Model Predictive Control in Industrial Applications

Manfred Morari
Automatic Control Laboratory, ETH Zürich
www.control.ethz.ch

Outline

- Overview
- Hydroelectric Power Plant Cascade
- Automotive Applications
  - Adaptive Cruise Control
  - Traction Control
  - Electronic Throttle Control
- Electric Energy Applications
  - Control of Switch-mode dc-dc Converters
  - Direct Torque Control of Induction Motors
  - Emergency Voltage Regulation in Power Systems
- Vibration Control

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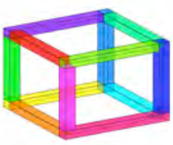
Multi Parametric Toolbox

- All results were obtained with the MPT toolbox



http://control.ethz.ch/~mpt

- MPT is a MATLAB toolbox that provides efficient code for
  - (Non)-Convex Polytopic Manipulation
  - Multi-Parametric Programming
  - Control of PWA and LTI systems

Contributors

Michal Kvasnica, Mato Baotić, Pascal Grieder

Miroslav Barić	Frank J. Christophersen	Marco Lüthi
Alberto Bemporad	Eric Kerrigan	Saša V. Raković
Pratik Biswas	Adam Lagerberg	Raphael Suard
Francesco Borrelli	Arne Linder	Kari Unneland

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Alex Kurzhanski	(Ellipsoidal Toolbox)	Gianni Ferrari-T.	(HIT)

MPT in the World

9000+ downloads in 5 years

List of Application Projects at IfA

- Control of Cogeneration Power Plant
- **Power Plant Cascade**
- Scheduling of Cement Kilns and Mills
- Supermarket Refrigeration System
- **Traction Control**
- **Adaptive Cruise Control**
- **Electronic Throttle Control**
- Control of Anaesthesia
- Control of Thermal Printheads
- **Control of dcdc Converters**
- **Direct Torque Control**
- **Emergency Voltage Control in Power Systems**
- Brake Squeal Reduction
- **Vibration Control**

River Power Plants

Physical Setup:

- Turbines and weirs (adjustable water flow)
- Cascade of hydroelectric power plants
- Storage capacity of channel

Control Objectives:

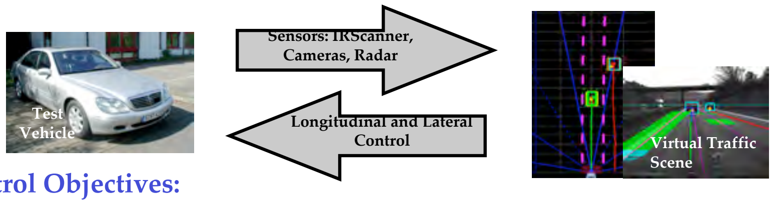
- Keep concession level close to reference
- Respect constraints on concession level
- Minimize flow changes at weirs and turbines

Optimal coordination between plants leads to
1.) Major damping of upstream water flow disturbances;
2.) Strict respect of concessions level constraints

Adaptive Cruise Control

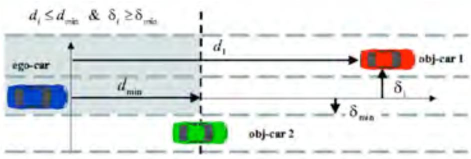
DAIMLERCHRYSLER

Physical Setup:



Control Objectives:

- Track reference speed
- Respect traffic rules
- Consider all objects on all lanes



Optimal state-feedback control law successfully implemented and tested on a research car Mercedes E430 with 80ms sampling time

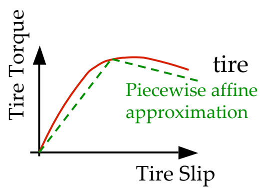
Traction Control

Physical Setup:

- Improve driver's ability to control vehicle under adverse external conditions (wet or icy roads)
- Tire torque is nonlinear function of slip
- Uncertainties and constraints

Control Objectives:

- Maximize tire torque by keeping slip close to the desired value

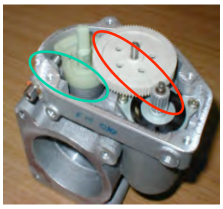


Experimental results: 2000 Ford Focus on a Polished Ice Surface; Receding Horizon controller with 20 ms sampling time

Electronic Throttle Control

Physical Setup:

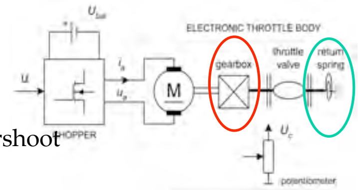
- Valve (driven by DC motor) regulates



to the car engine
- Friction nonlinearity
- Limp-Home nonlinearity
- Physical constraints

Control Objectives:

- Minimize steady-state regulation error
- Achieve fast transient behavior without overshoot

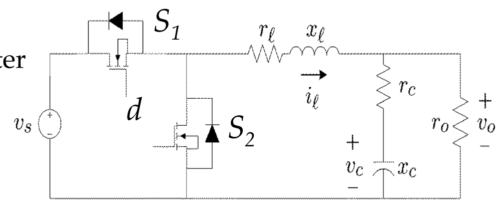


Systematic controller synthesis procedure. On average twice as fast transient behavior compared to state-of-the-art PID controller with ad-hoc precompensation of nonlinearities.

Control of Switch-mode dc-dc Converters

Physical Setup:

- Synchronous dc-dc buck converter feeding ohmic load
- Switched circuit topology



Control Objectives:

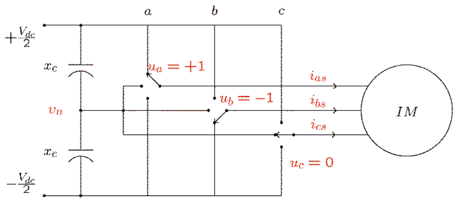
- Steer load voltage to desired reference value
- Maintain regulation in face of voltage source/load variations

Explicit feedback controller allows for implementation on physical circuit

Direct Torque Control

Physical Setup:

- Three-level DC link inverter driving a three-phase symmetric induction motor
- Binary control inputs



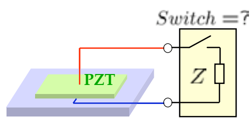
Control Objectives:

- Keep torque, stator flux and neutral point potential within given bounds
- Minimize average switching frequency (losses)

Reduction of switching frequency by up to 45 % (in average 25 %) with respect to ABB's commercial DTC scheme (ACS 6000)

Vibration Control Through Smart Damping Materials

- **Demands**
  - Device *suppresses vibration*
  - *External power* source for operation is not required
  - *Weight* and *size* of the device have to be kept to a minimum
- **Idea**
  - *Switched Piezoelectric (PZT) Patches*



- **Problem**
  - *What is the optimal switching law for optimal vibration suppression?*

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Application of Model Predictive Control to a Cascade of River Power Plants

MANFRED MORARI

ADRIENNE HEINRICH, CORNELIA SETZ, P. ROSTALSKI, G. PAPAFOTIOU

Automatic Control Laboratory, ETH Zürich

WWW.CONTROL.ETHZ.CH

SCIETEC kompetenzzentrum für flussmanagement

Automatic Control Laboratory

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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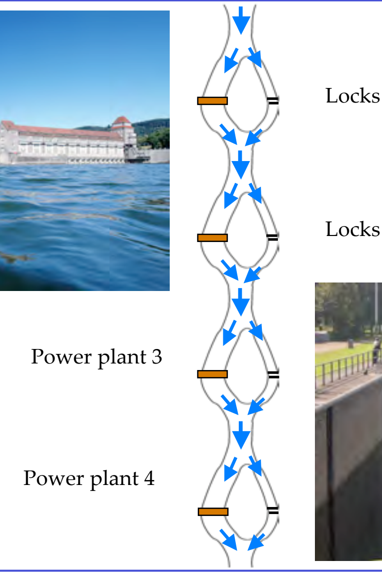
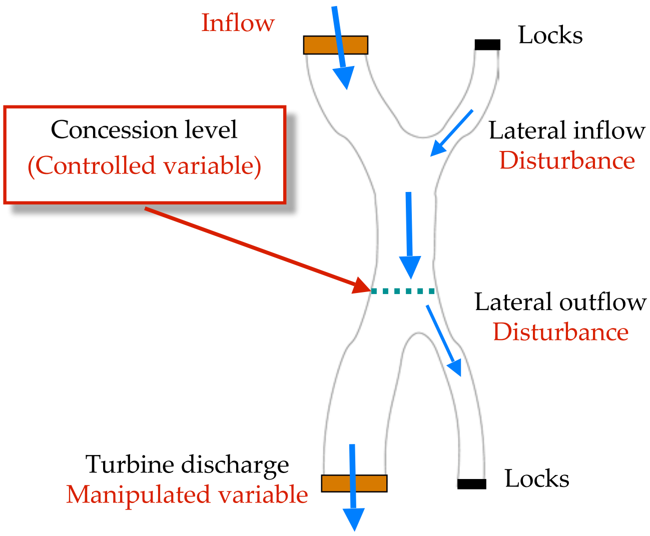
Physical System
Power Plant Cascade in Main

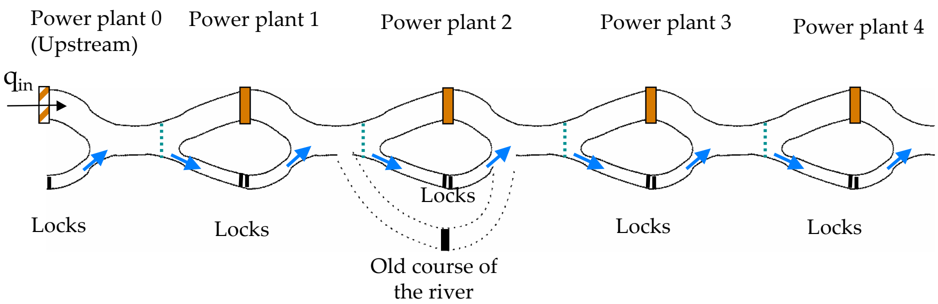


Physical System
Single River Segment



Physical System
Complete Cascade

Inflow



q_{in}	Upstream turbine discharge	Inflow
	Turbine discharges	Manipulated variabels
	Concession levels	Controlled variabels
	Lateral in- and outflows	Disturbances

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Power Plant Cascade
Control Problem

Manipulate turbine discharges to:

Minimize:

- Deviations of concession levels from operating point
- Turbine discharge variations
- Average number of control moves

Respect:

- Constraints on concession levels
- Constraints on turbine discharges

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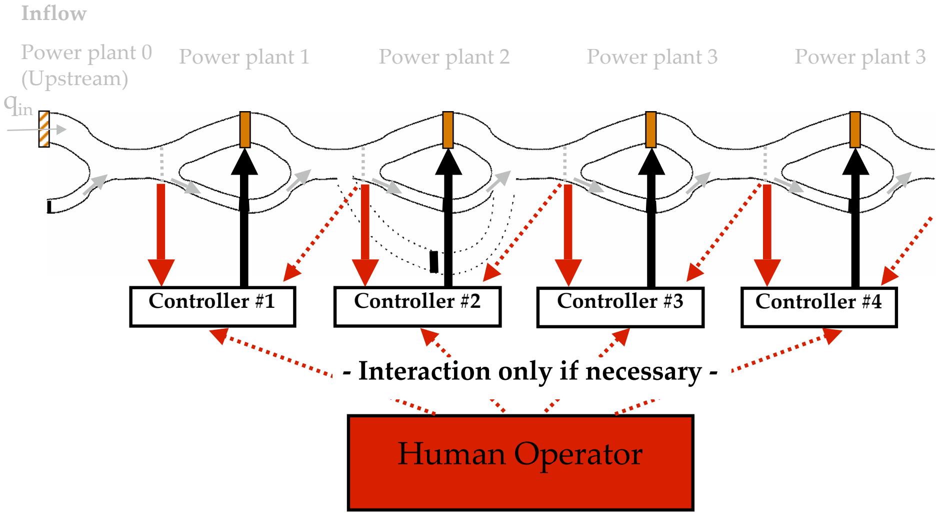
Current Approach:
Local Controllers + Human Operator



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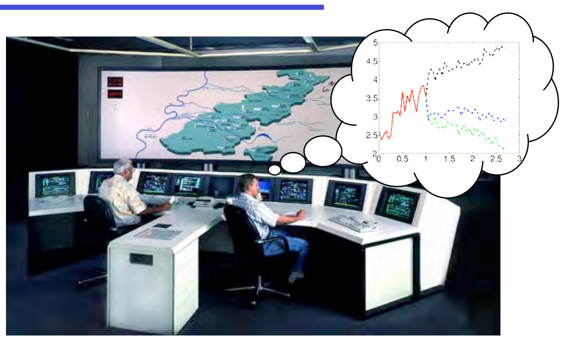
Current Approach:
Local Controllers + Human Operator

Steps:

1. Inspect measurements
2. Predict behaviour (based on experience)
3. Interact, if needed (apply "good" inputs)
4. Inspect consequences (start with 1.)



