The Role of Theory in Control Practice

Manfred Morari

Automatic Control Laboratory, ETH Zürich

UCONN | UNIVERSITY OF CONNECTICUT

SCHOOL OF ENGINEERING

UTC Institute for Advanced Systems Engineering

United Technologies

UTC BUSINESSES

Commercial

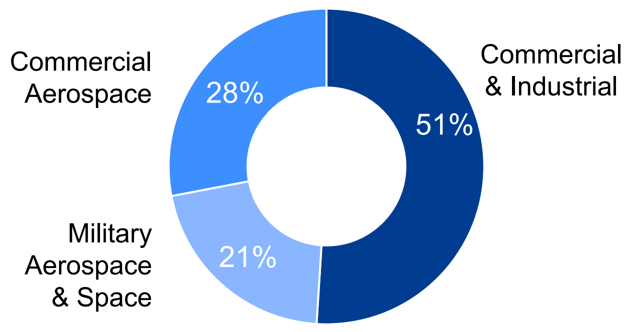
OTIS

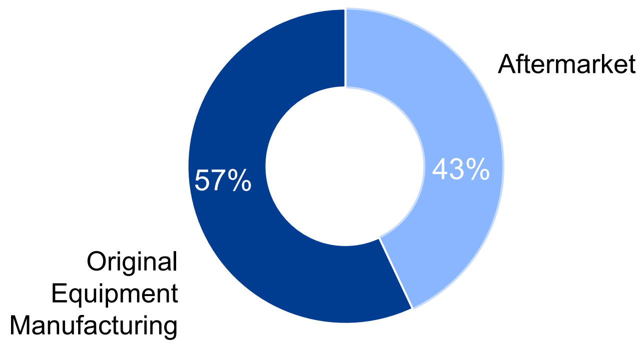
Aerospace

PERFORMANCE

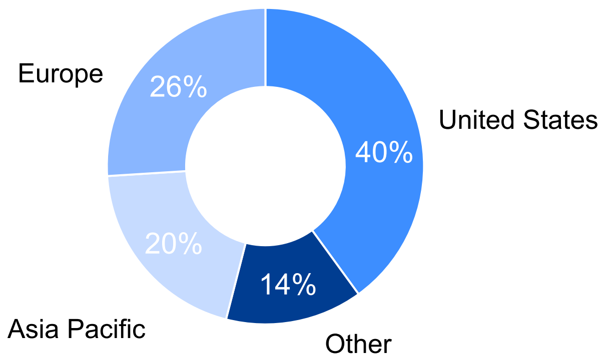
2012 net sales $57.7 billion

TYPE

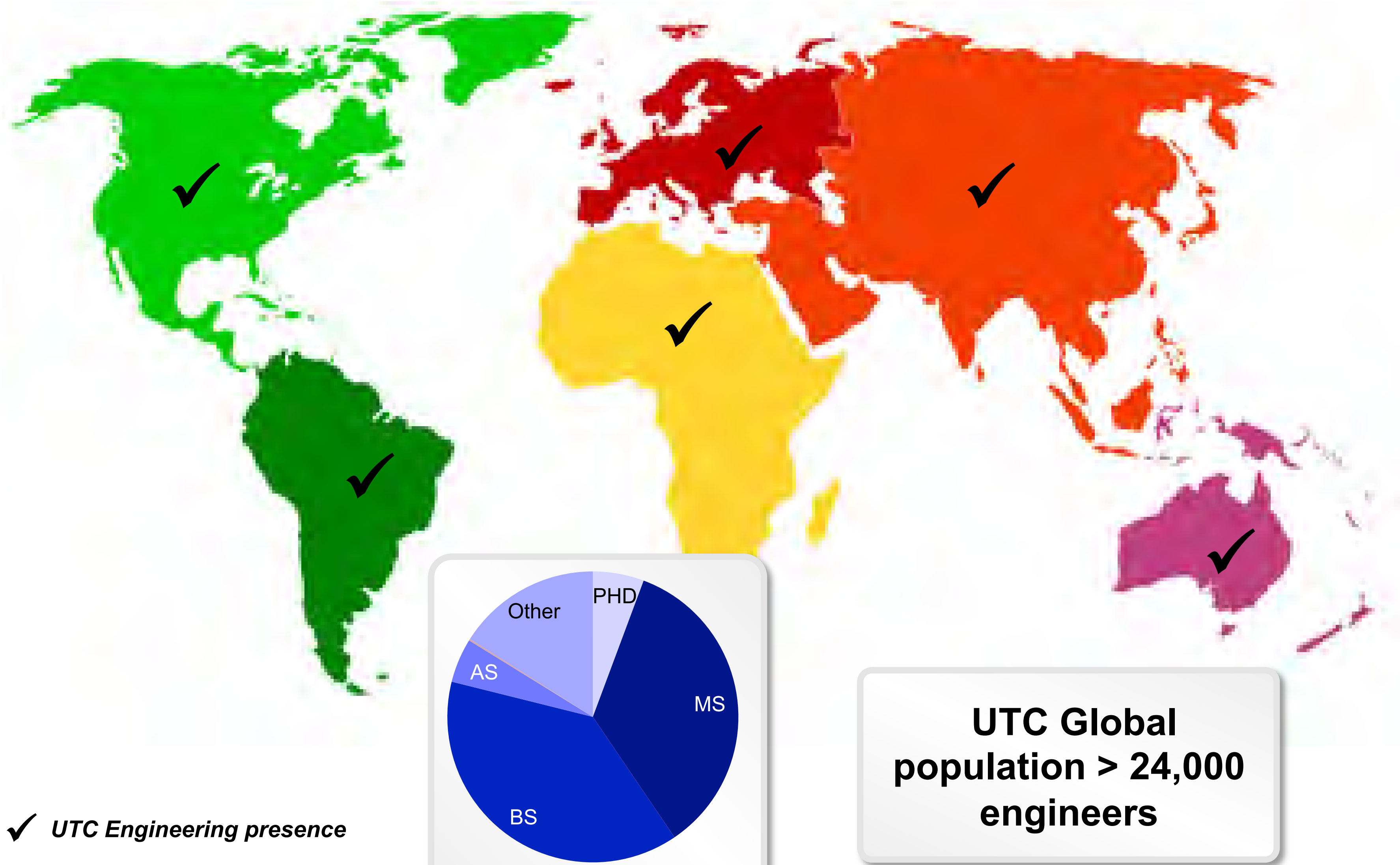




GEOGRAPHY



2013 ENGINEERING POPULATION



✓ *UTC Engineering presence*

US Engineering Degrees

UTC Global population > 24,000 engineers

ETH Zurich at a glance

Founded 1855

- Driving force of industrialisation in Switzerland

ETH Zurich today

- One of the leading international universities for technology and the natural sciences
- Place of study, research and employment for approximately 25,000 people from over 100 different countries

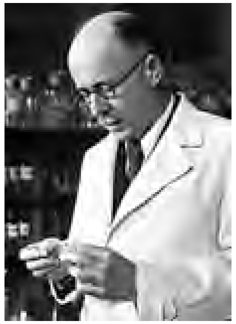
Some Numbers:

- 8500 BS + 4800 MS + 3900 PhD = 18200
- 500 Professors
- 8000 Personnel
- Budget CHF 1.5 (370 Mill third party)

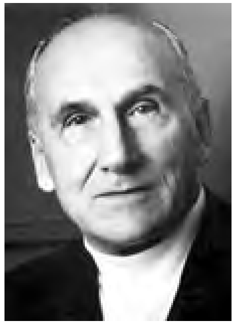
21 Nobel Laureates

1901	Physics	**Wilhelm Conrad Röntgen**
1912	Chemistry	**Alfred Werner**
1915	Chemistry	**Richard Willstätter**
1918	Chemistry	**Fritz Haber**
1920	Physics	**Charles-Edouard Guillaume**
1921	Physics	**Albert Einstein**
1936	Chemistry	**Peter Debye**
1938	Chemistry	**Richard Kuhn**
1939	Chemistry	**Leopold Ruzicka**
1943	Physics	**Otto Stern**
1945	Physics	**Wolfgang Pauli**
1950	Medicine	**Tadeusz Reichstein**
1952	Physics	**Felix Bloch**
1953	Chemistry	**Hermann Staudinger**
1975	Chemistry	**Vladimir Prelog**
1978	Medicine	**Werner Arber**
1986	Physics	**Heinrich Rohrer**
1987	Physics	**Georg Bednorz / Alexander Müller**
1991	Chemistry	**Richard Ernst**
2002	Chemistry	**Kurt Wüthrich**


