Control and Operations

Manfred Morari

In memory of Reuel Shinnar 1923-2011

FOCAPO / CPC 2012, Savannah

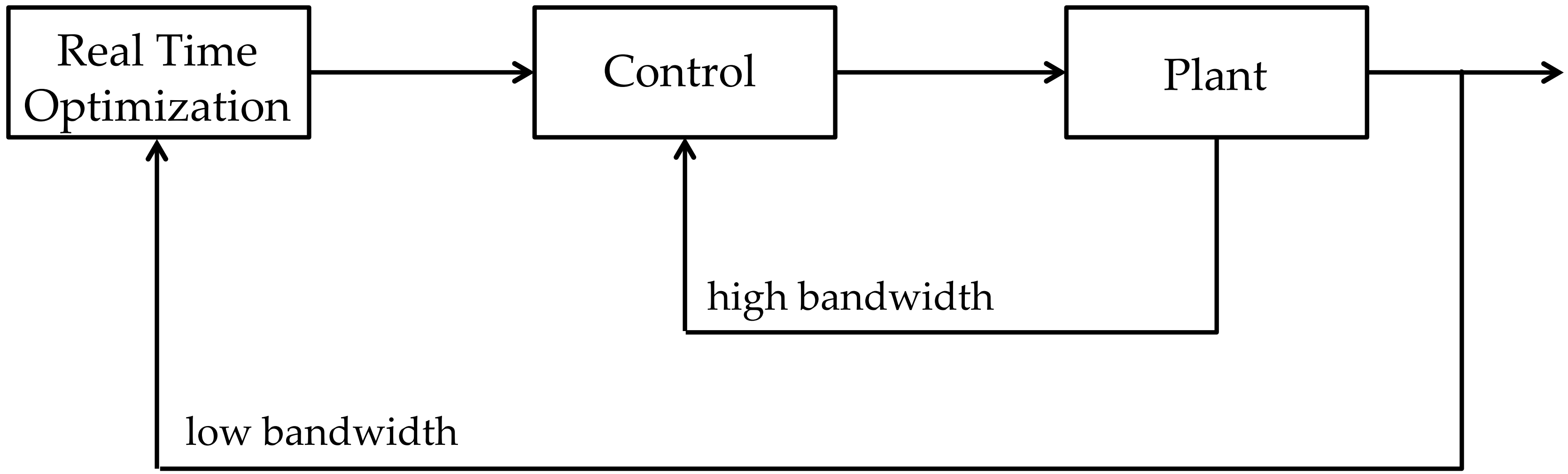
Automatic Control Laboratory, ETH Zürich

Control and Operations

- Goals
  - Control for operability
  - Operations for economics
- Design Tools
  - Similar optimization techniques
- Is combination elusive?
  - Optimal feedback controllers with economic objectives, or
  - Real-time dynamic economic optimization

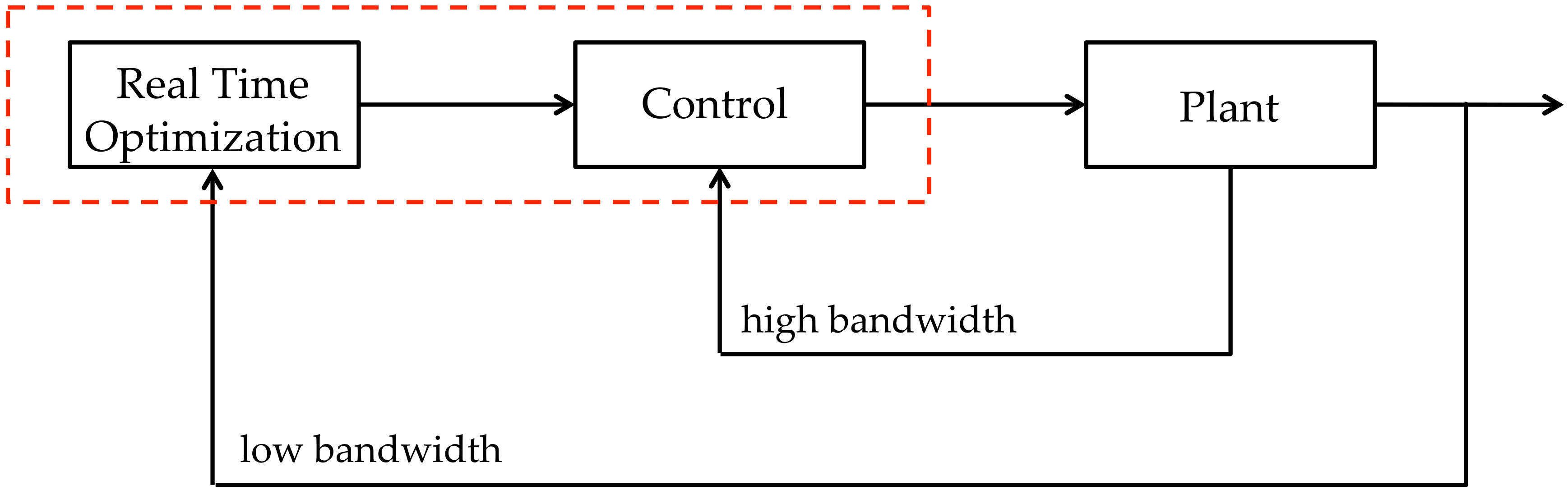
Edgar, CompChE 2004

Control and Operations



Control and Operations

Is this a good idea?



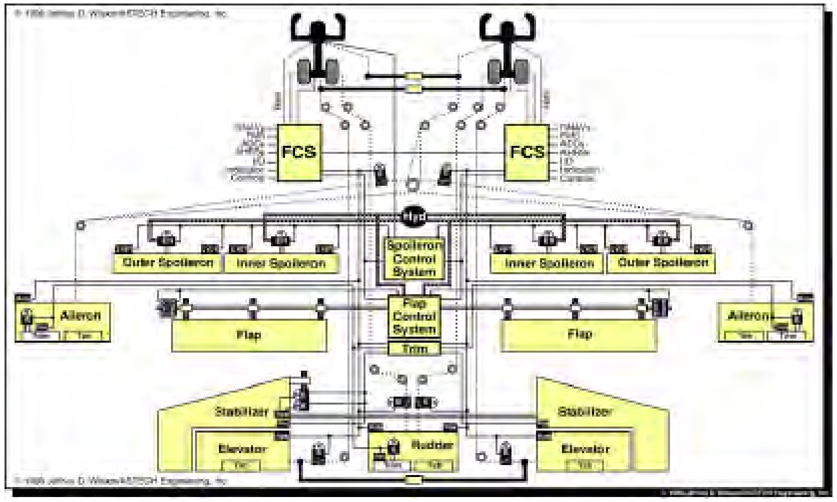
Is it just a question of time scale separation and computational complexity?

Controllers with economic objectives

Often the wrong idea

Automotive and aircraft control

- Control designed according to stringent safety specs
- Control layer must not be confused by fuel efficiency
- Operations and control are strictly hierarchical



Car on Autopilot

the institute alert

IEEE

The IEEE member news source

10 January 2012

TECH FOCUS

Crash-Free Commutes

There are about 33 000 traffic deaths annually in the United States and 39 000 in European Union countries. Ninety percent of roadway deaths could be avoided simply by making cars smarter, according to Alberto Broggi and Azim Eskandarian of the IEEE Intelligent Transportation Systems Society. Their solution: Get rid of the drivers and let the cars drive themselves. Learn more

Controllers with economic objectives

Idea that did not catch on

The Use of Economic Performance Measures to Synthesize Optimal Control Systems

Prasad S. R. K. Chintapalli and J. M. Douglas*

University of Massachusetts, Amherst, Massachusetts 01002

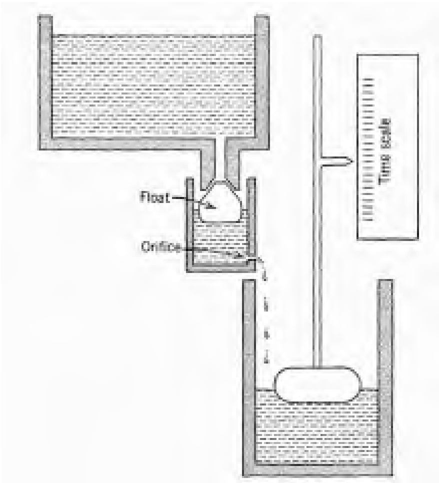
Care must be taken in the synthesis of control systems which maximize the profitability of a plant because optimization equations do not always have a solution. When a typical process was constrained to instantaneously give the design product rate, a linear feedback controller was almost equivalent to the most profitable controller and was superior to most other multivariable systems. Perturbation techniques can be used to assess the significance of the process nonlinearities and to develop multivariable, nonlinear feedback controllers that are simple to implement.

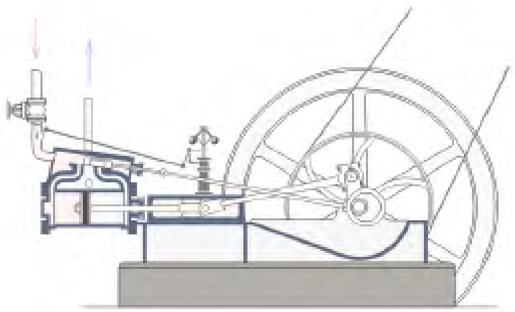
Ind. Eng. Chem., Fundam., Vol. 14, No. 1, 1975

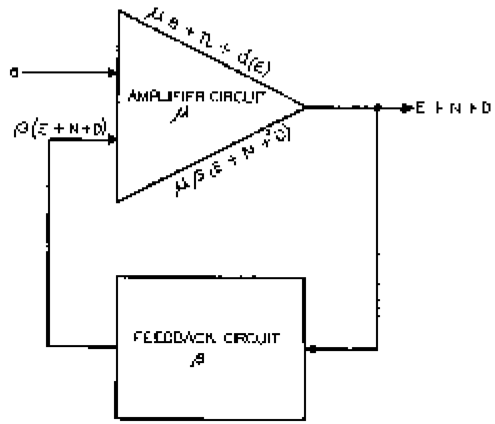
Outline

- Purpose of Feedback
- MPC Practice
- "Separation theorem" for Control and Operations
- Importance of real world problems

Early History of Control







Objectives:

- Stability (Maxwell, Routh, Stodola, Hurwitz,..)
- Remove effect of uncertainty (Bode, Nyquist, Nichols,...)