Disadvantages:

- Decisions depend on experience of operator
- "Qualitative" predictions
- Emergency-handling (overriding "local control")

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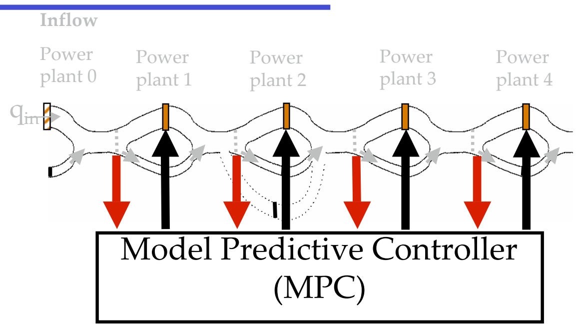
Our Approach:
Model Predictive Control

Steps:

1. Take measurements
2. Predict behaviour
   (based on river model)
3. Apply "optimal" inputs
4. Inspect consequences
   (return to 1.)



Requires:

- Quantitative measure of "good" performance
- Prediction model for the river
- Optimization procedure

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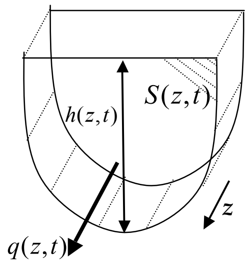
Modeling
Physical Model of River Hydraulics

- **Assumption**
  – 1-dimensional water flow

- **Model Type**
  – based on Saint Venant equations

$$\frac{\partial q}{\partial z}+\frac{\partial S}{\partial t}=0$$

$$\frac{1}{g}\frac{\partial}{\partial t}\left(\frac{q}{S}\right)+\frac{1}{2g}\frac{\partial}{\partial z}\left(\frac{q^2}{S^2}\right)+\frac{\partial h}{\partial z}+I_f-I_0=0$$



- **Characteristics**
  – Pair of coupled non-linear PDEs

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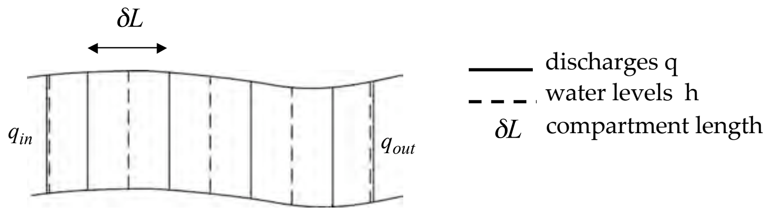
Modeling
Linear, Discrete-Time Model (1/3)

- **Linearization**
  for a given operating point

- **Discretization**
  in time and space



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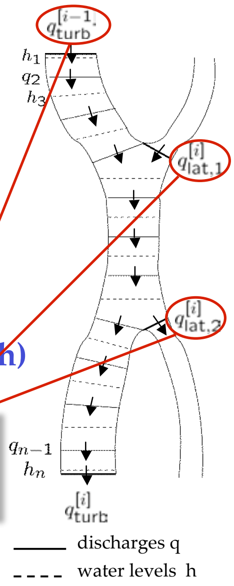
Modeling
Linear, Discrete-Time Model (2/3)

- **State vector (single reach)**

$$x^{[i]}(k) = \begin{pmatrix} h_1(k) \\ q_2(k) \\ h_3(k) \\ \vdots \\ q_{n-1}(k) \\ h_n(k) \\ q_{\text{turb}}^{[i]}(k-1) \end{pmatrix} \qquad \text{for} \quad i = 1, \dots, 4$$

- **Affine state space description (single reach)**

$$x^{[i]}(k+1) = \mathbf{A}^{[i]} x^{[i]}(k) + \mathbf{B}^{[i]} \Delta q_{\text{turb}}^{[i]}(k) + f^{[i]}(k)$$
$$y^{[i]}(k) = \mathbf{C}^{[i]} x^{[i]}(k)$$



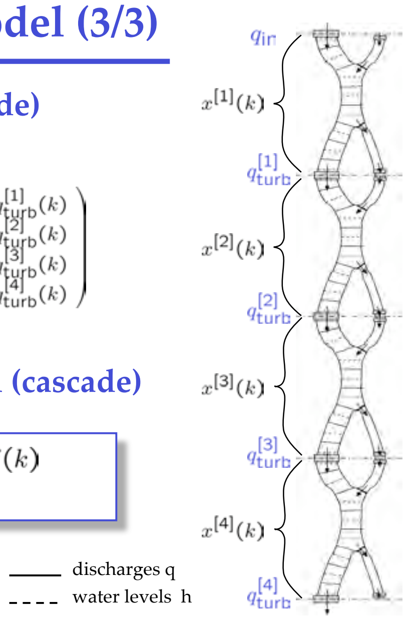
Modeling
Linear, Discrete-Time Model (3/3)

- **State and input vectors (cascade)**

$$x(k) = \begin{pmatrix} x^{[1]}(k) \\ x^{[2]}(k) \\ x^{[3]}(k) \\ x^{[4]}(k) \end{pmatrix} \qquad \Delta u(k) = \begin{pmatrix} \Delta q_{\text{turb}}^{[1]}(k) \\ \Delta q_{\text{turb}}^{[2]}(k) \\ \Delta q_{\text{turb}}^{[3]}(k) \\ \Delta q_{\text{turb}}^{[4]}(k) \end{pmatrix}$$

- **Affine state space description (cascade)**

$$x(k+1) = \mathbf{A}x(k) + \mathbf{B}\Delta u(k) + f(k)$$
$$y(k) = \mathbf{C}x(k)$$



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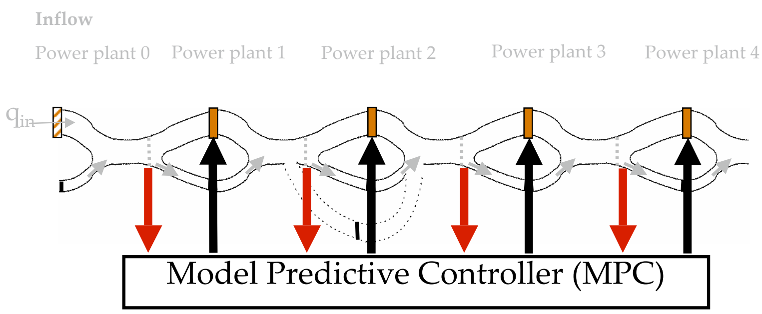
Model Predictive Control General Concept



Elements:
- Model
- Objectives (cost function)
- Constraints
- Receding horizon policy

Power Plant Cascade Control Problem

Manipulate turbine discharges to:

Minimize:

- Deviations of concession levels from operating point
- Turbine discharge variations
- Average number of control moves

Respect:

- Constraints on concession levels
- Constraints on turbine discharges

Contradictory control objectives

Cost Function

$$J_N(x(0), \Delta u, s_{\mathrm{em}}, s_{\mathrm{fo}}) = \sum_{k=0}^{N-1} x^T(k|t) Q x(k|t) + \Delta u^T(k|t) R \Delta u(k|t) + s_{\mathrm{em}}^T(k|t) Q_{s,\mathrm{em}} s_{\mathrm{em}}(k|t) + s_{\mathrm{fo}}^T(k|t) Q_{s,\mathrm{fo}} s_{\mathrm{fo}}(k|t)$$

x: State vector
Δu: Input sequence
N: Prediction horizon
s_{em}: First slack variable
s_{fo}: Second slack variable

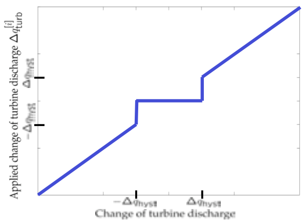
Slack weights ($Q_{s,\mathrm{em}}$, $Q_{s,\mathrm{fo}}$)

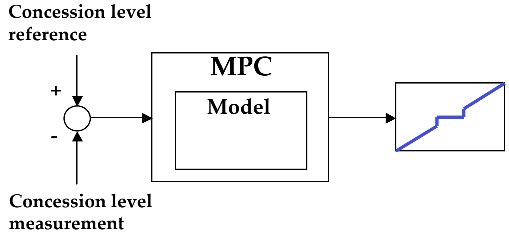
Penalty on concession level deviations $h_{\mathrm{c}}^{[i]}$ (Q)

Penalty on slew rates $\Delta q_{\mathrm{turb}}^{[i]}$ (R)

Reduce Number of Control Moves

- Current approach
  - External hysteresis
- MPC approach





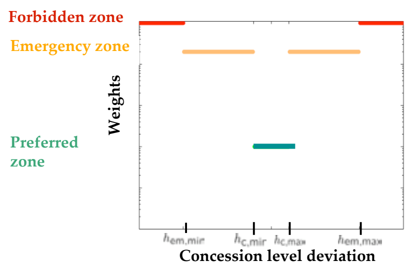
Constraints

- Hard Constraints

$$
\begin{aligned}
\Delta q_{\text{hyst}} &\leq |\Delta q_{\text{turb}}^{[i]}| \quad \text{or} \quad \Delta q_{\text{turb}}^{[i]} = 0, \quad i = 1, \ldots, 4 \\
q_{\text{turb,min}} &\leq q_{\text{turb}}^{[i]} \leq q_{\text{turb,max}} \\
\Delta u_{\text{min}} &\leq \Delta q_{\text{turb}}^{[i]} \leq \Delta u_{\text{max}}
\end{aligned}
$$

- Soft constraints

$$
\begin{aligned}
h_{\text{c,min}} - s_{\text{em}}^{[i]} &\leq h_{\text{c}}^{[i]} \leq h_{\text{c,max}} + s_{\text{em}}^{[i]} \\
h_{\text{em,min}} - s_{\text{fo}}^{[i]} &\leq h_{\text{c}}^{[i]} \leq h_{\text{em,max}} + s_{\text{fo}}^{[i]} \\
0 &\leq s_{\text{em}}^{[i]} \\
0 &\leq s_{\text{fo}}^{[i]}
\end{aligned}
$$



MLD Formulation (1/2)

- **Hybrid systems**
  - Discrete events
  - Continuous dynamics

  } Logical conditions including binary and continuous variables

- **MLD formulation**

$$
\begin{aligned}
x(k+1) &= Ax(k) + B_1\Delta u(k) + B_2 d(k) + B_3 z(k) \\
y(k) &= Cx(k) + D_1\Delta u(k) + D_2 d(k) + D_3 z(k) \\
E_2 d(k) + E_3 z(k) &\leq E_1\Delta u(k) + E_4 x(k) + E_5
\end{aligned}
$$

$d \in \{0,1\}^{b}$: auxiliary binary variable vector

$z \in \mathbb{R}^{c}$: auxiliary continuous variable vector

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MLD Formulation (2/2)

