Beyond Process Control

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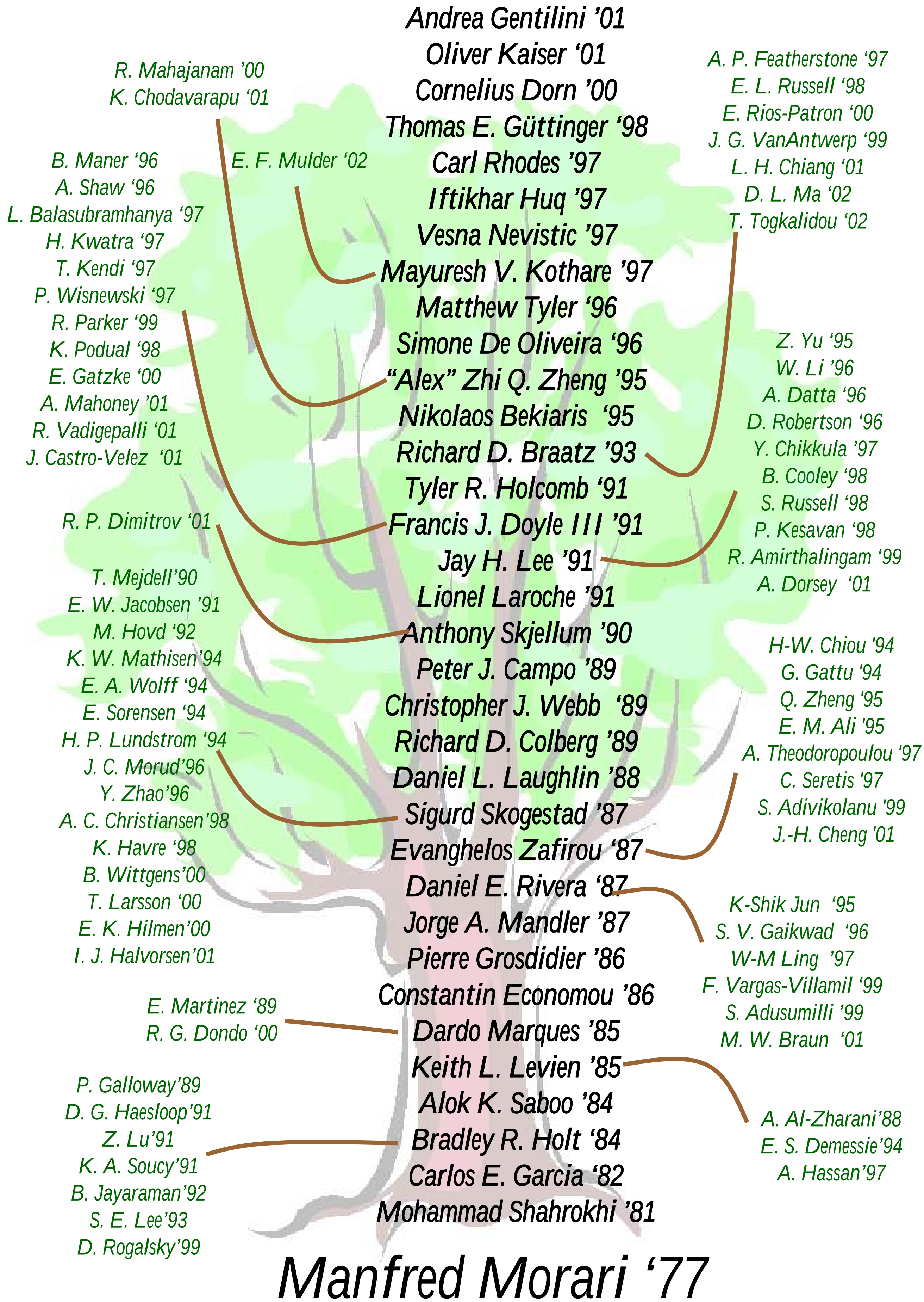
www.control.ethz.ch



Compiled on 11.04.2001

Conclusions

- Process Control has been leading many important developments.

- Process Control tools can have significant impact in a wide range of other application areas.

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Nathaniel B. Nichols 1914-97

MS Physics, U. Mich..
Taylor Instruments (with Ziegler)
MIT with Draper & Brown (Nichols Chart)
Taylor Instruments
University of Minnesota
Raytheon

Chemical Engineering Science, 1956, Vol. 5, pp. 81 to 92. Pergamon Press Ltd.

Optimum temperature gradients in tubular reactors—I

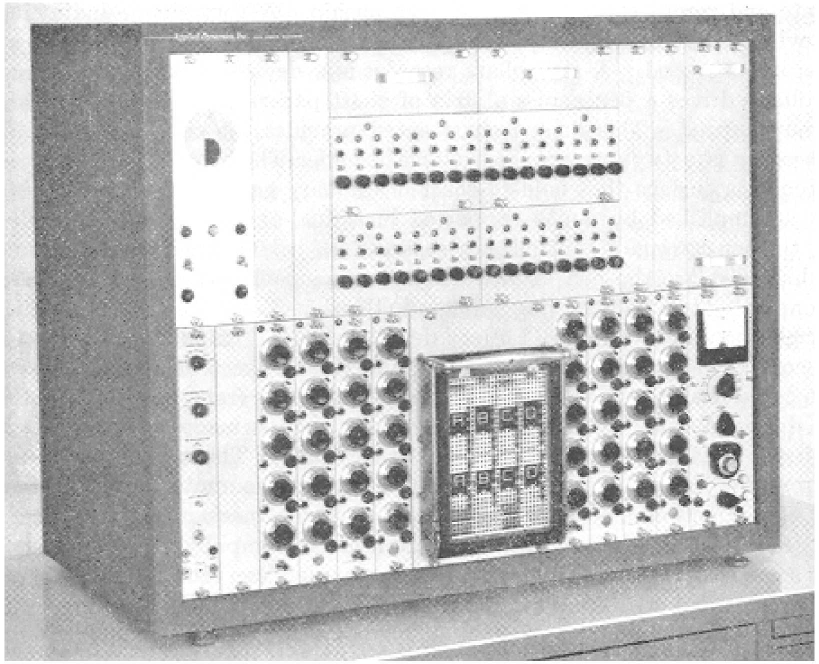
General theory and methods

OLEGH BILOUS* and NEAL R. AMUNDSON
University of Minnesota, Minneapolis 14, Minnesota

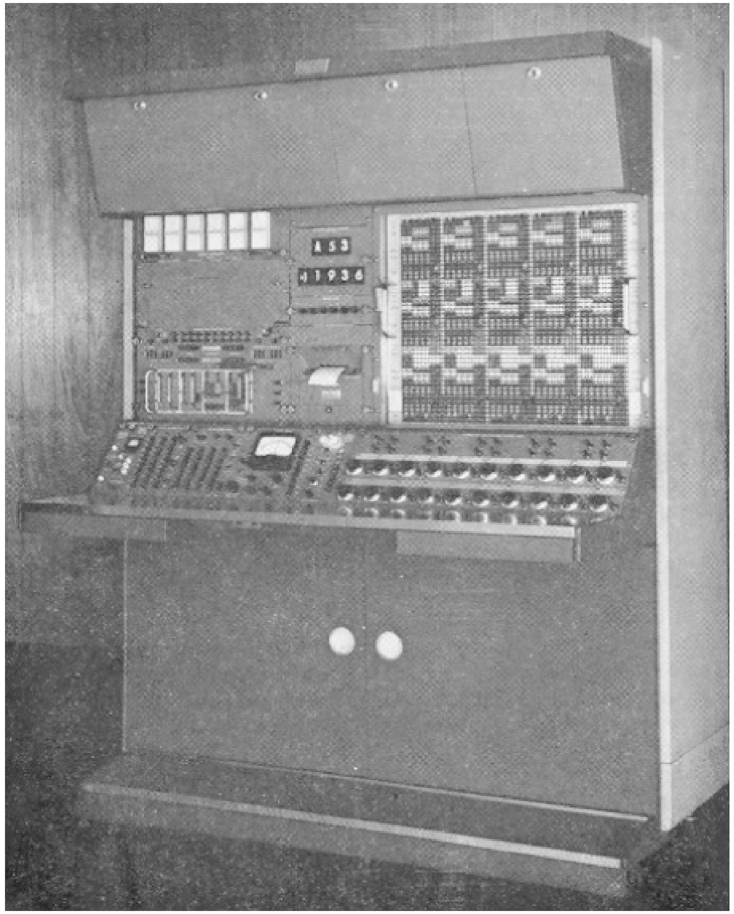
(*Received* 28 *May* 1955)

Abstract—In this paper the mathematical techniques necessary for the determination of the optimum temperatures profile in a tubular reactor to insure maximum yields or minimum contact times are developed, and applications are made to reversible and consecutive reaction systems. The problem is shown to be reducible to a system of ordinary non-linear differential equations. The solution of these differential equations can be made by conventional numerical methods, and will allow the specification of the temperatures in the reactor. In a succeeding paper numerical calculations obtained with an analogue computer (REAC) will be presented. The problem of two consecutive reactions $A \rightarrow B \rightarrow C$, in which the reactions are of first or second order, is discussed in detail. The method of attack on more complicated problems is sketched. It is shown in general that appreciable gains in the yield may be obtained if the optimum temperature distribution is used.