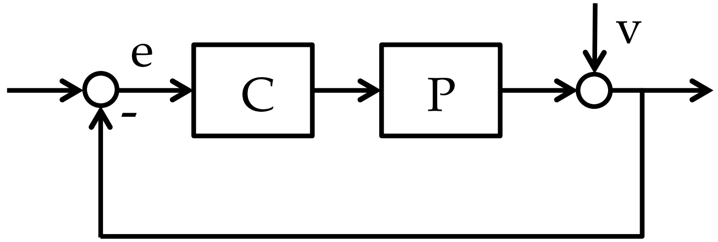
- Know what you don't know!

Controller Synthesis – Linear Systems

LQ optimal control: Wiener, Kalman

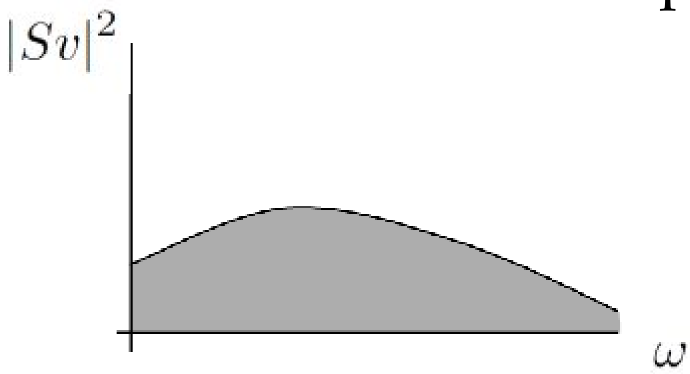
$$e = \frac{1}{1+PC} v = Sv$$

$$\int_0^\infty e^2 \mathrm{d}t \triangleq \|e\|_2^2$$



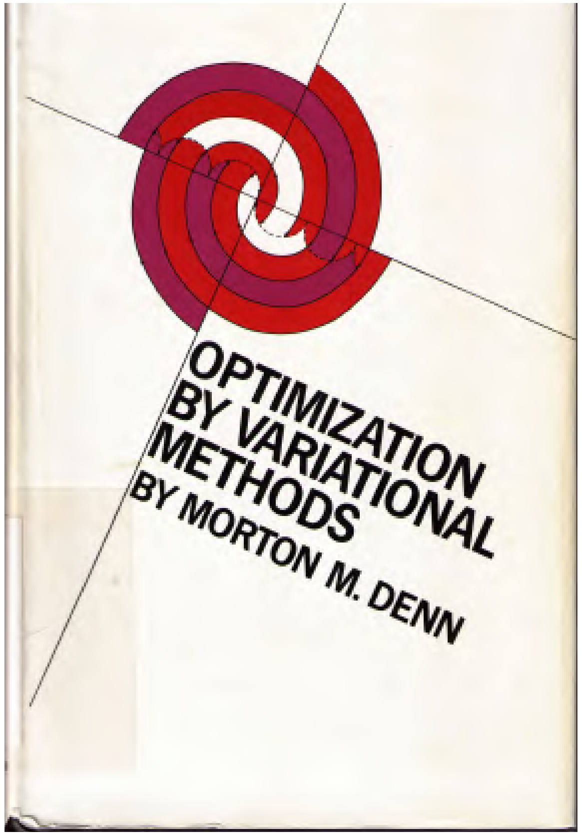
H$_2$: $$\min_C \|e\|_2^2 = \min_C \|Sv\|_2^2 = \min_C \frac{1}{2\pi} \int_{-\infty}^{\infty} |S(j\omega)\, v(j\omega)|^2 \, \mathrm{d}\omega$$

Optimization for *one* particular input v

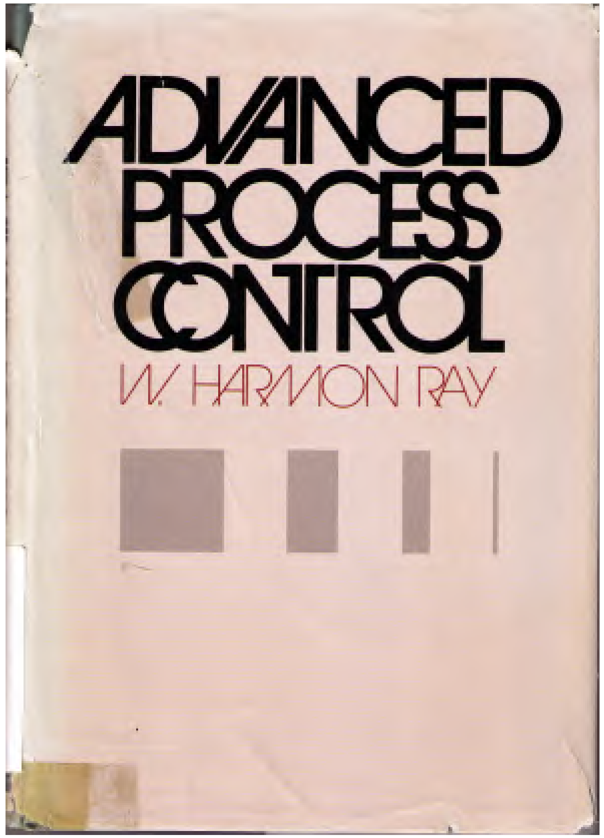


Controller Synthesis – Nonlinear Systems

- Pontryagin, control vector parametrization,
  Dynamic Programming (Hamilton-Jacobi-Bellman)



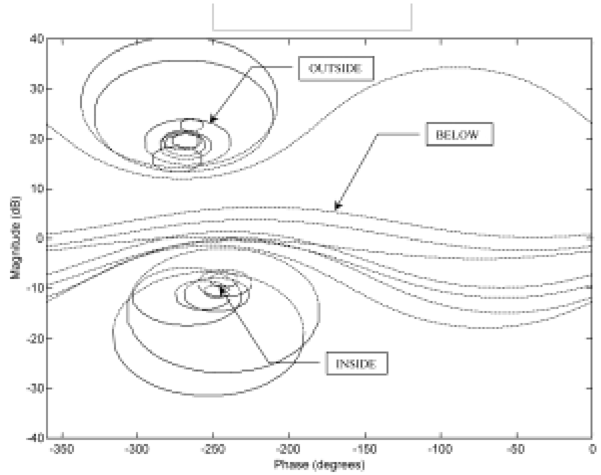
1969



1981

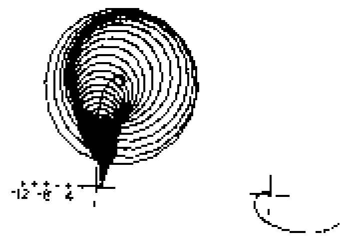
Controller Synthesis – Linear Systems

In the spirit of Bode and Nichols

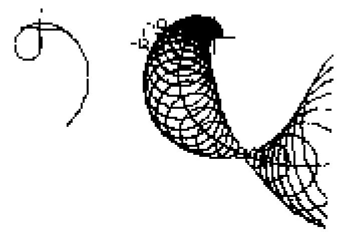


- Quantitative Feedback Theory QFT
  (Horowitz, 1963)

- Inverse Nyquist Array
  (Rosenbrock , 1969)



- Characteristic Loci
  (Kouvaritakis & MacFarlane, 1974)



=> Ideas did not catch on

Erik Ydstie – CAST Award 2007

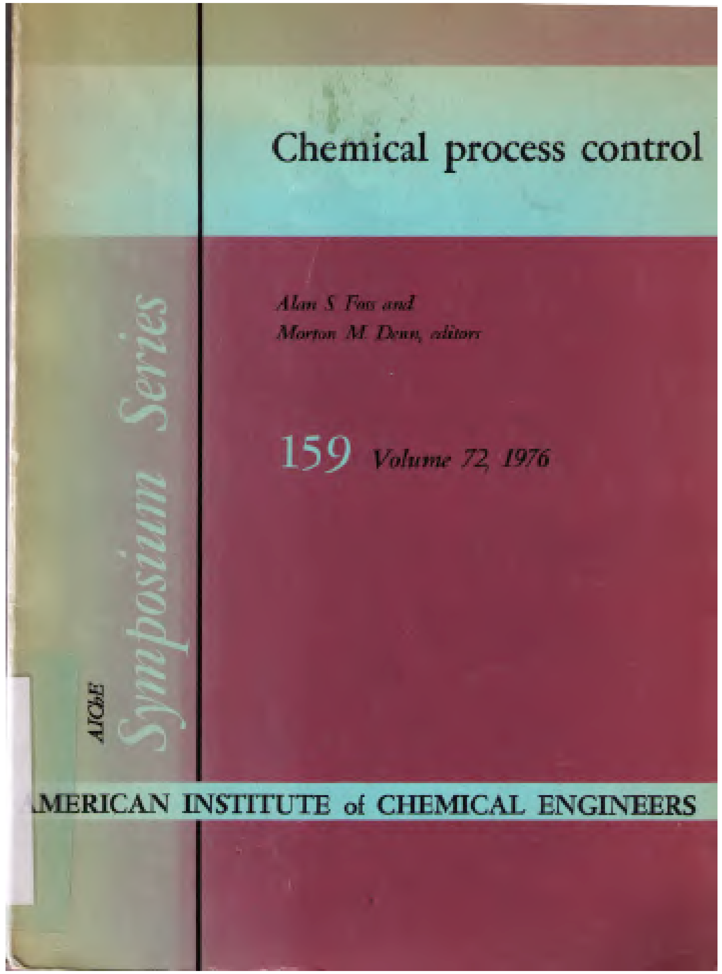
Theory-Practice Gap

Main theme of CPC I in 1976

Explosive development of theory had taken place

- Industry did not understand theory
- Academia had no clue about real controller design

Exceptions: Aström, Gilles, Balchen,…



CPC 1 Editorial (Mort Denn, Alan Foss)

The status of chemical process control has been a subject of intense controversy in recent years. We are now two decades into the era of modern control theory, and many theorists, pointing to the apparent advanced applications in the aerospace industry, wonder at the slow pace of application in the process industries. Control practitioners conventionally argue that the modern theory is not relevant to chemical process control and that classical techniques and designer experience will always lead to a satisfactory and perhaps optimal solution. Publications by members of these groups have done little to establish a satisfactory dialogue; few practitioners have more than a superficial knowledge of modern control theory, and modern control researchers have produced few convincing examples of successful process applications.