Albert Einstein


Leopold Ruzicka


Wolfgang Pauli

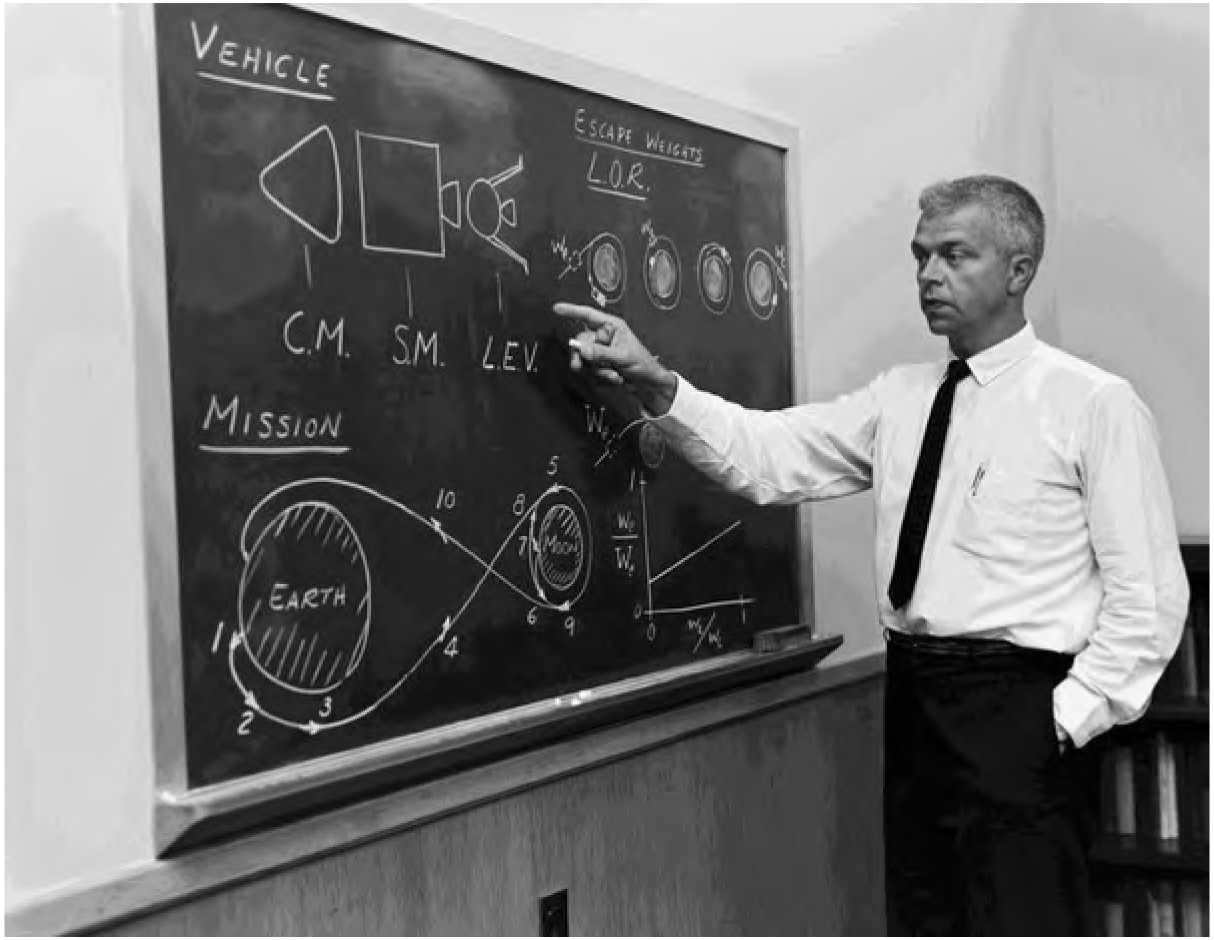

Vladimir Prelog


Richard Ernst


Kurt Wüthrich

John Houbolt
NASA Innovator Behind Lunar Module, Dies at 95

Dr. sc. ETH 1958



The New York Times

APRIL 27, 2014

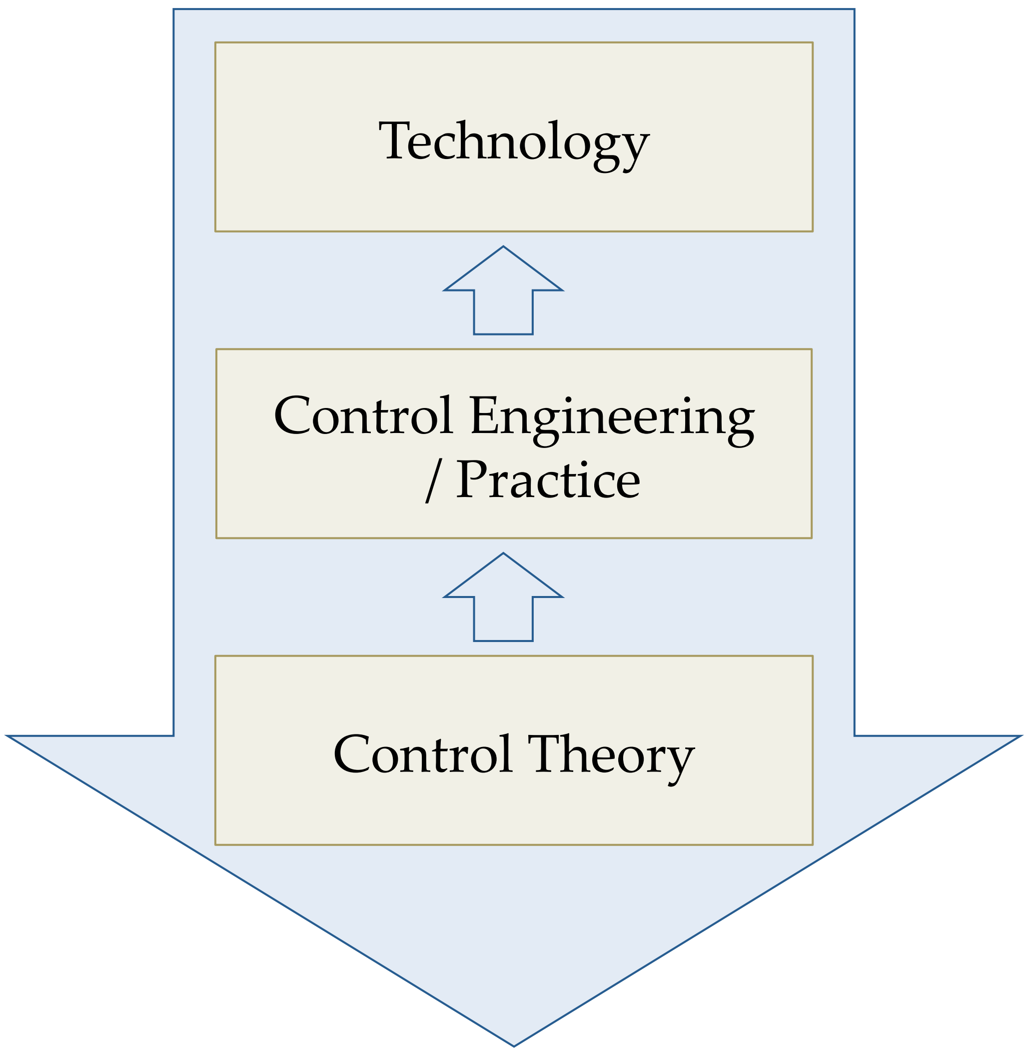
The Role of Theory in Control Practice

Manfred Morari

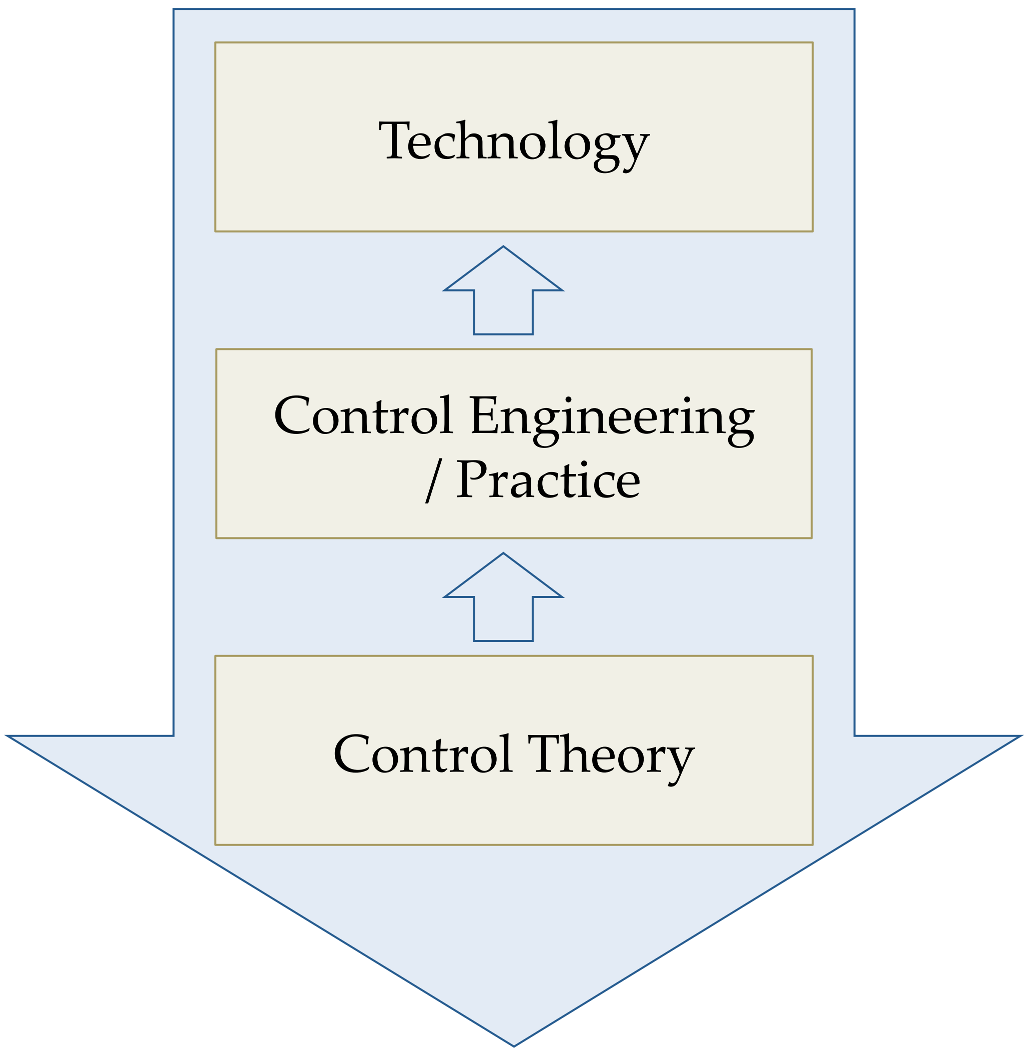
with thanks to
Colin Jones, Paul Goulart,
Alex Domahidi, Stefan Richter
and many other collaborators

Automatic Control Laboratory, ETH Zürich

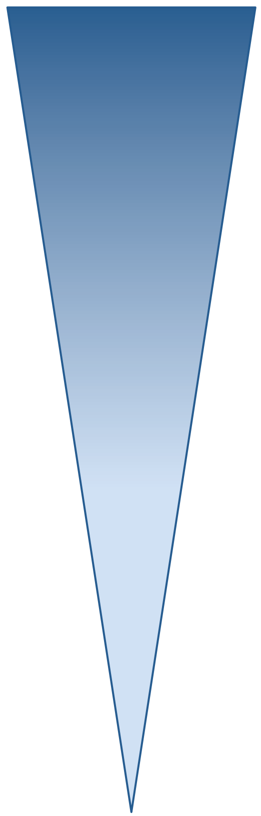
Drivers of Control Innovation



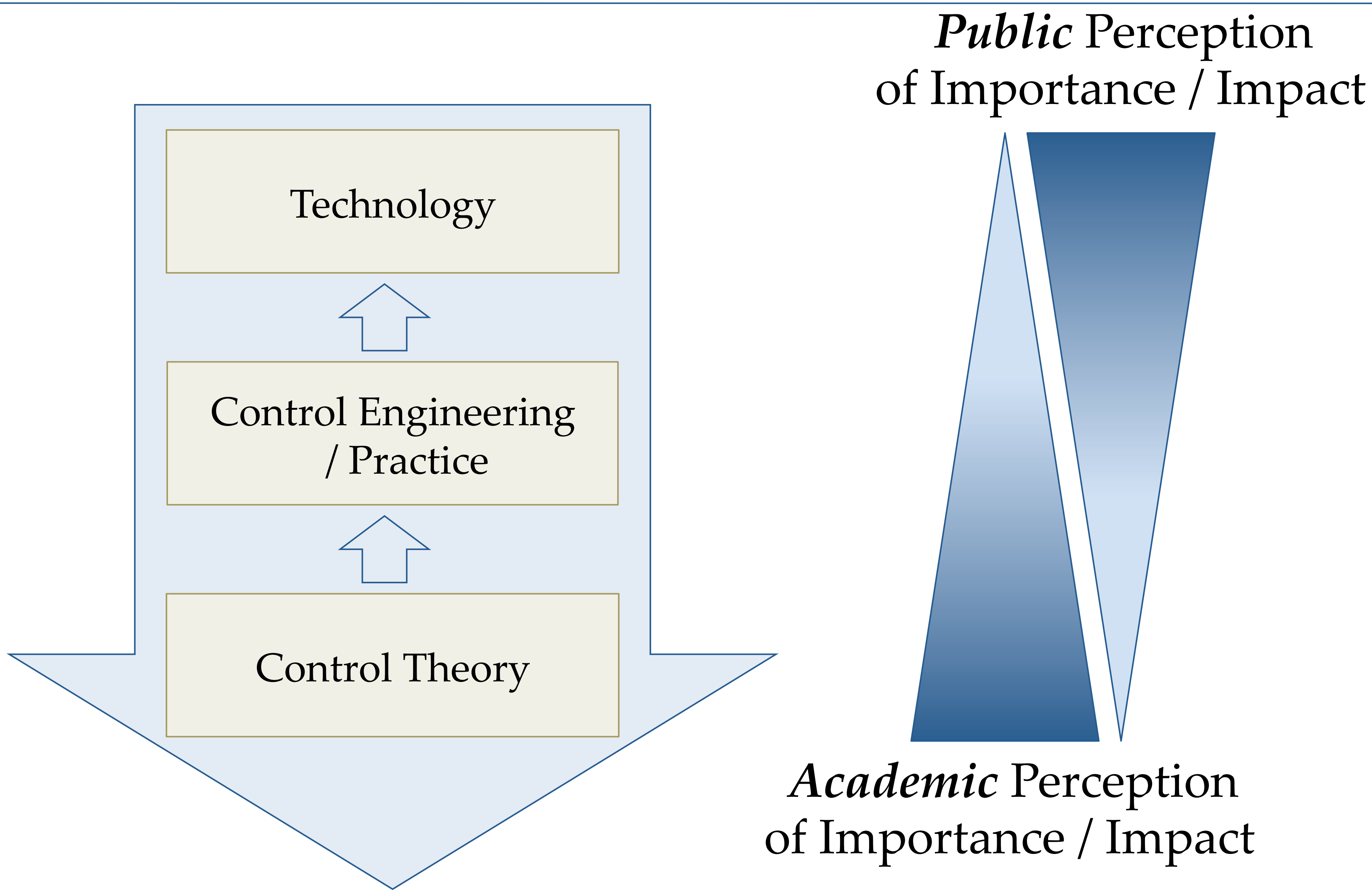
Drivers of Control Innovation



Public Perception
of Importance / Impact



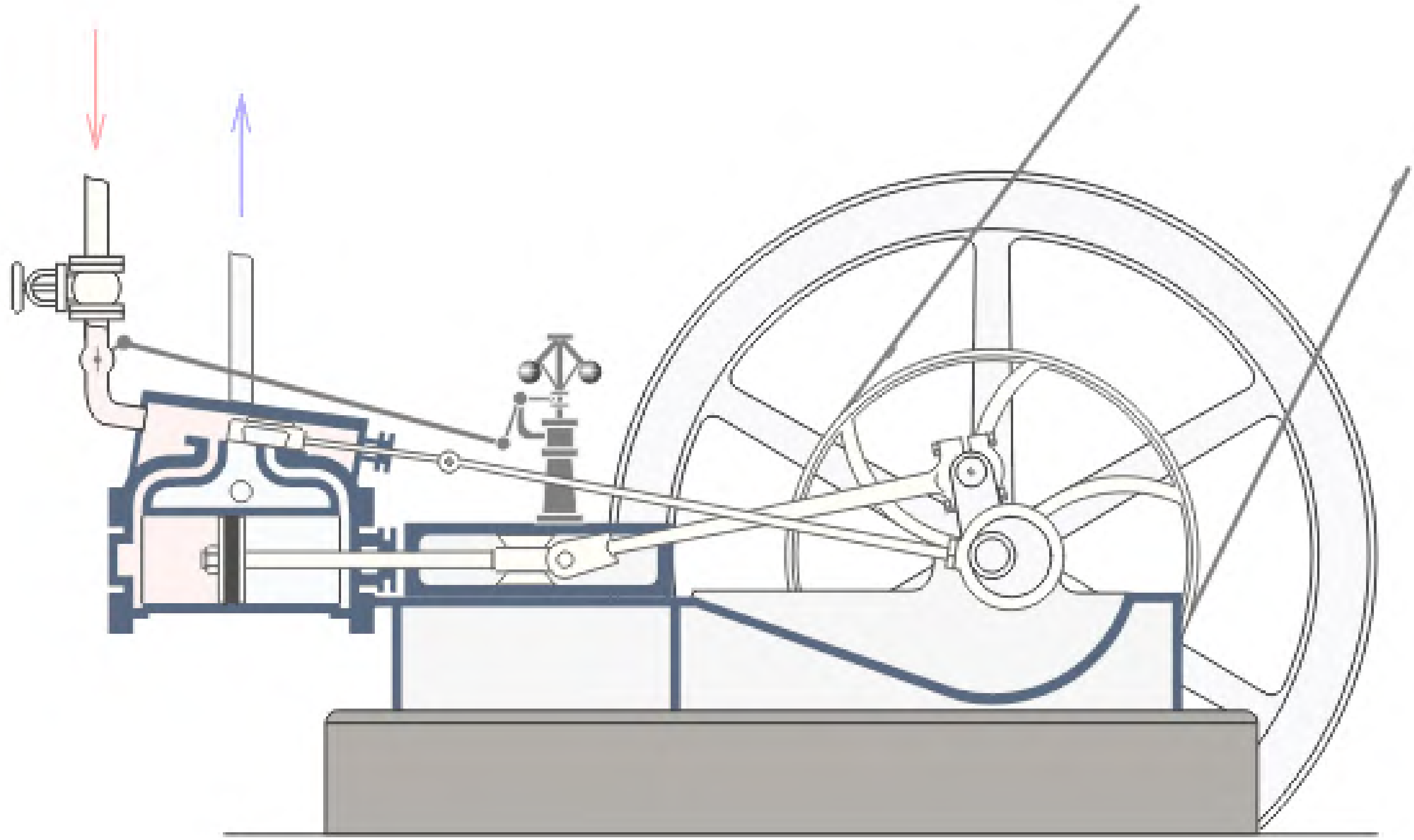
Drivers of Control Innovation



Outline

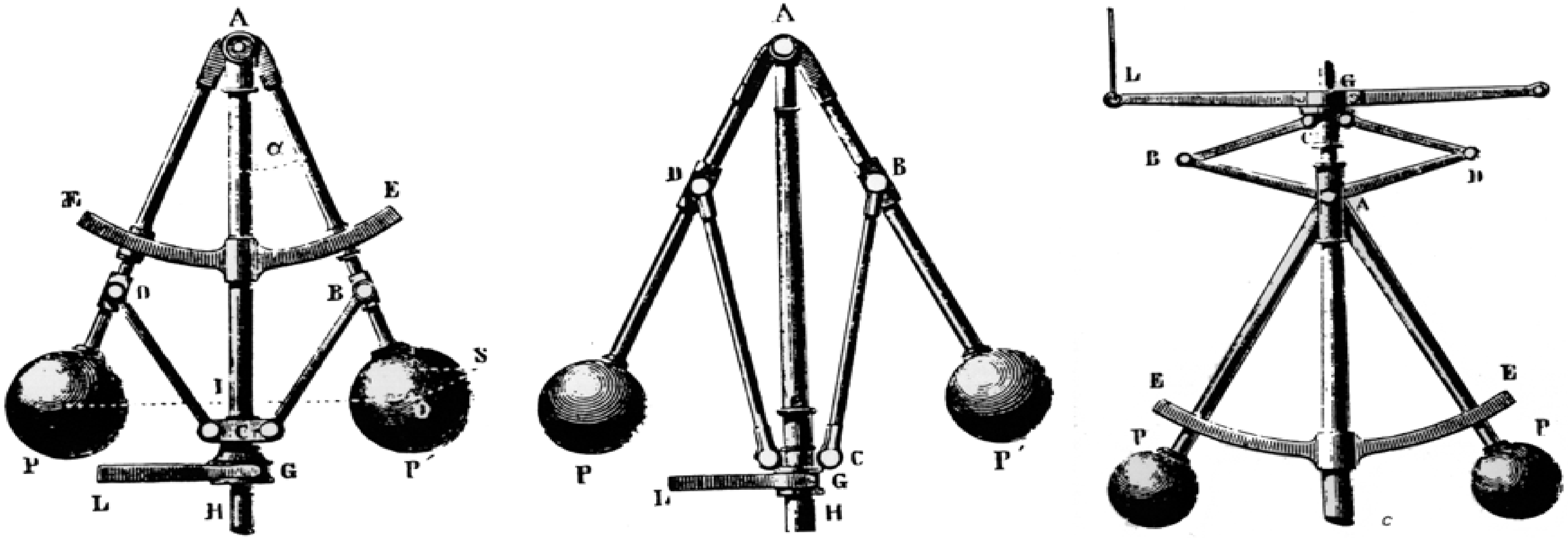
- History
- MPC
- Complexity
- Fast MPC
- Future

Technology: Analog Control Hardware



Steam Engine (1789-1800) *[wikipedia]*

Control Engineering: Governor



England 1868: 75’000 governors
USA 1836 – 1900: 1000 patents for governors

Problem: “hunting”

[Governors analyzed by Poncelet; Bennett, 1979]

Control Theory

J. C. Maxwell (1868) *Proc. Roy. Soc.*
"On Governors"

Maxwell asked “ if any member present could point out a method of determining in what cases all the possible [real] parts of the impossible [complex] roots of an equation are negative”

E.J. Routh (1876/77) *MacMillan, London* (Adams Prize)
"A treatise on the stability of a given state of motion"

[Bennett, 1979]

The Impact of Theory on Practice

'On Governors' (1868) was terse and enigmatic

Basic ideas, however, quickly taken up by E.J. Routh

- "Rigid Dynamics" (2nd Ed. 1868)
- Leading book on dynamics for 50 years

[Bennett, 1979]

