Eindhoven Line-Up and WIDE-Related Activities

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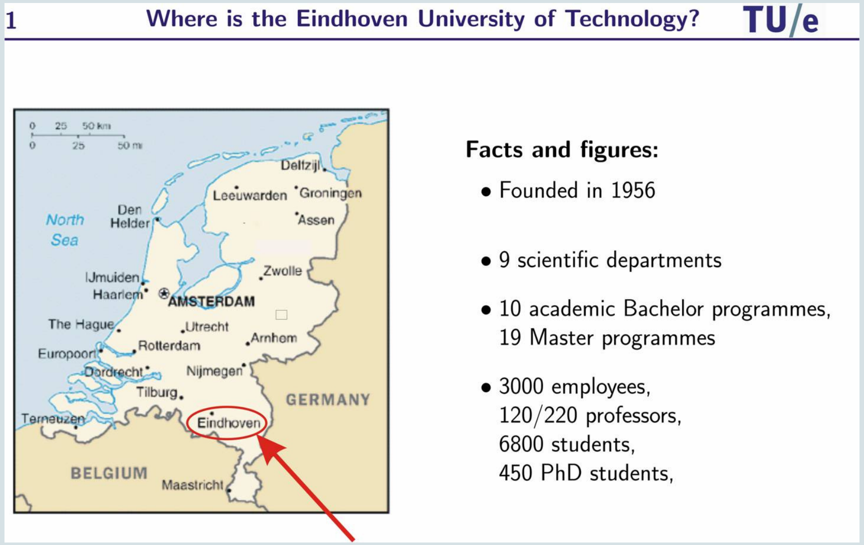
WIDE kick-off meeting

Outline

- Overview of our group
- Past and current research activities related to WIDE
    - Networked Control Systems
    - Model predictive control
- Conclusions towards WIDE



1 **Where is the Eindhoven University of Technology?** TU/e

Facts and figures:

- Founded in 1956
- 9 scientific departments
- 10 academic Bachelor programmes, 19 Master programmes
- 3000 employees, 120/220 professors, 6800 students, 450 PhD students,

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Department of Mechanical Engineering

Dynamics and Control Technology (DCT) group (www.dct.tue.nl)

- Control Systems Technology (CST chaired by Prof. Maarten Steinbuch)
- Dynamics & Control (D& C chaired by Prof. Henk Nijmeijer)

Some facts and figures:

- Staff:
    - 2 full profs, 5 associate profs, 8 assistant profs
    - 6 postdocs, 34 PhD students
- 200 students in the Master Program, 80 MSC/year
- Both groups 100% scores in recent international research evaluations

People involved in WIDE

Staff:

- Nathan van de Wouw (D& C group, associate prof)
- Maurice Heemels (CST group, associate prof)

PhD students:

- Nick Bauer (University of California at Santa Barbara) - full time
- Tijs Donkers (TU/e) - part time (toolbox/communication constraints)

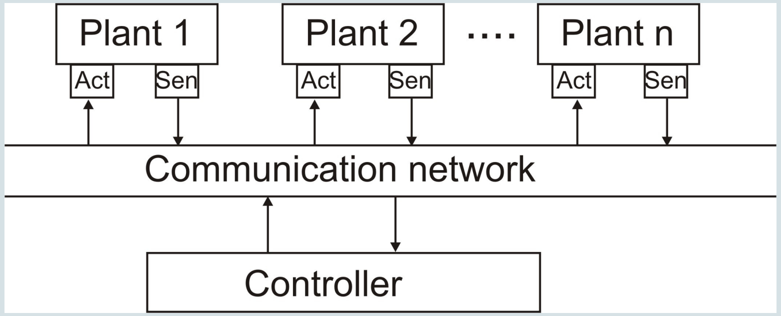
Prof. Maarten Steinbuch (CST) will be their supervisor (‘Dutch system’).