Discrete state	$d_1^{[i]}$	$d_2^{[i]}$
$\Delta q_{\mathrm{turb}}^{[i]} = 0$	0	0
$\Delta q_{\mathrm{turb}}^{[i]} \leq -\Delta q_{\mathrm{hyst}}$	0	1
$\Delta q_{\mathrm{turb}}^{[i]} \geq \Delta q_{\mathrm{hyst}}$	1	0
Unused state	1	1

$$
\left.
\begin{aligned}
\Delta q_{\mathrm{turb}}^{[i]} &\geq \Delta q_{\mathrm{hyst}} \cdot d_1^{[i]} + \Delta u_{\mathrm{min}} \cdot d_2^{[i]} \\
\Delta q_{\mathrm{turb}}^{[i]} &\leq -\Delta q_{\mathrm{hyst}} \cdot d_2^{[i]} + \Delta u_{\mathrm{max}} \cdot d_1^{[i]} \\
q_{\mathrm{turb,min}} &\leq q_{\mathrm{turb}}^{[i]} \\
q_{\mathrm{turb,max}} &\geq q_{\mathrm{turb}}^{[i]} \\
h_{\mathrm{c}}^{[i]} &\geq h_{\mathrm{c,min}} - s_{\mathrm{em}}^{[i]} - s_{\mathrm{fo}}^{[i]} \\
h_{\mathrm{c}}^{[i]} &\leq h_{\mathrm{c,max}} + s_{\mathrm{em}}^{[i]} + s_{\mathrm{fo}}^{[i]} \\
0 &\leq s_{\mathrm{em}}^{[i]} \\
0 &\leq s_{\mathrm{fo}}^{[i]} \\
d_1^{[i]} + d_2^{[i]} &\leq 1
\end{aligned}
\right\}
\quad E_2 d(k) + E_3 z(k) \leq E_1\Delta u(k) + E_4 x(k) + E_5
$$

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Optimal Control Problem

$$J_N^*(x(0)) = \min_{\substack{\Delta u \\ s_{\text{em}} \\ s_{\text{fo}}}} \sum_{k=0}^{N-1} x^T(k|t)Qx(k|t) + \Delta u^T(k|t)\mathcal{R}\Delta u(k|t)$$

$$+ s_{\text{em}}^T(k|t)Q_{s,\text{em}}s_{\text{em}}(k|t) + s_{\text{fo}}^T(k|t)Q_{s,\text{fo}}s_{\text{fo}}(k|t)$$

s. t.

$$\begin{aligned} x(k+1) &= Ax(k) + B_1\Delta u(k) + B_2 d(k) + B_3 z(k) \\ y(k) &= Cx(k) + D_1\Delta u(k) + D_2 d(k) + D_3 z(k) \\ E_2 d(k) + E_3 z(k) &\leq E_1\Delta u(k) + E_4 x(k) + E_5 \end{aligned}$$

- Mixed integer quadratic program (MIQP)
- Hard and soft constraints
- MLD formulation of the dynamics

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Computational Complexity

- **Internal hysteresis**

$|\Delta q_{\text{turb}}(k|t)| \geq \Delta$ … $q_{\text{turb}}(k|t) = 0$

for $k = 0$ …

High computational complexity due to binary states

…mplexity by

i. …pplying hysteresis to fewer control moves during prediction horizon
ii. Permitting less control moves during prediction horizon

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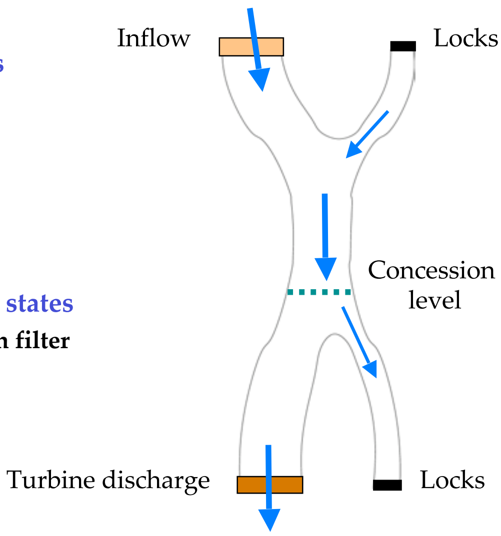
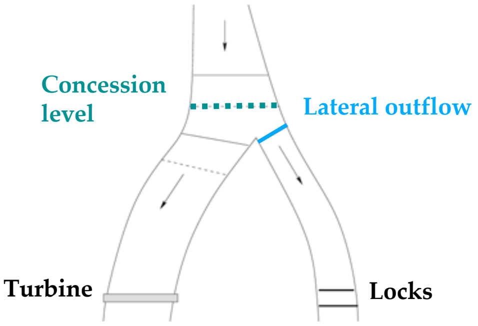
State Estimation

- **Available measurements**
  - Inflow
  - Turbine discharges of controlled power plants
  - Concession levels
- **Estimation of remaining states**
  - **Apply standard Kalman filter**



Estimation of Lateral Flows

- Up to **50 %** of nominal discharge flow through locks
- Measurement not helpful, since concession levels too close to branching points



Lateral flow anticipation is beneficial

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Lock Disturbance Prediction `Button'

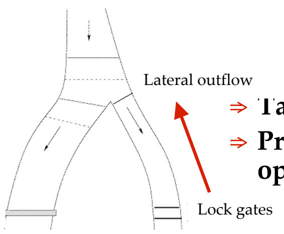
Assume knowledge of

Starting time of lock operation

+

Duration of lock operation

Discharge behaviour at lock gate



⇒ **Take advantage of lock channel propagation delay**

⇒ **Prediction of lateral flow during current lock operation**

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Case Studies

- **Tuning with priority on \`Concession Levels´ (no control move reduction)**
  - Without lock operation
  - With lock operation
- **Tuning with priority on \`Discharges´ (control move reduction included)**
  - Without lock operation
  - With lock operation

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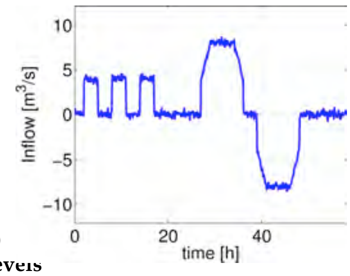
Case Studies

- **Tuning with priority on `Concession Levels´ (no control move reduction)**
  - Without lock operation
  - With lock operation
- **Tuning with priority on `Discharges´ (control move reduction included)**
  - Without lock operation
  - With lock operation

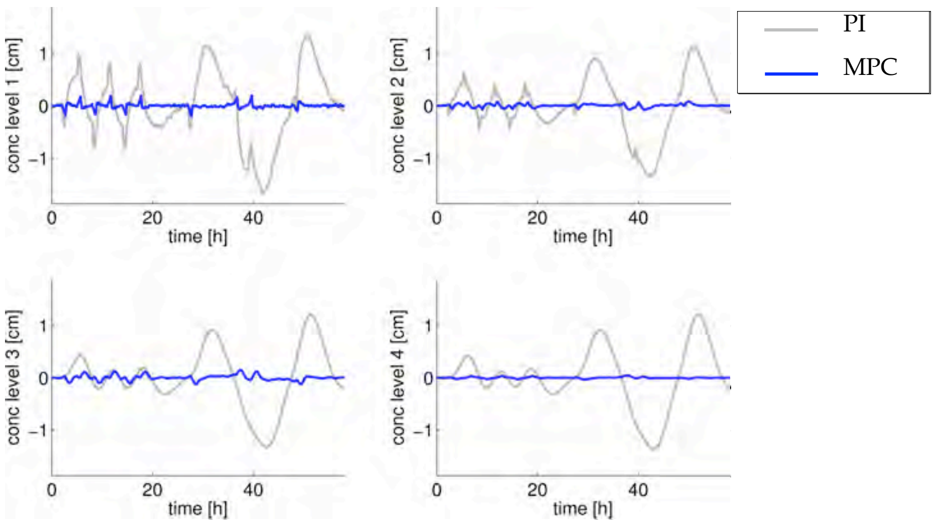
Scenario without Lock Operation Simulation Setup

- **Scenario**
  - Inflow to the cascade: Generic for ship traffic blockade period
  - Without lock operation

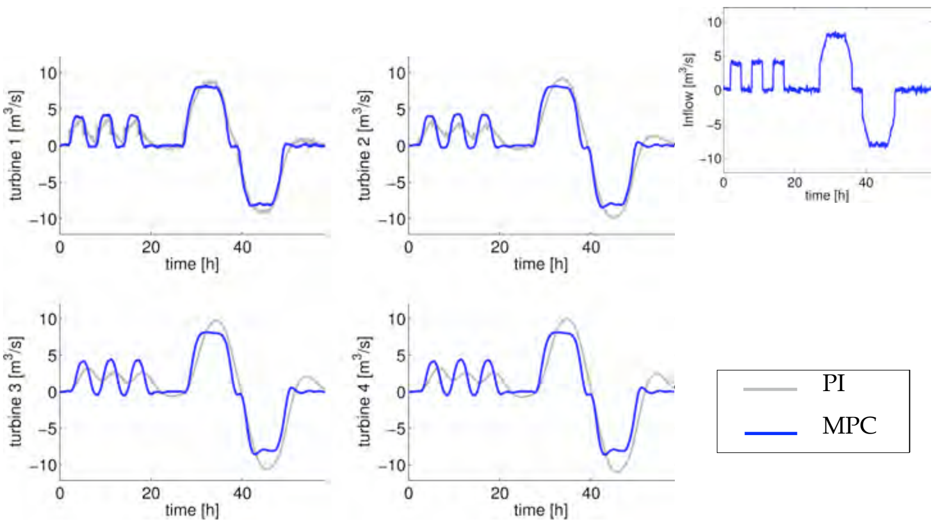


- **Internal Model**
  - Lock information: **None**
  - Number of states: 135
  - Operating point: 43 m^3/s
- **Controller**
  - Sampling time: 6 min
  - Prediction horizon: 25 steps (2,5 h)
  - Priority on: **Concession Levels**
  - Preferred zone of concession levels: +/- 2 cm
  - Constraints: 25 $m^3/s \leq q_{turb} \leq 120\ m^3/s$; -50 $m^3/s \leq \Delta q_{turb} \leq 50\ m^3/s$
  - Control move reduction: **Off**
  - Computation time: 1,45 s with Intel Pentium 4 @ 2,2 GHz; 1GB RAM

Scenario without Lock Operation
Concession Levels



Scenario without Lock Operation
Turbine Discharges



Case Studies

- **Tuning with priority on `Concession Levels´ (no control move reduction)**
  - Without lock operation
  - With lock operation
- **Tuning with priority on `Discharges´ (control move reduction included)**
  - Without lock operation
  - With lock operation

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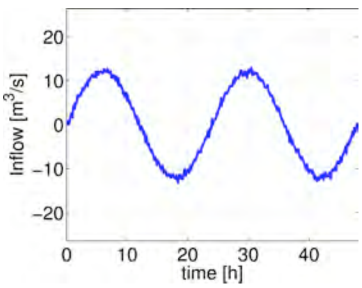
Scenario with Lock Operation Simulation Setup

- **Scenario**
  - Inflow to cascade: Generic, sine wave with white noise
  - With lock operation (20 times per day between 5.00 a.m. – 10.00 p.m.)



- **Internal Model**

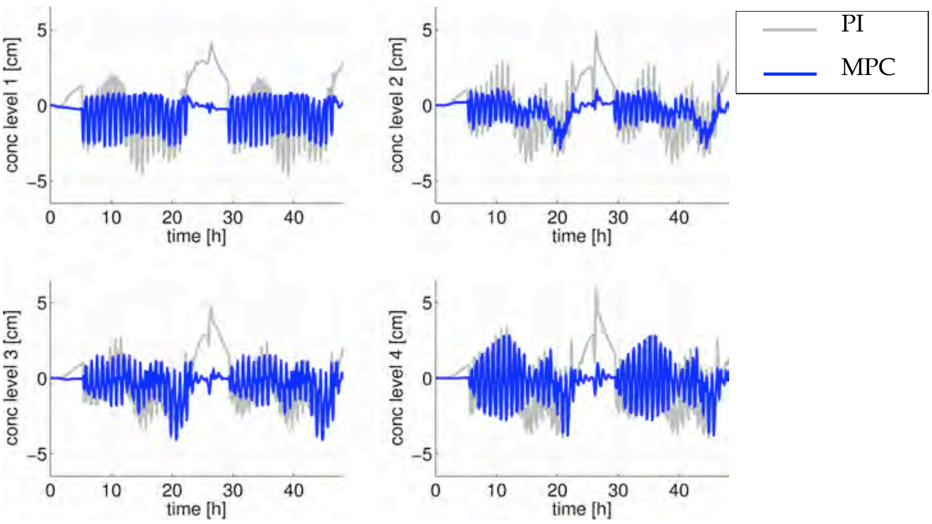
– Lock information	**`Button´**
– Number of states:	135
– Operating point:	43 m^3/s