The Impact of Theory on Practice

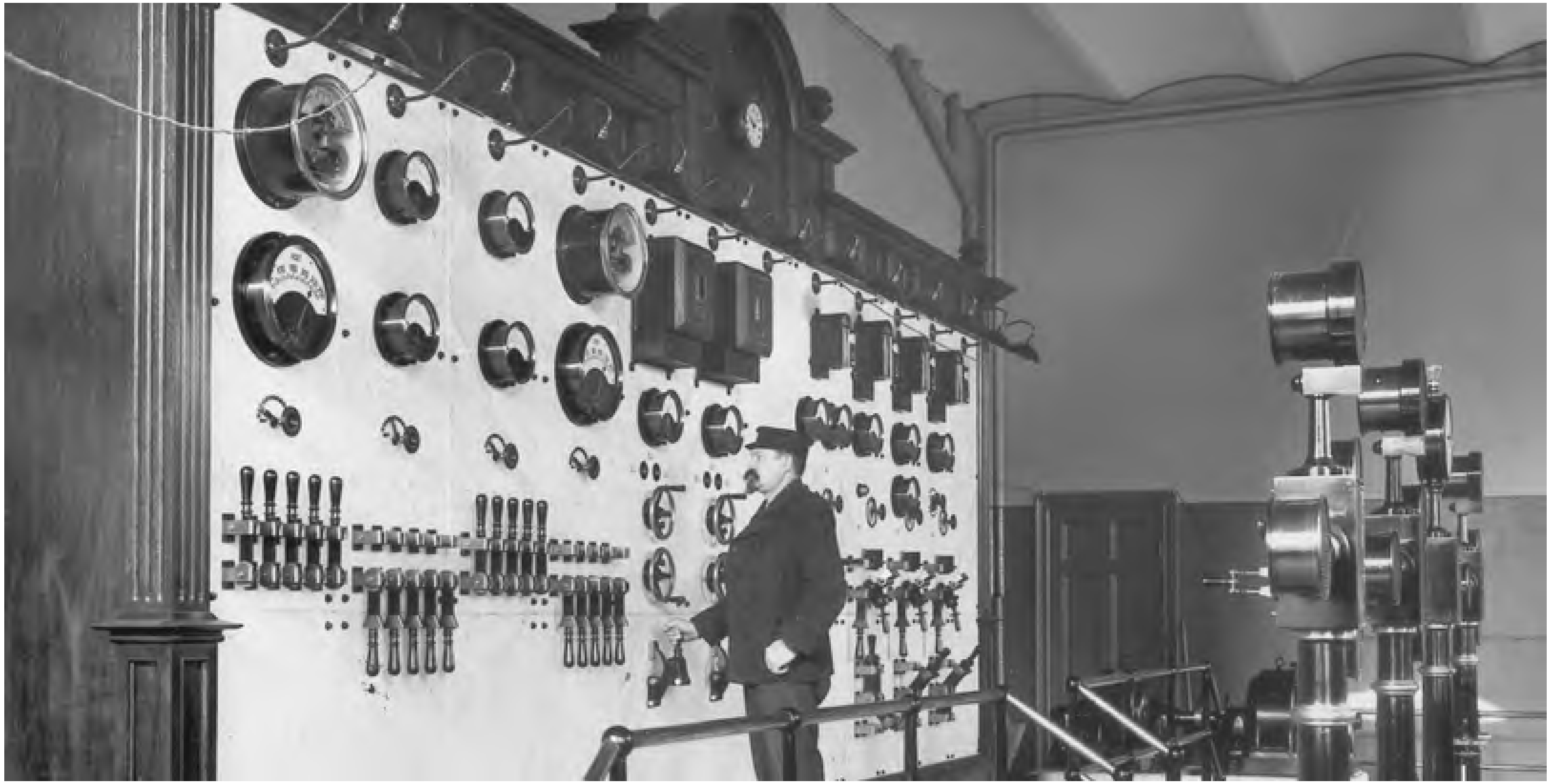
'On Governors' (1868) was terse and enigmatic

Basic ideas, however, quickly taken up by E.J. Routh
- "Rigid Dynamics" (2nd Ed. 1868)
- Leading book on dynamics for 50 years

"When Routh's work became widely available in the 1880s the problem of violent oscillations of engine governors had largely been solved…."

[Bennett, 1979]

Control Technology in Switzerland



BBC, around 1910

Control Engineering at ETH Zurich

A.B. Stodola (1893),
Schweizer Bauzeitung

"Über die Regulierung von Turbinen"

"On the Control of Turbines"

Control Theory at ETH Zurich

A. Hurwitz (1895),
Mathematische Annalen

"Über die Bedingungen, unter welchen eine Gleichung nur Wurzeln mit negativen reelen Theilen besitzt"

"On the conditions under which an Equation has only roots with negative real parts"

The Impact of Theory on Practice

Footnote in the paper by Hurwitz

"Herr Stodola benutzt mein Resultat...deren Ergebnisse bei der Turbinenanlage des Badeortes Davos mit glänzendem Erfolge Anwendung gefunden haben".

"These results were applied at the Davos Spa Turbine Plant with brilliant success"

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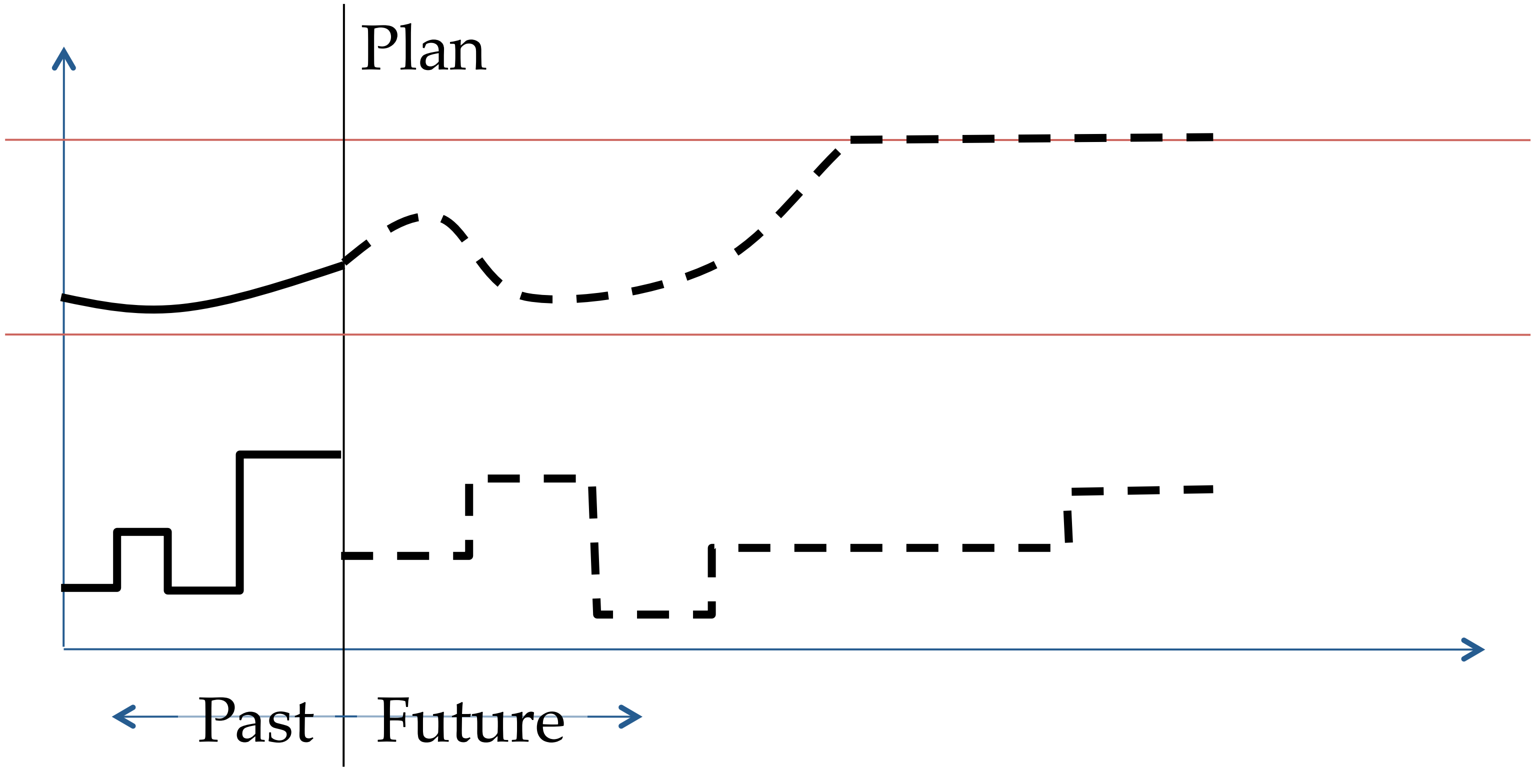
Technology: Digital Control Computer

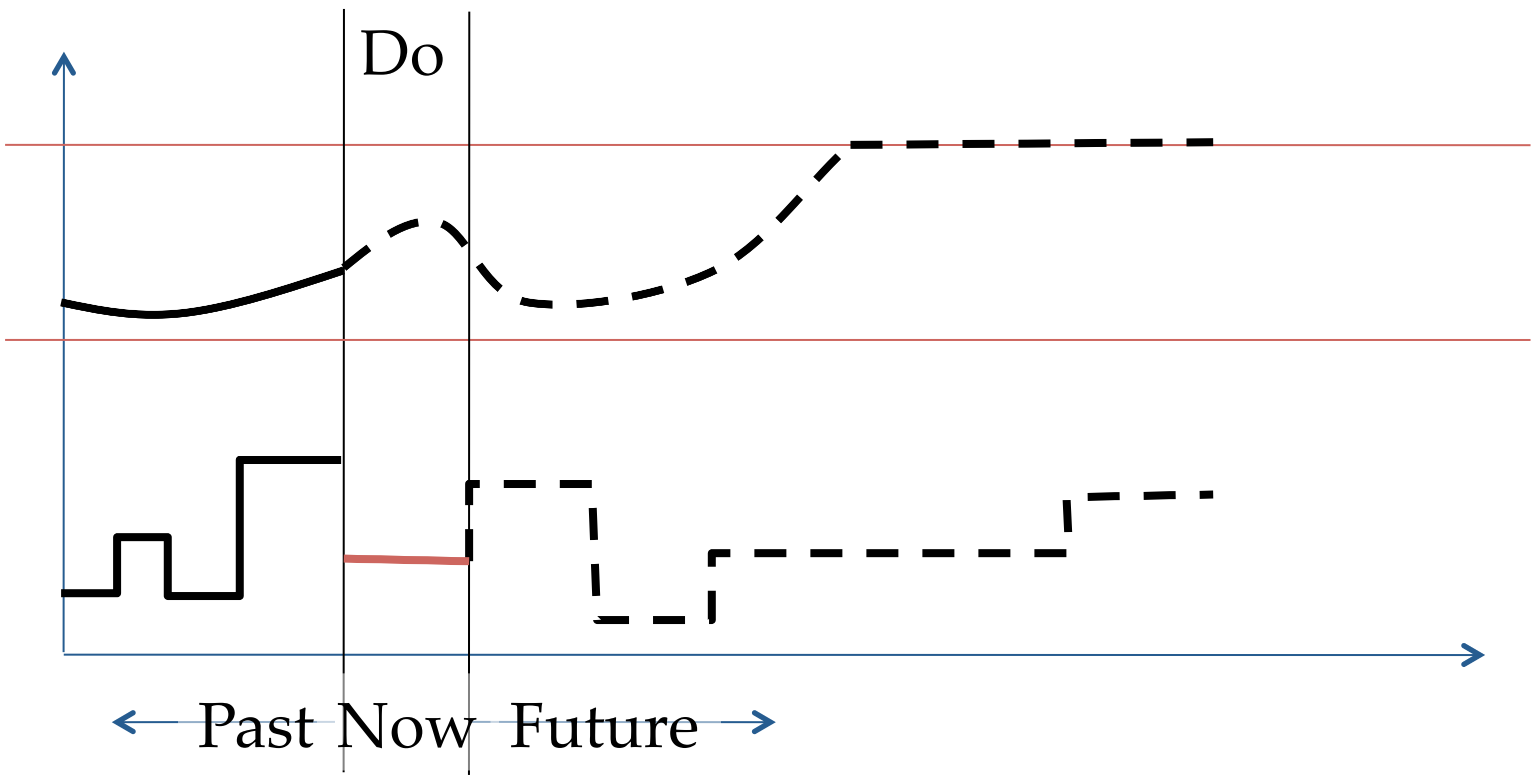
IBM 1800 (introduced 1964)

[wikipedia]