Theory-Practice Gap: Model Uncertainty

- Control Objective did not address robustness / uncertainty directly. Indirect effect of tuning parameters was not understood (Horowitz, Shinnar, J. Doyle,…)

8 Ind. Eng. Chem. Process Des. Dev., Vol. 18, No. 1, 1979

Design of Sampled Data Controllers

Zalman J. Palmor[1] and Reuel Shinnar*

Department of Chemical Engineering, The City College of The City University of New York, New York, New York 10031

linearized models. A good design procedure must take into account that there is a finite but unknown deviation between the model used for design and the real description of the process. This also applies to probabilistic models of the disturbance.

5. The Controller Must Be Reasonably Insensitive to Changes in System Parameters. It must be stable and perform well over a reasonable range of system parameters.

Theory-Practice Gap: Model Uncertainty

Guaranteed Margins for LQG Regulators

JOHN C. DOYLE

Abstract—There are none.

Introduction

Considerable attention has been given lately to the issue of robustness of linear–quadratic (LQ) regulators. The recent work by Safonov and Athans [1] has extended to the multivariable case the now well-known guarantee of 60° phase and 6 dB gain margin for such controllers. However, for even the single-input, single-output case there has remained the question of whether there exist any guaranteed margins for the full LQG (Kalman filter in the loop) regulator. By counterexample, this note answers that question; there are none.

A standard two-state single-input single-output LQG control problem is posed for which the resulting closed-loop regulator has arbitrarily small gain margin.

IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. AC-23, NO. 4, AUGUST 1978

Theory-Practice Gap: Model Uncertainty

Effect of Design on the Stability and Control of Fixed Bed Catalytic Reactors with Heat Feedback. 1. Concepts

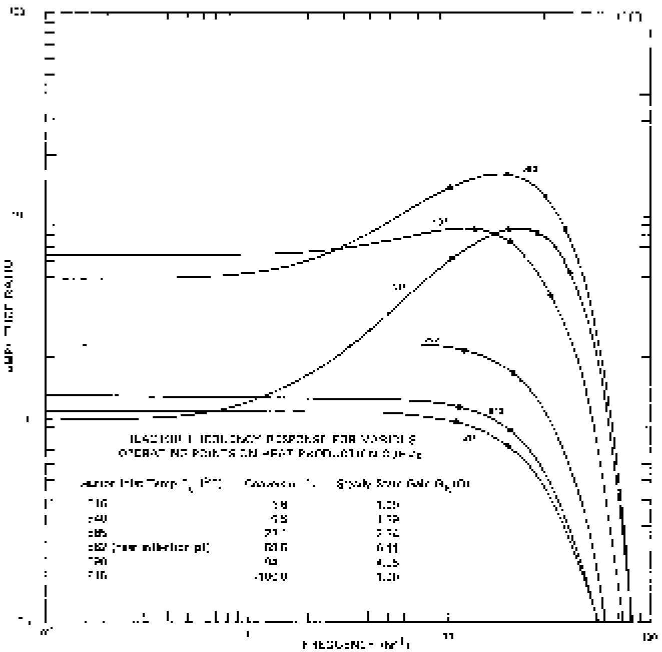
Jeffrey L. Silverstein* and Reuel Shinnar

Chemical Engineering Department, The City College of New York, City University of New York, New York, New York 10031

A problem with criterion (5) is that phase lags are difficult to estimate; they depend strongly on an exact piping configuration. One solution is to use a more conservative stability criterion which demands that

$$|G^*(\omega)| < 1.0 \qquad \text{all } \omega \tag{5a}$$

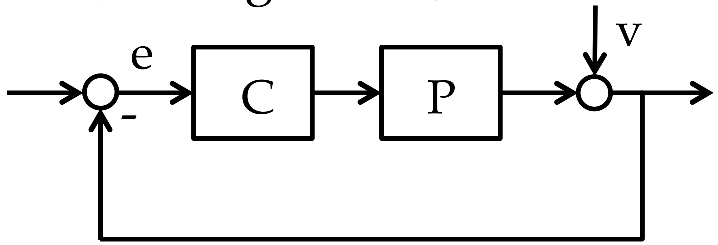
This is a sufficient but not a necessary condition for stability. However, in practice, for this type of reactor it is really not very conservative as we will see later.



Theory-Practice Gap resolved

H_∞ optimal control and Structured Singular Value μ:
Zames, Helton, Doyle, Stein, Francis, Safonov, Khargonekar, Tannenbaum,…

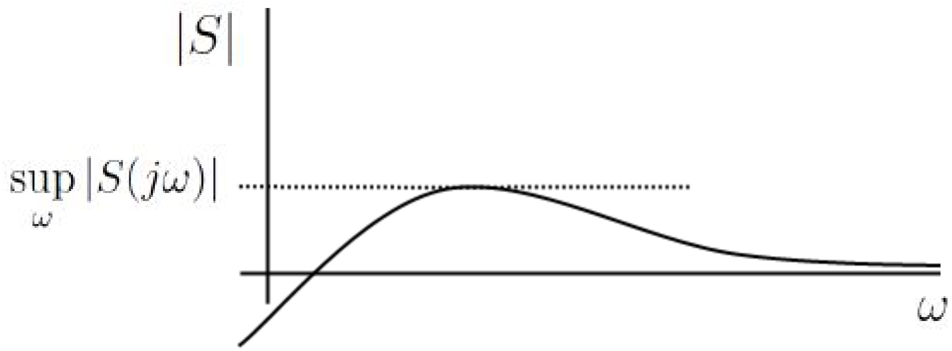
$$e = \frac{1}{1+PC} v = Sv$$



Set $\mathcal{V} := \{v : \|v\|_2^2 \leq 1\}$

H_∞: $\min_C \sup_{v \in \mathcal{V}} \|e\|_2 = \min_C \sup_{v \in \mathcal{V}} \|Sv\|_\infty \leq \min_C \sup_\omega |S(j\omega)|$

Optimization for *set* $\mathcal{V}$ of inputs v



Theory-Practice Gap resolved

IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 33, NO. 12, DECEMBER 1988

Robust Control of Ill-Conditioned Plants: High-Purity Distillation

SIGURD SKOGESTAD, MANFRED MORARI, MEMBER, IEEE, AND JOHN C. DOYLE

Axelby Award for Best Paper in IEEE TAC, 1990

Zames (1996):

- Feedback reduces the effect of model uncertainty
- Model uncertainty limits the performance of feedback

Optimal Feedback Control - Conclusions

- Uncertainty/robustness determine achievable performance
- Optimal feedback control was largely a failure until robustness (considerations) were made explicit in the objective function and/or the design process.

Outline

- Purpose of Feedback
- MPC Practice
- “Separation theorem” for Control and Operations
- Importance of real world problems

Model Predictive Control Theory

Propoi, A. I. (1963) *Automation and Remote Control*

"Use of LP methods for synthesizing sampled-data automatic systems"

- On-line use of simulation models for control
- On-line optimization
- Moving (receding) horizon

Technology: Digital Control Computer

IBM 1800 (introduced 1964)

[wikipedia]

Model Predictive Control Engineering

SHELL OIL CO.
P.O. Box 3105
HOUSTON
TX 77001

DYNAMIC MATRIX CONTROL --- A COMPUTER CONTROL ALGORITHM

presented by

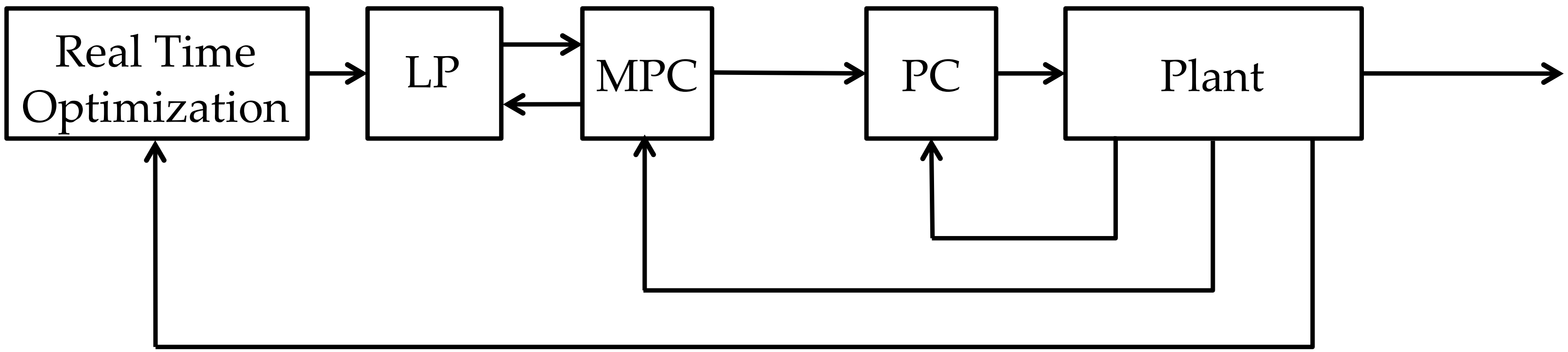
C. R. CUTLER and B. L. RAMAKER

at the 86th NATIONAL MEETING of

THE AMERICAN INSTITUTE OF CHEMICAL ENGINEERS

Cutler & Ramaker (1979)
AIChE National Mtg.
based on Cutler (1969)

Typical Implementation



- LP determines (x,u) targets
  (was always standard in DMC, see also Pannocchia & Rawlings, AIChE J 2003)