Analog Computers ~1960

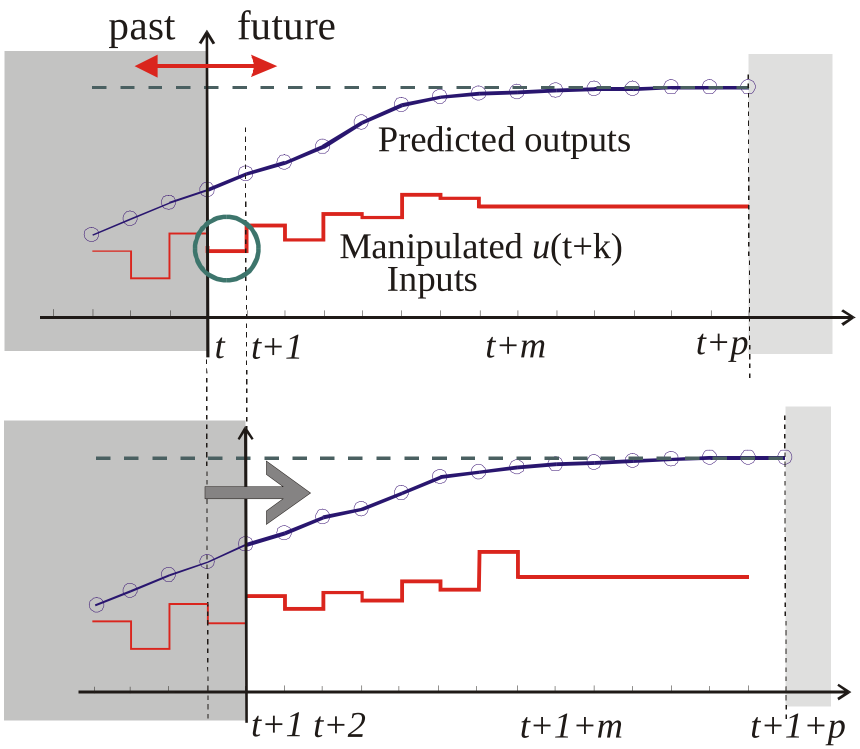


32-amplifier desk-top computer.
(Courtesy of Applied Dynamics, Inc.)



Large-size (100-amplifier) computer.
(Courtesy of Electronic Associates, Inc.)

Model Predictive Control



- Optimize at time *t* (new measurements)
- Only apply the first optimal move *u(t)*
- Repeat the whole optimization at time *t +1*
- Advantage of on-line optimization ⇨ FEEDBACK

Model Predictive Control: A Singular Success Story

- Impact on industrial automation
- Impact on academic research

MPC Vendor Applications by Areas

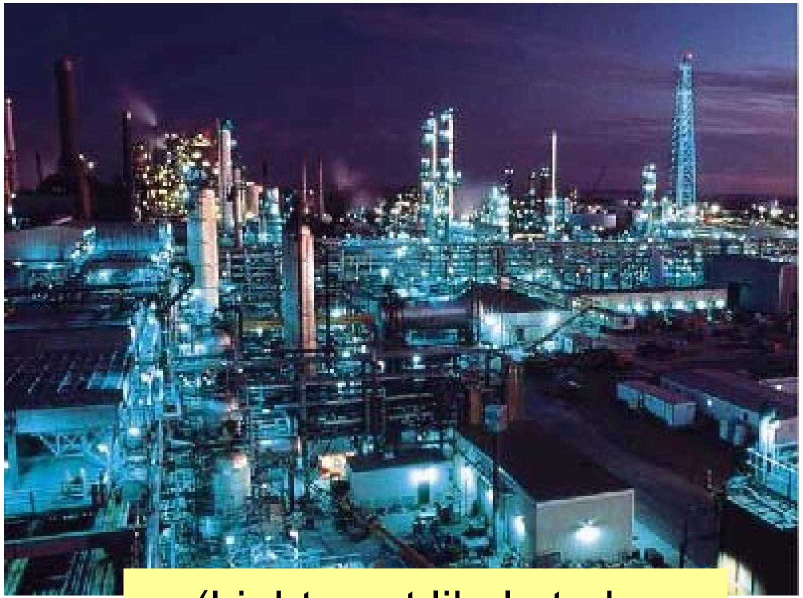
Area	Aspen Technology	Honeywell Hi-Spec	Adersa[b]	Invensys	SGS[c]	Total
Refining	1200	480	280	25		1985
Petrochemicals	450	80	—	20		550
Chemicals	100	20	3	21		144
Pulp and paper	18	50	—	—		68
Air & Gas	—	10	—	—		10
Utility	—	10	—	4		14
Mining/Metallurgy	8	6	7	16		37
Food Processing	—	—	41	10		51
Polymer	17	—	—	—		17
Furnaces	—	—	42	3		45
Aerospace/Defense	—	—	13	—		13
Automotive	—	—	7	—		7
Unclassified	40	40	1045	26	450	1601
Total	1833	696	1438	125	450	4542
First App.	DMC:1985	PCT:1984	IDCOM:1973			
	IDCOM-M:1987	RMPCT:1991	HIECON:1986	1984	1985	
	OPC:1987					
Largest App.	603 × 283	225 × 85	—	31 × 12	—	

Qin & Badgwell, Control Engineering Practice, 2003

Increasing Autonomy in Industrial Processes

- An emphasis on reducing operators in process plants
- A telling metric: “loops per operator”
- United States refining industry data:
  - 1980: 93,000 operators, 5.3 bbl production
  - 1998: 60,000 operators, 6.2 bbl production

  (U.S. Bureau of the Census, 1999)



(Lights not likely to be turned off anytime soon)

Conclusions

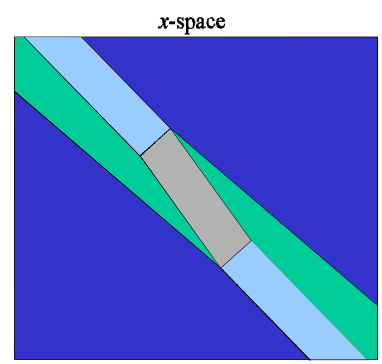
- Process Control has been leading many important developments.

- Process Control tools can have significant impact in a wide range of other application areas.

Developments extending the reach of MPC beyond PC

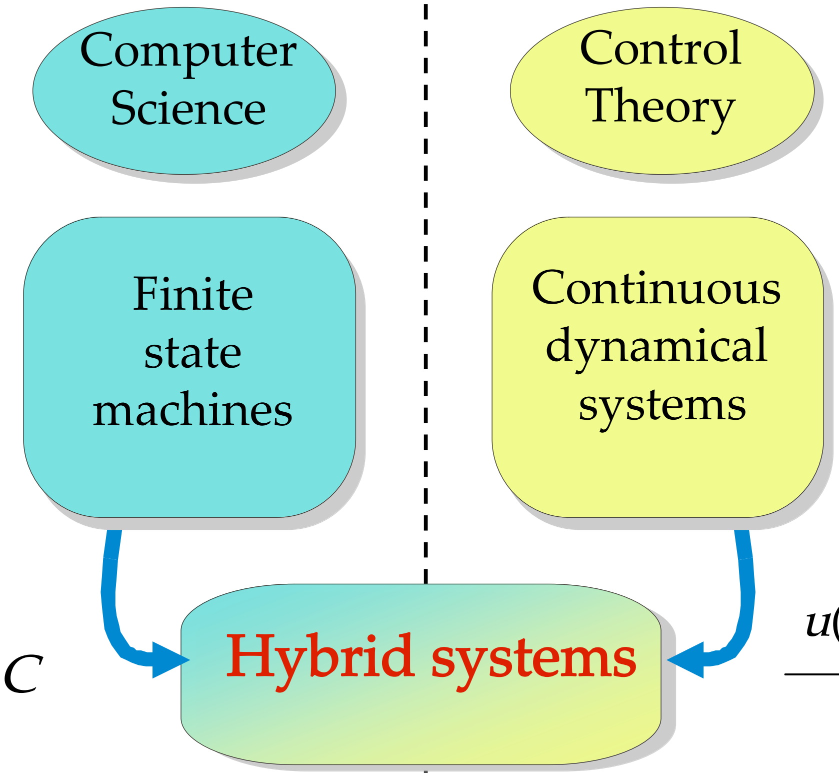
- Faster & cheaper computers
- Extension of MPC to switched/ hybrid systems
- On line optimization ⇒ look up table

Different linear controller for each region of the state space

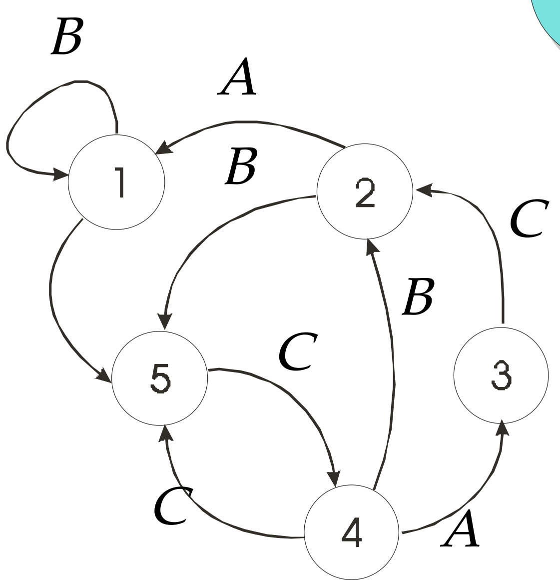


Hybrid Systems

$X = \{1, 2, 3, 4, 5\}$
$U = \{A, B, C\}$



$x \in \mathbb{R}^n$
$u \in \mathbb{R}^m$
$y \in \mathbb{R}^p$



$$\begin{cases} x(k+1) & = & f(x(k), u(k)) \\ y(k) & = & g(x(k), u(k)) \end{cases}$$

Optimal Control for Constrained PWA Systems

System

- Discrete ***PWA*** Dynamics $x(k+1) = f_{\text{PWA}}(x(k), u(k))$
- Constraints on the state $x(k) \in \mathcal{X}$
- Constraints on the input $u(k) \in \mathcal{U}$

$$\left.\begin{array}{l} x(k) \in \mathcal{X} \\ u(k) \in \mathcal{U} \end{array}\right\} C^x x(k) + C^u u(k) \leq C^0$$

Objectives

- Stability (feedback is stabilizing)
- Feasibility (feedback exists for all time)
- Optimal Performance

Constrained Finite Time Optimal Control of PWA Systems

Linear Performance Index (p=1,∞)

$$J^*(x) := \min_U \|Px_T\|_p + \sum_{k=0}^{T-1} \|Qx_k\|_p + \|Ru_k\|_p$$

Constraints

$$\begin{cases} x_0 = x, \\ x_{k+1} = f_{\mathrm{PWA}}(x_k, u_k), \\ C^x x_k + C^u u_k \leq C^0 \end{cases}$$