- **Controller**

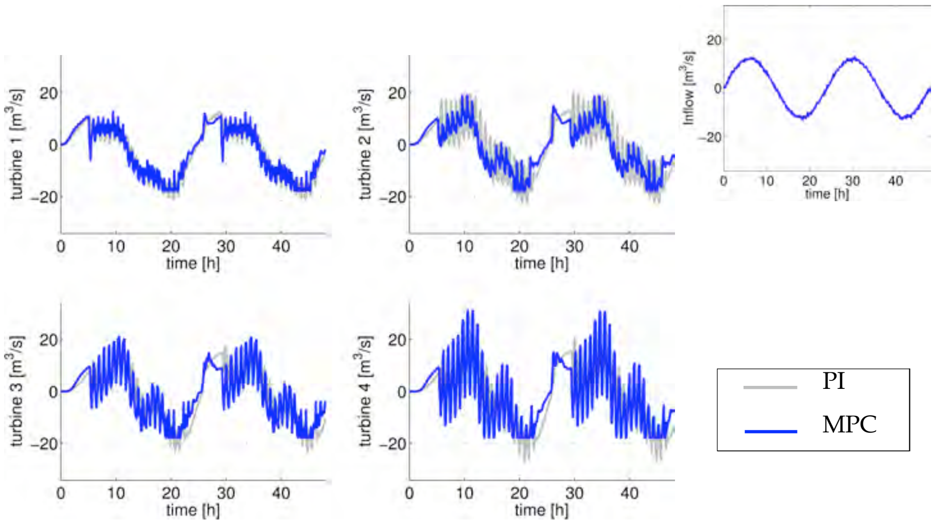
– Sampling time:	6 min
– Prediction horizon:	25 steps (2,5 h)
– Priority on:	**Concession Levels**
– Preferred zone of concession levels:	+/- 2 cm
– Constraints:	25 $m^3/s \leq q_{turb} \leq$ 120 m^3/s -50 $m^3/s \leq \Delta q_{turb} \leq$ 50 m^3/s
– Control move reduction:	**Off**
– Computation time:	1,45 s with Intel Pentium 4 @ 2,2 GHz; 1GB RAM

ETH

Scenario with Lock Operation Concession Levels



Scenario with Lock Operation Turbine Discharges



Outline

- Introduction and Motivation
- Modeling
- Control
- Estimation
- Case Studies
- Conclusions and Outlook

ETH

Conclusions

- **MPC well suited**
  - Control objectives easily mathematically formulated
  - High flexibility
  - Constraints explicitly handled
- **Control move reduction**
  - MLD formulation suited for incorporating hysteresis constraint
  - Successful complexitiy reduction
  - Optimization problem solvable on standard computer within sampling interval of real plant
- **Tuning with priority \`Concession Levels´**
  - Anticipation of lock operation disturbances (\`Button') beneficial
- **Tuning with priority \`Discharges´ including control move reduction**
  - Long term lock information profitable

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Outlook

- Presentation and knowledge transfer to partners
- Extension to cascade of 40 power plants
  - Distributed control using longitudinal alignment
  - Sub-optimal relaxations
- Integration into current infrastructure
  - Feasibility study
  - Preparation for industrial commissioning

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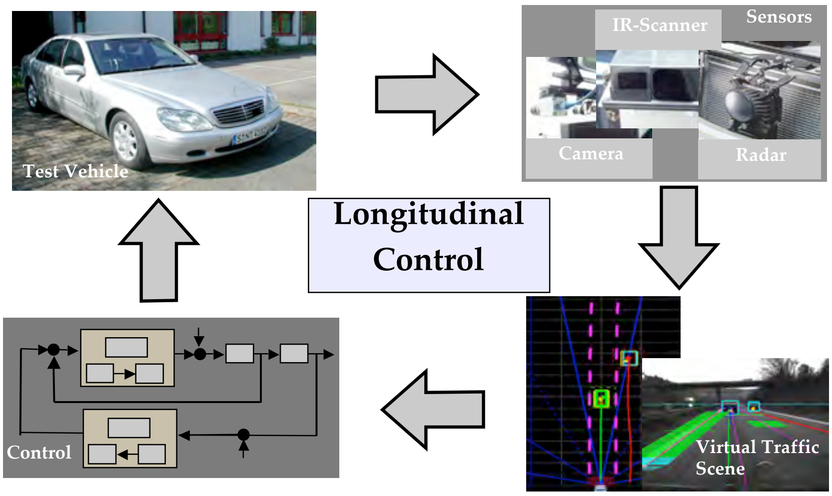
Driver Assistance System

DaimlerChrysler

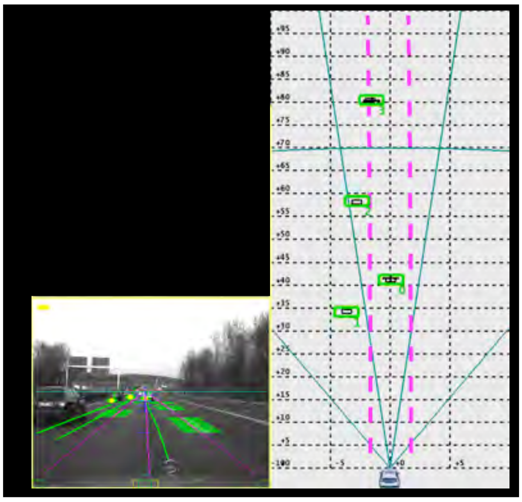


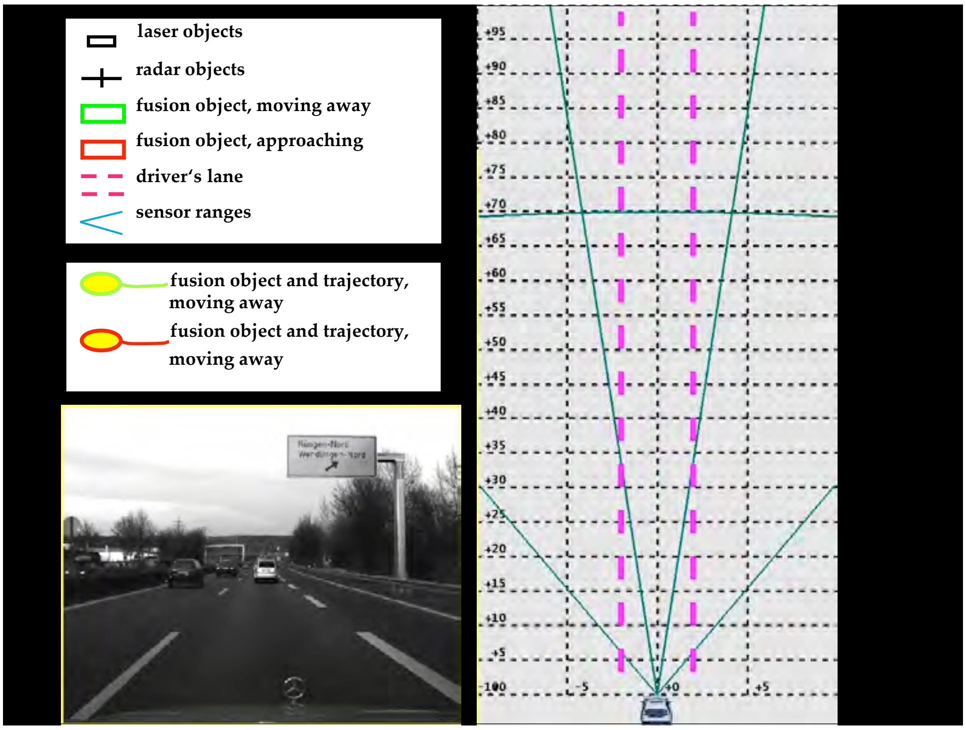
Sensor Fusion

IR-Laser and radar

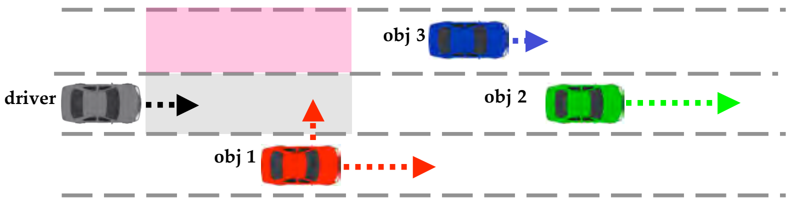
- laser objects
- radar objects
- fusion object, moving away
- fusion object, approaching
- driver's lane
- sensor ranges

- fusion object and trajectory, moving away
- fusion object and trajectory, moving away





Driver Assistance System



OVER FUTURE HORIZON

IF any **obj** closer than safety distance d_{min}
  IF obj in the right lane
    THEN maintain reference speed v_{ref}
  ELSE
    keep safety distance d_{min}
    IF $v_{obj} < v_{ref}$
      THEN track **obj** speed v_{obj}
    ELSE
    ⋮

High Level Control

Objectives:

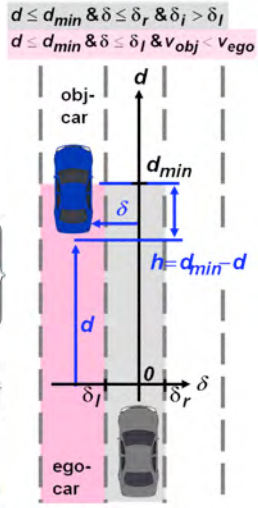
respect minimum distance, adapt speed to other road users, consider all objects on all lanes, consider future situation, avoid right side overtaking, track driver set speed.

Cost Function:

$$h_i(k) = \begin{cases} d_{min} - d_i(k) & \text{if } d_i(k) \le d_{min} \ \& \ \delta_i(k) \le \delta_r \ \& \ \delta_i(k) > \delta_l(k) \\ & \text{or } d_i(k) \le d_{min} \ \& \ \delta_i(k) \le \delta_l(k) \ \& \ v_{obj,i}(k) < v_{ego}(k) \\ 0 & \text{else} \end{cases}$$

$$g_i(k) = \begin{cases} v_{obj,i}(k) - v_{ego}(k) & \text{if } v_{obj,i}(k) < v_{ego}(k) \ \& \ \delta_i(k) \le \delta_r \\ 0 & \text{else} \end{cases}$$

$$J = \sum_{k=0}^{T-1} (v_{ego}(k) - v_{set})^2 Q_v + \sum_{i=1}^{\#obj} (h_i(k))^2 Q_h + (g_i(k))^2 Q_g$$



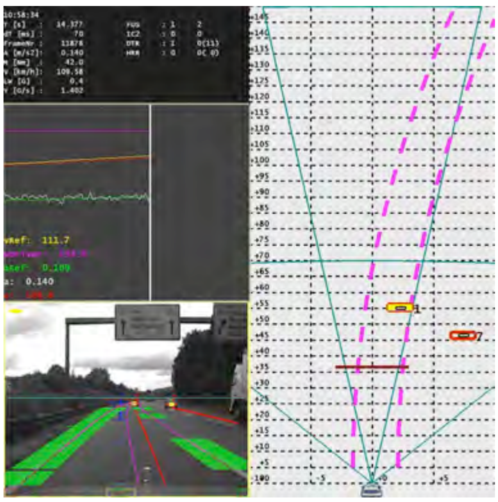
Test Drive Results

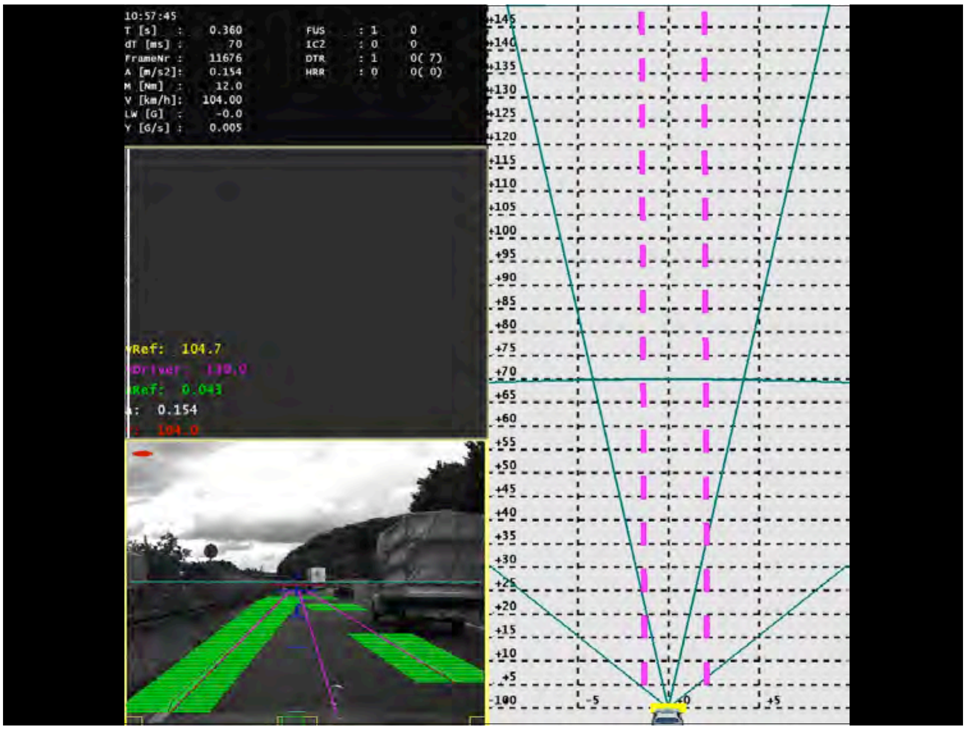
Cutting-Out Vehicle

early reaction to cutting-out vehicle

- minimum distance
- laser objects
- radar objects
- fusion object, moving away
- fusion object, approaching
- relevant object (best cost)
- driver's lane
- sensor ranges