Typical Implementation

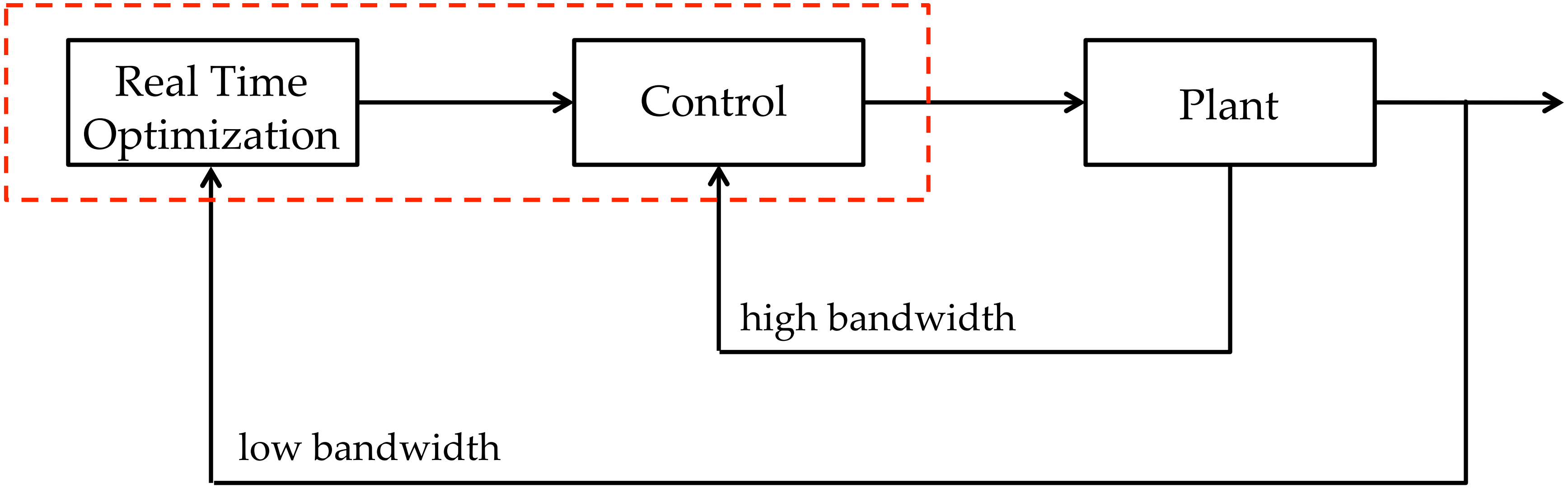
- PC should remove uncertainty and nonlinearities
- MPC may use linear (even static – cf. M. Morshedi) model
- MPC tuned loosely (open loop response speed) to tolerate model uncertainty
- MPC mostly used for constraint management

Model Predictive Control - Conclusions

- MPC is a type of optimal feedback control
- Uncertainty / robustness limit achievable performance
- If uncertainty is not dominant one may
  - move economics into MPC objective
  - take constraint handling into RTO / D-RTO layer

Control and Operations

Is this a good idea?

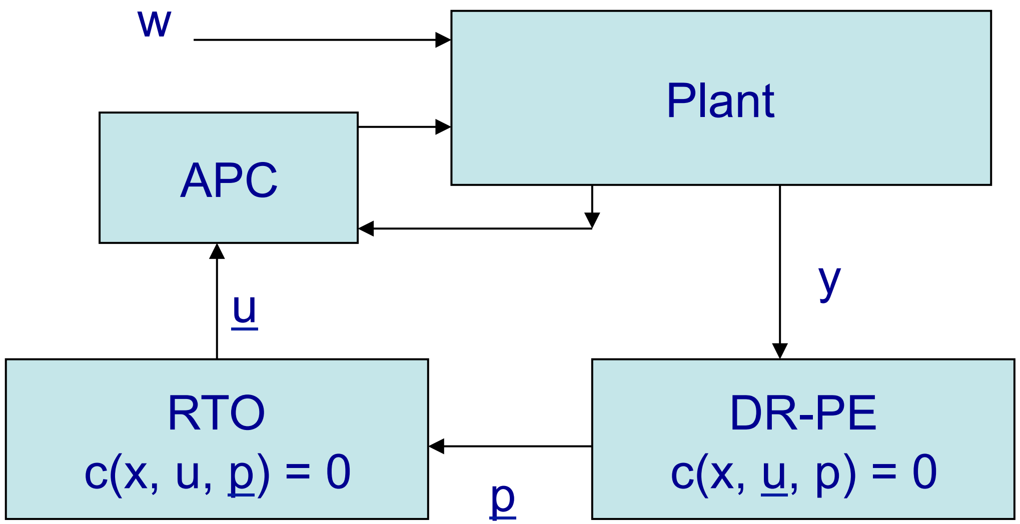


Is it just a question of time scale separation and computational complexity? NO

- The separation of RTO and Control is determined by uncertainty. RTO is sensitive to uncertainty.

Biegler, 2011

RTO – State of the Art



Real-time optimization

- Steady state model for states (x)
- Supply setpoints (u) to APC (control system)
- Model mismatch, measured and unmeasured disturbances (w)

$$\begin{aligned} &\mathrm{Min}_u \;\; F(x, u, w) \\ &\text{s.t. } c(x, u, \underline{p}, w) = 0 \\ &x \in X,\; u \in U \end{aligned}$$

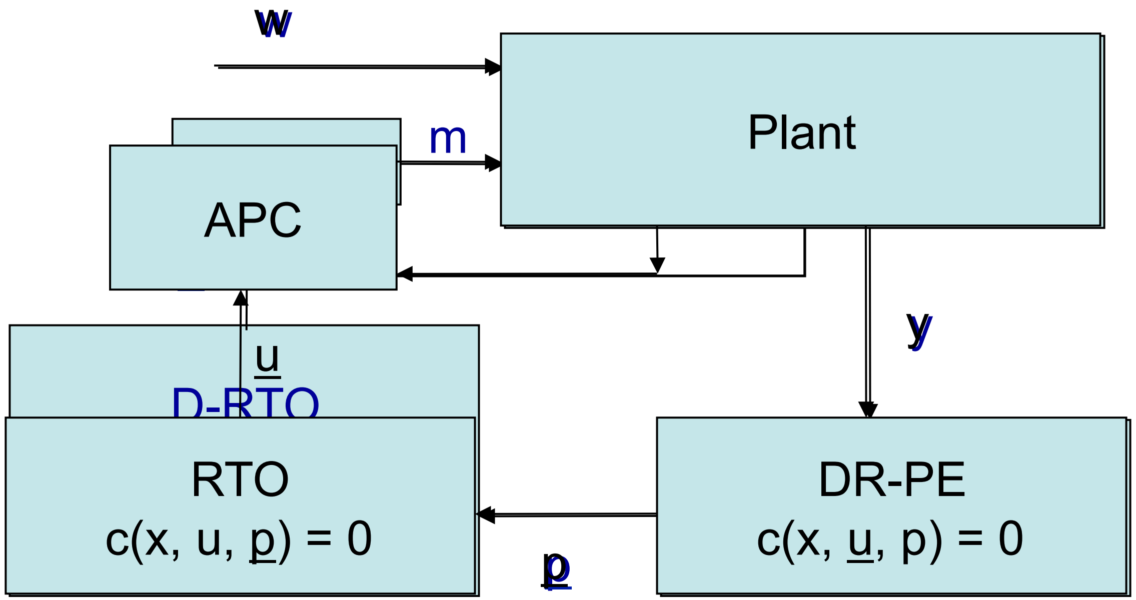
Data Reconciliation & Parameter Identification

- Estimation problem formulations
- Steady state model
- Maximum likelihood objective functions considered to get parameters (p)

$$\begin{aligned} &\mathrm{Min}_p \;\; \Phi(x, y, p, w) \\ &\text{s.t. } c(x, \underline{u}, p, w) = 0 \\ &x \in X,\; p \in P \end{aligned}$$

Biegler, 2011

Dynamic On-line Optimization:



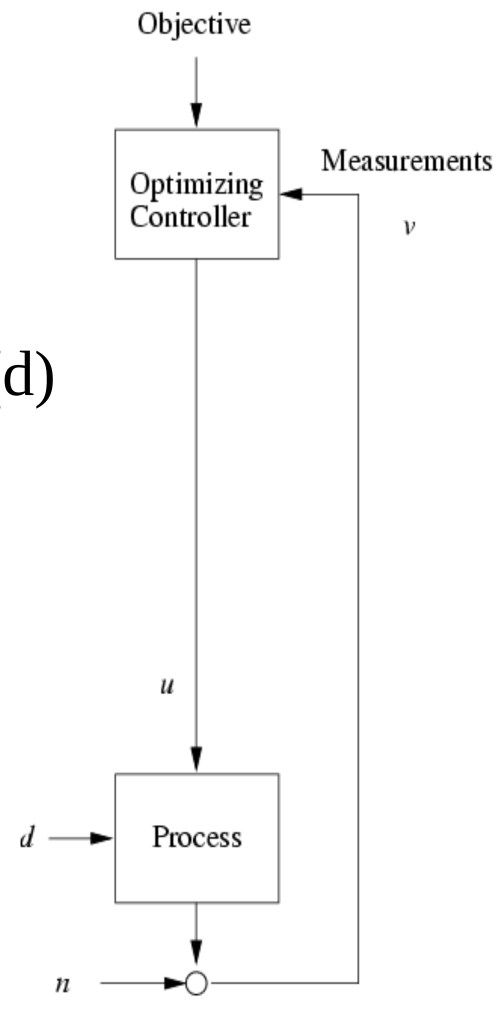
Integrate On-line Optimization with APC (Engell, 2007)

- Consistent, first-principle dynamic models
- Consistent, feed-forward optimization
- Increase in computational complexity
- Time-critical calculations

Essential for:

- Feed changes
- Nonstandard operations
- Optimal disturbance rejection

1. ”Obvious” solution: Optimizing control = ”Feedforward”