Algebraic manipulation ➡ Mixed Integer Linear Program (MILP)

$$U^*(x) = \{u_0^*, u_1^*, \dots, u_{T-1}^*\}$$

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Algebraic manipulation ⇒ Mixed Integer Linear Program (MILP)

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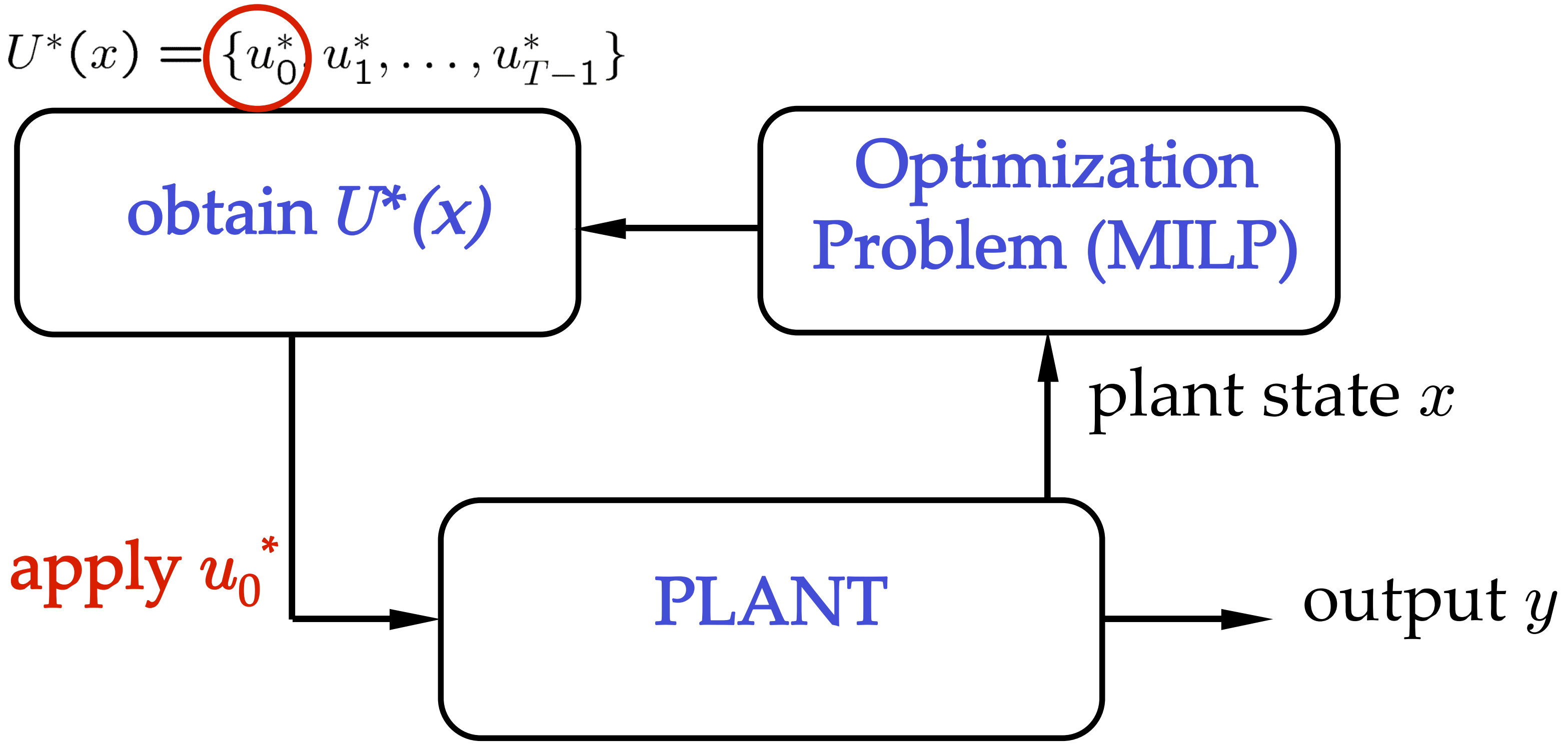
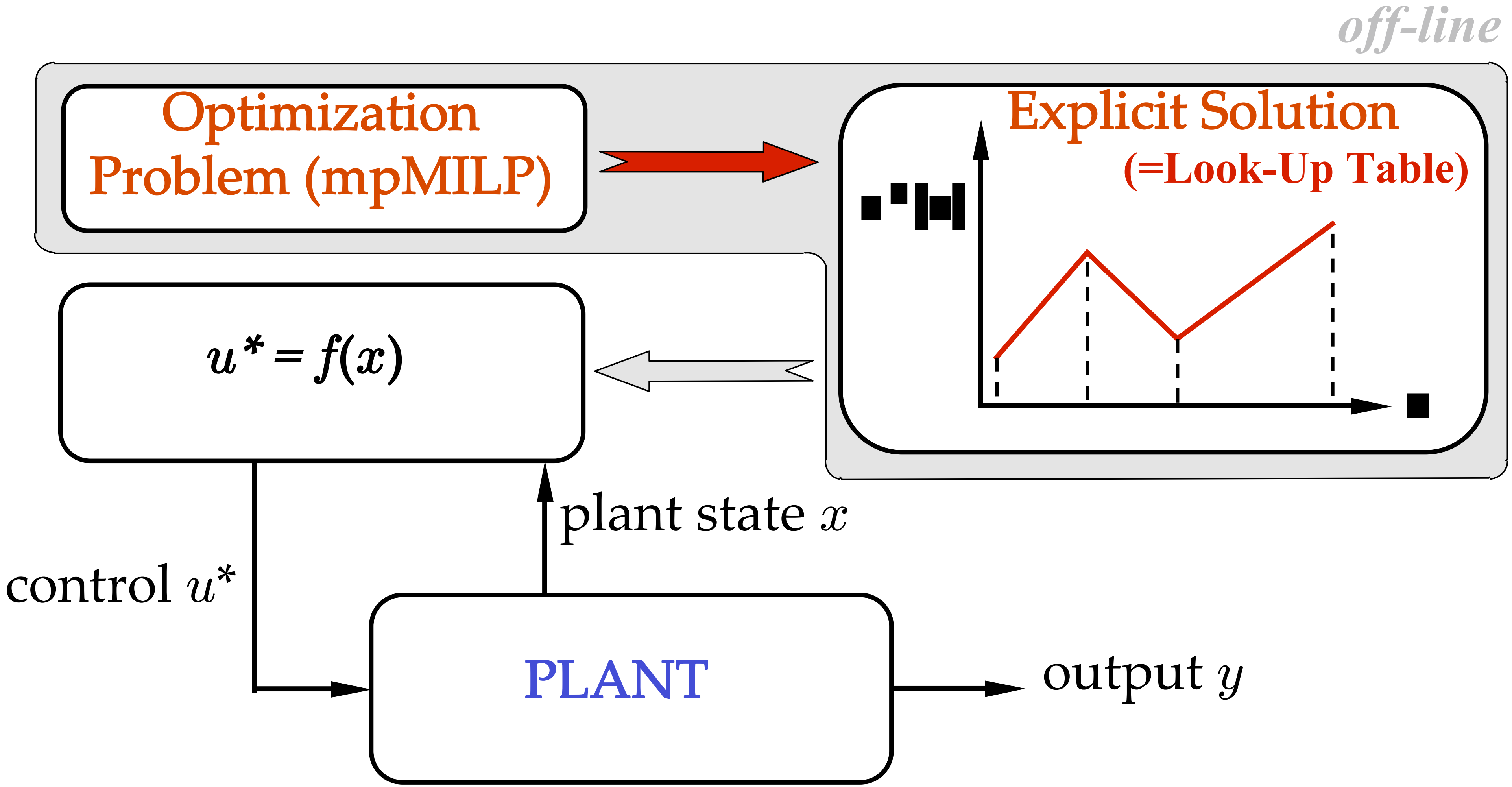
Receding Horizon Control

Receding Horizon Control
On-Line Optimization



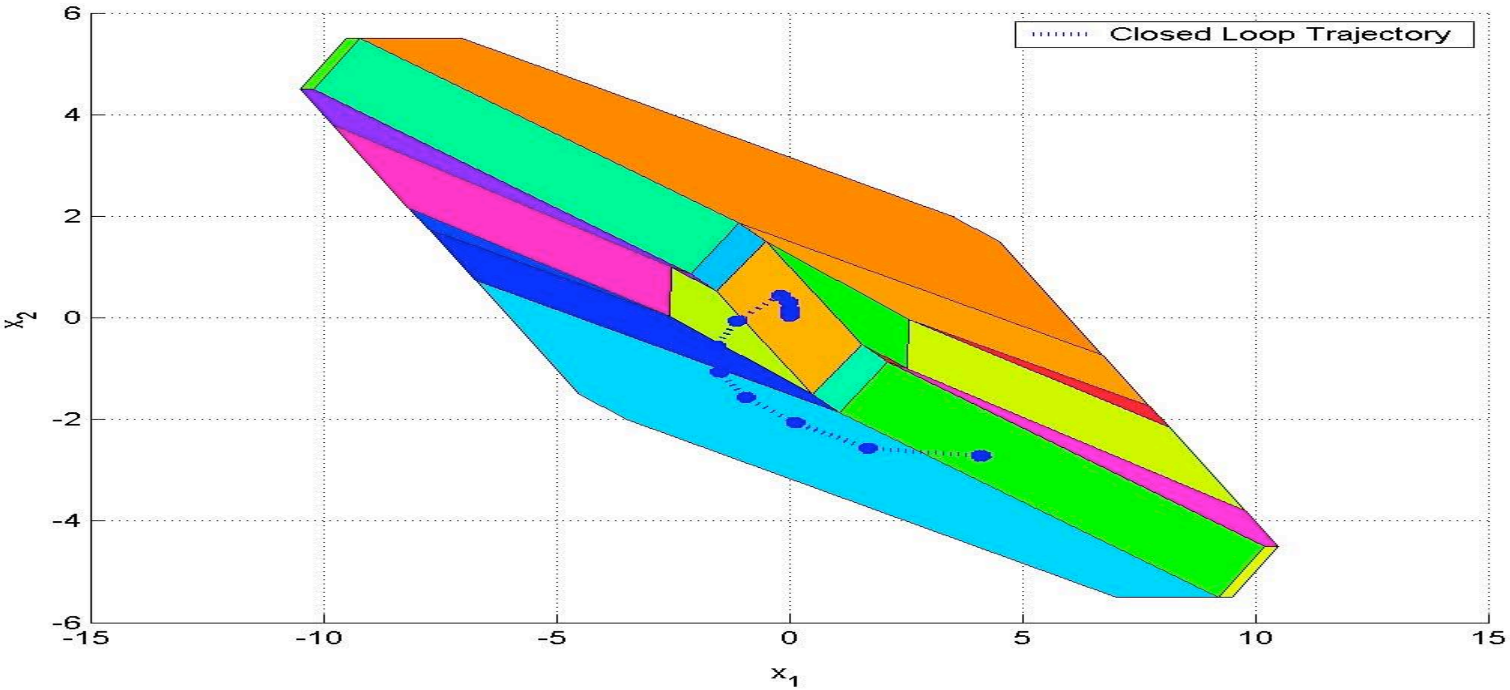
Receding Horizon Policy
Off-Line Optimization



Why Compute an Explicit Solution?