- fusion object and trajectory, moving away
- fusion object and trajectory, moving away





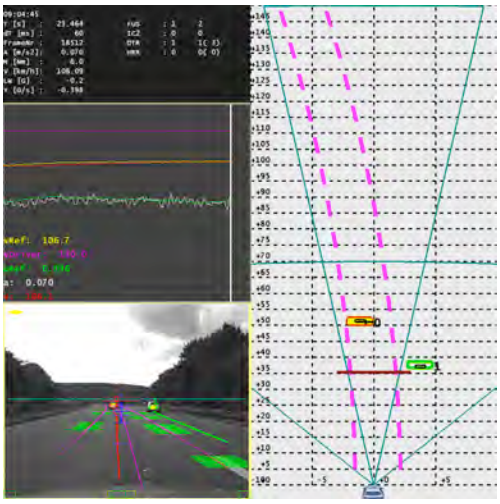
Test Drive Results

Cutting-Through Vehicle

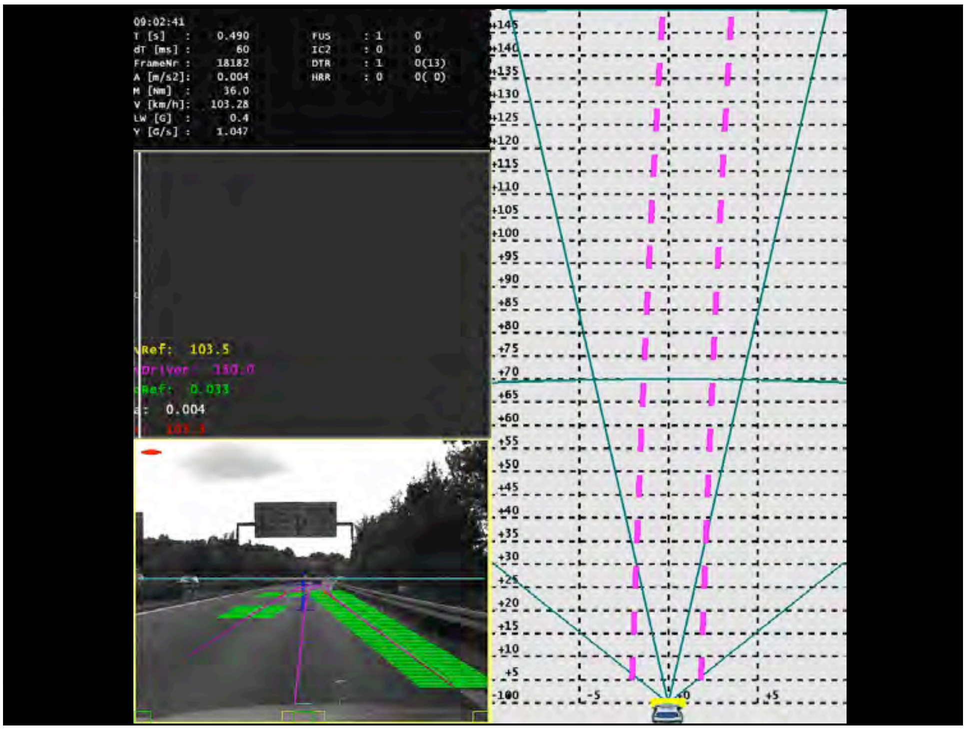
no reaction on cutting-through vehicle

- minimum distance
- laser objects
- radar objects
- fusion object, moving away
- fusion object, approaching
- relevant object (best cost)
- driver's lane
- sensor ranges

- fusion object and trajectory, moving away
- fusion object and trajectory, moving away



ETH

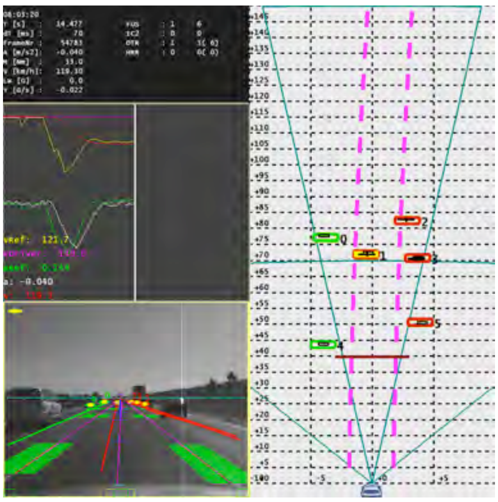


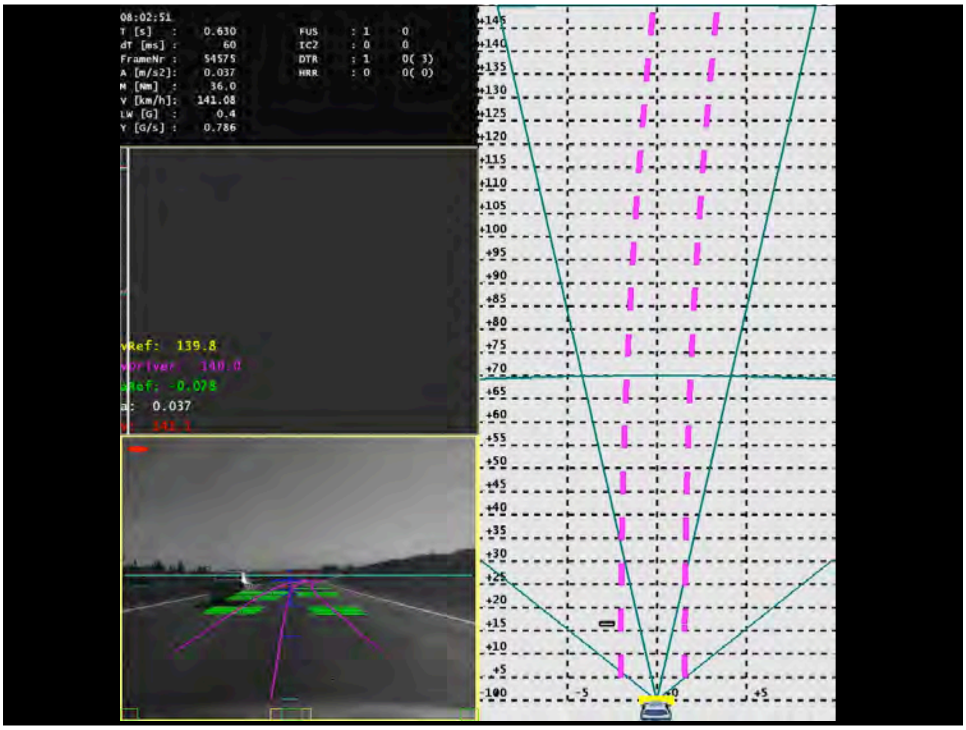
Test Drive Results

Complex Scenario

- minimum distance
- laser objects
- radar objects
- fusion object, moving away
- fusion object, approaching
- relevant object (best cost)
- driver's lane
- sensor ranges

- fusion object and trajectory, moving away
- fusion object and trajectory, moving away





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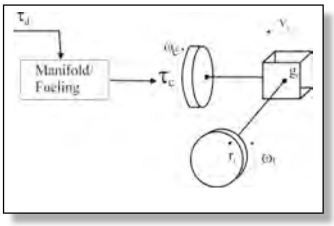
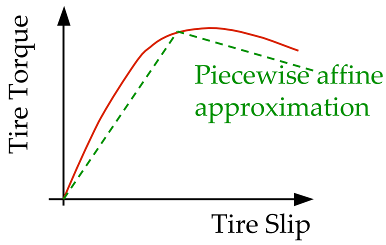
Traction Control





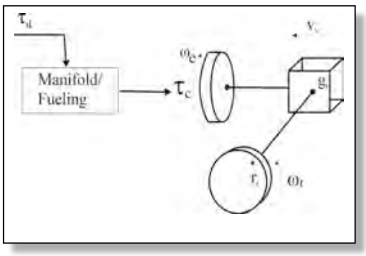
Problem Description

Motivation

Improve driver's ability to control a vehicle under adverse external conditions (wet or icy roads)

Model

Nonlinear, uncertain, constraints



Mechanical system

$$\dot{\omega}_e = \frac{1}{J_e}\left(\tau_c - b_e\omega_e - \frac{\tau_t}{g_r}\right)$$

$$\dot{v}_v = \frac{\tau_t}{m_v r_t}$$

Manifold/fueling dynamics

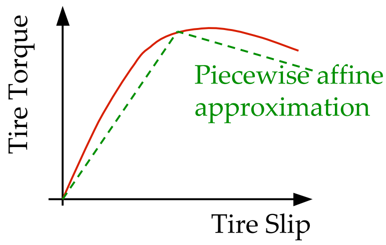
$$\dot{\tau}_c = b_i\tau_d(t - \tau_f)$$

Non-linearities

- Tire torque τ_t is a nonlinear function of slip $\Delta\omega$

$$\Delta\omega = \frac{\omega_e}{g_r} - \frac{v_v}{r_t}$$ Tire slip

- System is approximately piecewise affine with two operation regions



Objective & Constraints

- Control Objective:

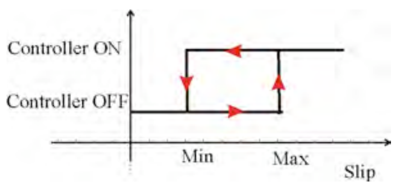
$$\min \sum_{k=0}^{N} \left| Q\left[\Delta\omega(k|t) - \omega_{des}\right] \right| + \left| R\Delta\tau_d \right|$$

- Constraints:

$$-20 \text{ Nm} \leq \tau_d \leq 176 \text{ Nm}$$

$$-2000 \text{ Nm/s} \leq \frac{\Delta\tau_d}{\Delta t} \leq 2000 \text{ Nm/s}$$

- Hysteresis:



Controller Setup

COMPLEXITY OF CONTROLLER COMPUTATION

Sampling Time	0.02 s
States	5
Input	1
Switch	1

RECEDING HORIZON CONTROLLER

Horizon ≤ 5
Number of regions: 31 - 508

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Experimental Setup

2000 Ford Focus, 2.0l 4-cyl Engine, 5-speed Manual Trans

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Experimental Setup

Polished Ice Test Surface

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Experimental Setup

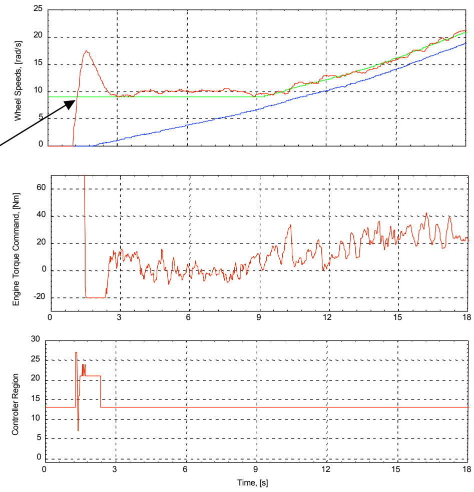
266 MHz Pentium 2-based Laptop for Control