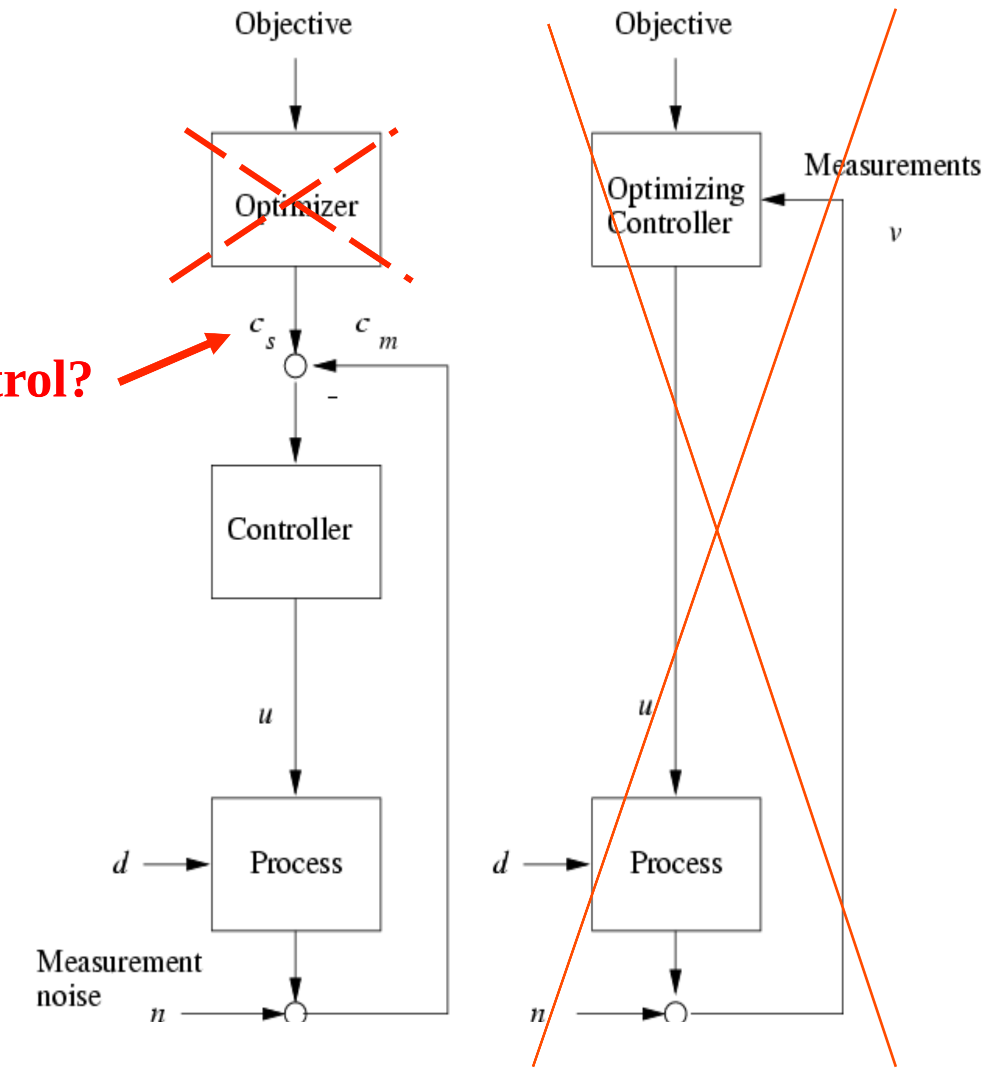


Estimate d and compute new $u_{opt}(d)$

Probem: Complicated and sensitive to uncertainty

2. In Practice: Feedback implementation

Issue:
What should we control?



What should we control?

- CONTROL ACTIVE CONSTRAINTS!
  - Optimal solution is usually at constraints, that is, most of the degrees of freedom are used to satisfy "active constraints", $g(u_0,d) = 0$
  - Implementation of active constraints is usually simple.

- WHAT MORE SHOULD WE CONTROL?
  - But what about the **remaining unconstrained degrees of freedom?**
  - **Look for "self-optimizing" controlled variables!**

Optimal operation – Runner

– Cost: J=T

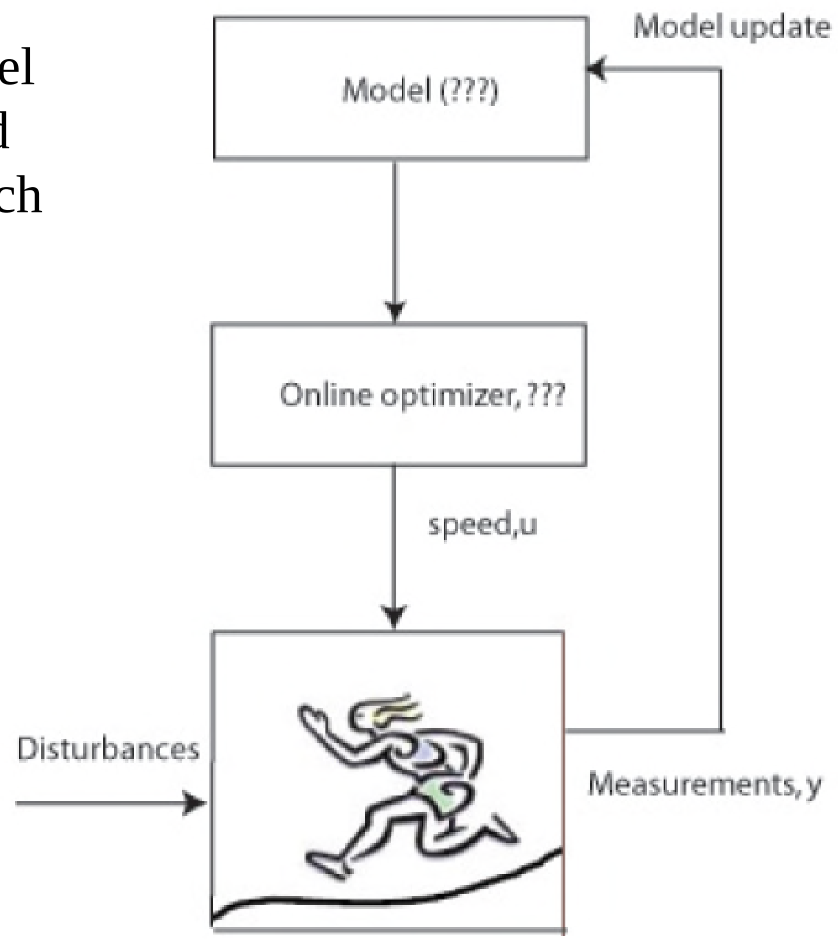
– One degree of freedom (u=power)

– Optimal operation?

Solution 1: Optimizing control

- Even getting a reasonable model requires > 10 PhD's ☺ … and the model has to be fitted to each individual….

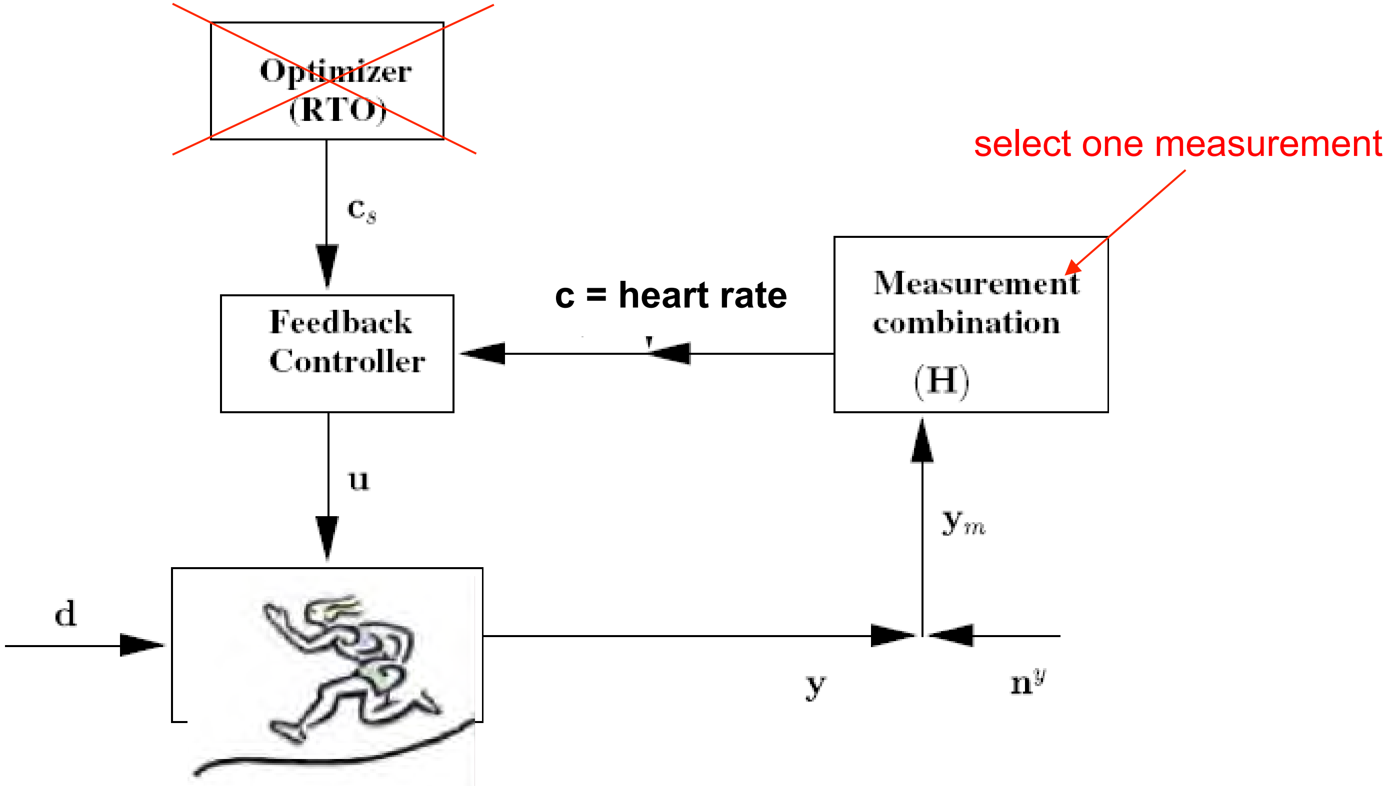
- Clearly impractical!



Solution 2 – Feedback (Self-optimizing control)

– What should we control?