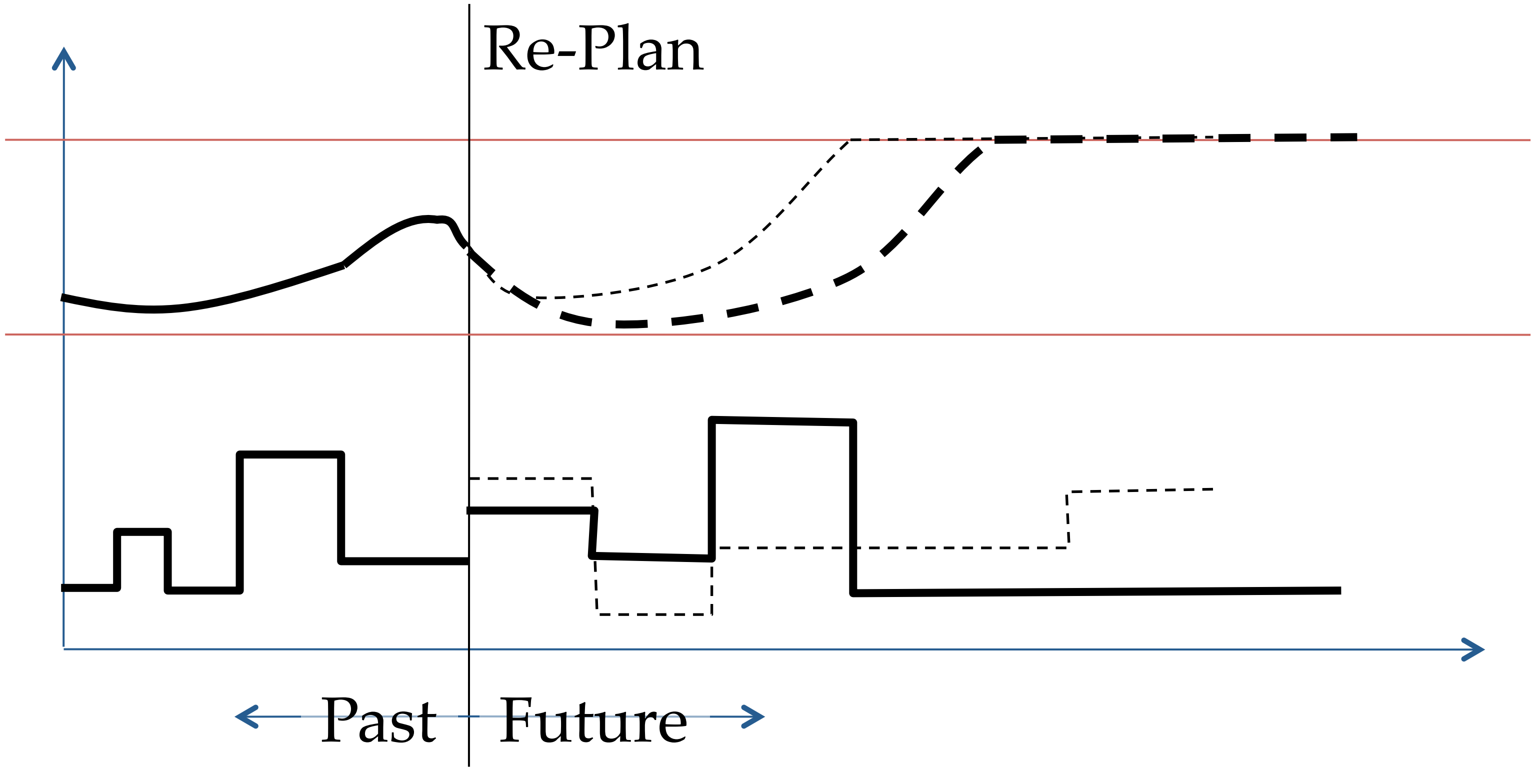
Model Predictive Control - MPC



Model Predictive Control - MPC



Model Predictive Control - MPC



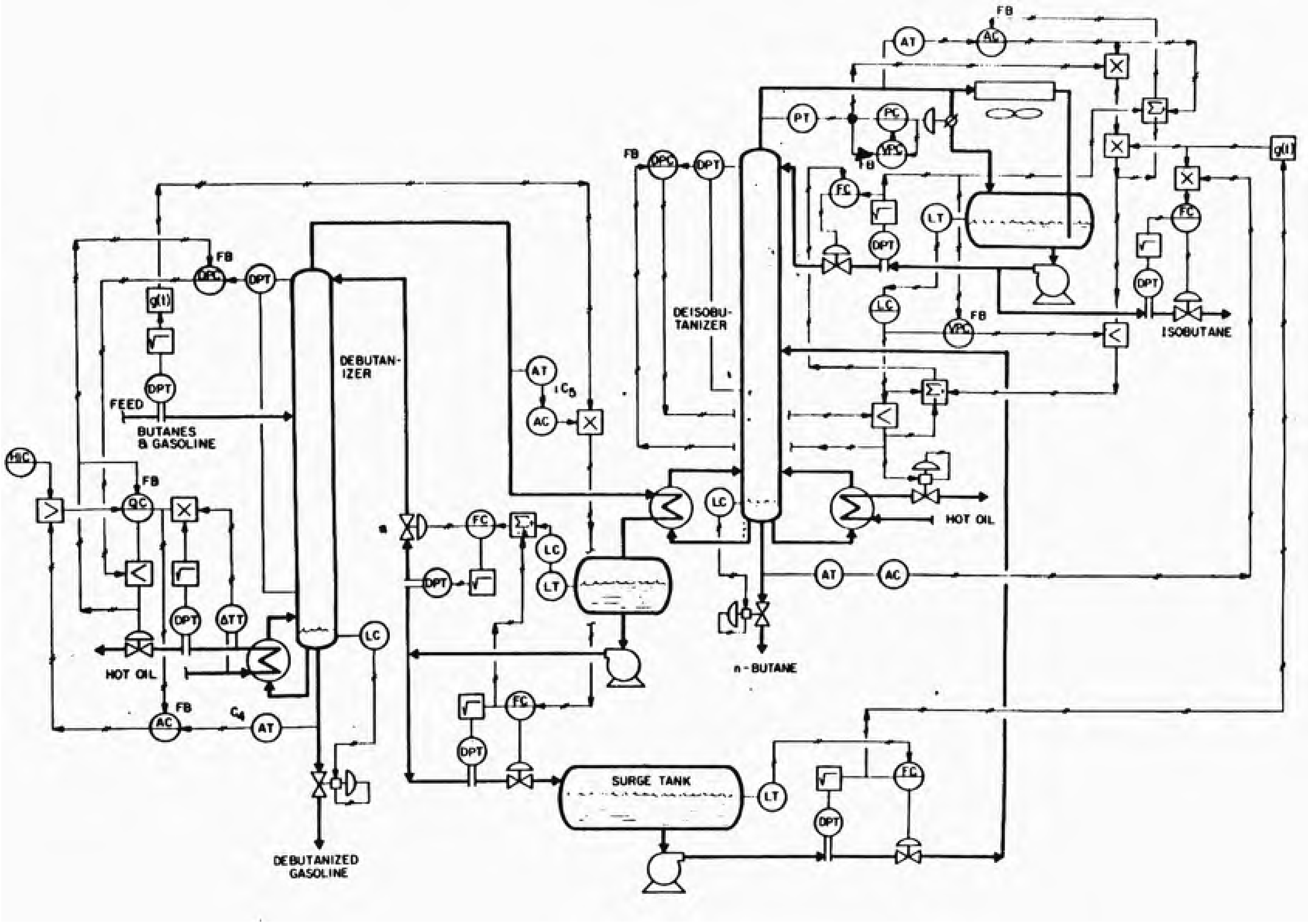
Model Predictive Control Theory

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

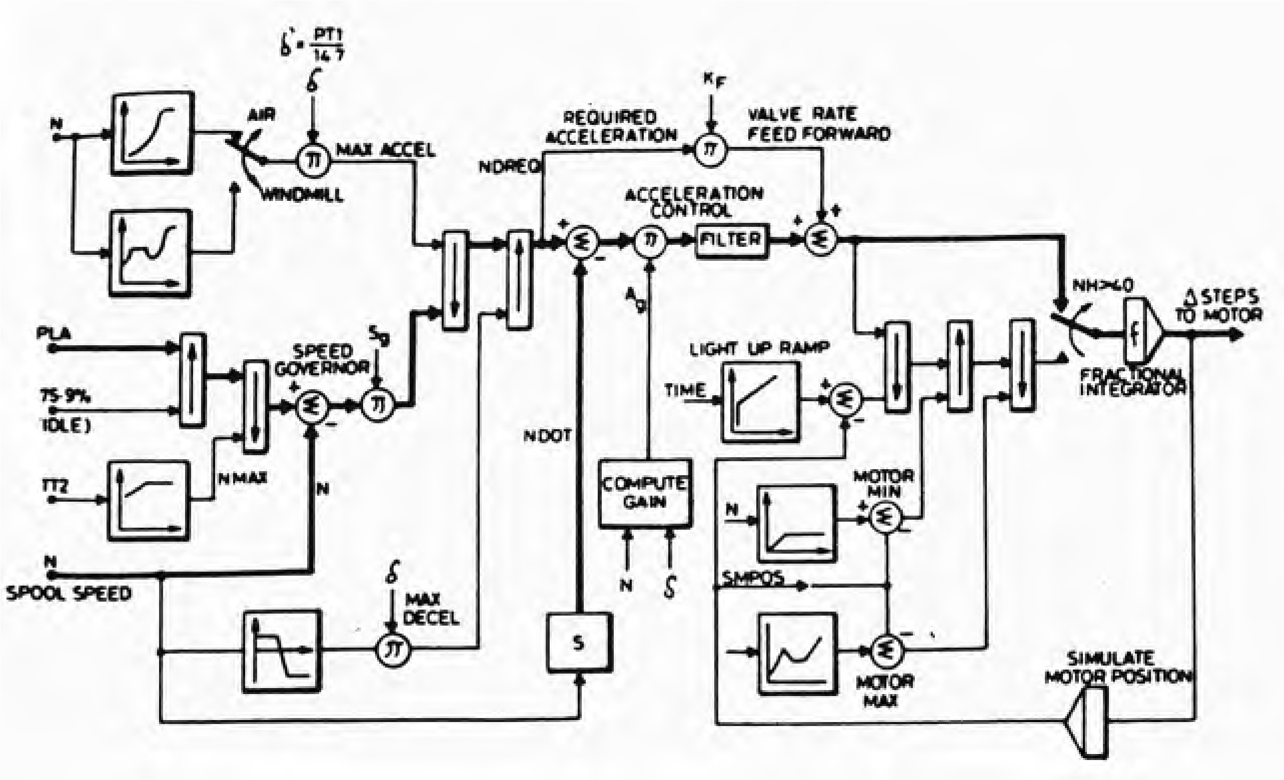
"Use of LP methods for synthesizing sampled-data automatic systems"

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

A typical Piping & Instrumentation Diagram



Gas Turbine Fuel Control



8% Classic loops

15% Inner servo loops

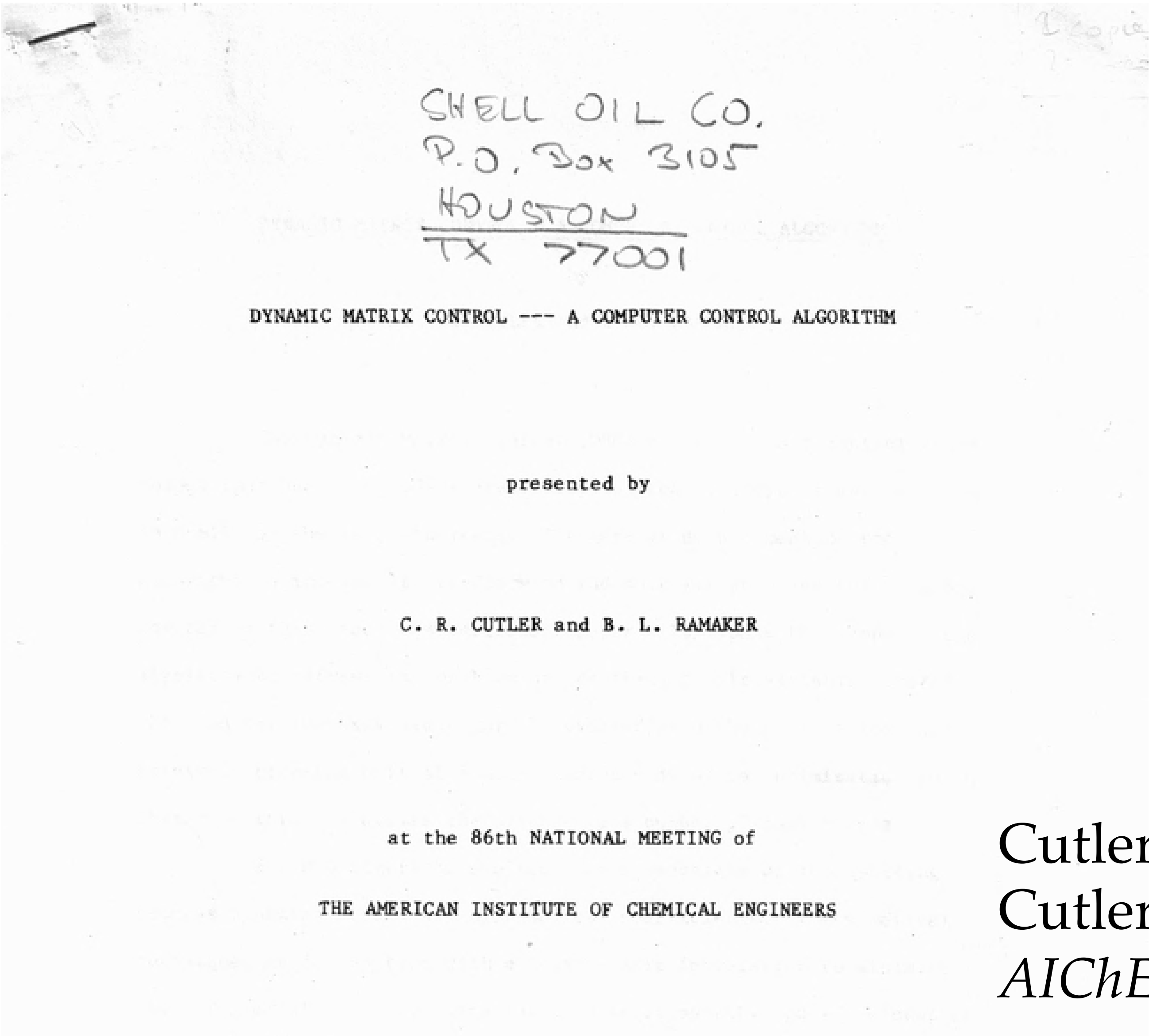
77% Logic/schedule

J.R. Cassidy

Director, UTRC

ACC ’ 93

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, PhD Proposal, 1969
Cutler & Ramaker, 1979
AIChE National Mtg.

Cutler & Ramaker (1979)

To incorporate the control of more than one output variable in the DMC Algorithm, the matrix of coefficients is expanded below to illustrate the case of two manipulated inputs and two outputs:

$$\delta O_1{}^1 = a_1 \Delta I_1^1 + b_1 \Delta I_2^1 \qquad (7)$$

$$\delta O_2{}^1 = a_2 \Delta I_1^1 + a_1 \Delta I_1^2 + b_2 \Delta I_2^1 + b_1 \Delta I_2^2$$

$$\delta O_3{}^1 = a_3 \Delta I_1^1 + a_2 \Delta I_1^2 + a_1 \Delta I_1^3 + b_3 \Delta I_2^1 + b_2 \Delta I_2^2 + b_1 \Delta I_2^3$$

$$\vdots$$

$$\delta O_i{}^1 = a_i \Delta I_1^1 + a_{i-1} \Delta I_1^2 + a_{i-2} \Delta I_1^3 + \ldots b_i \Delta I_2^1 + b_{i-1} \Delta I_2^2 + b_{i-2} \Delta I_2^3 + \ldots$$

$$\delta O_1{}^2 = c_1 \Delta I_1^1 + d_1 \Delta I_2^1$$

$$\delta O_2{}^2 = c_2 \Delta I_1^1 + c_1 \Delta I_1^2 + d_2 \Delta I_2^1 + d_1 \Delta I_2^2$$

Plenary at ACC '91

There is very little theory to support
the use of constrained MPC…

MPC Theory

Keerthi & Gilbert (1988), *JOTA*

"Optimal Infinite-Horizon Feedback Laws for a General Class of Constrained Discrete-Time Systems: Stability and Moving-Horizon Approximations"

Rawlings & Muske (1993), *IEEE-TAC*

"Stability of Receding Horizon Control."

Mayne, Rawlings, Rao, Scokaert (2000), *Automatica*

"MPC: Stability & Optimality (Survey Paper). "

– Automatica: most cited article ever

MPC Vendor Applications
Qin & Badgwell (2003), *Control Eng. Practice*

S.J. Qin, T.A. Badgwell / Control Engineering Practice 11 (2003) 733 764 745

Table 6
Summary of linear MPC applications by areas (estimates based on vendor survey; estimates do not include applications by companies who have licensed vendor technology)[a]

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	—	

Impact of MPC Theory

- Improved maintainability of algorithms and software – a prerequisite for application at scale
- Controllers for large constrained systems with stability and performance guarantees by design
- Academic respectability
- Vast improvement in education

MPC Workshop 1998

Nonlinear Model Predictive Control Workshop
Frank Allgöwer, Alex Zheng
Ascona, 1998

Dominated by Process Control

MPC Workshop 2008

INTERNATIONAL WORKSHOP ON ASSESSMENT AND FUTURE DIRECTIONS OF NONLINEAR MODEL PREDICTIVE CONTROL

September 5-9, 2008
Pavia, Italy

University of Pavia
CeRS - IUSS Pavia

Lalo Magni, Davide Raimondo,
Frank Allgöwer

Process Control has almost disappeared

Applications in automotive, power electronics,…

What happened?

- Faster, different types of computers

- Faster optimization algorithms and software

- New driver: complexity

- New algorithms: “fast MPC”

What happened?

- Faster, different types of computers
- Faster optimization algorithms and software
  - 1989-2004: Speedup of LP by factor 10^6 *[Bixby et al., 2004]*
- New driver: complexity
- New algorithms: "fast MPC"

Embedded Model Predictive Control

Traditional MPC

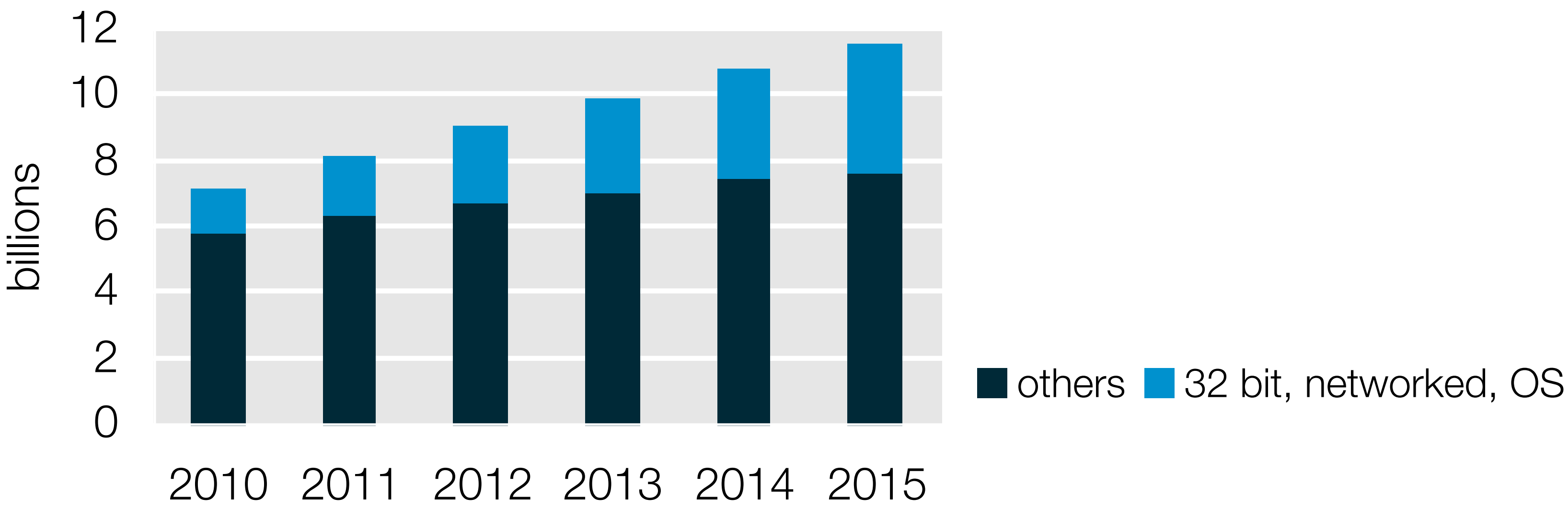
- Successful in process industries
- Sampling times of minutes
- Powerful computing platforms

Embedded MPC

- Small, high performance plants
- Sampling times of ms to ns
- Limited embedded platform

Embedded Systems by the Numbers

Worldwide unit shipments of embedded computing platforms:



Source: *Intelligent Systems: The Next Big Opportunity*, IDC 2011

ARM's 32-bit embedded systems growing at 20% p.a.