ETH

Experimental Results

Typical Launch on Ice

- The controller is triggered when the average driven wheel speed (red) first exceeds the target (green).
- The blue trace is average non-driven wheel speed.
- A 250 ms transport delay from commanded to delivered engine torque accounts for the initial overspin



Experimental Results - Video

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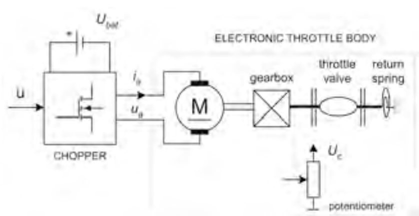
Electronic Throttle Overview



Main challenges

- Friction (gearbox)
- Limp-Home nonlinearity (return spring)
- Constraints
- Quantization (dual potentiometer + A/D)

PWA Model of the Throttle

- State vector $x = [\omega_m^*, \theta]'$
- Friction: 5 affine parts
- Limp-Home: 3 affine parts
- Zero Order Hold

15 (discrete time) PWA dynamics

$$\begin{aligned} x(t+1) &= f_{\text{PWA}}(x(t), u(t)) \\ &= A_i x(t) + B_i u(t) + f_i \quad \text{if} \quad H_i x(t) + L_i u(t) \leq K_i \\ & \quad i = 1, \ldots, 15 \end{aligned}$$

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Optimal Control Problem

Cost

$$\min_U \|P(y(T) - r(T))\|_2^2 + \sum_{k=0}^{T-1} \|Q(y(k) - r(k))\|_2^2 + \|R \cdot \Delta u(k)\|_2^2$$

System

$T_s = 5ms$, $T = 5$, $y(k) = \theta(k)$, $\Delta u(k) = u(k) - u(k-1)$
extended state vector $\bar{x}(k) = [\omega_m(k),\ \theta(k),\ u(k-1),\ r(k)]'$

Constraints

$i_a(k) \in [-3,\ 3]$, $\omega_m(k) \in [-300,\ 300]$
$\theta(k) \in [11,\ 90]$, $u(k) \in [-5,\ 5]$
$\Delta u(k) \in [-5,\ 5]$, $r(k) \in [11,\ 90]$

Weights

$P = 2,\ Q = 1.5,\ R = 1.5$

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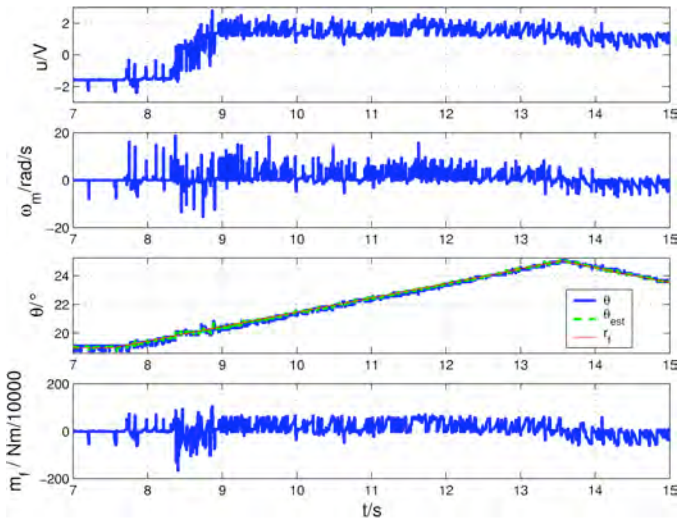
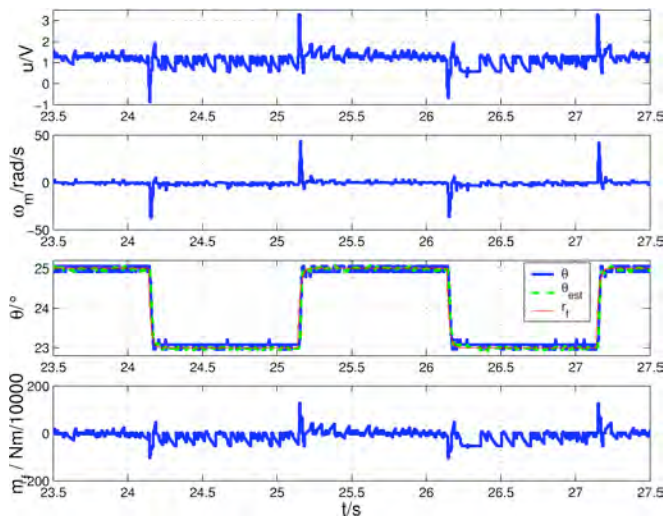
Experimental Results



ETH

Experimental Results



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Voltage Converters Overview

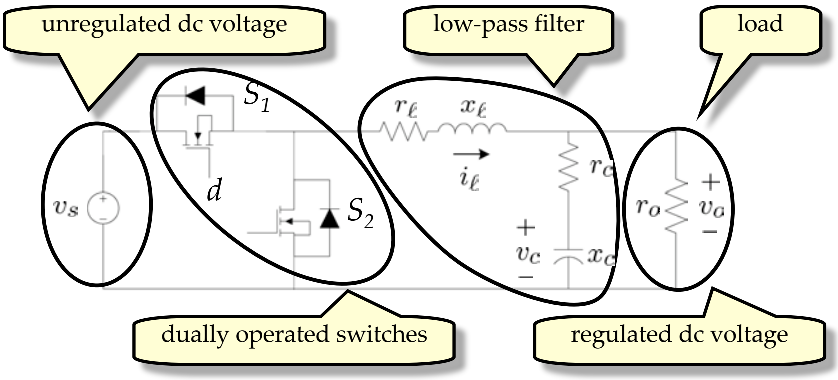
dc-dc (and ac-dc) conversion in

- Power supplies, UPS, battery chargers,…
- dc Motor Drives
- Power Systems (HVDC transmission, …)
- Demanding applications (air and space, …)

Switch-mode dc-dc Converter

Switched circuit: supplies power to load with constant dc voltage

Illustrating example: **synchronous step-down** dc-dc converter



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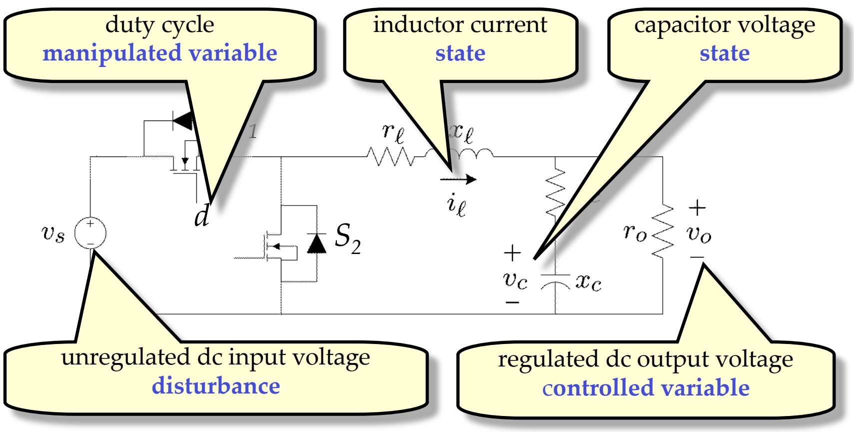
The Control Problem

Regulate dc output voltage by appropriate choice of duty cycle



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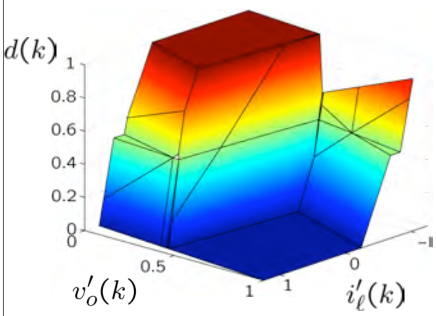
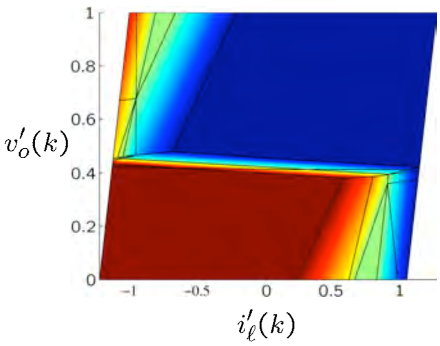
State-feedback Controller: Control Law

For $d(k-1) = 0.5$, $v'_{o,ref}(k) = 0.4167$, $i'_{\ell,max}(k) = 1$





92 polyhedra in 5-dim. state space
in ~30s computation time (MPT toolbox)

Optimal controller given by **look-up table**

ETH

Experimental Results

- **Converter parameters**
  - Filter: C = 220μF, L = 1mH, $R_c \approx 0.5\Omega$, $R_L \approx 1.5\Omega$
  - Input voltage: $V_s = 10V$
  - Load: $R_o = 8.9\Omega$
  - Switching frequency: $f_s = 20kHz$
- **Control hardware**
  - dSpace™ DS1103 PPC Controller
- **Scenarios examined**
  - Start-up from zero initial condition
  - Current limit activation

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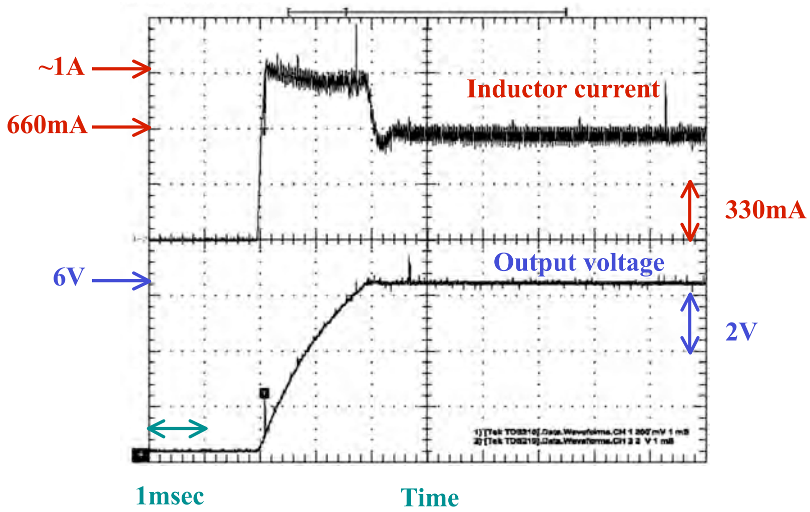
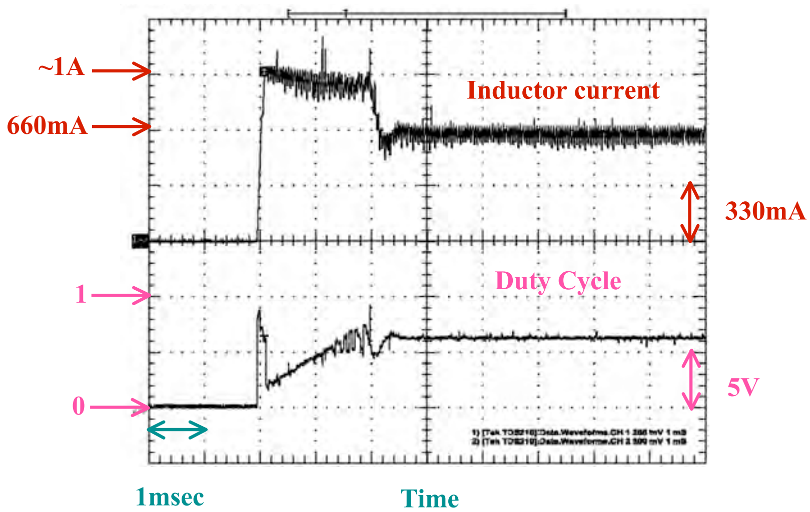
Start up: Experiment (1/2)

