A Control Perspective on Cyber-Physical Systems

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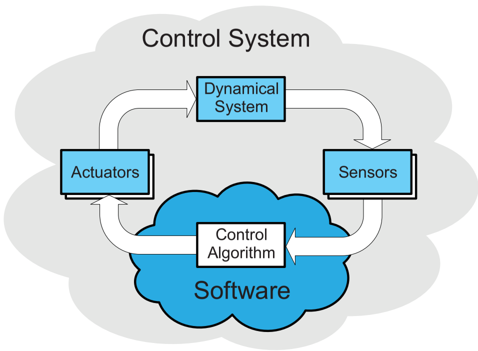
Where innovation starts

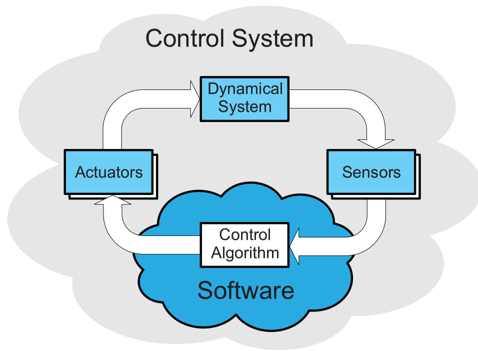
Outline

- Control systems: Privileged technology?
- When do control systems become cyber-physical systems?
- Opportunities for control in cyber-physical systems
  - Networked (wireless) control systems
  - Smart mobility
  - Resource-aware control
- Outlook

Control of Dynamical Systems



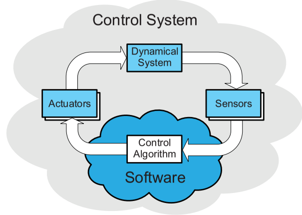
Control of Dynamical Systems

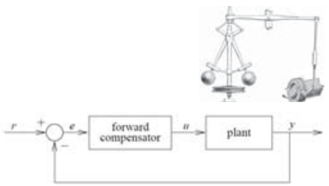


- Common simplifying assumption in standard control textbooks:
  - Data can be processed without any restrictions

Control systems

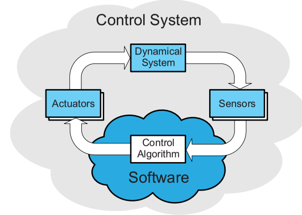
Privileged Technology??

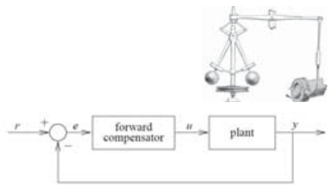


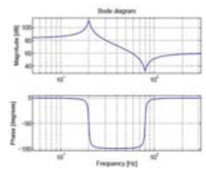


Control systems

Privileged Technology??







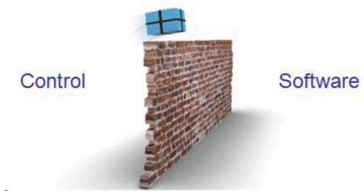
- Same formalism for
  - Plant / dynamical system
  - Control system

$$\begin{aligned} \dot{x}_p &= Ax_p + Bu \\ y &= Cx_p + Du_p \end{aligned}$$

$$\begin{aligned} \dot{x}_c &= Kx_c + L(y - r) \\ u &= Mx_c + Nu_p \end{aligned}$$

Control of Dynamical Systems

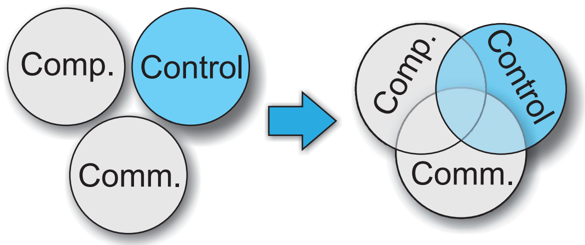
Mono-disciplinary view ...