1. Understand the Controller

- Powerful
- Nice tool
- Visualization: e.g. saturation of the controller



Why Compute an Explicit Solution?

2. Fast Implementation

Parallelization Possible $$u(x) = F_r x + G_r, \quad \text{if } H_r x \leq K_r$$

versus

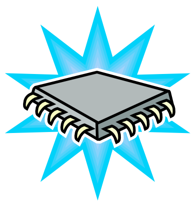
Interior-Point Methods
⇒ Sequential

$$J^*(x) := \min_U \|Px_T\|_p + \sum_{k=0}^{T-1} \|Qx_k\|_p + \|Ru_k\|_p$$

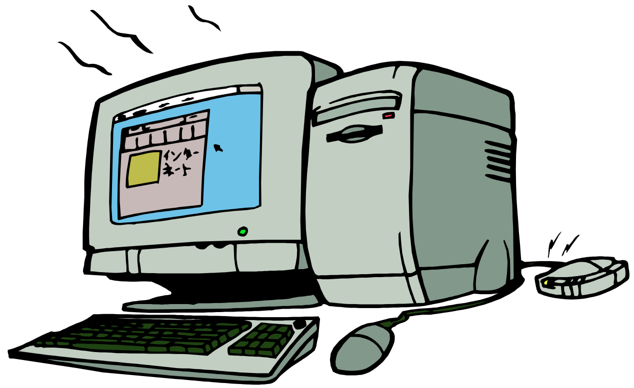
$$\text{subj. to} \begin{cases} x_0 = x, \\ x_{k+1} = Ax_k + Bu_k, \\ C^x x_k + C^u u_k \leq C^0 \end{cases}$$

Why Compute an Explicit Solution?

3. Cheap Implementation



versus



~$10

(Look-up-Table & μP)

~$10000

(PC & CPLEX)

Multi-parametric controllers

Algorithms have been developed for over 5 years:

…Minimization of linear and quadratic objectives

(Baotic, Baric, Bemporad, Borrelli, De Dona, Dua, Goodwin, Grieder, Johansen, Mayne, Morari, Pistikopoulos, Rakovic, Seron, Toendel)

…Minimum-Time controller computation

(Baotic, Grieder, Kvasnica, Mayne, Morari, Schroeder)

…Infinite horizon controller computation

(Baotic, Borrelli, Christophersen, Grieder, Morari, Torrisi)

…Computation of robust controllers

(Borrelli, Bemporad, Kerrigan, Grieder, Maciejowski, Mayne, Morari, Parrilo, Sakizlis)

⇒ Computation schemes are mature !

Multi-parametric controllers

PROs:

- Easy to implement
- Fast on-line evaluation
- Analysis of closed-loop system possible

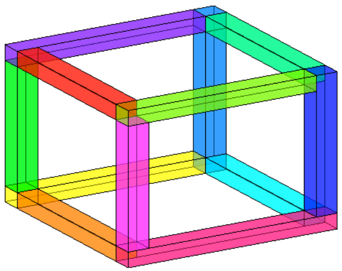
CONs:

- Number of controller regions can be large
- Off-line computation time may be prohibitive
- Computation scales badly.

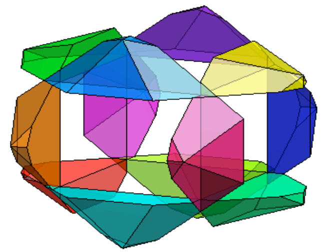
$\Rightarrow$ controller complexity is the crucial issue

Multi Parametric Toolbox

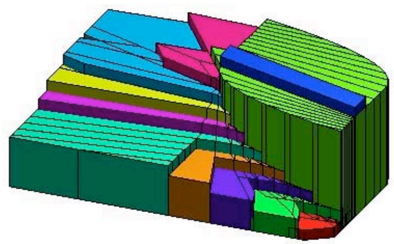
- All results and plots were obtained with the MPT toolbox