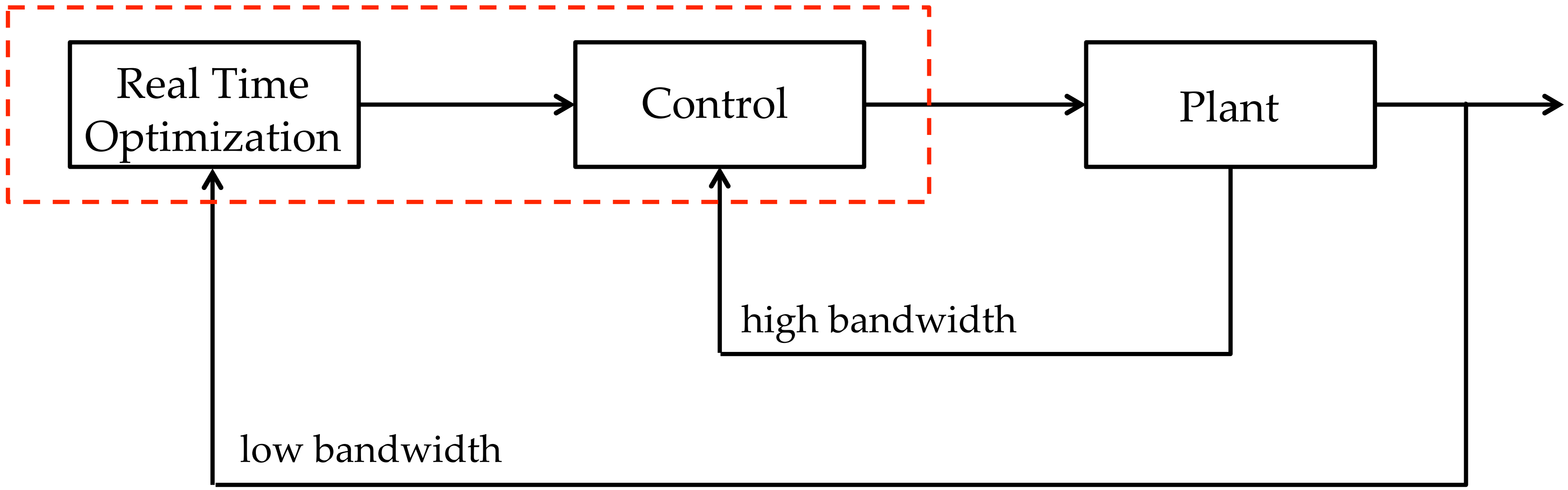
Conclusion Marathon runner



- Simple and robust implementation
- Disturbances are indirectly handled by keeping a constant heart rate
- <u>May</u> have infrequent adjustment of setpoint (heart rate)

Control and Operations

Is this a good idea?



Is it just a question of time scale separation and computational complexity? NO

The separation of RTO and Control is determined by

- Uncertainty: RTO is sensitive to uncertainty.
-

Control and Operations

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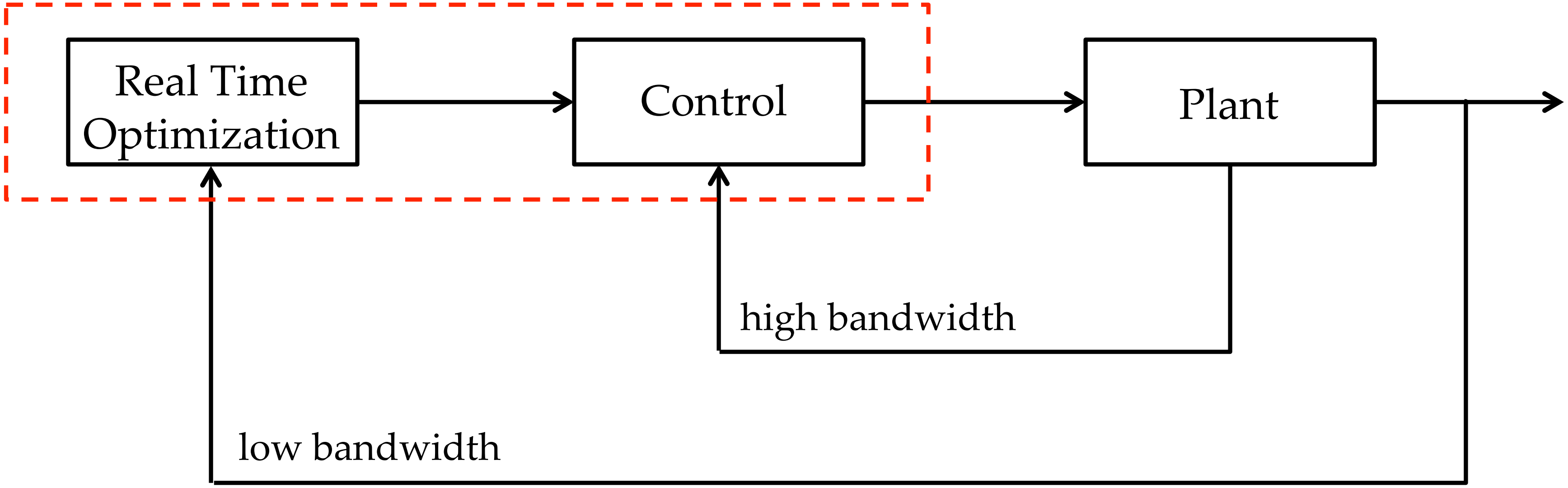
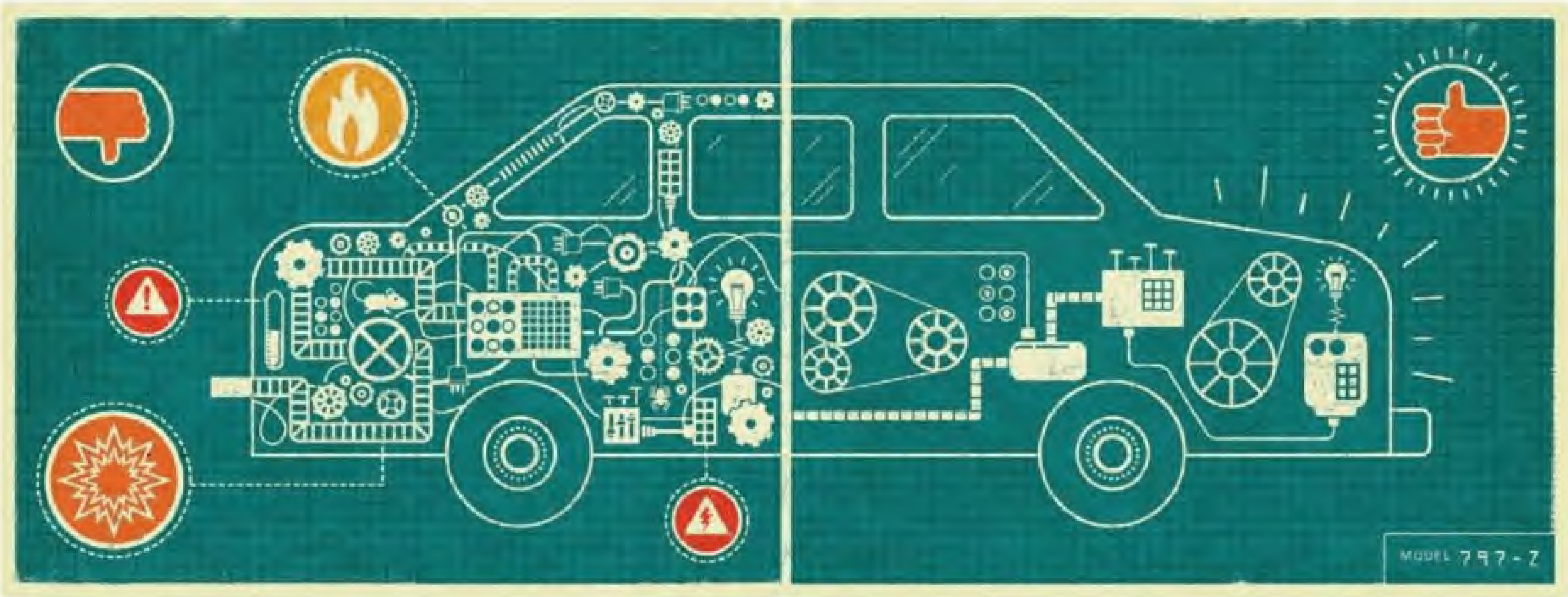


Is it just a question of time scale separation and computational complexity? NO

The separation of RTO and Control is determined by

- Uncertainty: RTO is sensitive to uncertainty.
- Complexity: Decomposition simplifies verification

Harvard Business Review



FIRST

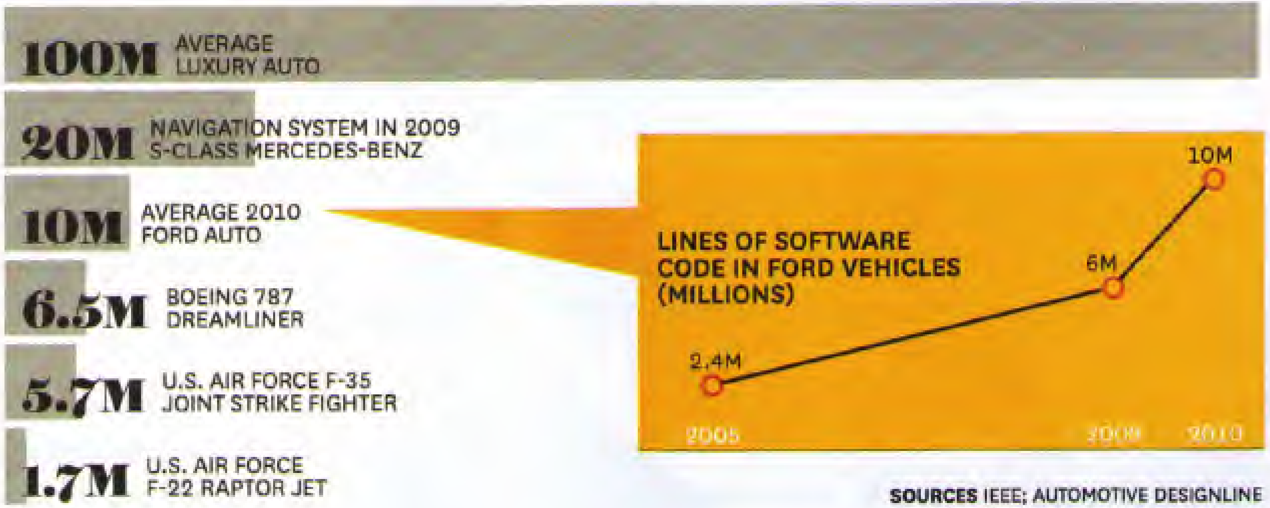
Why Dinosaurs Will Keep Ruling the Auto Industry

Get ready for the complexity revolution. *by John Paul MacDuffie and Takahiro Fujimoto*

June 2010

MORE COMPLEX THAN A FIGHTER JET

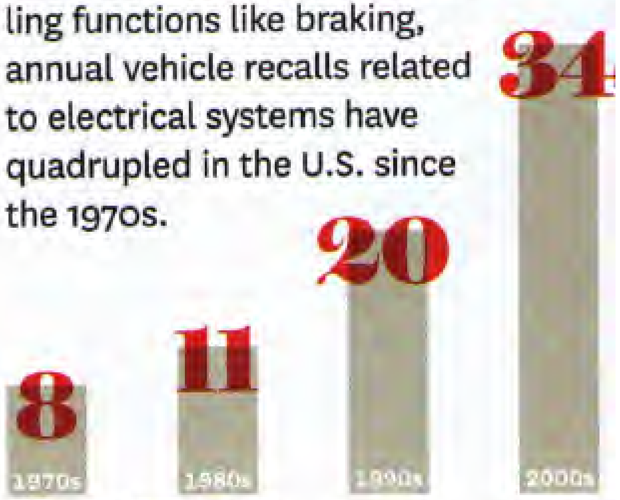
Safety regulations and consumer demand for performance and convenience have led to an exponential spike in cars' software complexity.