Input voltage @10V, Output voltage reference @6V, Current limit @1A



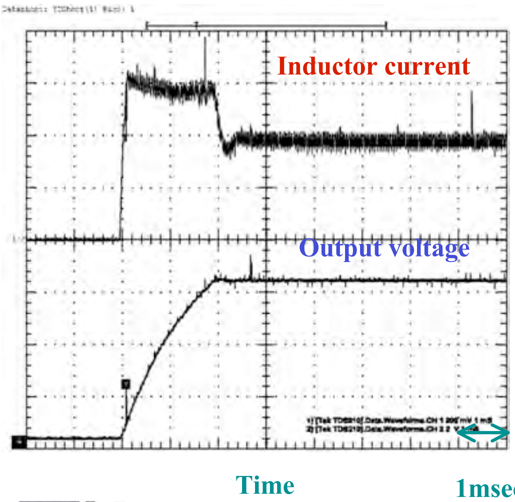
Start up: Experiment (2/2)

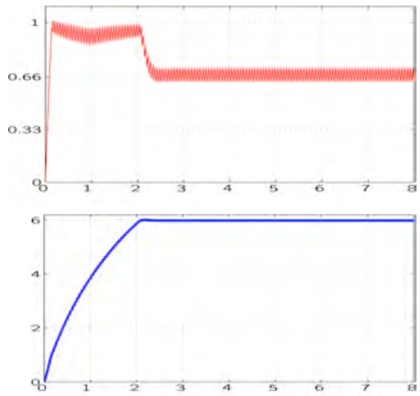
Input voltage @10V, Output voltage reference @6V, Current limit @1A



Start up: Experiment vs. Simulation

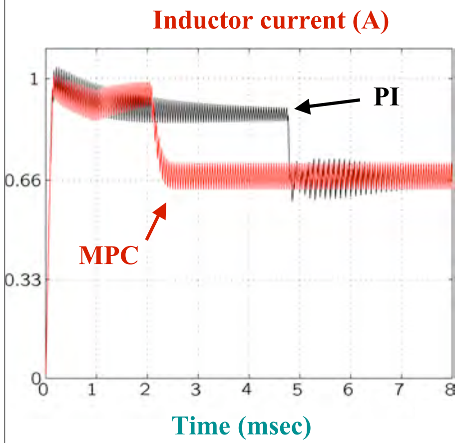
Input voltage @10V, Output voltage reference @6V, Current limit @1A

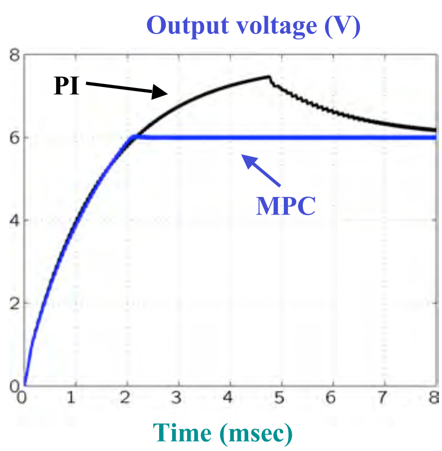




Start up:
MPC vs. PI (Current mode control)

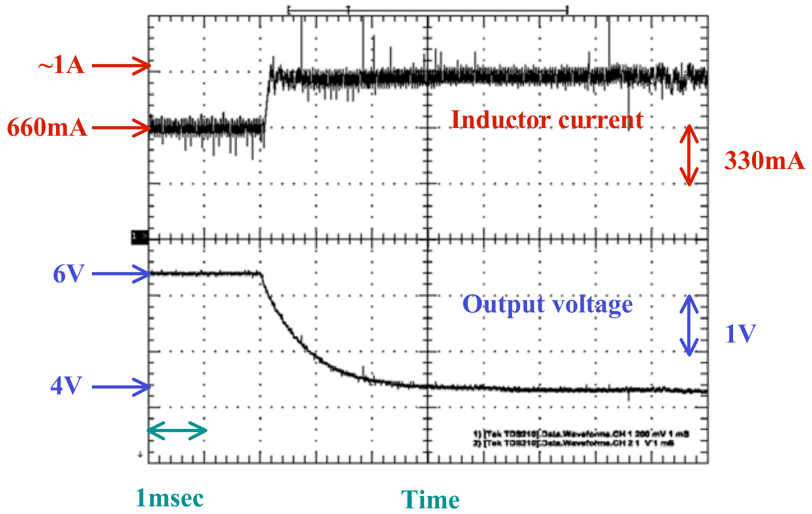
Input voltage @10V, Output voltage reference @6V, Current limit @1A





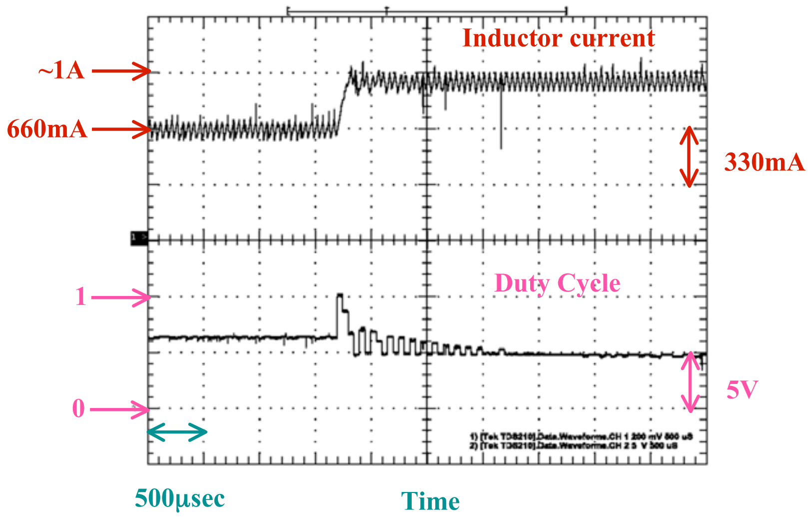
Current Limit Activation (1/2)

Load resistance drop from 8.9Ω to 4Ω, Current limit @1A



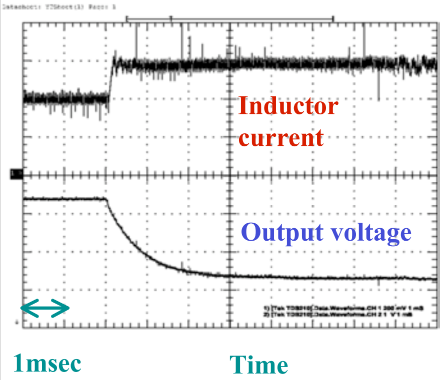
Current Limit Activation (2/2)

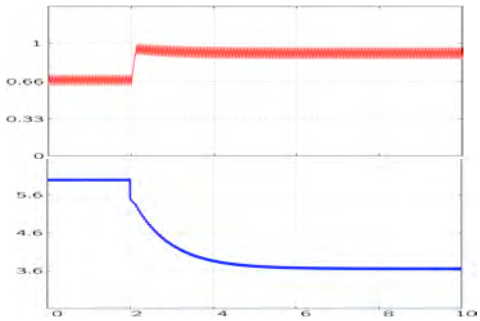
Load resistance drop from 8.9Ω to 4Ω, Current limit @1A



Current Limit Activation: Experiment vs. Simulation

Load resistance drop from 8.9Ω to 4Ω, Current limit @1A





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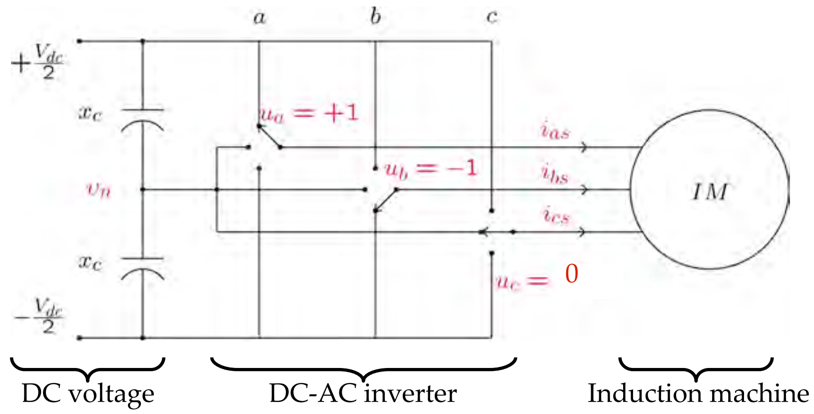
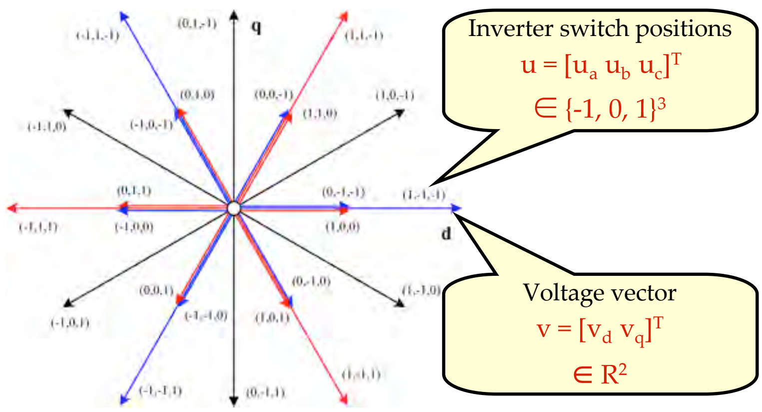
Physical Setup

ABB



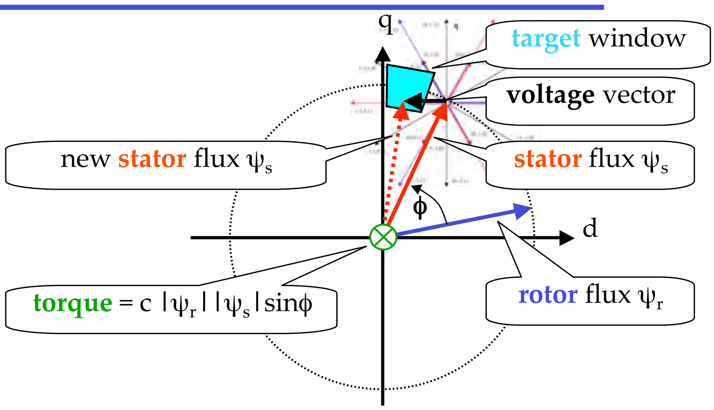
Three-level DC link inverter driving a three-phase induction motor

Voltage Vectors



The 27 different switch positions u produce 27 voltage vectors v on the dq plane

Control Principle



Choose one of 27 voltage vectors (switch combinations) **s.t.:**

- **Torque**, **stator flux** and **NPP** are kept in target window
- Average **switching frequency** is minimized

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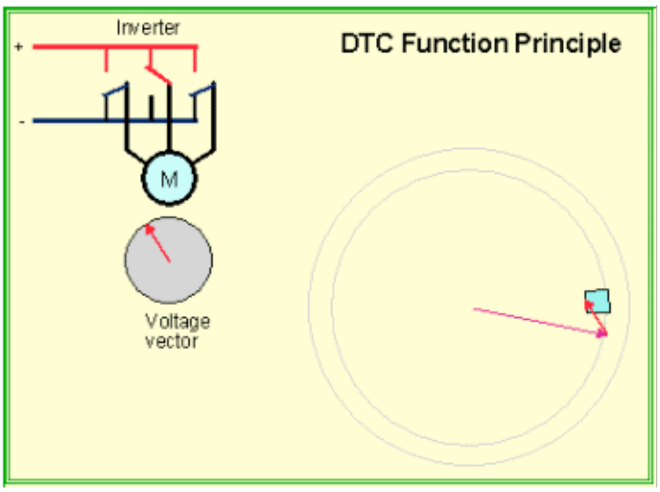
Control Principle (ctd.)



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MPC based on Extrapolation: Algorithm

For u(k) = u(k-1):
Are controlled variables kept for at least *N* **steps** within the bounds?