Relevant background to WIDE

- Networked control systems: stability analysis and controller synthesis
  - Communication delays, varying sampling intervals, packet loss
  - Communication constraints
- Model predictive control
  - Hybrid & Nonlinear Systems: stability and robustness
  - Low complexity & suboptimality

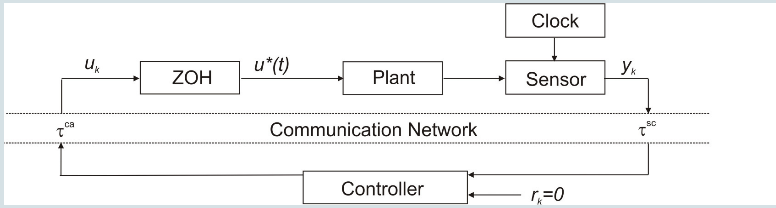
Networked Control Systems

Networked Control Systems



- Network effects
  - Varying delays, varying sampling times
  - Information loss
  - Communication constraints
- Influence of these (uncertain) effects on stability and performance

Networked control systems



Assumptions:

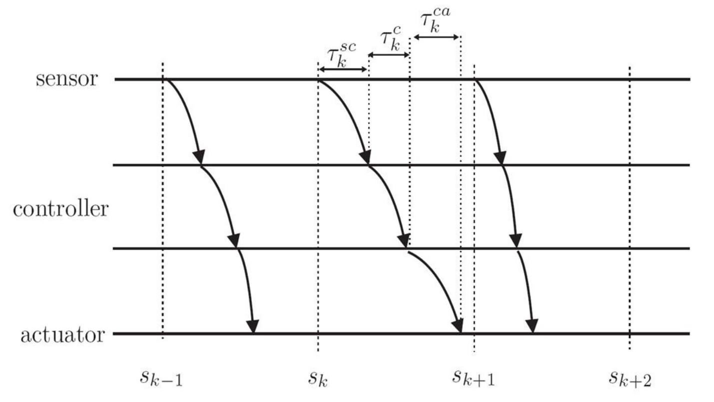
- Time-driven sensor ($s_k = kh$, $k \in \mathbb{N}$)
- Event-driven controller
- Event-driven actuator

Time-delays:

- Network induced delays:
  - Sensor-to-controller $\tau_{sc,k}$
  - Controller-to-actuator $\tau_{ca,k}$
- Computational delay $\tau_{c,k}$

$$\tau_k = \tau_{sc,k} + \tau_{ca,k} + \tau_{c,k}$$

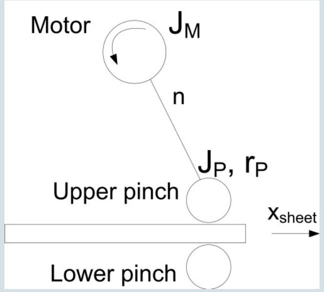
Networked control Systems



Motivating example [Cloosterman et al, CDC'06]

Example to motivate the importance of investigating the influence of time-varying delays on stability

$$\dot{x}(t) = Ax(t) + Bu^*(t)$$
$$u^*(t) = u_k, \text{ for } t \in [s_k+\tau_k, s_{k+1}+\tau_{k+1})$$



$$A = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad B = \begin{pmatrix} 0 \\ \frac{nr_P}{J_M+n^2J_P} \end{pmatrix}$$

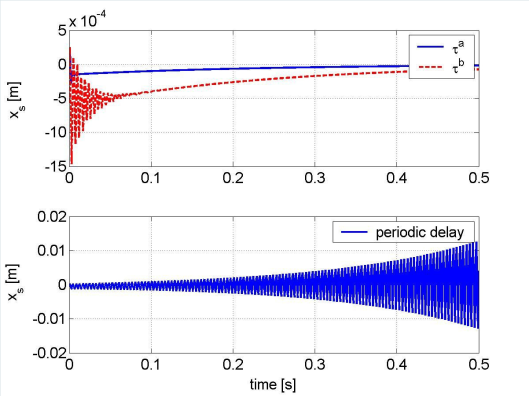
$$x(t) = \begin{pmatrix} x_s(t) \\ \dot{x}_s(t) \end{pmatrix}$$

$$u_k = Kx_k$$

Motivating example

$h = 1\text{ms}$
$\tau^a = 0.2\text{ms}$
$\tau^b = 0.6\text{ms}$
$K = \begin{pmatrix} K_1 & K_2 \end{pmatrix}$
$= \begin{pmatrix} 50 & 11.8 \end{pmatrix}$