Control of Dynamical Systems

- Validity of this assumption is lost when
  - Systems are large
  - Systems are fast/accurate
  - Communication platform is unreliable

Cyber-physical systems



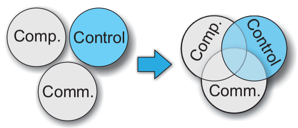
- Separation of concerns no longer works
- Cyber-physical systems: combining the physical world and the cyber world (control, computation and communication)

Cyber-physical systems

- Growth of CPS: physical, biological and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core.

- Need for fundamental understanding of interaction control, computation, communication (cyber) and physical behavior

Opportunities

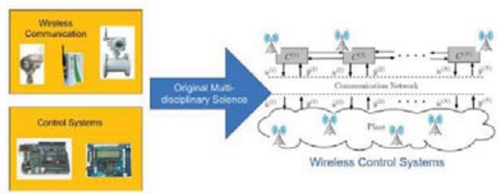


- Making computation / communication (cyber) infrastructure “perfect”
  - Impossible
  - Extremely costly from financial or design point of view
- Analyze effects of “imperfect” cyber structure on physical (control) performance, and deal with it on the cyber-physical level

Examples:

- Networked (wireless) control systems & Smart mobility
- Resource-aware control

Wireless control

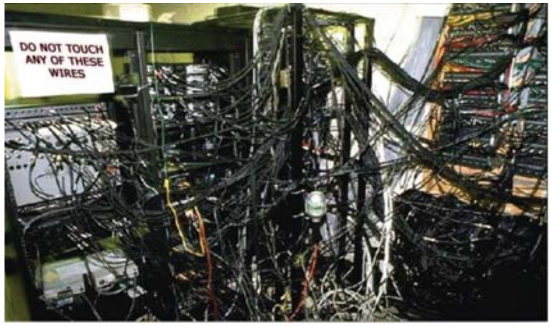


Appealing advantages of WCSs

- Ease of installation and maintenance
- Large flexibility
- Deployment in harsh environments
- Lower costs
- Less wires = less wear, less weight, less disturbances

“Current control solution”

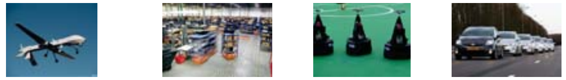
- Sensors, controllers, actuators connected through dedicated point-to-point connections



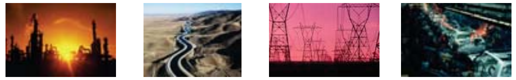
Application potential WCS

- High-tech and Automotive Systems

- Autonomous Vehicles

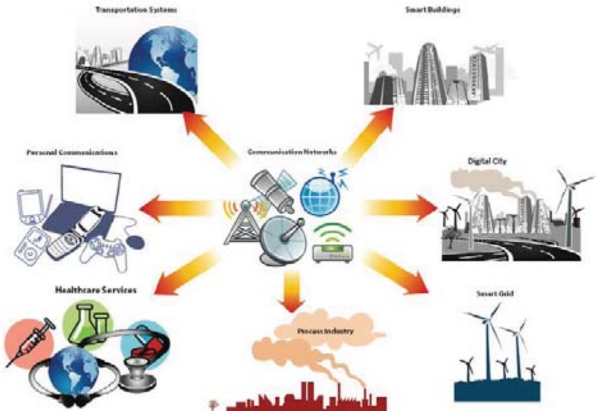


- Large-scale Systems



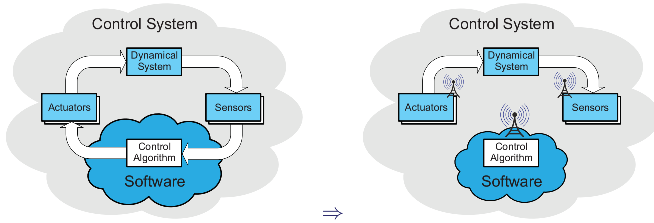
Application potential WCS

Large-scale networked control systems applications



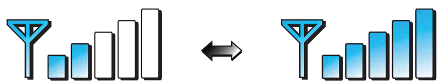
Networked Control Systems

- Communication through a shared (wireless) network



Networked Control Systems

- Communication through a shared (wireless) network
  - Dropouts: data can get lost
  - Delays: data takes some time to arrive
  - Sampling variations (jitter): data consists of discrete measurements
  - Scheduling: not all data arrives simultaneously