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



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



Multi Parametric Toolbox

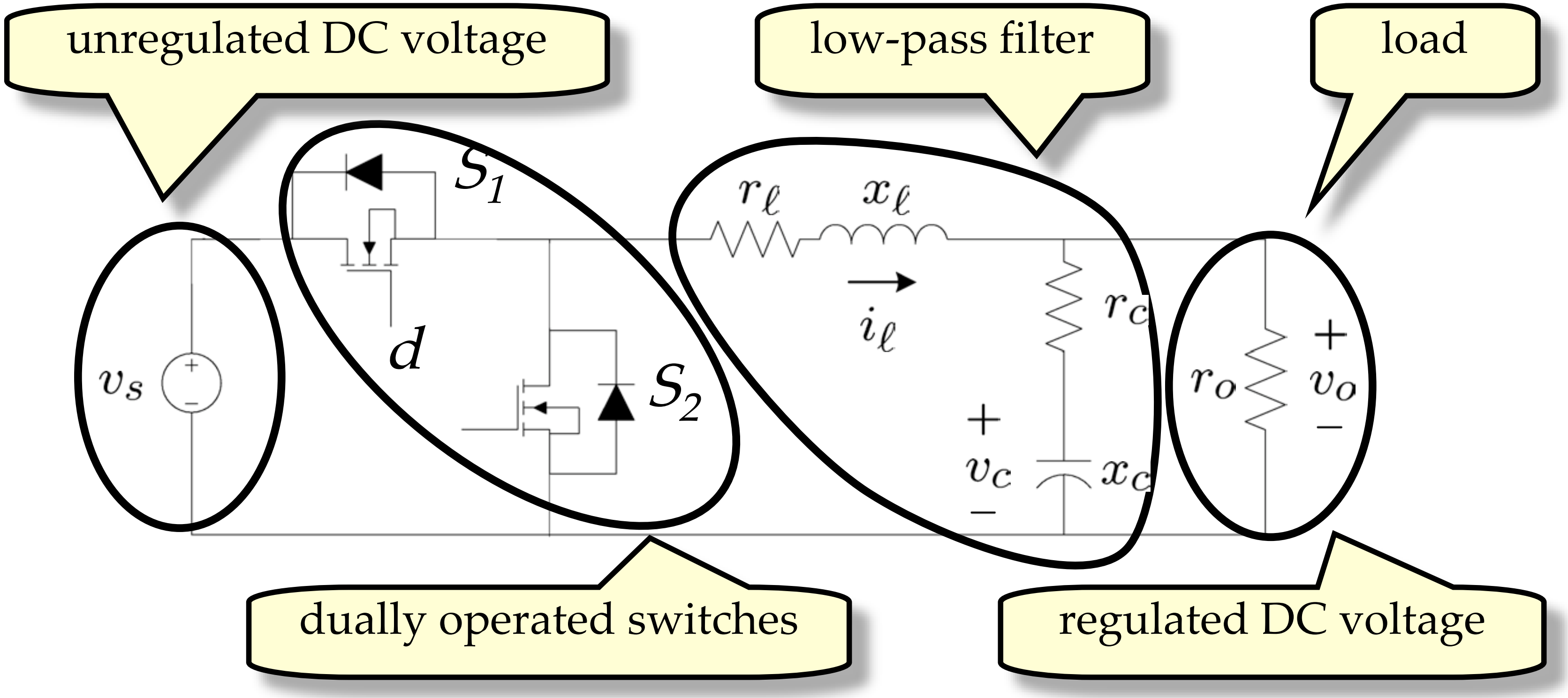
4000+ downloads

Rated 4.5 / 5 on `mathworks.com`

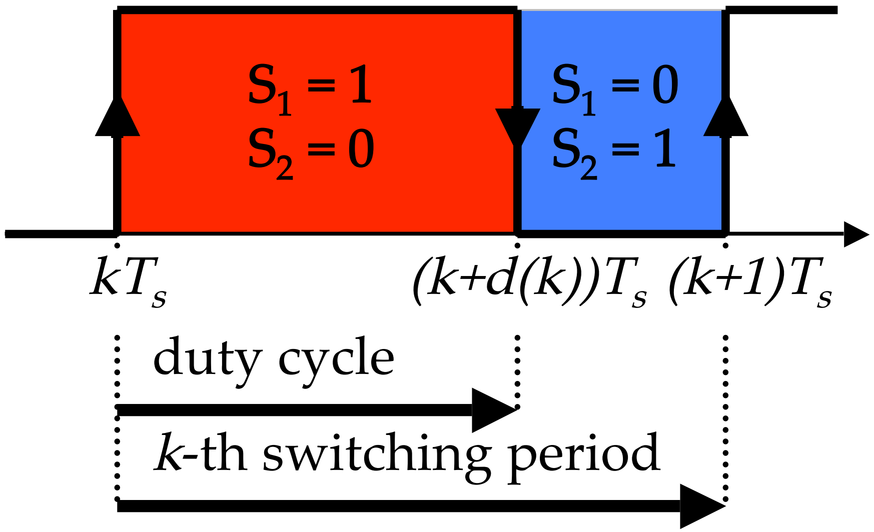
Switch-mode DC-DC Converter

Switched circuit: supplies power to load with constant DC voltage

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

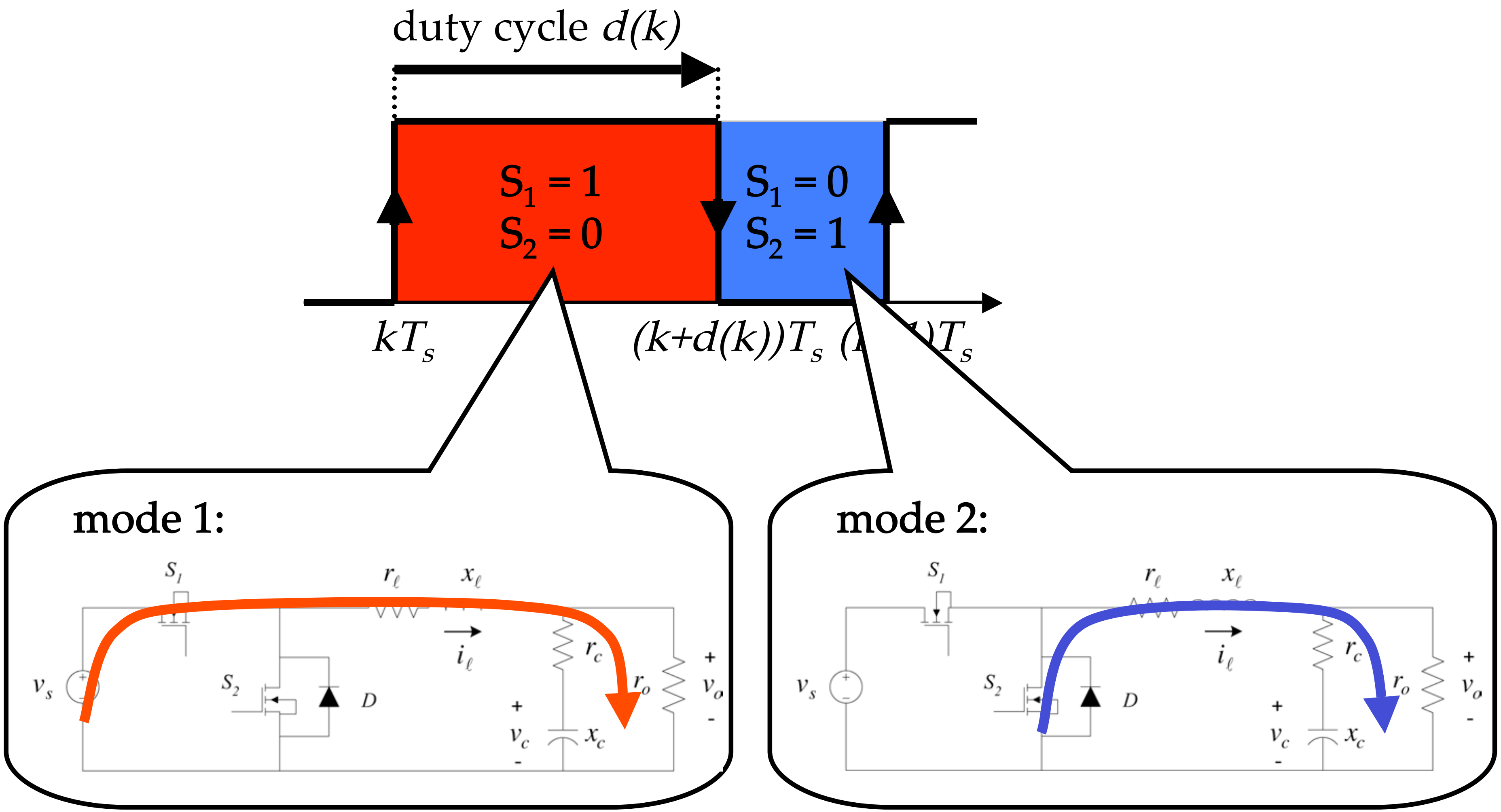


Operation Principle



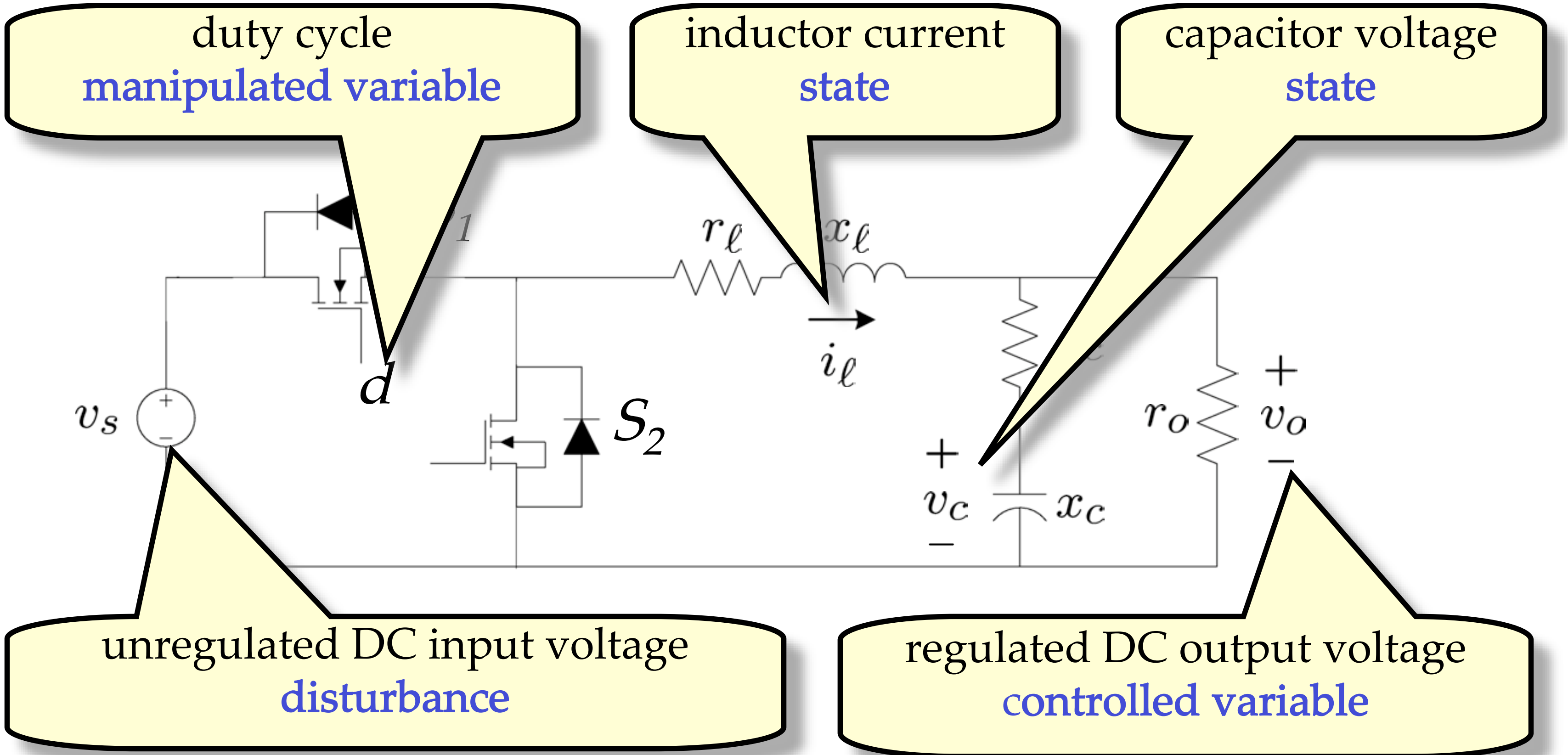
- Length of **switching period** T_s constant ***(fixed switching frequency)***
- **Switch-on** transition at kT_s, $k \in N$
- **Switch-off** transition at $(k+d(k))T_s$ ***(variable pulse width)***
- **Duty cycle** $d(k)$ is real variable bounded by 0 and 1

Mode 1 and 2



Control Objective

Regulate DC output voltage by appropriate choice of duty cycle



Control Objectives

Minimize (average) **output voltage** error and changes in **duty cycle**

Respect **constraint** on current limit

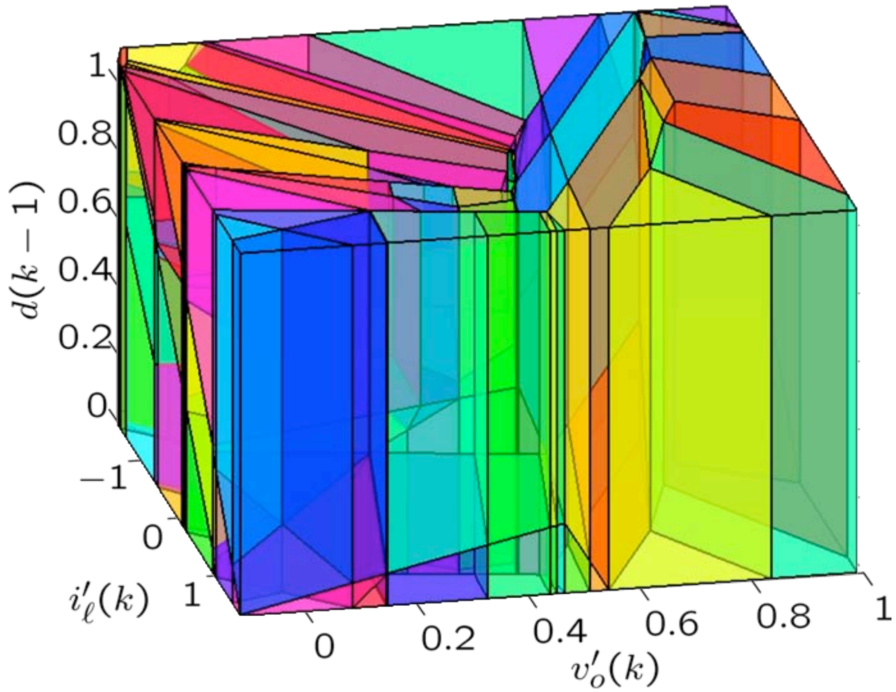
Translate in **Receding Horizon Control** (RHC) problem