Yes → **Re-apply** last control input

No → **Compute new** control input

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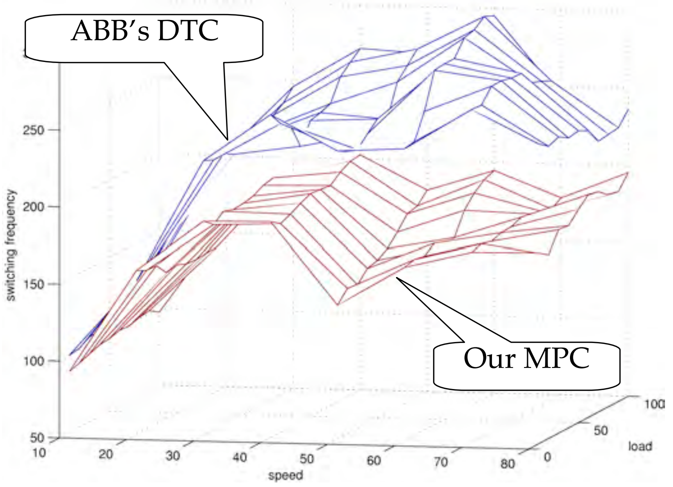
1. Compute trajectories over horizon *N*
2. Determine candidate trajectories
3. Extrapolate
4. Minimize cost

Performance Improvement for all Operating Points



Reduction of switching frequency by **up to 45 %** (on **average 25 %**)

MPC based on Extrapolation: Features

- **Simplicity:** **absence of tuning parameters**
- **Flexibility:** **model-based design**, trivial adaptation of model parameters
- **Performance:** **improvement** compared to ABB's DTC (*N*=2: 25% in avg.; *N*=1: 16% in avg.)
- **Computation:** **feasibility** expected for online implementation (in particular for *N*=1)

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- **Computation:** **feasibility** expected for online implementation (in particular for *N=1*)

- Control scheme simple, flexible and computationally feasible
- European patent pending
- ABB implementation underway

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MPC based on Extrapolation: Implementation & Extension

- Implementation work currently **underway at ABB**
- Induction motor running with MPC on **Nov. 2006**
- Extension of controller setup to **synchronous** motor topology

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Outline

- Overview
- Hydroelectric Power Plant Cascade
- Automotive Applications
  - Adaptive Cruise Control
  - Traction Control
  - Electronic Throttle Control
- Electric Energy Applications
  - Control of Switch-mode dc-dc Converters
  - Direct Torque Control of Induction Motors
  - Emergency Voltage Regulation in Power Systems
- Vibration Control

Why Vibration Control?

- **Conventional passive damping materials**
  - Very large materials against low frequency vibration
  - Heavy, bulky and expensive
- **Alternative: vibration control**
  - At low frequency
  - Less weight
  - Cheap

Smart Damping Materials

Midé

Head

Sikorsky

- **Demands:**
  - — Efficient vibration suppression
  - — No power supply
  - — Minimal weight and size
  - — Simple and self-contained unit

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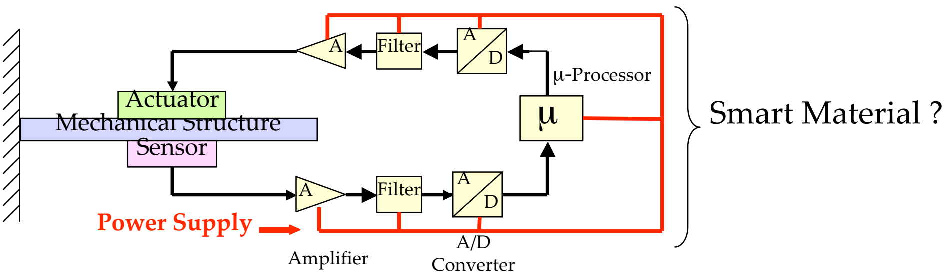
Conventional Active Vibration Control



- **Requires power for operation**
- **Large instrumentation overhead**
  - – Bulky and expensive
- **Need for simple, integrated controllers**

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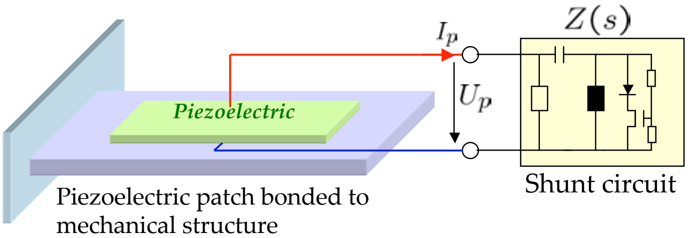
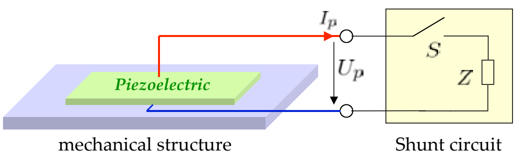
Smart Damping Materials

- **Idea: Shunted Piezoelectric Materials**
  - No sensor required
  - High integration
  - No power supply
  - Cheap



New Approach: Switching Shunt Circuits

- **Demands**
  - High integration
  - No power supply
  - Cheap

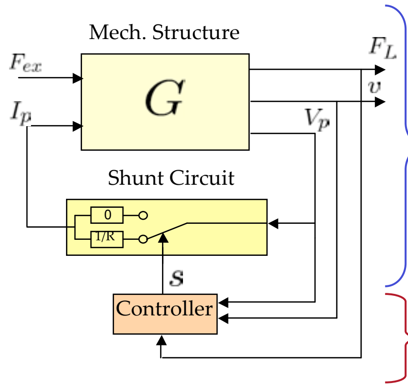


- **Switching Shunts**
  - Simple
  - Good damping performance
  - Possible implementation without power requirement

but

- Hybrid system
- How to switch optimally?

Optimal Switching Sequence



- **Hybrid System Structure**

$$x(k+1) = \begin{cases} A_1 x(k) + B_1 u(k) & : \; S = 0 \\ A_2 x(k) + B_2 u(k) & : \; S = 1 \end{cases}$$

$$y(k) = C x(k)$$

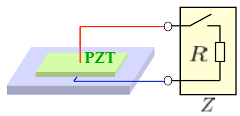
- **Modeling of the MLD Structure using Hysdel**
- **Optimization Problem:**

$$\min_{S \subset S_t, \ldots, S_{t+m-1}} \sum_{k=0}^{m-1} \| v(k) \|_2^2$$

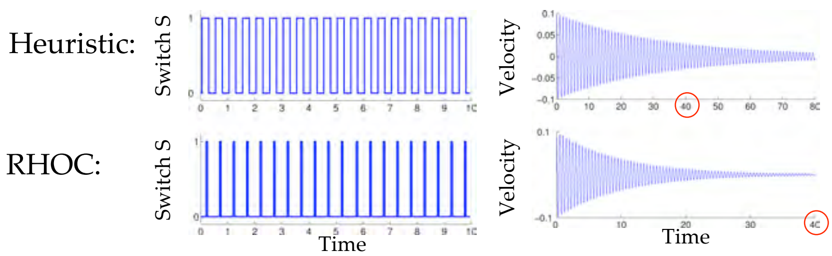
$$\text{subj. to} \begin{cases} S_i \in [0, 1] \\ x(k+1) = \begin{cases} A_1 x(k) + B_1 u(k) & : \; S_i = 0 \\ A_2 x(k) + B_2 u(k) & : \; S_i = 1 \end{cases} \\ v(k) = \begin{pmatrix} 0 & 1 & 0 \end{pmatrix} x(k) \end{cases}$$

Simulations: Switching R Shunt

- **Control Design using Receding Horizon Optimal Control (RHOC)**
  - Solving MIQP *online*



- **Simulations**
  - Comparison: Heuristic vs. RHOC



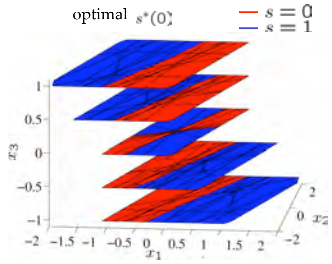
Optimal Feedback using Multi-Parametric Programming

- **Optimal $s^*(0)$ as a function of state $x(0)$**
  - Multi-parametric programming

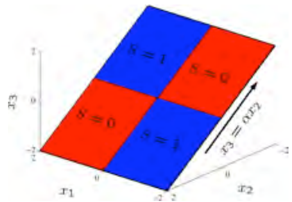
$$J_N^*(x(0)) = \min_{s_0,\dots,s_{N-1}} \sum_{k=0}^{N-1} \| v(k) \|_2^2$$

$$\text{subj. to} \quad GS_N \le W + Ex_0$$

  - State-space is partitioned into regions where $s^*(0)$ is either 1 or 0.



- **After some simplifications**



$x_2 = x$

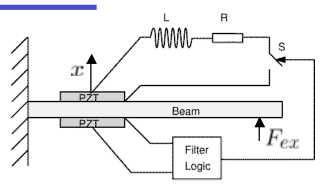
$x_1 = -c\frac{dx}{dt}$

$x \cdot \dot{x} \ge 0 \Rightarrow s = 0$
else $s = 1$

Former Heuristic Controller
[Clark et al., J.Int.Mat.S.S. 2000]

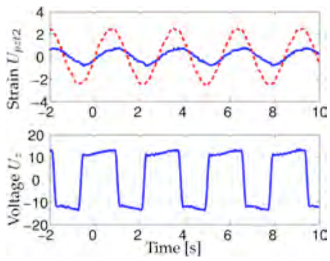
Experiments

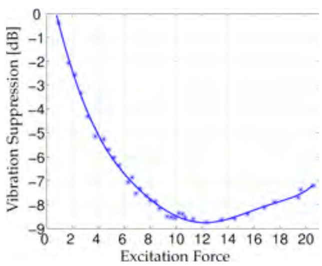
- **One-side clamped beam**



- **Switching R-L Shunt**
  - Reduction of almost 9 dB
  - Damping depends on vibration magnitude

Open
Shunted





BACK

Application: Brake Squeal Reduction

INSTITUT FÜR MECHANIK der Universität Hannover

Neubauer, Popp

- **Friction induced vibration in brakes**
  - Strong vibration radiates unwanted noise
  - One frequency, small bandwidth
  - Frequency can vary

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Brake Squeal Reduction using Shunt Control

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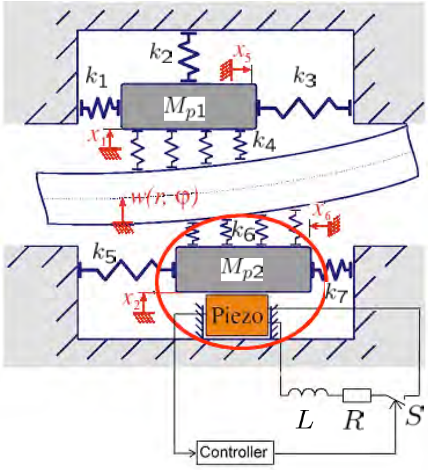
- **Vibration reduction**
  - Piezoelectric actuator between brake pad and calliper
  - Switching shunt control
- **Advantages**
  - Tracks resonance frequency
  - Cheap solution
  - No electrical power required



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References

Traction Control	*[F. Borrelli et al., Proc. of HSSC 2001]*
Adaptive Cruise Control	*[R. Moebus et al., Proc. of HSSC 2003]*
Electronic Throttle Control	*[M. Vasak et al., IJC, vol. 79, 2006]*
Control of dcdc Converters	*[G. Papafotiou et al., Proc. IEEE COMPEL 2004]* *[T. Geyer et al., Proc. of HSSC 2004]*
Direct Torque Control	*[G. Papafotiou et al., Proc. of IEEE CDC 2004]* *[T. Geyer & G. Papafotiou, Proc. of HSSC 2005]*
Emergency Voltage Control in Power Systems	*[T. Geyer et al., Proc. of ECC 2003]*
Vibration Control	*[D. Niederberger et al., IEEE Trans. on Mechatronics, vol. 11, no.1, 2006]* *[D. Niederberger & M. Morari, Journal of Smart Materials & Structures, vol.1 5, 2006]*

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List of Application Projects at IfA

Project	Partner
Control of Cogeneration Power Plant	ABB
Power Plant Cascade	SCIETEC
Scheduling of Cement Kilns and Mills	ABB
Supermarket Refrigeration System	Danfoss
Traction Control	Ford
Adaptive Cruise Control	DaimlerChrysler
Electronic Throttle Control	Ford
Control of Anaesthesia	Inselspital Universitätsspital Bern
Control of Thermal Printheads	Avery Dennison
Control of dcdc Converters	ST
Direct Torque Control	ABB
Emergency Voltage Control in Power Systems	ABB
Brake Squeal Reduction	Institut für Mechanik der Universität Hannover IfM
Vibration Control	The University of Newcastle / EMPA

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