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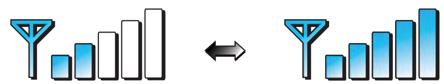
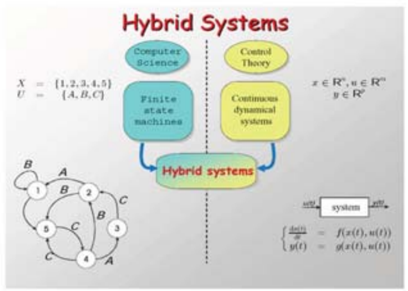


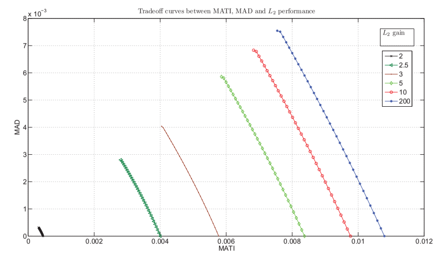
How to analyse and design Networked Control Systems?

Hybrid systems



- Understanding CPS and NCS requires hybrid models:
  - discrete models such as finite state machines/automata for describing e.g. scheduling protocol and packet loss behaviour
  - continuous models such as differential equations for describing e.g. physics of plants and continuous control algorithms

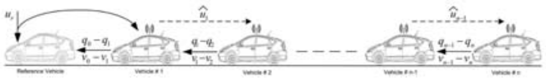
Multidisciplinary tradeoffs



- Analyze effects of “imperfect” cyber structure on physical (control) performance, and deal with it on the cyber-physical level
- Quality-of-Service (Maximum Allowable Delay/Transmission Interval) vs. Quality-of-Control
- Multi-disciplinary tradeoffs

Smart mobility

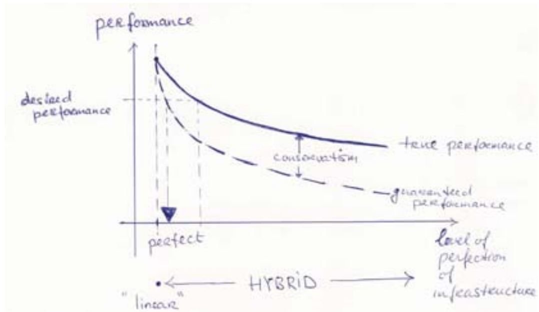
→



- "Integrated design approach for safety-critical real-time automotive systems"
- Project in rCPS program with NXP, TNO-Automotive, TU/e and UT.

Grand Challenge

- Abandoning linear control domain and moving to hybrid domain:
  - (More) difficult to assess stability & performance
  - Conservative



Grand Challenge

20/25

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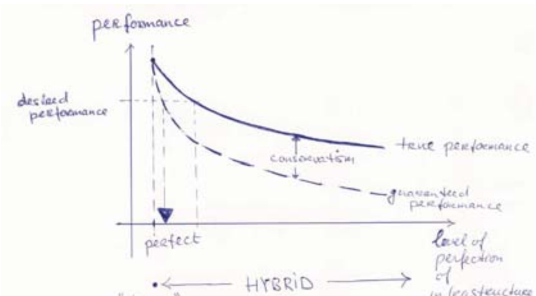


How to unite accurate linear control design methods and hybrid (CPS) tools ?