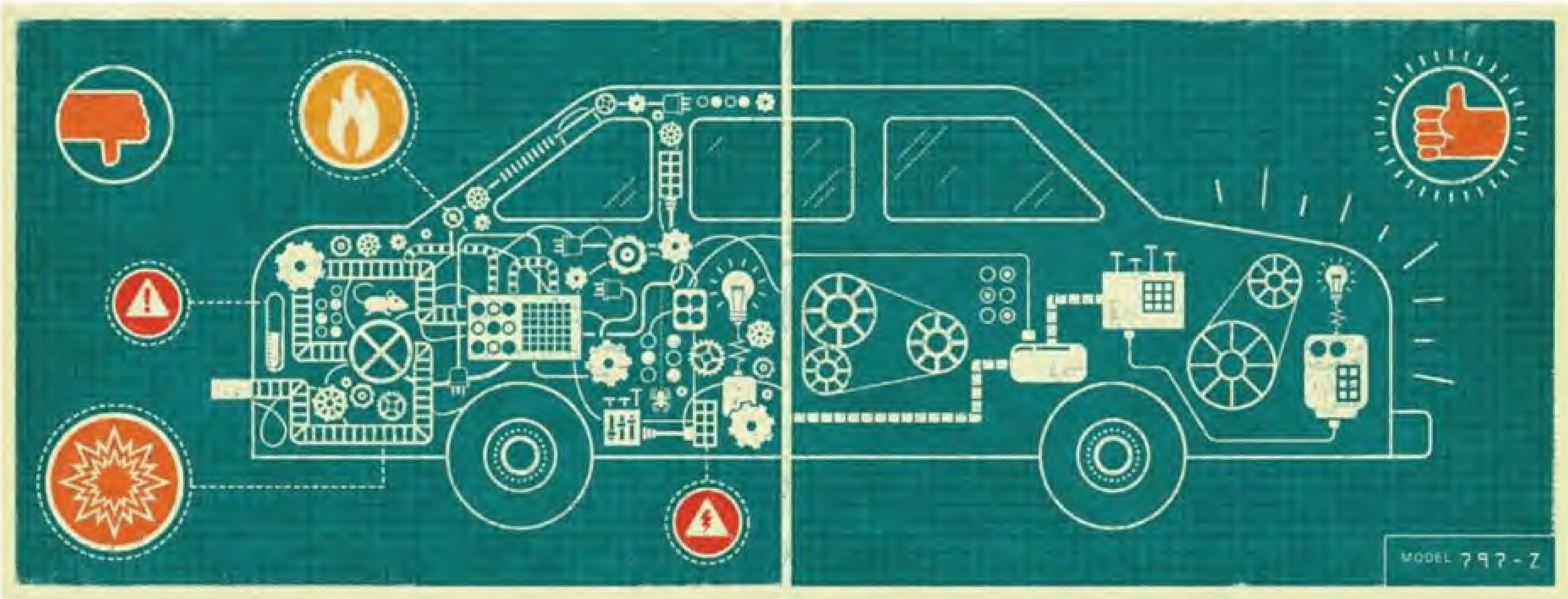
Source: Keith Clarke, ARM Vice President, *Keynote at CDNLive*, May 2013

New opportunity for automated decision making based on optimization

Outline

- History
- MPC
- Complexity
- Fast MPC
- Future

Harvard Business Review



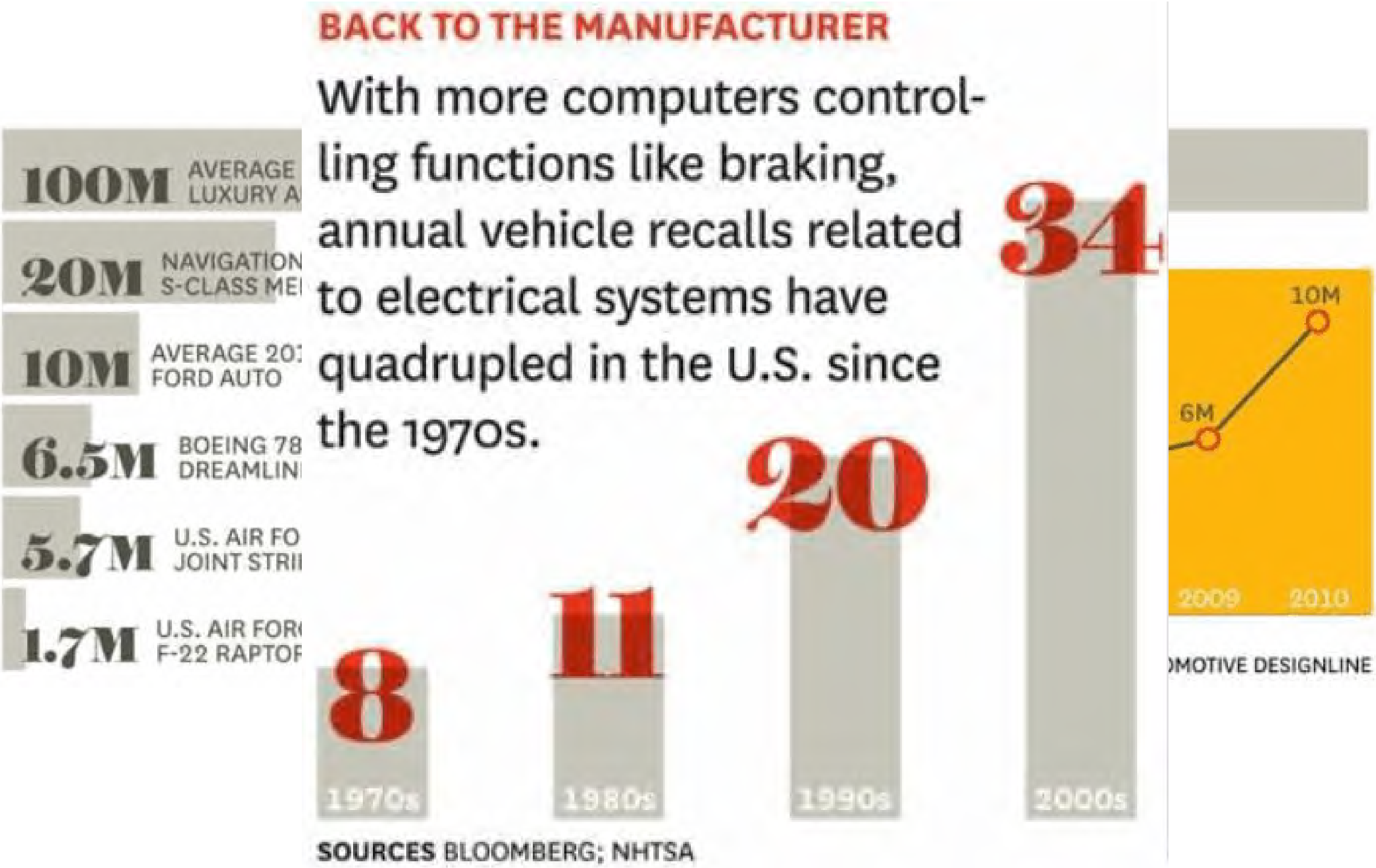
FIRST

Why Dinosaurs Will Keep Ruling the Auto Industry

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

June 2010

Harvard Business Review



Formal Verification of Embedded Software in Model Based Design

- Model checking of safety properties for Simulink Models
- Avionics distributed control system complexity:
  - 10K-250K simulink blocks
  - 40k-150K binary raw variables
  - Hundred to few thousand bin's after *simplification/abstraction*
- Automotive single controller complexity:
  - 5K-80K simulink blocks
  - Few thousand bin's after *simplification/abstraction*
- FormalSpecsVerifier tool environment (NuSMV)

Source: Alberto Ferrari

Advanced Laboratory on Embedded Systems S.r.l.

United Technologies

Abstraction / Simplification

- Fast MPC provides performance and real time execution guarantees
- Fast MPC may be an essential enabler for simplification and abstraction required for validation and verification

Outline

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Synthesis of Optimal Control Laws

Infinite-Horizon Optimal Control

$$J^*(x) = \min_{u_i \in U} \sum_{i=0}^{\infty} l(x_i, u_i)$$
$$\text{s.t. } x_{i+1} = f(x_i, u_i)$$
$$x_i \in X$$

Dynamic Programming

$$J^\star(x) = \min_u \; l(x,u) + J^\star(f(x,u))$$
$$\text{s.t. } (f(x,u),u) \in X \times U$$

- Challenge is computation!

Synthesis of Optimal Control Laws

Infinite-Horizon Optimal Control

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$$\text{s.t. } (f(x,u),u) \in X \times U$$

- Challenge is computation!
- Closed-form solution for linear systems, no constraints only: LQR,…

Synthesis of Optimal Control Laws

Infinite-Horizon Optimal Control

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Dynamic Programming

$$J^\star(x) = \min_u \; l(x,u) + J^\star(f(x,u))$$
$$\text{s.t. } (f(x,u), u) \in X \times U$$

Explicit calculation of control law $u^\star(x)$ *offline*

Model Predictive Control

$$J^*(x_0) = \min_{u_i} \sum_{i=0}^{N} l(x_i, u_i) + V_f(x_N)$$
$$\text{s.t. } (x_i, u_i) \in X \times U, \; x_N \in X_f$$
$$x_{i+1} = f(x_i, u_i)$$

Online optimization problem defines control action $u_0^\star(x)$

Model Predictive Control : Properties

Theory is well-established

Mayne, Rawlings, Rao, Scokaert (2000), *Automatica*

"MPC: Stability & Optimality (Survey Paper). "

- **Recursive feasibility**: Input and state constraints are satisfied
- **Stability** of the closed-loop system
  - $J^*(x)$ is a convex Lyapunov function

- **Assuming** the real-time optimization problem is solved to ε-optimality

Verifiable Control Synthesis

Offline	Online
Explicit MPC	1st Order–Fast Gradient
Approx. Explicit MPC	Interior Point Opt.

Verifiable Control Synthesis

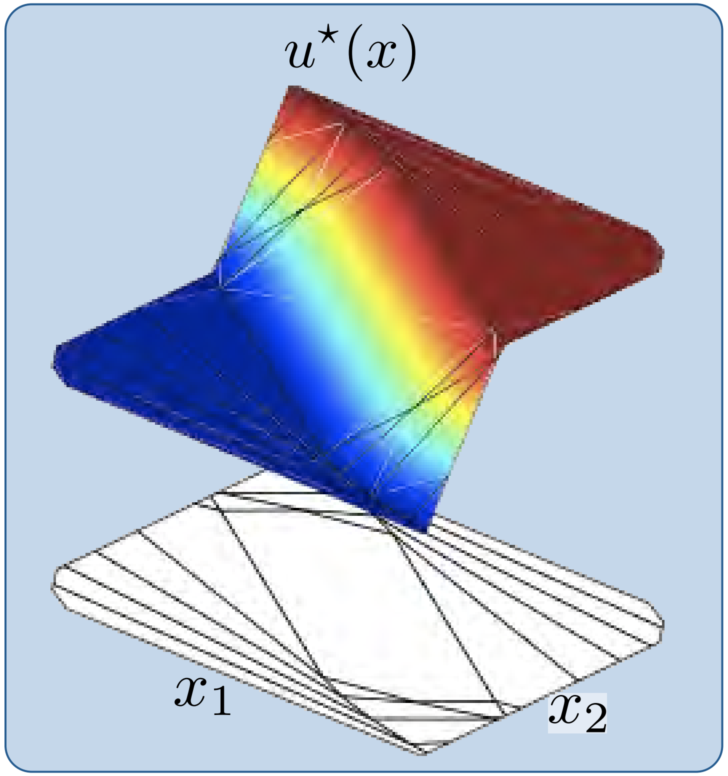
Offline	Online
Explicit MPC	1^{st} Order–Fast Gradient
Approx. Explicit MPC	Interior Point Opt.

Explicit MPC : Online => Offline Processing

- Optimization problem is parameterized by state
- Control law piecewise affine for linear systems / constraints
- Pre-compute control law as function of state x (parametric optimization)

Result : Online computation dramatically reduced

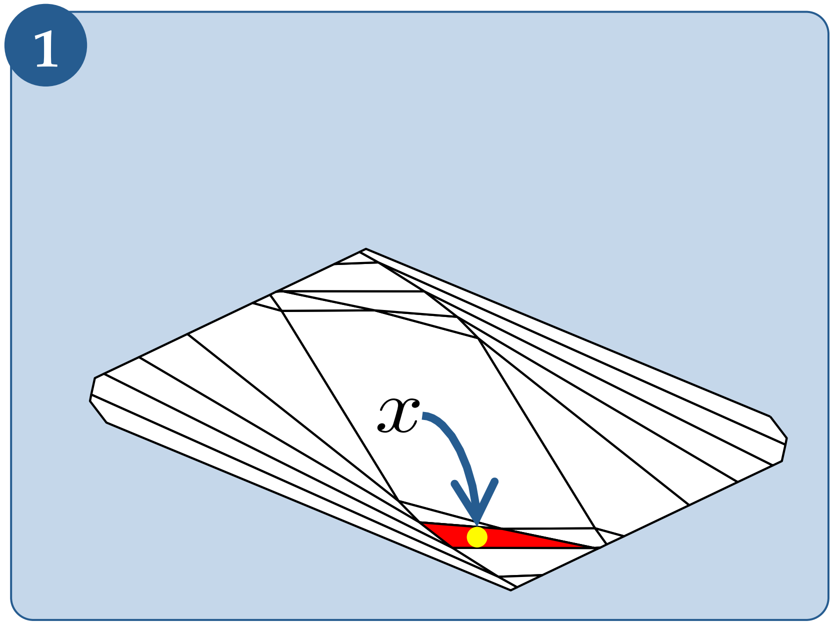
$$
\begin{aligned}
u^\star(x_0) = \operatorname*{argmin}_{u_i} \ & \sum_{i=0}^{N} l(x_i, u_i) + V_f(x_N) \\
\text{s.t. } & (x_i, u_i) \in X \times U \\
& x_{i+1} = f(x_i, u_i) \\
& x_N \in X_f
\end{aligned}
$$

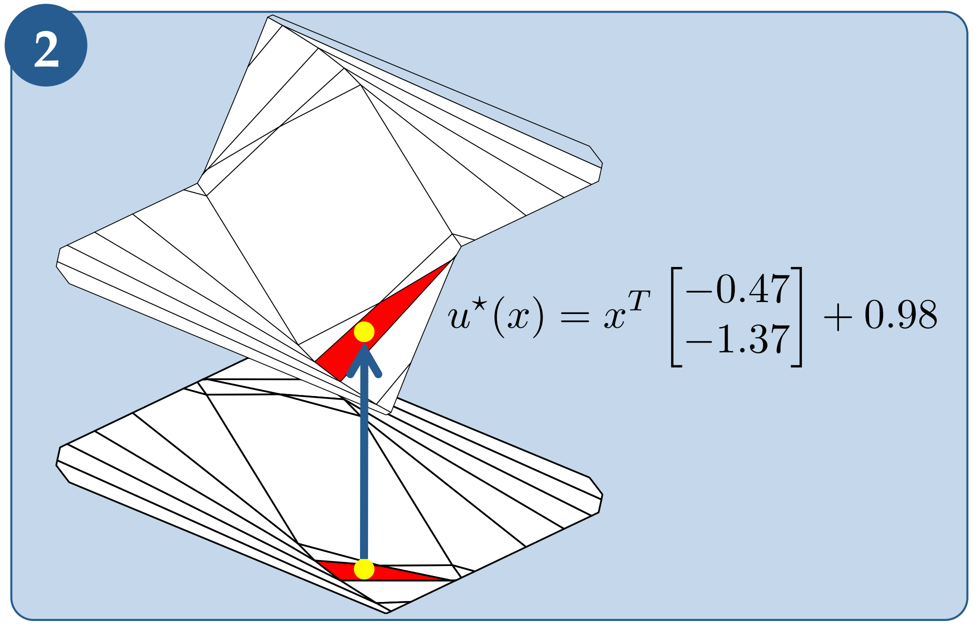


[M.M. Seron, J.A. De Doná and G.C. Goodwin, 2000]
[T.A. Johansen, I. Peterson and O. Slupphaug, 2000]
[A. Bemporad, M. Morari, V. Dua and E.N. Pistokopoulos, 2000]