Switching sequence:
$\tau^a, \tau^b, \tau^a, \tau^b, \ldots$



- Also possible for varying sampling intervals h_k showing similar effects

Network effects on stability, robustness and performance

⋆ LMI-based (efficient!) methods for

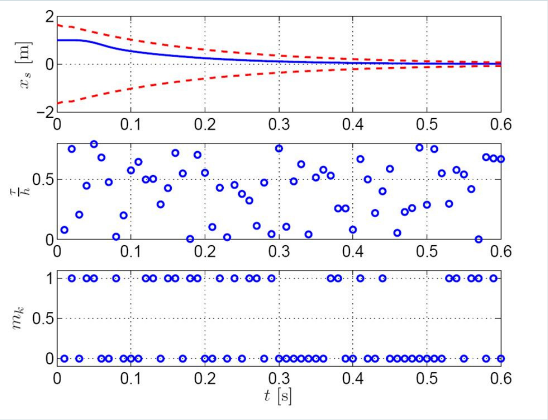
- Analysis for stability and performance of these NCS (linear systems)
- Feedback control synthesis methods guaranteeing stability
    - guarantees on decay rates
    - different type of control structures (not MPC at this moment)

⋆ Results incorporate:

- Time-varying delays $\tau_k \in [\tau_{min}, \tau_{max}]$ (possibly $>$ sampling time!)
- Time-varying sample times $h_k \in [h_{min}, h_{max}]$
- Possible packet loss given a maximal number of sequent drops

`[Cloosterman et al: CDC 06, CDC 07, ACC 08, Trans. Aut. Control ]`

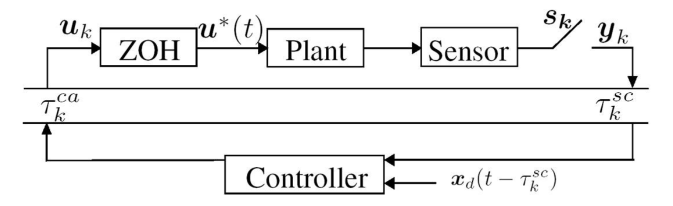
Simulation with packet loss: synthesis augm. state feedback



$$h = 0.01s,\ \gamma = 0.1, \tau_{min} = 0, \tau_{max} = 0.8h \text{ and } \bar{\delta} = 2$$

Tracking control for NCS

- Nathan van de Wouw, Marieke Cloosterman (TU/e)
- Payam Naghshtabrizi, Joao Hespanha (Univ. California Santa Barbara)



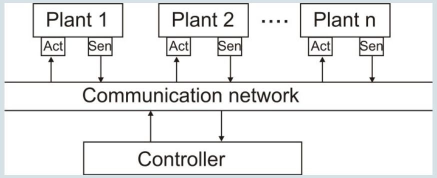
$$u_k = u_{ff}(s_k) - K(x_k - x^d(s_k))$$

Time-stamping of messages needed!

`[van de Wouw et al, CDC 07]`

Communication constraints & protocols

- Previous results based on single loop perspective
- No protocol or scheduling of communication



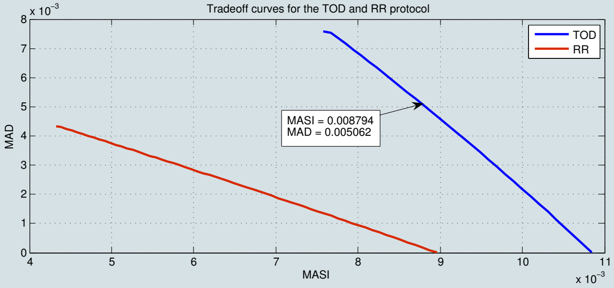
- Every sampling time one actuator/sensor (possibly grouped in nodes) gets access to network, e.g. RR, TOD, ...
- Protocol determines which node gets access
- Sampling interval might vary over time: $T \in [0, MASI]$
- Delays in communication $\tau \in [0, MAD]$

Can we guarantee stability or performance?

Communication constraints & protocols

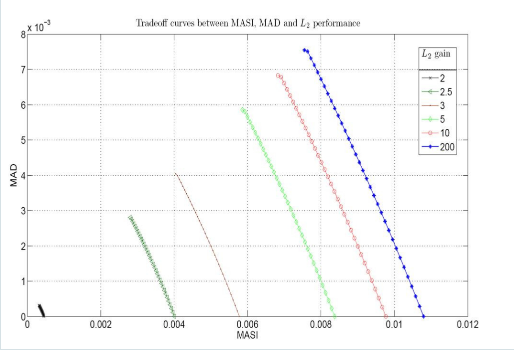
- Given controller, plant, protocol: we can analyze stability and performance
- Joint work with Andy Teel (UCSB) & Dragan Nesic (Univ. of Melbourne)