SOURCES IEEE; AUTOMOTIVE DESIGNLINE

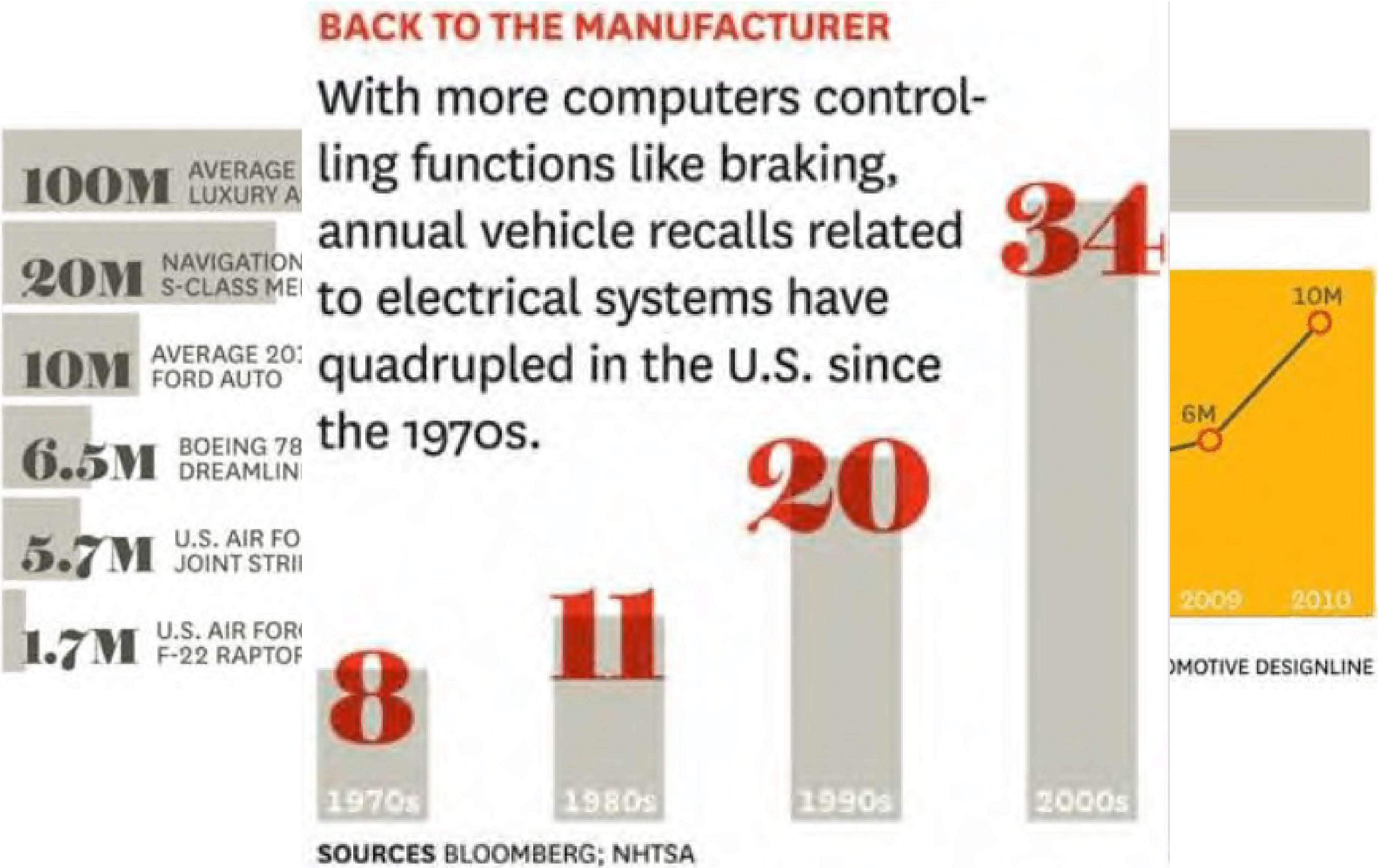
BACK TO THE MANUFACTURER

With more computers controlling functions like braking, annual vehicle recalls related to electrical systems have quadrupled in the U.S. since the 1970s.



SOURCES BLOOMBERG; NHTSA

Harvard Business Review



Validation and Verification (V&V) Requirements

- Large system is composed of well defined and well behaved (through feedback!) parts
- Parts can be readily abstracted for analysis at a higher level of the hierarchy

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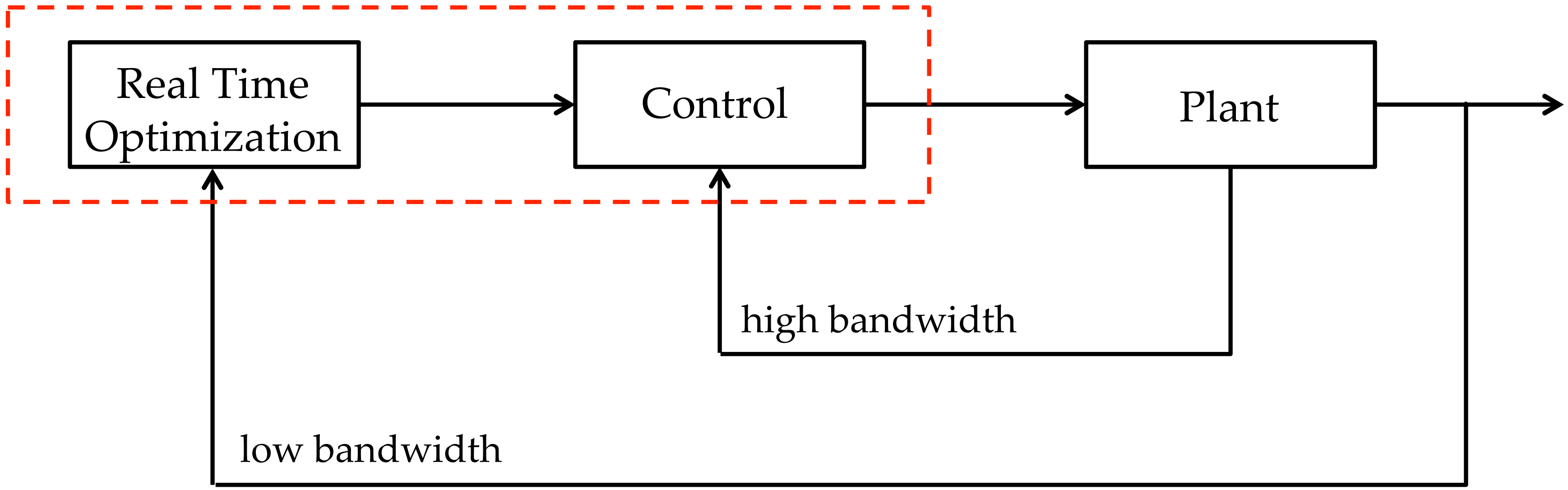
Control and Operations - Conclusions

Is this a good idea?



Is it just a question of time scale separation and computational complexity? NO

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Research Question

Uncertainty analysis is central but

- toolset is very limited
- rarely used

- "Mathematical Foundations of Verification, Validation, and Uncertainty Quantification" National Academies Report 2012
- Software: GoSUM by AIMdyn (Igor Mezic)

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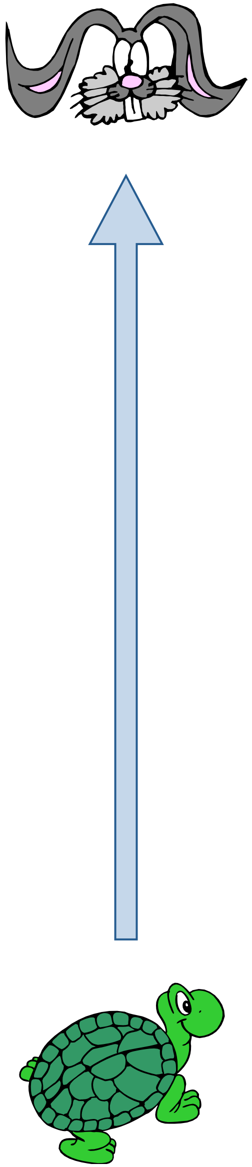
Applications by the Automatic Control Lab