Explicit MPC : Fast online evaluation

- Online evaluation reduced to:
  1. Point location
  2. Evaluation of affine function
- Online complexity is governed by point location
  - Function of number of regions in cell complex
  - Milli- to microseconds possible if small number of regions





Verifiable Control Synthesis

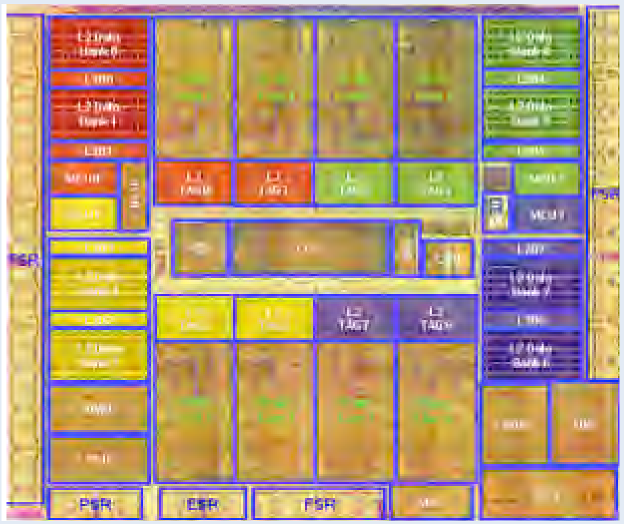
Offline	Online
Explicit MPC • < 5 states • Simple look-up • < μs sampling	**1st Order–Fast Gradient**
Approx. Explicit MPC	**Interior Point Opt.**

Verifiable Control Synthesis

Offline	Online
Explicit MPC • < 5 states • Simple look-up • < μs sampling	**1st Order–Fast Gradient**
Approx. Explicit MPC	**Interior Point Opt.**

Example : Temperature Regulation of Multi-Core Processor

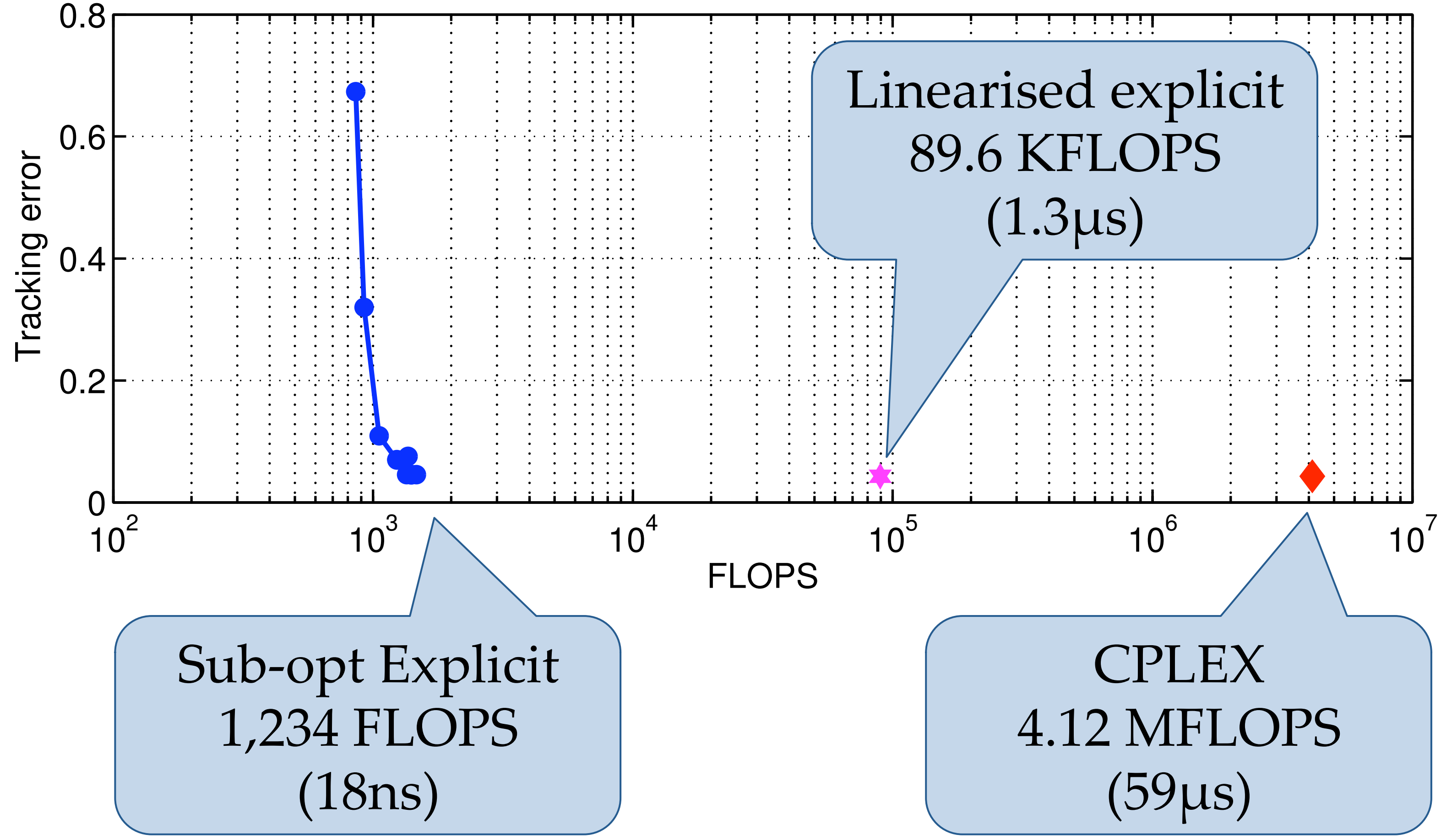
- Goals
  - Track workload requests
  - Minimize power usage
  - Respect temperature limits
- Quadratic nonlinear dynamics
  - Exact convex relaxation
- Stringent computational and storage requirements



[F. Zanini, C.N. Jones, D. Atienza, and G. De Micheli, 2010]

$$
\begin{aligned}
J^\star(x_0, w) = \min_{f_i} \ & \sum_{t=0}^{N} \sum_{i=0}^{t} (w_i - f_i) \\
\text{s.t.} \ & x_{i+1} = A x_i + B f_i^2 \\
& \sum_{i=0}^{t} w_i \leq \sum_{i=0}^{t} f_i \\
& x_i \leq T_{\max} \\
& f_{\min} \leq f_i \leq f_{\max}
\end{aligned}
$$

Computational results for QCQP : >3,000× faster



(Assuming 70 GFLOPS / sec – e.g., Intel Core i7 965 XE)

>3,000× / 72× faster than CPLEX / lin. explicit

Verifiable Control Synthesis

Offline	Online
Explicit MPC • < 5 states • Simple look-up • < μs sampling	**1st Order–Fast Gradient**
Approx. Explicit MPC • < 10 states • Specified complexity • < μs sampling	**Interior Point Opt.**

Verifiable Control Synthesis

Offline	Online
Explicit MPC • < 5 states • Simple look-up • < µs sampling	**1st Order–Fast Gradient** • Any size • Simple and robust • µs – ms sampling
Approx. Explicit MPC • < 10 states • Specified complexity • < µs sampling	**Interior Point Opt.**

Verifiable Control Synthesis

Offline

Explicit MPC

- < 5 states
- Simple look-up
- < μs sampling

Approx. Explicit MPC

- < 10 states
- Specified complexity
- < μs sampling

Online

1^{st} Order–Fast Gradient

- Any size
- Simple and robust
- μs – ms sampling

Interior Point Opt.

The FORCES Code Generator

Multistage QCQP

$$\begin{aligned} \min \quad & \sum_{i=1}^{N} \tfrac{1}{2} v_i^T H_i v_i + f_i^T v_i \\ \text{s.t.} \quad & \underline{z}_i \le v_i \le \bar{v}_i \\ & A_i v_i \le b_i \\ & v_i^T Q_{i,j} v_i + l_{i,j}^T v_i \le r_{i,j} \\ & C_i v_i + D_{i+1} v_{i+1} = c_i \end{aligned}$$

Problem description

```
stage = MultiStageProblem(N+1);
for i = 1:N+1
% dimensions
stages(i).dims.n = 10;
stages(i).dims.r = 5;
stages(i).dims.lb = 3;

% cost
stages(i).cost.H = Hi;
stages(i).cost.f = fi;

% inequalities
stages(i).ineq.b.lbidx = 3:5;
stages(i).ineq.b.lb = zeros(3,1);

% equalities
stages(i).eq.C = Ci;
stages(i).eq.c = ci;
stages(i).eq.D = Di;
end
generateCode(stages);
```

?

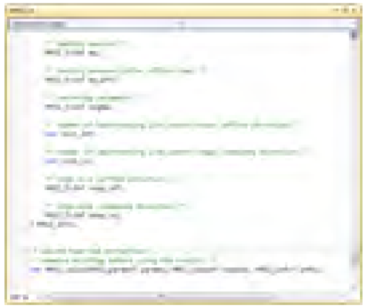
Embedded Hardware

FORCES

- C code generation of primal-dual Mehrotra interior point solvers
- LPs, QPs, QCQPs
- Parametric problems
- Multi-core platforms
- Library-free
- Available: forces.ethz.ch

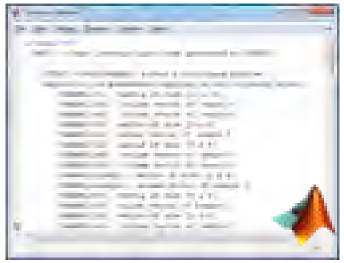
Generated Code

Solver (ANSI-C)



solver.h
solver.c
solver.m
solvermex.c
makemex

MATLAB MEX interface for rapid prototyping



Some Early Users of FORCES

KATHOLIEKE UNIVERSITEIT LEUVEN

Nonlinear MPC & MHE with ACADO

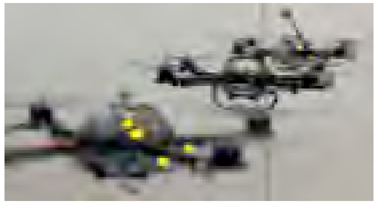
Milan Vukov, KU Leuven, 2012

ALSTOM

MPC for Wind Turbines

Marc Guadayol, ALSTOM, 2012

IDSC



Quadrotor Control

Marc Müller, IDSC, ETH Zurich, 2012

ABB

Adaptive MPC for Belt Drives

Kim Listmann, ABB Ladenburg, 2012

UNIVERSITY OF CAMBRIDGE

Danfoss

TUM TECHNISCHE UNIVERSITÄT MÜNCHEN

UNIVERSITÀ DI PAVIA

DTU

OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG

LMS ENGINEERING INNOVATION

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

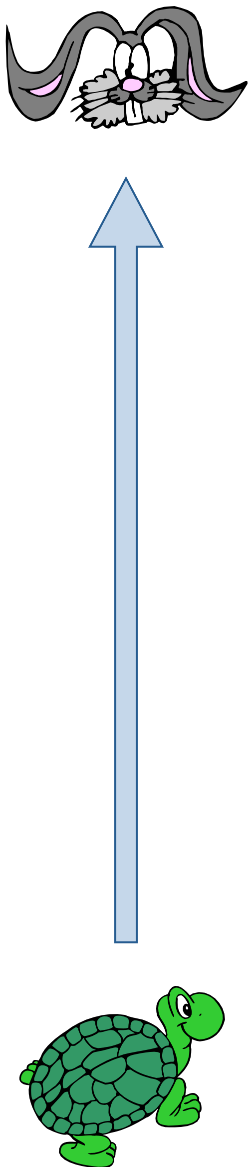
STANFORD UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

Verifiable Control Synthesis

Offline	Online
Explicit MPC • < 5 states • Simple look-up • < μs sampling	**1st Order–Fast Gradient** • Any size • Simple and robust • μs – ms sampling
Approx. Explicit MPC • < 10 states • Specified complexity • < μs sampling	**Interior Point Opt.** • Any size • Highly accurate • ms sampling

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]*

Micro-scale Race Cars

- 1:43 scale cars – 106mm
- Top speed: **5 m/s**
  (774 km/h scale speed)
- Full differential steering
- Position-sensing: External vision
- 50 Hz sampling rate

Project goals:

1. Plan optimal path online in dynamic race environment
2. Demonstrate real-time control optimizing car performance
3. Beat all human opponents!

Challenges:

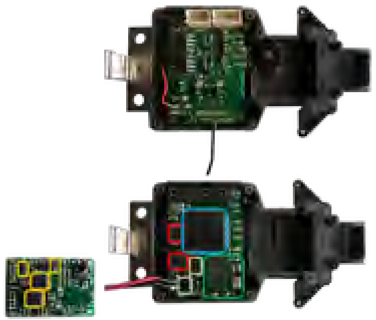
Interaction with multiple unpredictable opponents
Highly nonlinear dynamics
High-speed planning and control

System Details

Camera System

- Infrared spotlight
- Reflectors on cars
- 3.36 mm accuracy
- 100 Hz update rate at 1024 x 1200 pixels

Embedded Board



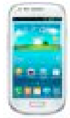
- Custom built electronics
- Bluetooth communication
- IMUs & Gyro
- H-bridges for DC Motors
- ARM Cortex M4

Tracks

- Custom built high grip track

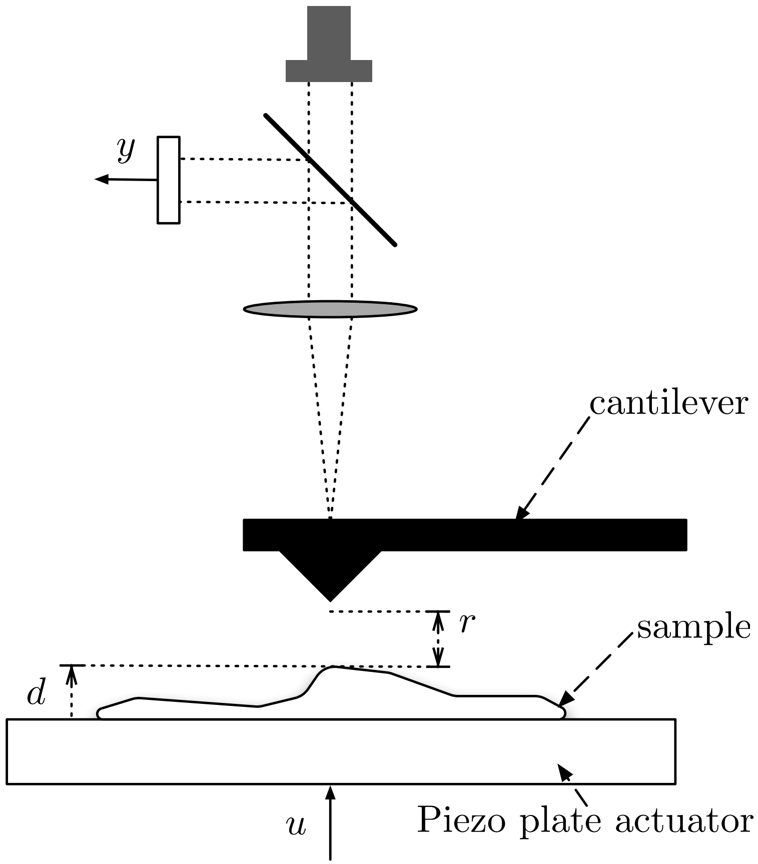
- Standard RCPtracks track

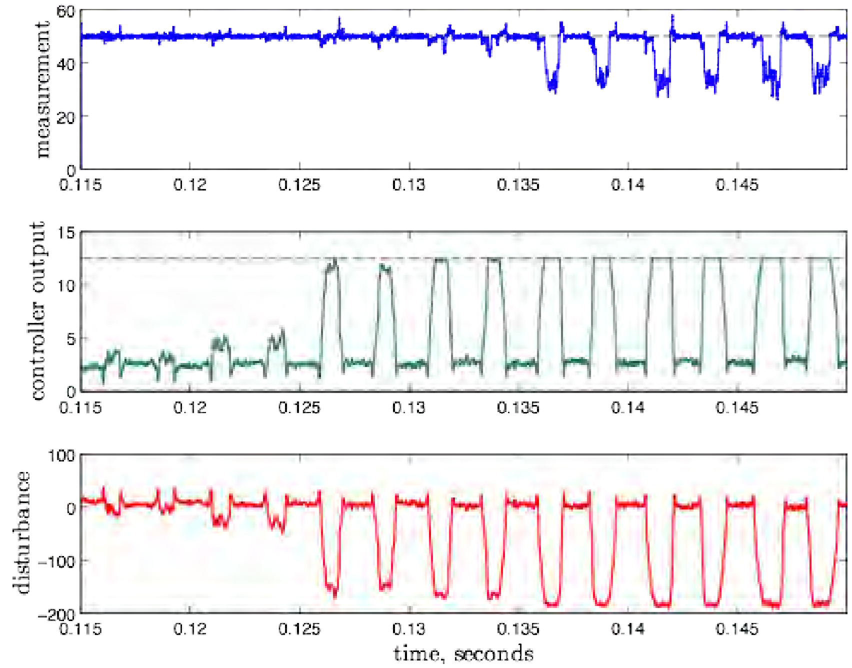
Autonomous RC Racing Using FORCES

- Reference tracking MPC solved in 3.3 ms on ARM Cortex A9 based chip 

Online MPC at Megahertz Rates using FPGAs

MPC of an Atomic Force Microscope, in collaboration with IBM





- ✓ Same tracking performance as double precision state-of-the-art solver
- ✓ 700 kilohertz on 1 Watt FPGA
- ✓ >1 megahertz on high-performance FPGA