Stability & different protocols: tradeoff curves



Communication constraints & protocols

Tradeoff curves between performance, delay, sampling interval for TOD protocol



Summary NCS

- Analysis and Control Synthesis methods (LMIs) for single loop NCS
  - Varying delays & sampling intervals
  - Possible packet loss
  - Both stabilization and tracking problems
  - Diverse methods (toolbox)
- Analysis methods for NCS with communication constraints
  - Various protocols
  - varying delays and sampling intervals
  - Recent developments (Tijs Donkers)

Model Predictive Control

MPC for hybrid / NL systems

Model of plant

$$x_{k+1} = g(x_k, u_k)$$

MPC problem set-up: Based on $x_{0|k} = x_k$

$$J(x_k, \mathbf{u}_k) \triangleq F(x_{N|k}) + \sum_{i=0}^{N-1} L(x_{i|k}, u_{i|k}),$$

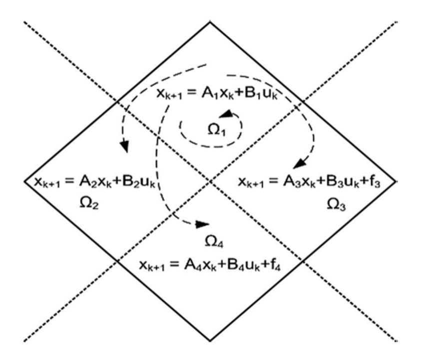
over all input sequences $\mathbf{u}_k \triangleq (u_{0|k}, \ldots, u_{N-1|k})$ subject to the constraints:

$$\begin{aligned} x_{i+1|k} &\triangleq g(x_{i|k}, u_{i|k}), \quad i = 0, \ldots, N-1,\\ x_{i|k} &\in \mathbb{X}, \quad \text{for all} \quad i = 1, \ldots, N,\\ u_{i|k} &\in \mathbb{U}, \quad \text{for all} \quad i = 0, \ldots, N-1. \end{aligned}$$

Receding horizon principle: $u_k = u^*_{0|k}$

Piecewise affine systems

$$x_{k+1} = A_i x_k + B_i u_k + f_i \text{ when } x_k \in \Omega_i$$



Strong relationships to MLD models (Bemporad/Morari) `[Heemels et al, Automatica, 2001]`

Stability and Robustness

$$J(x_k, \mathbf{u}_k) \triangleq F(x_{N|k}) + \sum_{i=0}^{N-1} L(x_{i|k}, u_{i|k}),$$

over all input sequences $\mathbf{u}_k \triangleq (u_{0|k}, \ldots, u_{N-1|k})$ subject to the constraints:

$$\begin{aligned} x_{i+1|k} &\triangleq g(x_{i|k}, u_{i|k}), \quad i = 0, \ldots, N-1,\\ x_{i|k} &\in \mathbb{X}, \quad \text{for all} \quad i = 1, \ldots, N,\\ u_{i|k} &\in \mathbb{U}, \quad \text{for all} \quad i = 0, \ldots, N-1. \end{aligned}$$

How to guarantee stability and robustness (ISS) of the closed-loop system?

$$x_{k+1} = g(x_k, u_k, w_k)$$

Joint work with Mircea Lazar & others ...

Results

Three methods for stability and robustness

- Terminal cost and constraint method: adding constraint $x_{N|k} \in X_T$
- Tightening of constraints (i.e. changing $x_{i|k} \in X_i$)
- Adding (rob.) stabilization cond. using artificial Lyapunov functions

Results

Three methods for stability and robustness

- Terminal cost and constraint method: adding constraint $x_{N|k} \in X_T$
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For instance,

- Stability PWA affine systems: terminal cost and constraint method `[Lazar et al, TAC, 2006]`, `[Alessio et al, Automatica, 2007]`
  Computation of F and polyhedral (!) X_T guaranteeing stability
- Stability and robustness for general nonlinear systems using a tightening approach: `[Lazar, Heemels, Automatica, 2008]`
- Adding stabilization constraint (allowing optimization of robustness!) for MPC of NL systems `[Lazar et al, IJRNC, 2008]`
- Robust stability using min-max MPC approach `[Lazar et al, SCL, 2008]`

$\longrightarrow$ low complexity MPC + effect of sub-optimality on performance!

Conclusions

- Two of our main research lines are coupled to WIDE's objectives:
  - Networked control systems
    - delays, varying sampling intervals, message loss, ...
    - communication constraints and protocols
  - Model predictive control
- Blending and extending them is "more or less" goal of WIDE ...
  ... keeping an eye on
  - Efficient implementation: decentralized methods (recently starting on this ... NMPC 08)
  - Interaction with wireless technology (match between theoretical results and actual behavior of WSN)