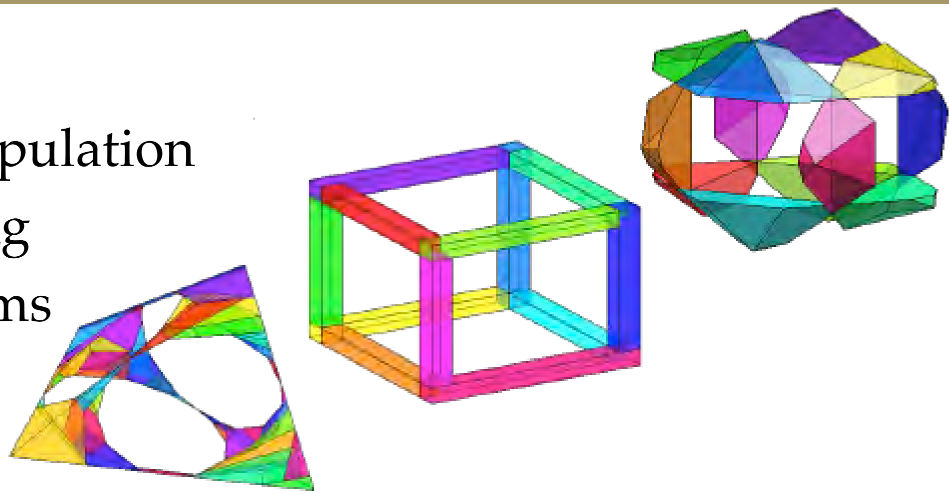
18 ns	Multi-core thermal management (EPFL) *[Zanini et al 2010]*
10 μs	Voltage source inverters *[Mariethoz et al 2008]*
20 μs	DC/DC converters (STM) *[Mariethoz et al 2008]*
25 μs	Direct torque control (ABB) *[Papafotiou 2007]*
50 μs	AC / DC converters *[Richter et al 2010]*
5 ms	Electronic throttle control (Ford) *[Vasak et al 2006]*
20 ms	Traction control (Ford) *[Borrelli et al 2001]*
40 ms	Micro-scale race cars
50 ms	Autonomous vehicle steering (Ford) *[Besselmann et al 2008]*
500 ms	Energy efficient building control (Siemens) *[Oldewurtel et al 2010]*

Computation

- Real-time MPC algorithms are highly complex
  - Codes span many fields: Geometry, Control, Optimization, …
  - Extremely sensitive to small numerical and coding errors
- Uptake requires provision of community-generated toolsets
  - CVX, ACADO, Hybrid toolbox, JModellica, …

Multi-Parametric Toolbox (MPT)

- Free and open-source
- (Non)-Convex Polytopic Manipulation
- Multi-Parametric Programming
- Control of PWA and LTI systems
- > 22,000 downloads to date



MPT 3.0 coming in 2012 *[Kvasnica et al.]*

Control Faculty at ETH

- Raff D'Andrea
- Lino Guzzella
- Heinz Köppel (Asst.Prof.)
- John Lygeros
- Manfred Morari
- Roy Smith

Flying Machine Arena

The Flying Machine Arena

Quadrocopter Ball Juggling

IDSC

ETH

Eidgenössische Technische Hochschule Zürich

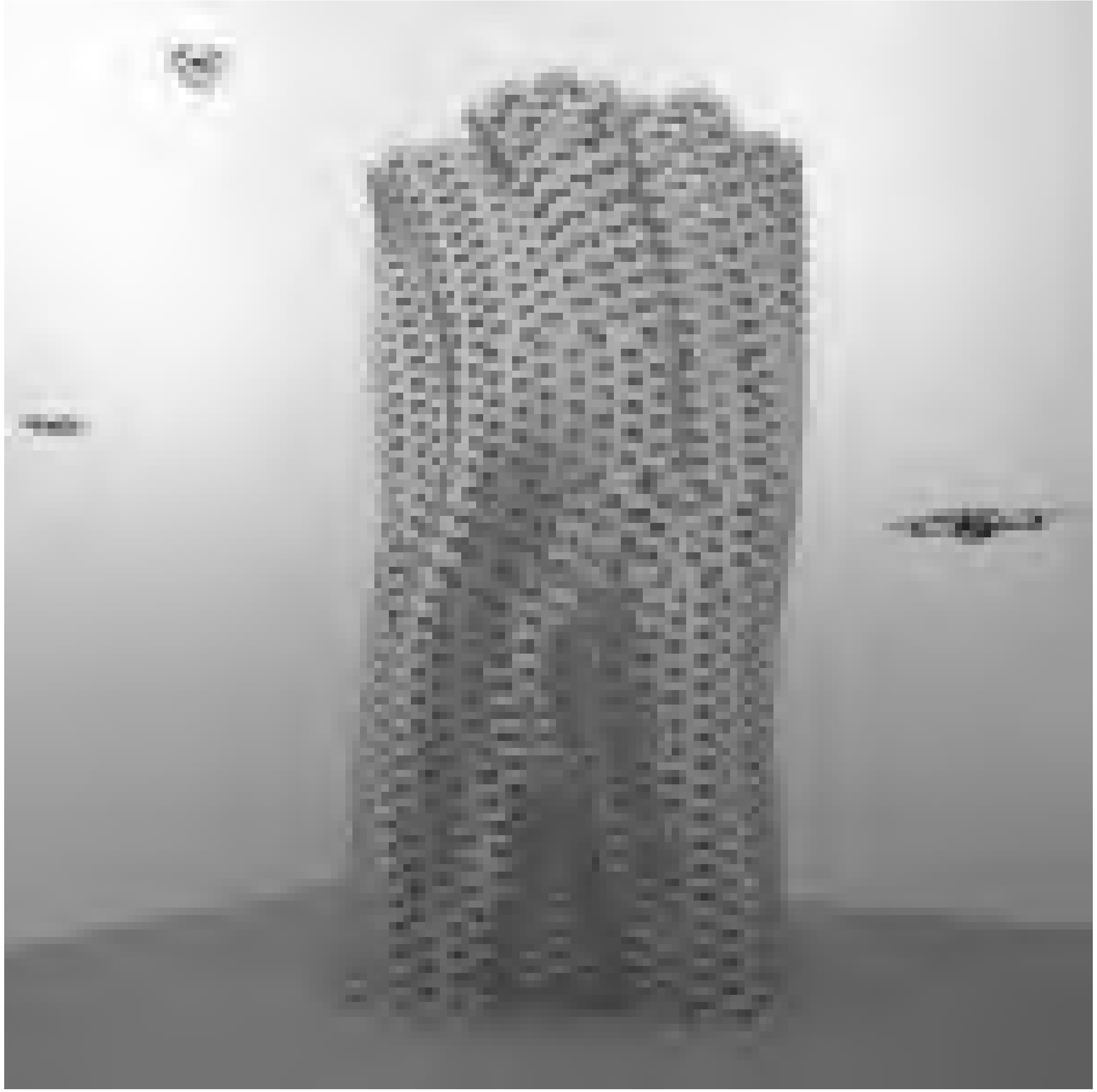
Swiss Federal Institute of Technology Zurich

[D'Andrea, IDSC, ETH Zurich]

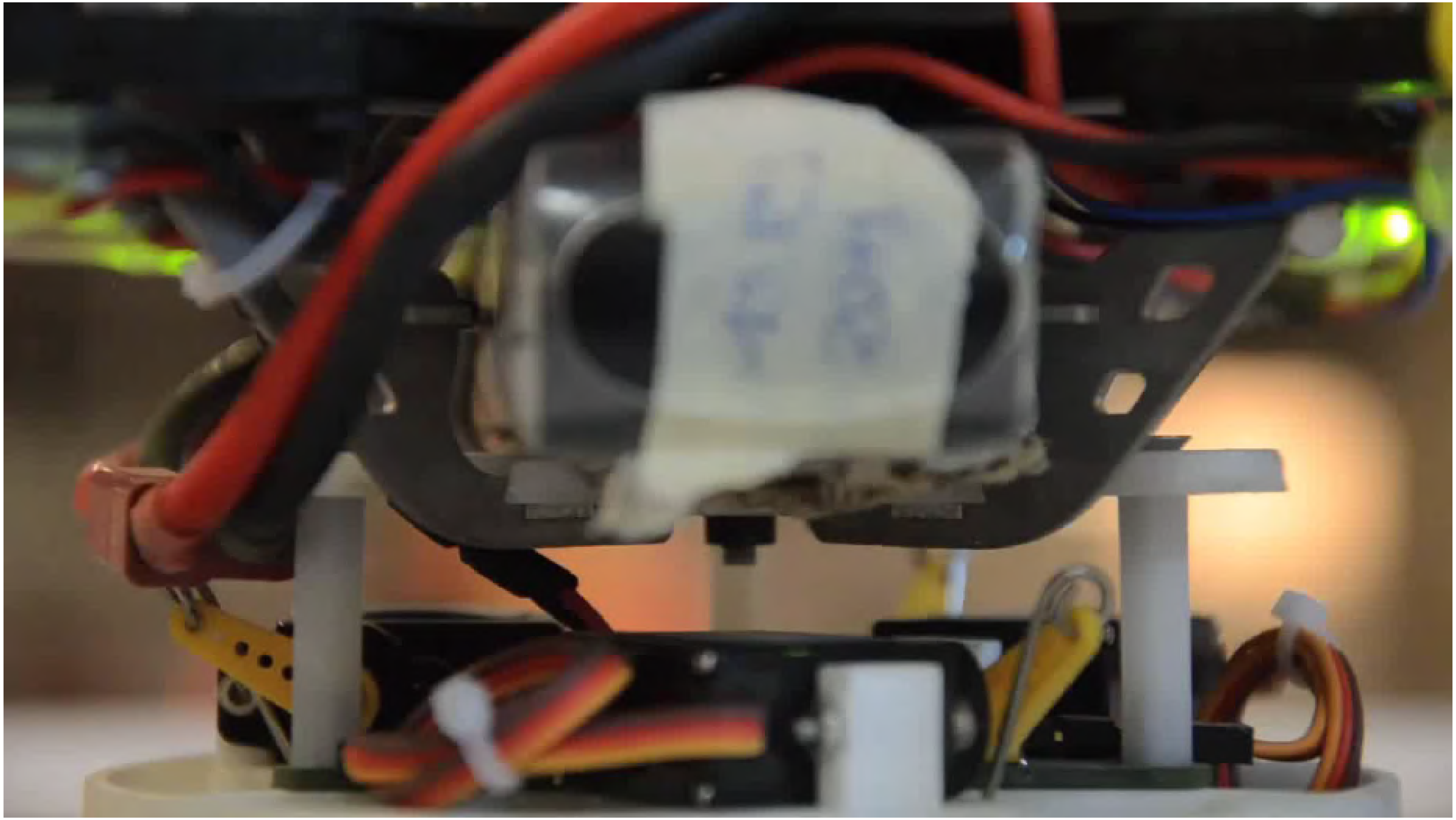
Flying Machine Arena

[D'Andrea, IDSC, ETH Zurich]

Flight Assembled Architecture



Flight Assembled Architecture



Graduate Course Enrollments ETH

- Raff D'Andrea
- Lino Guzzella
- John Lygeros
- Manfred Morari

	2008	2009	2010
MPC	32	44	67
Linear Systems	34	42	59
Dynamic Programming	72	101	140

Welcome to ECC13

The 12th Biannual European Control Conference