Jerez, Goulart, Richter, Constantinides, Kerrigan, Morari

Embedded Predictive Control on an FPGA using the Fast Gradient Method", in ECC 2013

Energy, Comfort, Security Needs in Buildings are Evolving
UTC presence in buildings creates opportunities and research challenges

United Technologies

Carbon-neutral buildings by 2030
Buildings must be 4X-5X more energy efficient

Customer-focused solutions
Enabled by integrated systems

Threats becoming more complex
98% false alarms

Brightbox Technologies Inc.
MPC for Building Energy Mgt

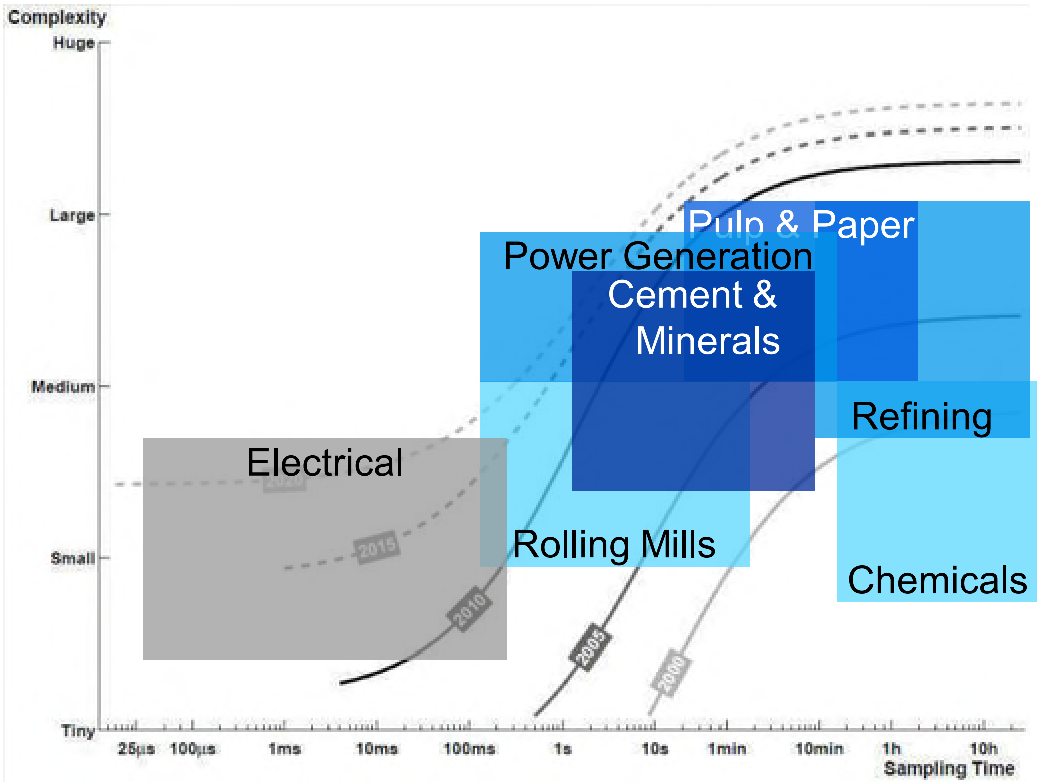
- Flawless operation in several commercial bldgs.
- Most complex building: 8 packaged units and 600 vav boxes
  - 18,176 signals processed every 5 min.
  - MPC: >300,000 vars. and >500,000 constraints (sampling time 5 mins)

Outline

- History
- MPC
- Complexity
- Fast MPC
- Future

"Closing the Loop", P. Terwiesch, IFAC 2011

Model predictive control: advancing the frontiers
Industry requirements vs available processing power



Source: C. Ganz/ABB

Graduate Course Enrollments ETH

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

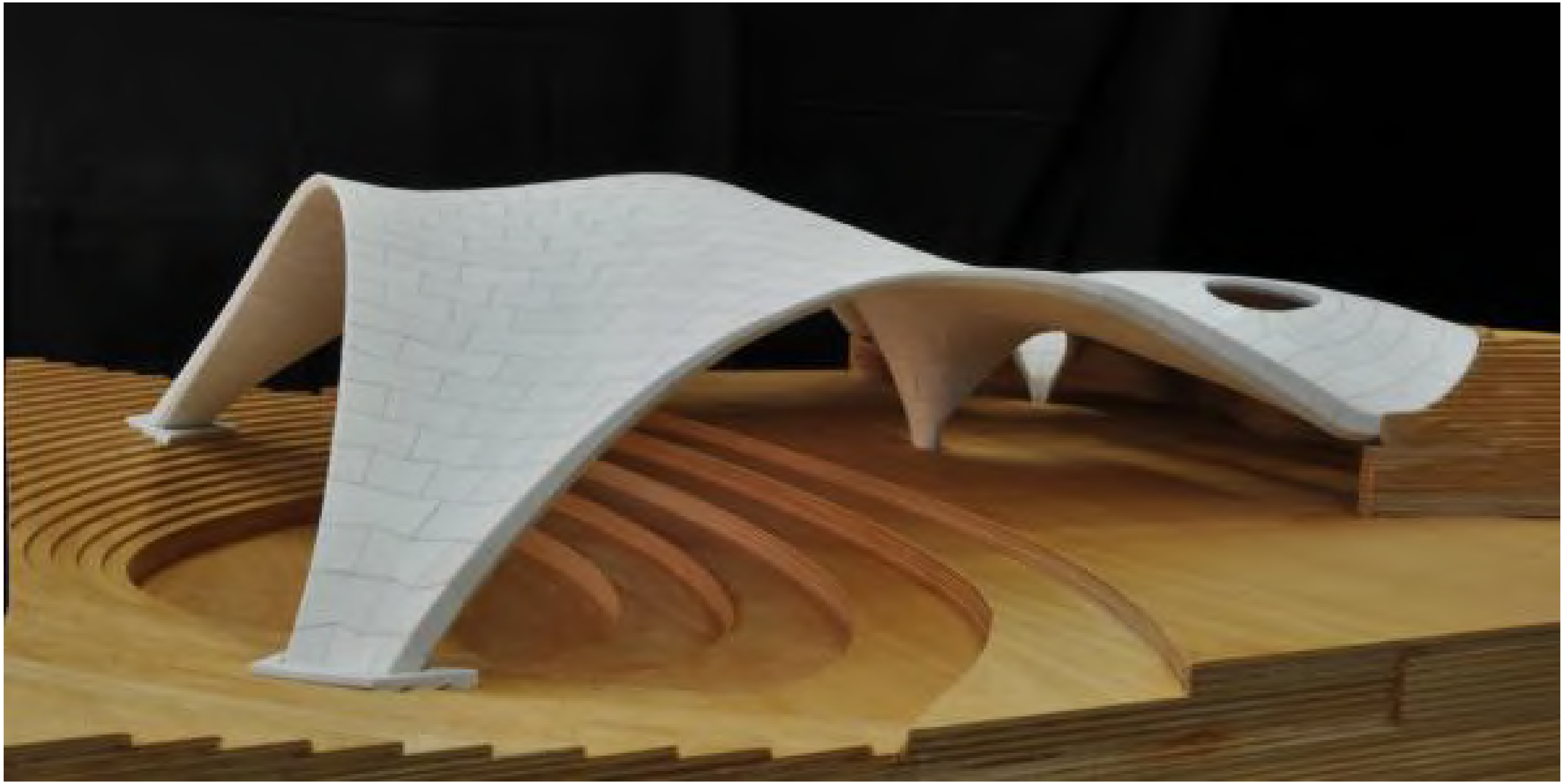
	2008	2009	2010
MPC	32	44	67
Linear Systems	34	42	59
Dynamic Programming	72	101	140

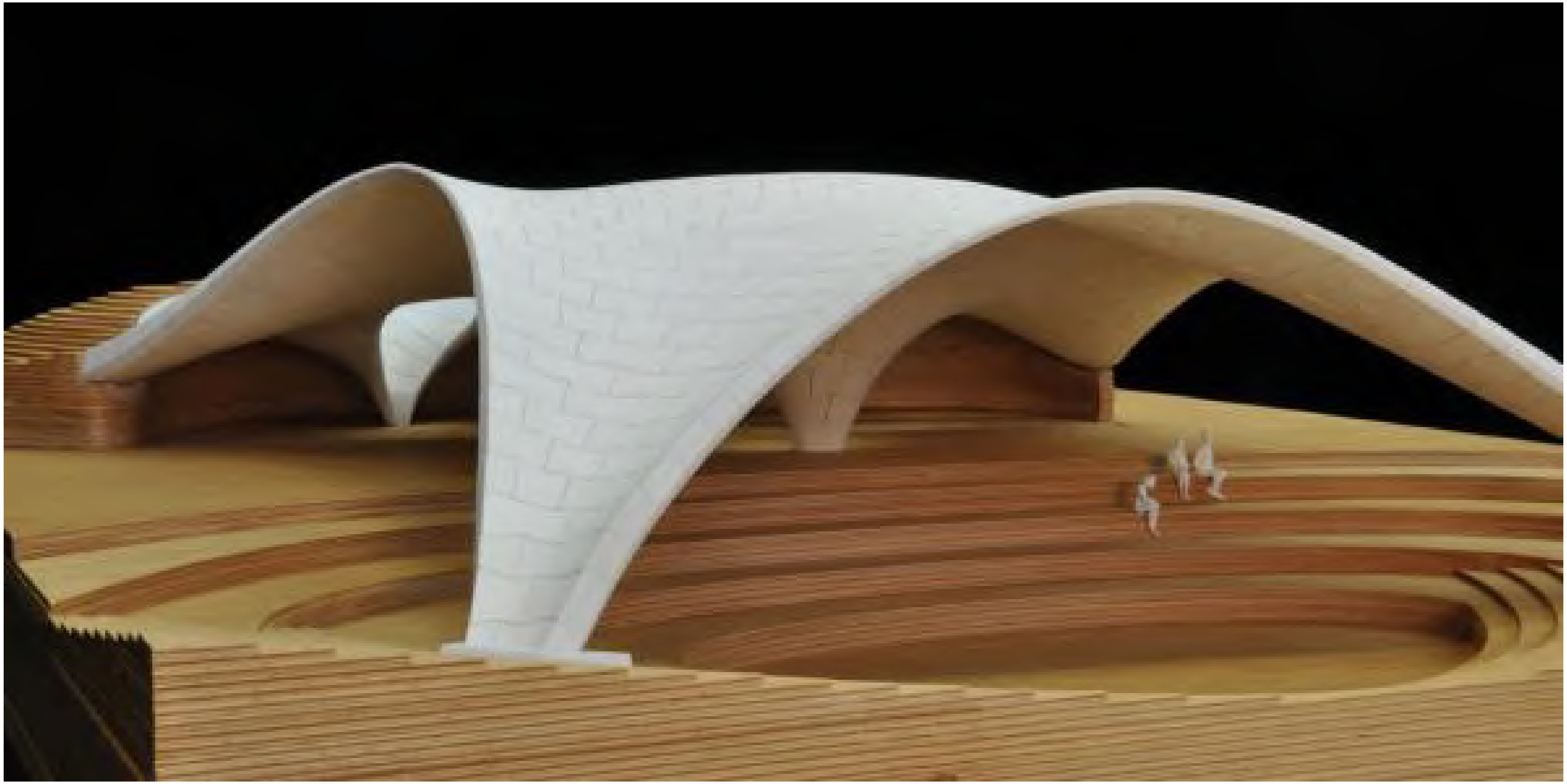
Conclusions

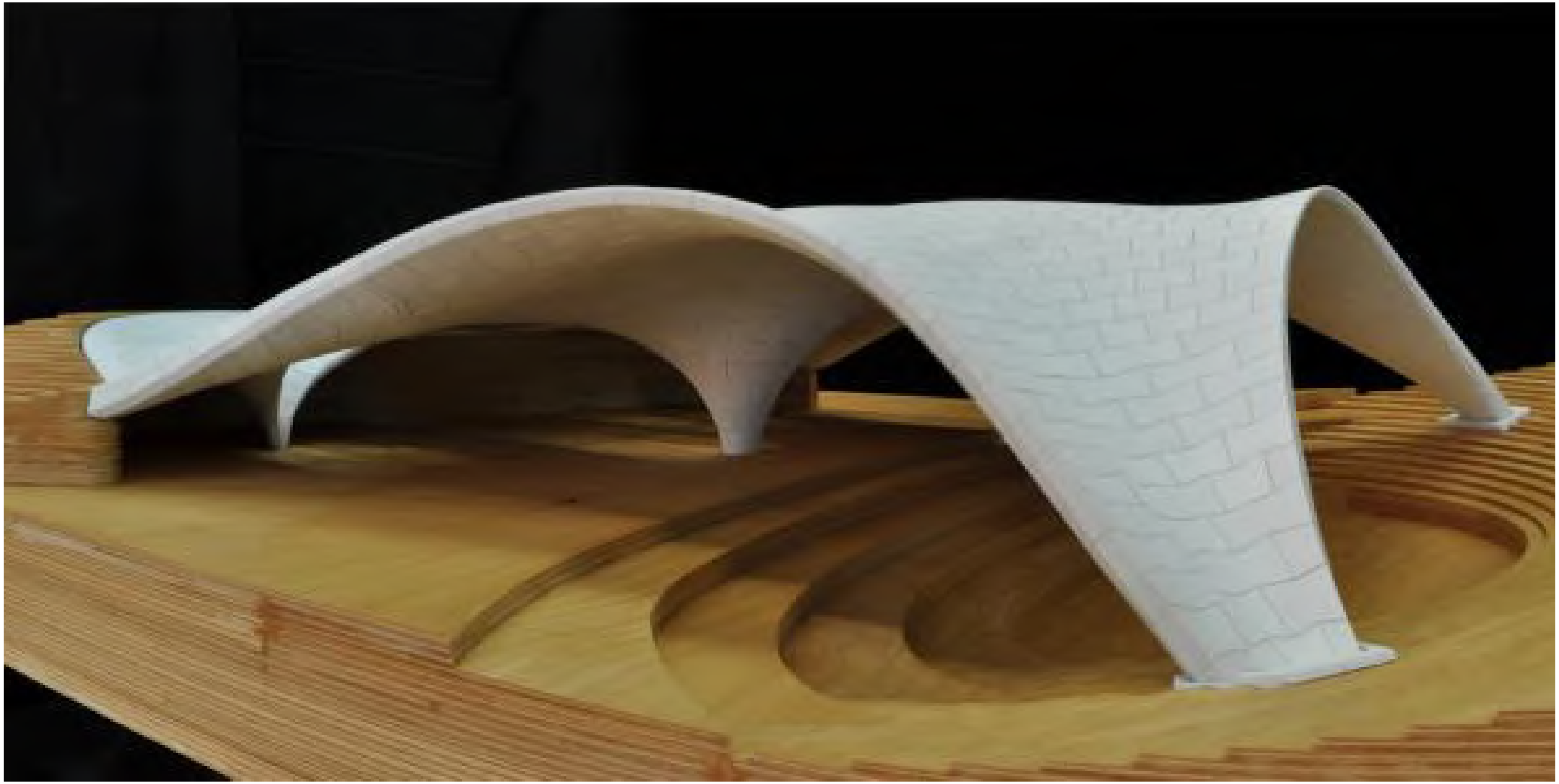
- The early phases of development are driven by the practitioners. Theory is needed to push the envelope and for communication.
- MPC is becoming the control technology of choice for many challenging applications.
- Computation is not limiting the application of MPC at any speed for any size problem