State-feedback Controller: Polyhedral Partition

PWA state-feedback control law:

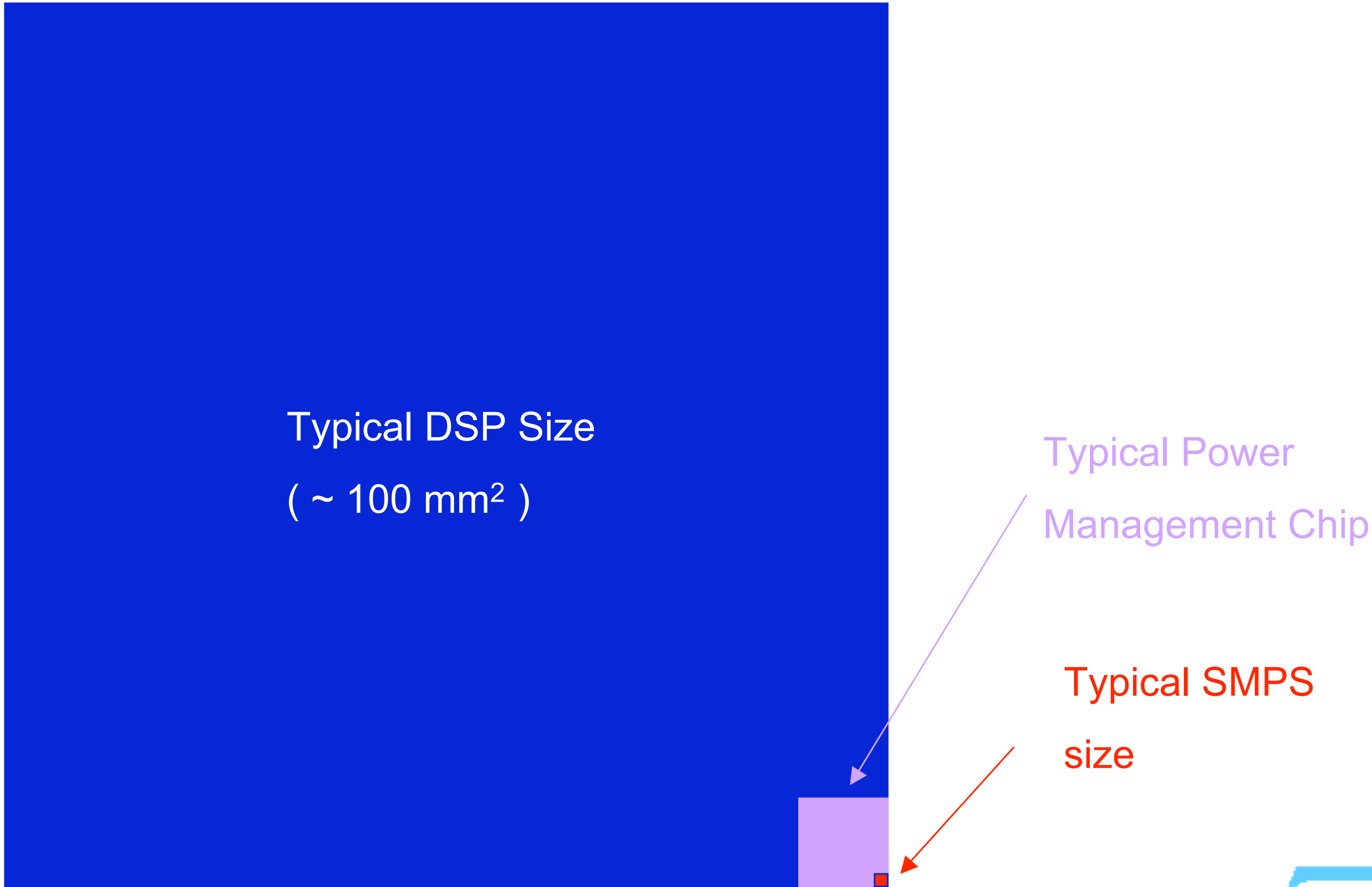
computed in 100s using the MPT toolbox

121 polyhedra after simplification with optimal merging



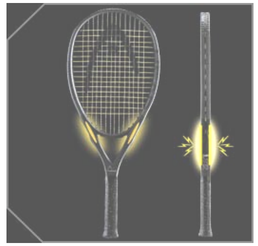
Colors correspond to the 121 polyhedra

DSP vs. PM IC

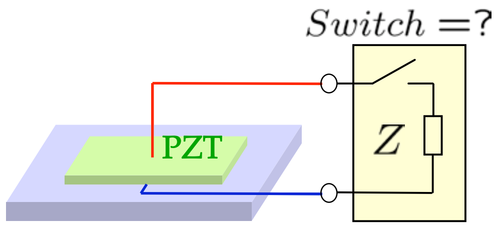

Typical DSP Size
(~ 100 mm2)
Typical Power
Management Chip
Typical SMPS
size

Smart Damping Materials

Niederberger, Moheimani

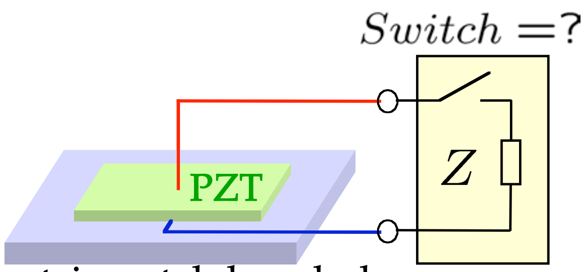


- **Demands**
  - Device *suppresses vibration*
  - *External power* source for operation is not required
  - *Weight* and *size* of the device have to be kept to a minimum



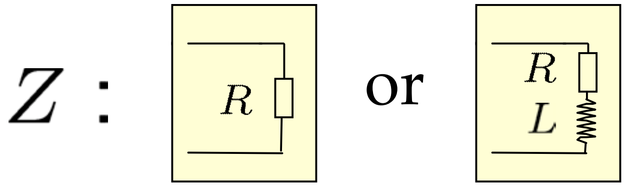
- **Idea**
  - *Switched Piezoelectric (PZT) Patches*
- **Problem**
  - *What is the optimal switching law for optimal vibration suppression?*

Idea of Shunt Damping



Piezoelectric patch bonded on mechanical structure

Shunt Circuit



- **How does it work?**
  - Piezoelectric device converts mechanical energy into electrical energy.
  - Shunt Circuit dissipates and stores electrical energy.
  - Stored energy is supplied back to the mechanical system at the right time.
- **Problem**
  - How to switch *optimally*?

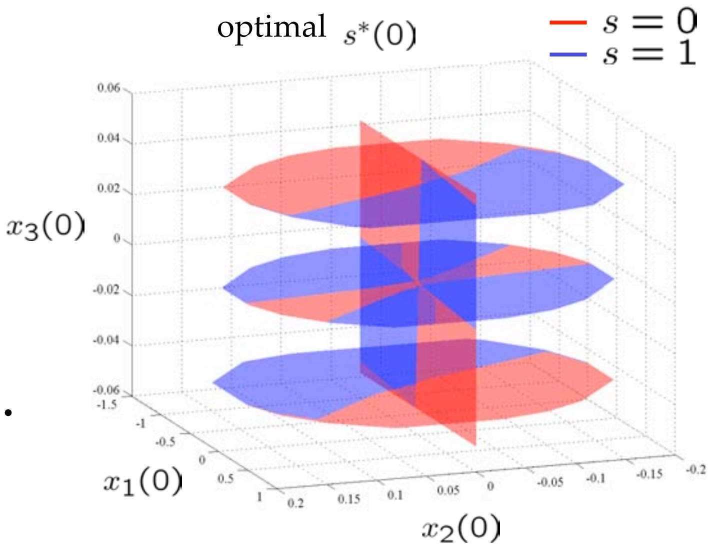
Optimal Feedback using Multi-Parametric Programming

- Optimal $s^*(0)$ as a function of state x_0
  - Multi-parametric programming

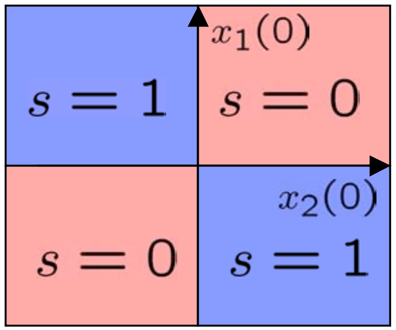
$$J_N^*(x(0)) = \min_{s_0,\ldots,s_{N-1}} \sum_{k=0}^{N-1} \| v(k) \|_2^2$$

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

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



- After some simplifications



$x_2 \sim -x_3$

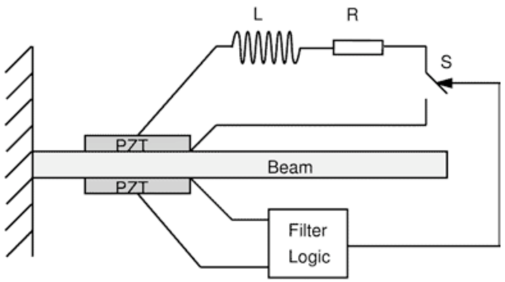
$$x_2 = x$$
$$x_1 = -c\frac{dx}{dt}$$

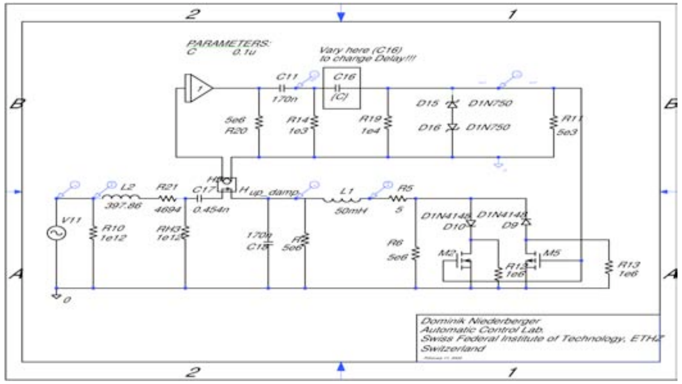
$$x \cdot \dot{x} \ge 0 \Rightarrow s = 1$$
$$\text{else} \quad s = 0$$

