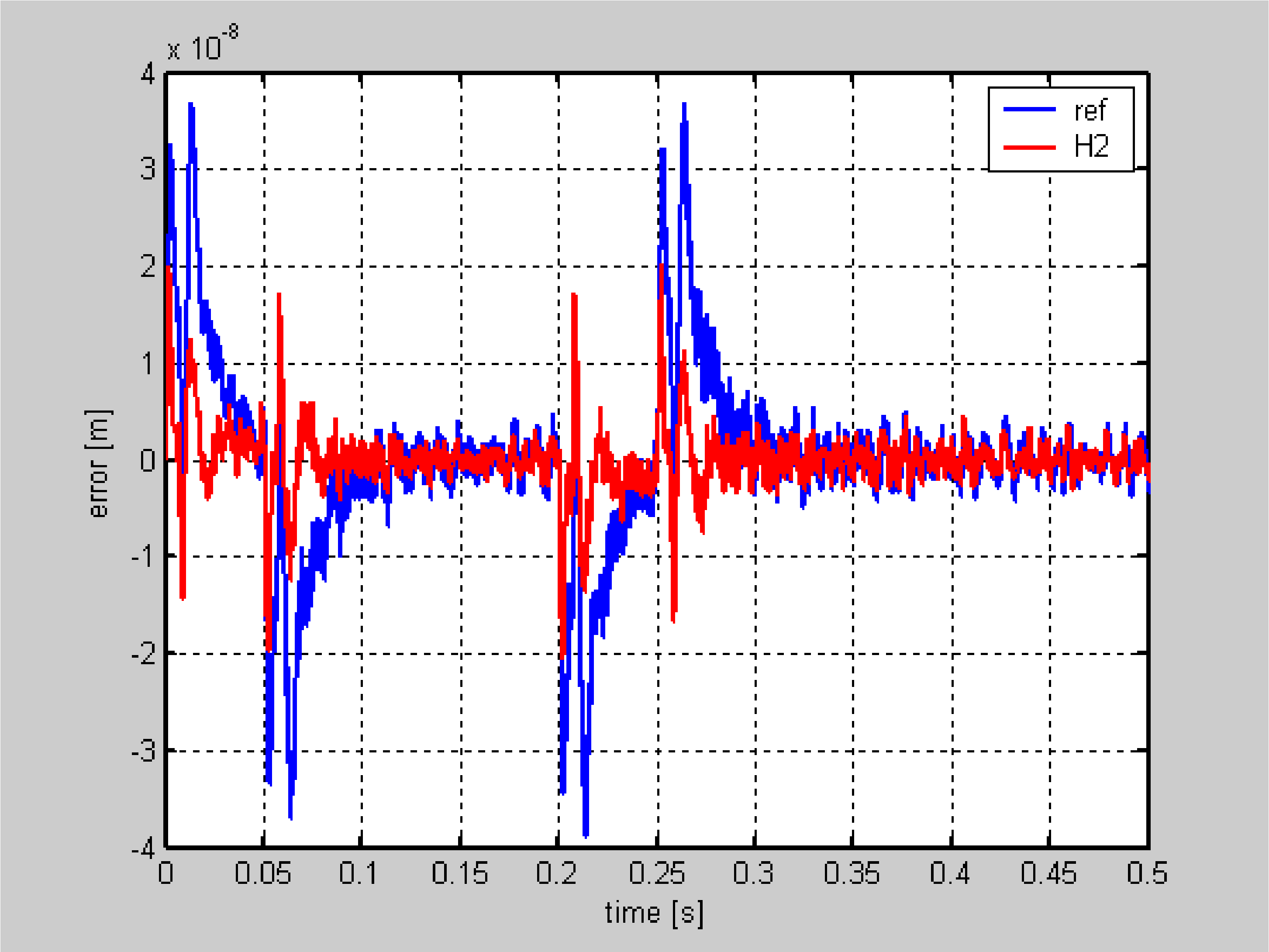




H2 optimal controller



Time domain simulation



Servo control research @ CFT
– Challenges

Challenges:

- Fixed-order/structure H_∞-controller design
  - Studied as part of a PhD project at Delft Univ. Tech.
  - The aim is to design H_∞-controllers with *a priori* specified
    - order (number of states),
    - controller configuration (such as multi-loop SISO controllers),
    - controller stability requirements (besides closed-loop stability requirements).

Challenges:

- Feasible MIMO FRF identification tools for relevant scale of problems
  - Studied as part of a PhD project at Delft Univ. Tech.
  - The aim is to obtain reliable 6x6 MIMO plant models from FRF data
    - Grasping common dynamics among DoF's
    - Accurate result over 2-3 decades of frequency range
    - Especially for off-diagonal elements (interactions)

Challenges:

- Position-dependent control design
  - Put more a priori physical knowledge and structure about nature of plant variations into LPV problem
  - Avoid conservatism (e.g. due to allowing infinitely fast variations)
    - Changing resonance dynamics as a function of position …
    - … which is a function of time.
    - Speed of variations depends on actual velocity, which is bounded!

Challenges:

- Position-dependent control design:
  - both LPV modeling and LPV controller synthesis are still too immature to be beneficial in our scale of problems.
  - LMI solvers for our scale of problems needs numerical improvement to produce feasible outcome
  - At the Delft Univ. Tech., these issues are currently under investigation and closely monitored by Philips CFT.

Challenges :

- 0-settling control
  - ILC: continue solving practical implementation challenges
    - Absorb certain types of trajectory changes (slightly different motion task) without repetition of learning process
    - Varying plant dynamics along operational range
    - Varying mix deterministic / stochastic content during motion along trajectory

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Challenges:

- Various:
  - Continue working on translation from abstract theory to specific classes of applications
  - Creative / non-conventional data usage
    - exploit increasing embedded software opportunities
    - Use information about events, external sensors, peripheral information,…

Challenges:

- Education:
  - Prepare engineers to travel the bridge between control theory and industrial practice (both ways!).
    - Keep the product and real process of interest in mind
    - Understand the relation: product performance <-> control metrics
    - Develop cost/economics awareness (a low H_inf norm will not convince without a clear monetary benefit at some point…)
    - Train project organisation & way-of-working (a kind of control loop)

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Challenges:

- Connecting control topics:
  - As we experienced, all four topics have interference and interaction with each other.
  - Need for more integral view and approach
  - Ultimate goal:
    - **MIMO position-dependent disturbance based 0-settling control**
    - **and much more!**

Closing remarks

Closing remarks

- CFT is a mechatronics center within Philips with high level of servo competence
- The relation with TU Delft has helped to develop this over the last 2 decades
- Servo competence spreads among our customers and applications
- Translation between theory (control problem formulation) and practice (product performance metrics) is essential
- Strong academic groups provide a solid basis to sustain our competitive edge: **so good luck DCSC: we will keep in touch!**

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