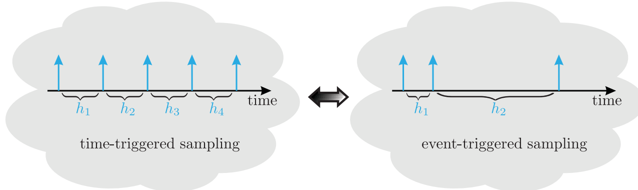
Resource-aware control

- Next generation wafer scanners:
  - More control loops
  - Higher sampling rates
- E.g. Non-rigid body motion control of the wafer stage
- Several crucial control applications will operate at significantly higher sampling rates than others
- Current design practice: Single rate

Resource-aware control

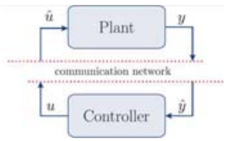
- Next generation wafer scanners:
  - More control loops
  - Higher sampling rates
- E.g. Non-rigid body motion control of the wafer stage
- Several crucial control applications will operate at significantly higher sampling rates than others
- Current design practice: Single rate (linear time-invariant systems)
- Multi-rate high-performance control (linear time-varying systems)
- Project in rCPS program with ASML, TNO-ESI, TU/e

Event- and self-triggered control



- Time-varying sampling times
- State/output based sampling
  - Minimum attention control
  - Event-triggered control
  - Self-triggered control

Example



$$\begin{cases} \dot{x}_p = \begin{bmatrix} 0 & 1 \\ -2 & -3 \end{bmatrix} x_p + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \hat{u} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} w \\ y = \begin{bmatrix} 1 & 0 \end{bmatrix} x_p \end{cases} \qquad \begin{cases} \dot{x}_c = \begin{bmatrix} -2 & 1 \\ -13 & -3 \end{bmatrix} x_c + \begin{bmatrix} -2 \\ -5 \end{bmatrix} \hat{y} \\ u = \begin{bmatrix} 5 & 2 \end{bmatrix} x_c \end{cases}$$

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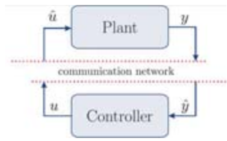

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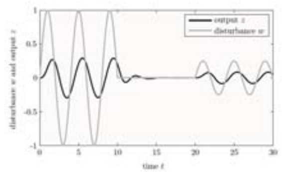

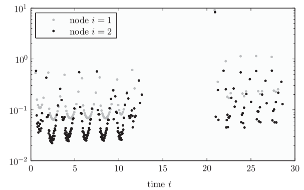

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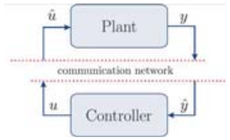

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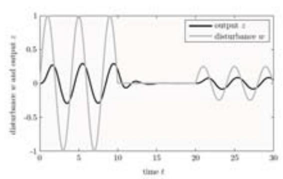
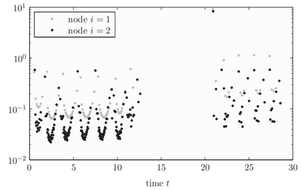
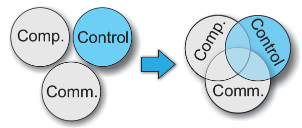




- Act when needed!
- Control loop becomes hybrid system - Grand Challenge!

Conclusions



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- Making computation / communication (cyber) infrastructure “perfect”
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- Analyze effects of “imperfect” cyber structure on physical (control) performance, and deal with it on the cyber-physical level

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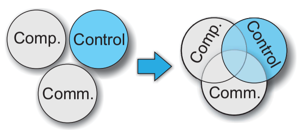

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- Making computation / communication (cyber) infrastructure “perfect”
  - Impossible / extremely costly
- Analyze effects of “imperfect” cyber structure on physical (control) performance, and deal with it on the cyber-physical level
- rCPS program good vehicle to
  - address the "Challenges and Opportunities”
  - build CPS eco-system to sustain future developments