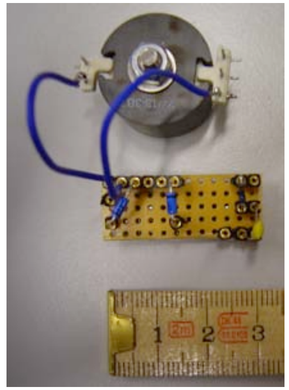
Former Heuristic Controller
[Clark et al., J.Int.Mat.S.S. 2000]

Experimental Results

- Implementation as Autonomous Circuit
  - Switching circuit without external power source



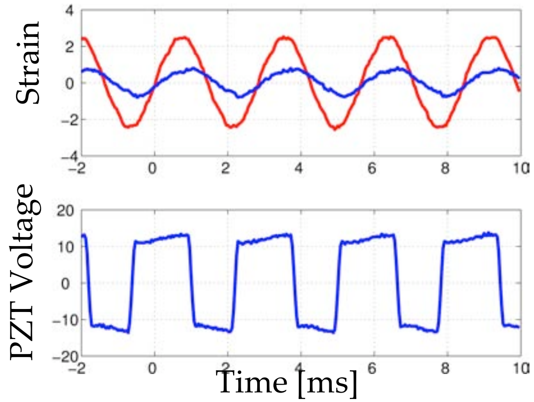




- Experiment with a Beam

(One-side clamped beam)

Results

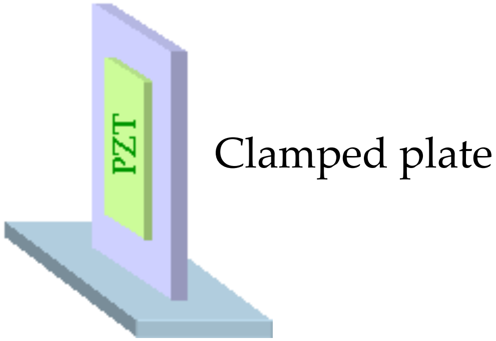


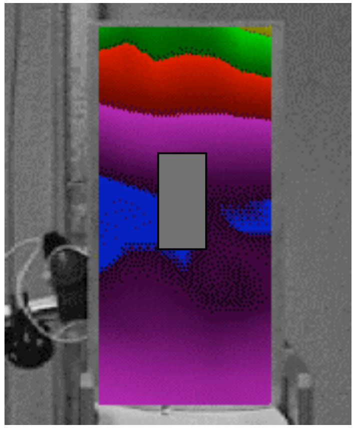
– 60% vibration suppression

uncontrolled
Switching Circuit (Autonomous)

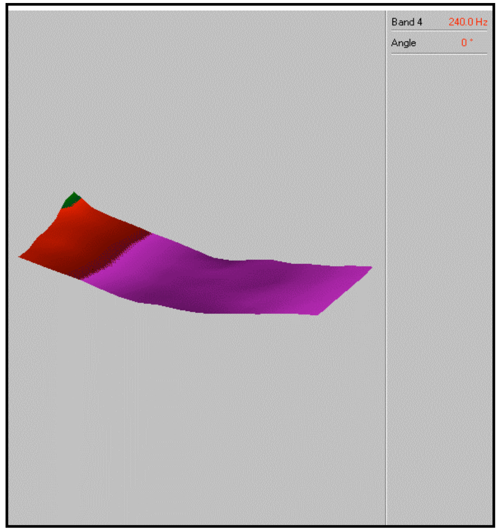
Experiments with a Plate

- **No Shunt Damping**
  (Open system)



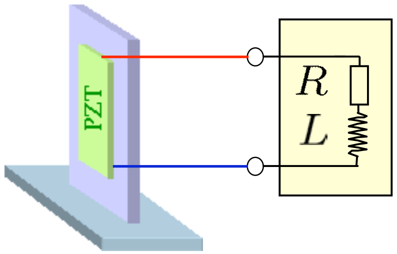


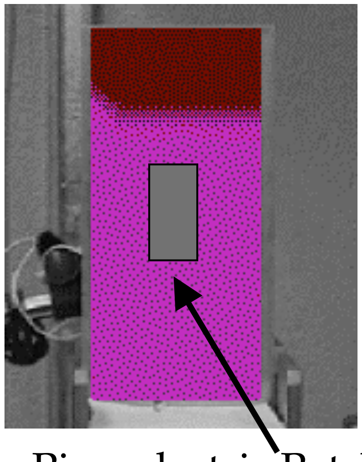
Measured Velocity



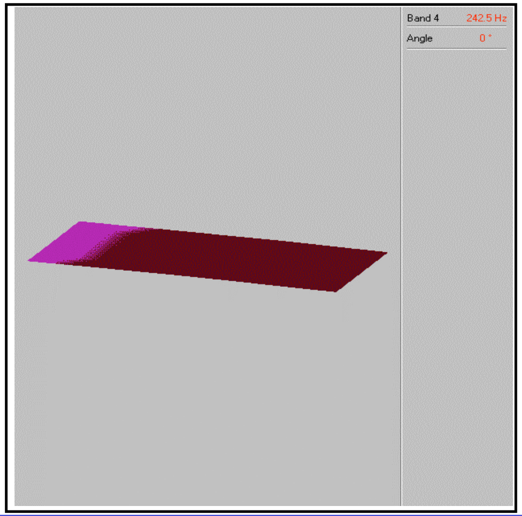
Measured Mode Shape

- **With Shunt Circuit**





Piezoelectric Patch



Application: Brake Squeal Reduction

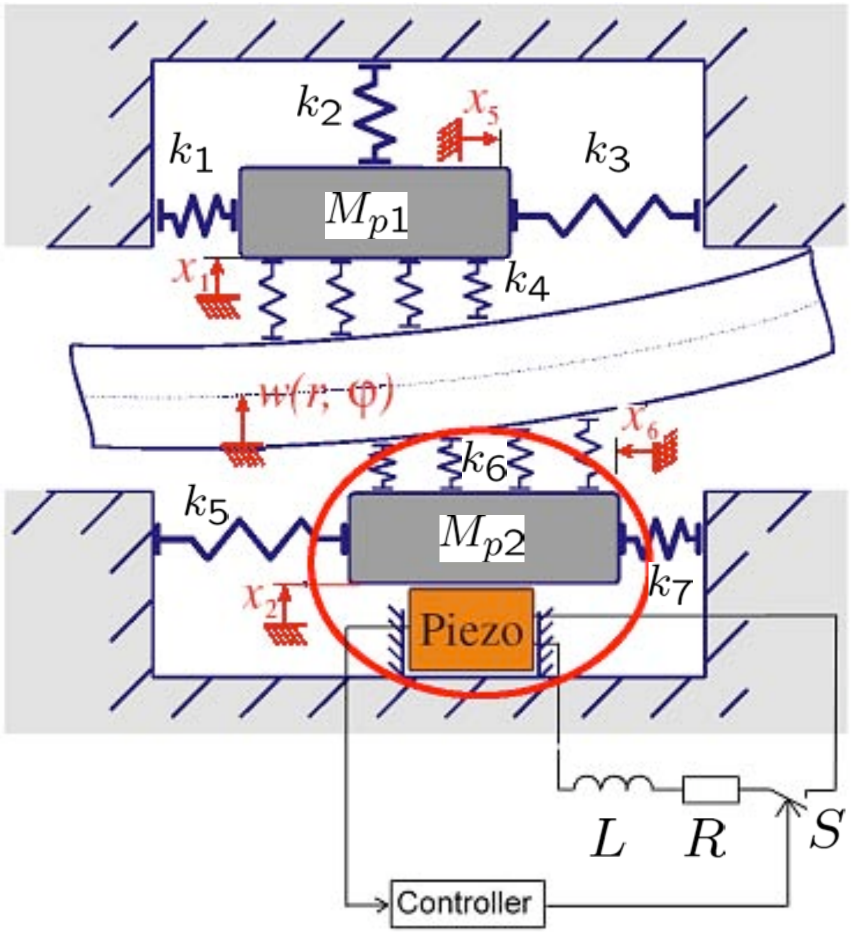
INSTITUT FÜR MECHANIK der Universität Hannover

Neubauer, Popp

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

Brake Squeal Reduction using Shunt Control

- Vibration reduction
  - Piezoelectric actuator between brake pad and calliper
  - Switching shunt control

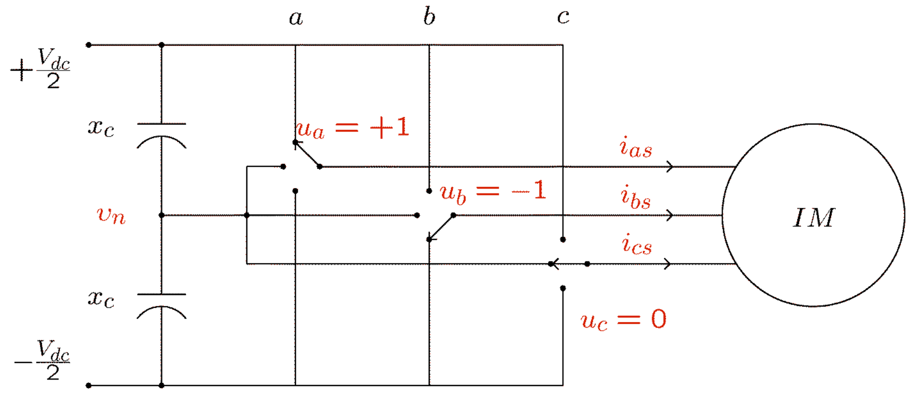


- Advantages
  - Tracks resonance frequency
  - Cheap solution
  - No electrical power required

Direct Torque Control

Physical Setup:

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



Control Objectives:

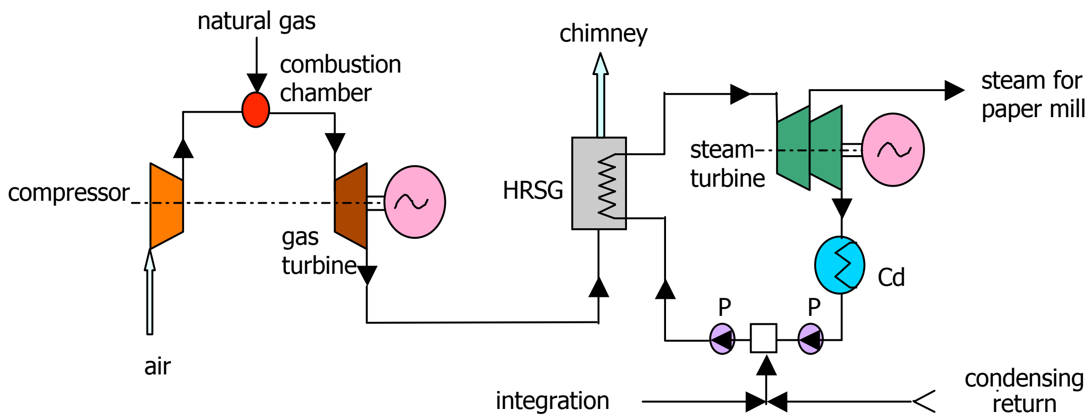
- Keep torque, stator flux and neutral point potential within given bounds
- Minimize average switching frequency (losses)

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

Control of Cogeneration Power Plants

Physical Setup:

- Gas and steam turbines
- Different start-ups
- Logic implications
- Operating constraints



Control Objective:

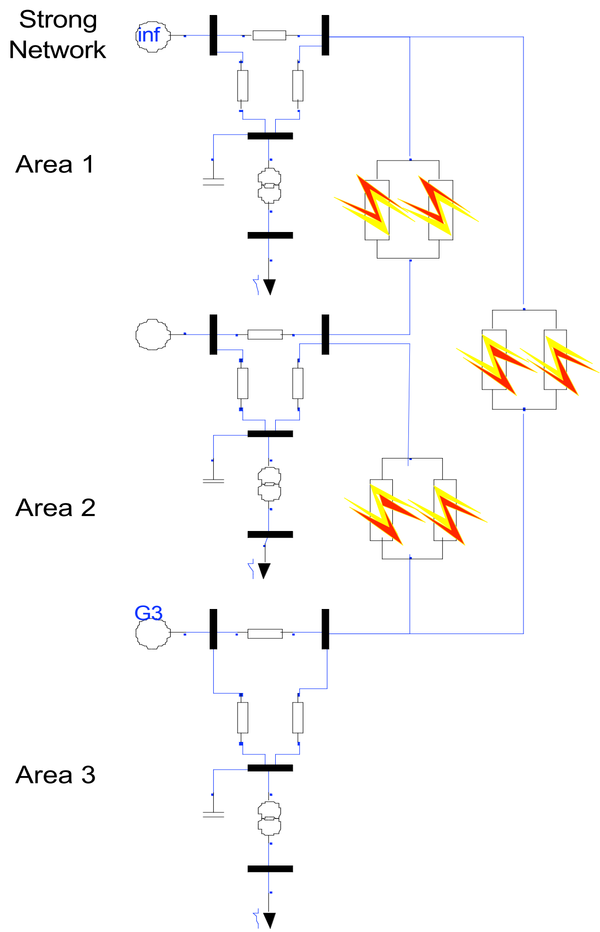
- Maximize profit (based on predicted profile of electricity price)

Emergency Voltage Control in Power Systems

ABB

Physical Setup:

- 3 area transmission system
- Integer control inputs
- Line outages trigger nonlinear network dynamics



Control Objectives:

- Stabilize voltages
- Minimize disruptive control actions (load shedding)

Voltages effectively maintained within security limits

Control of Anaesthesia

INSELSPITAL
UNIVERSITÄTSSPITAL BERN

Physical Setup:

- Patient undergoing surgery
- Analgesic infusion pump

Control Objectives:

- Minimize stress reaction to surgical stimulation (by controlling mean arterial pressure)
- Minimize drug consumption

Excellent performance of administration scheme,
mean arterial pressure variations kept within bounds

Control of Thermal Print-Heads

Physical Setup:

- Thermal print-head
  with ~ 1400 heat elements
- Binary control inputs
- Printing on a wide range
  of materials

Control Objectives:

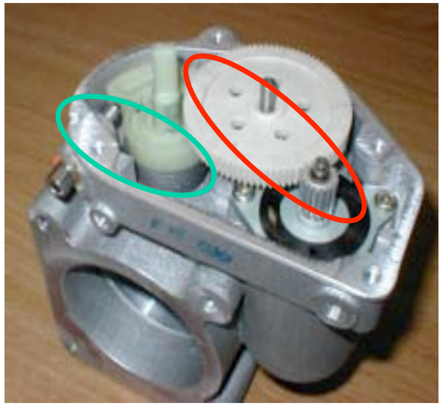
- Maximize printout quality
- Achieve robustness to parameter variations

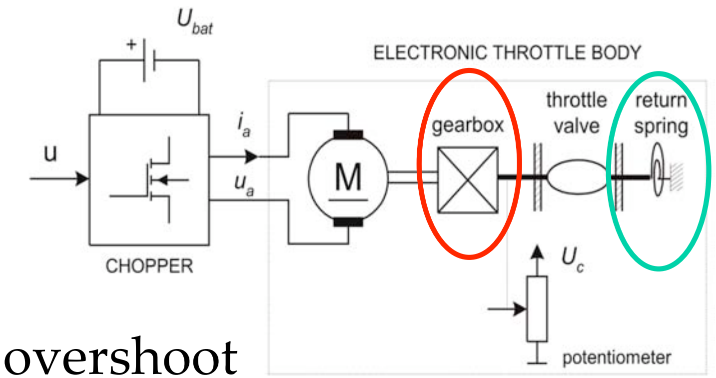
90% quality gain over traditional controllers [ANSI X3.182-1990];
Straight-forward design method for print-head controller

Electronic Throttle Control

Physical Setup:

- Valve (driven by DC motor) regulates air inflow 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.

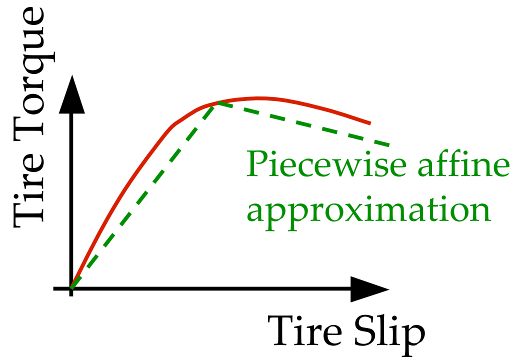
Traction Control

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 tire slip close to the desired value

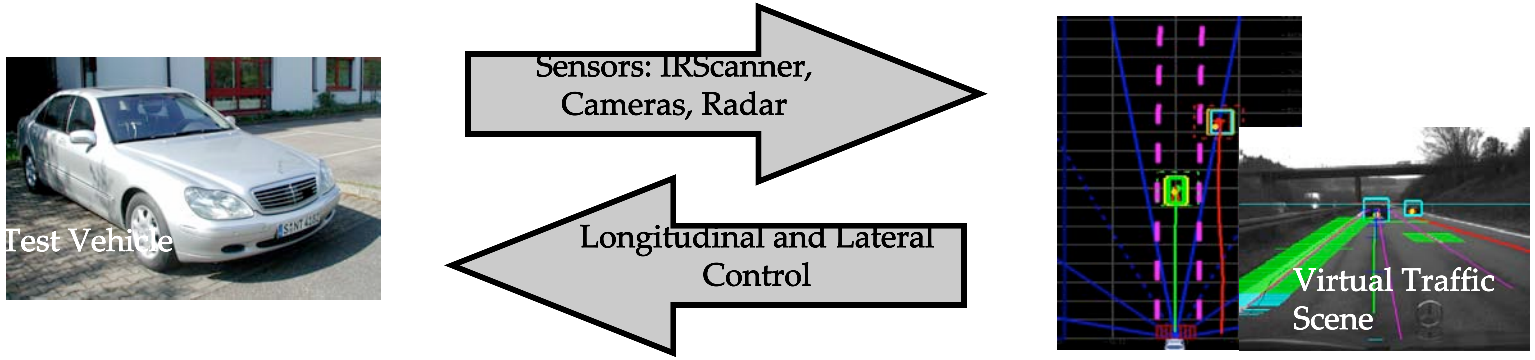


Experimental results: 2000 Ford Focus on a Polished Ice Surface;
Receding Horizon controller with 20 ms sampling time

Adaptive Cruise Control

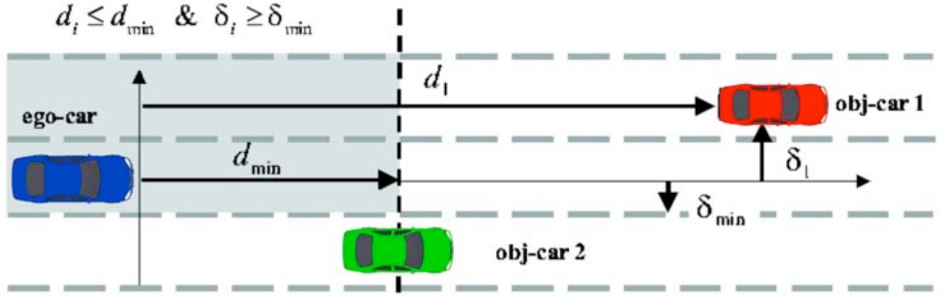
DAIMLERCHRYSLER

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

Conclusions

- Process Control has been leading many important developments.

- Process Control tools can have significant impact in a wide range of other application areas.