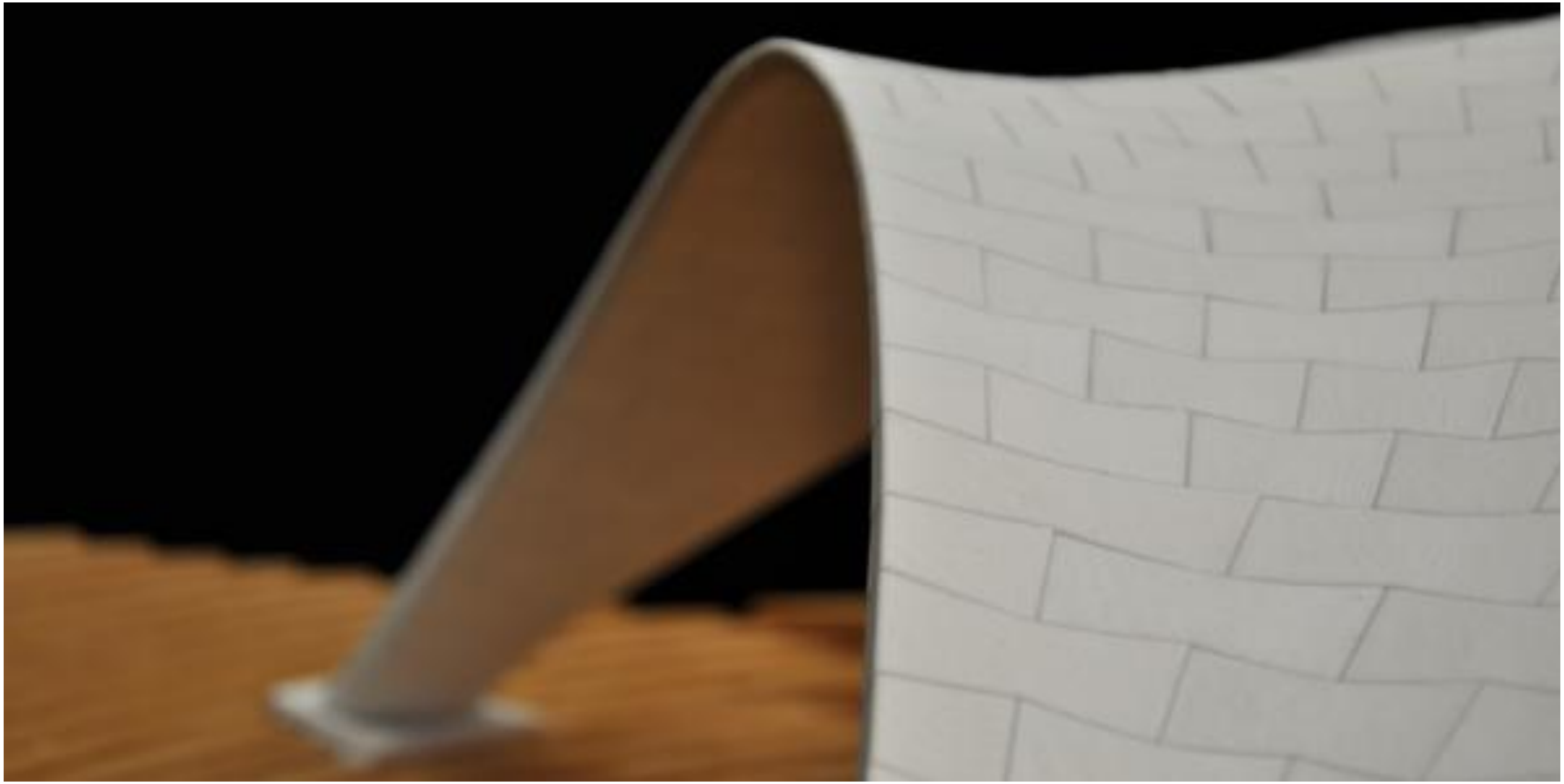
The Role of Theory in ~~Control~~ Practice of Architecture

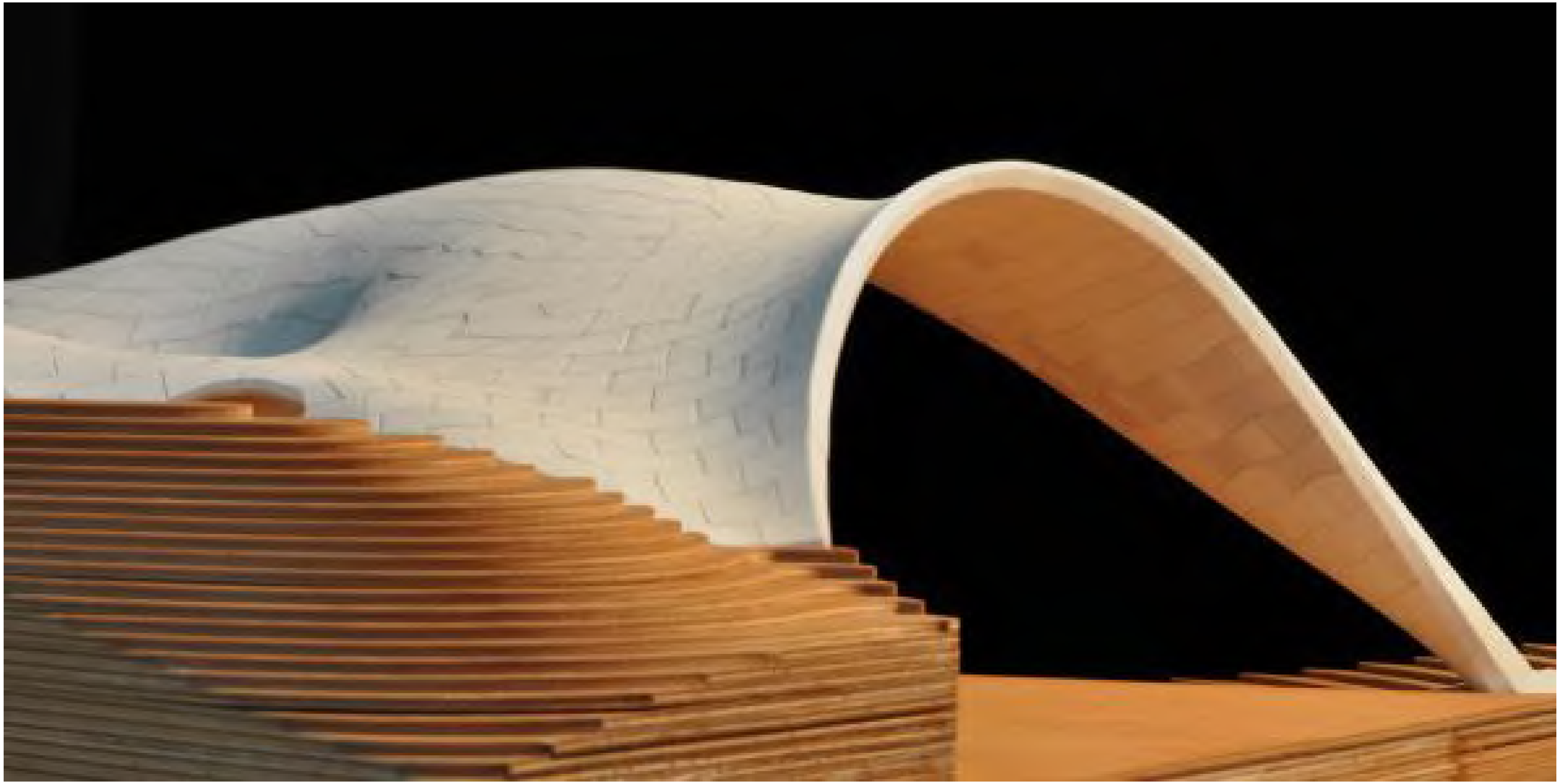
Prof. Dr. Philippe Block
Assistant Professor of Building Structure
Institute of Technology in Architecture
ETH Zurich







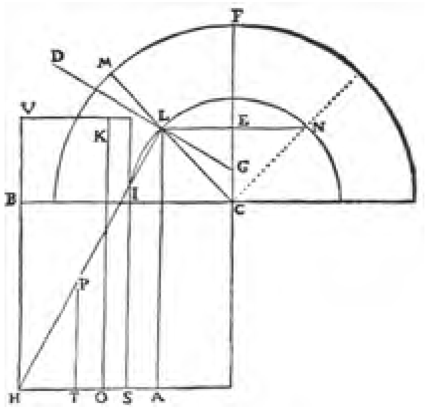




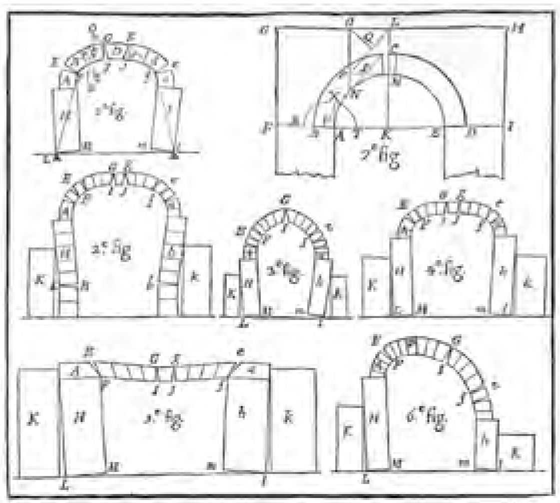
Arch Practice

Roman aqueduct near Nimes, France

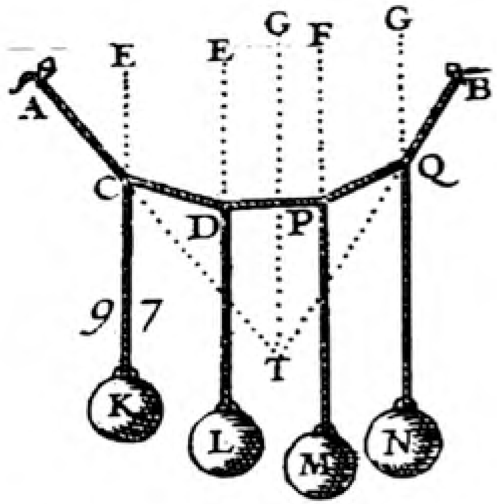
Arch Theory



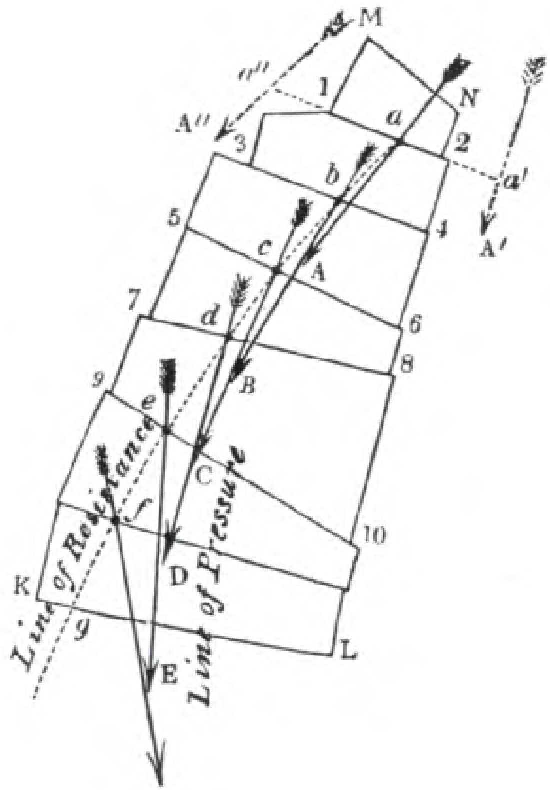
de Lahire (1695)



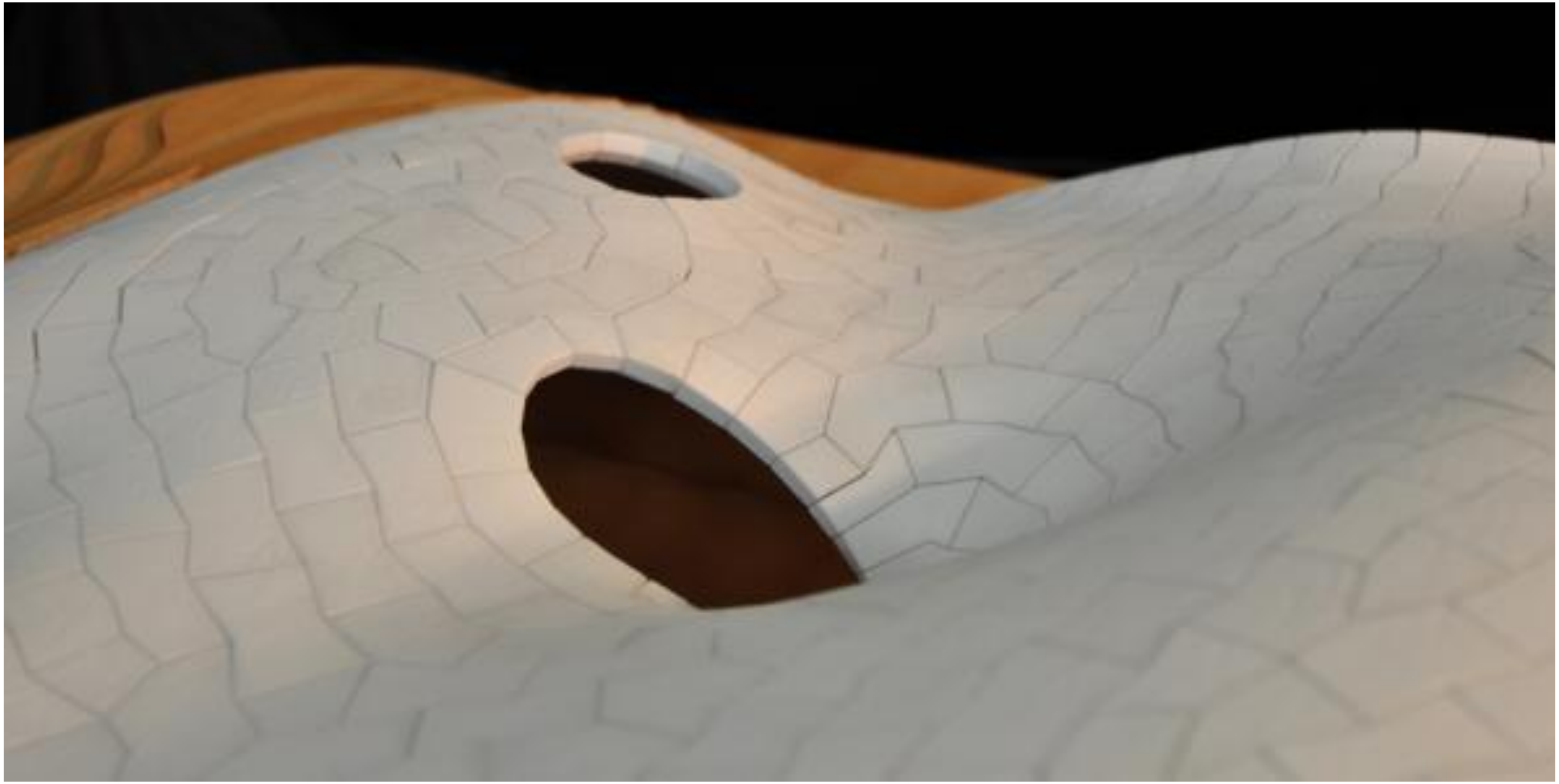
Danyzy (1732)

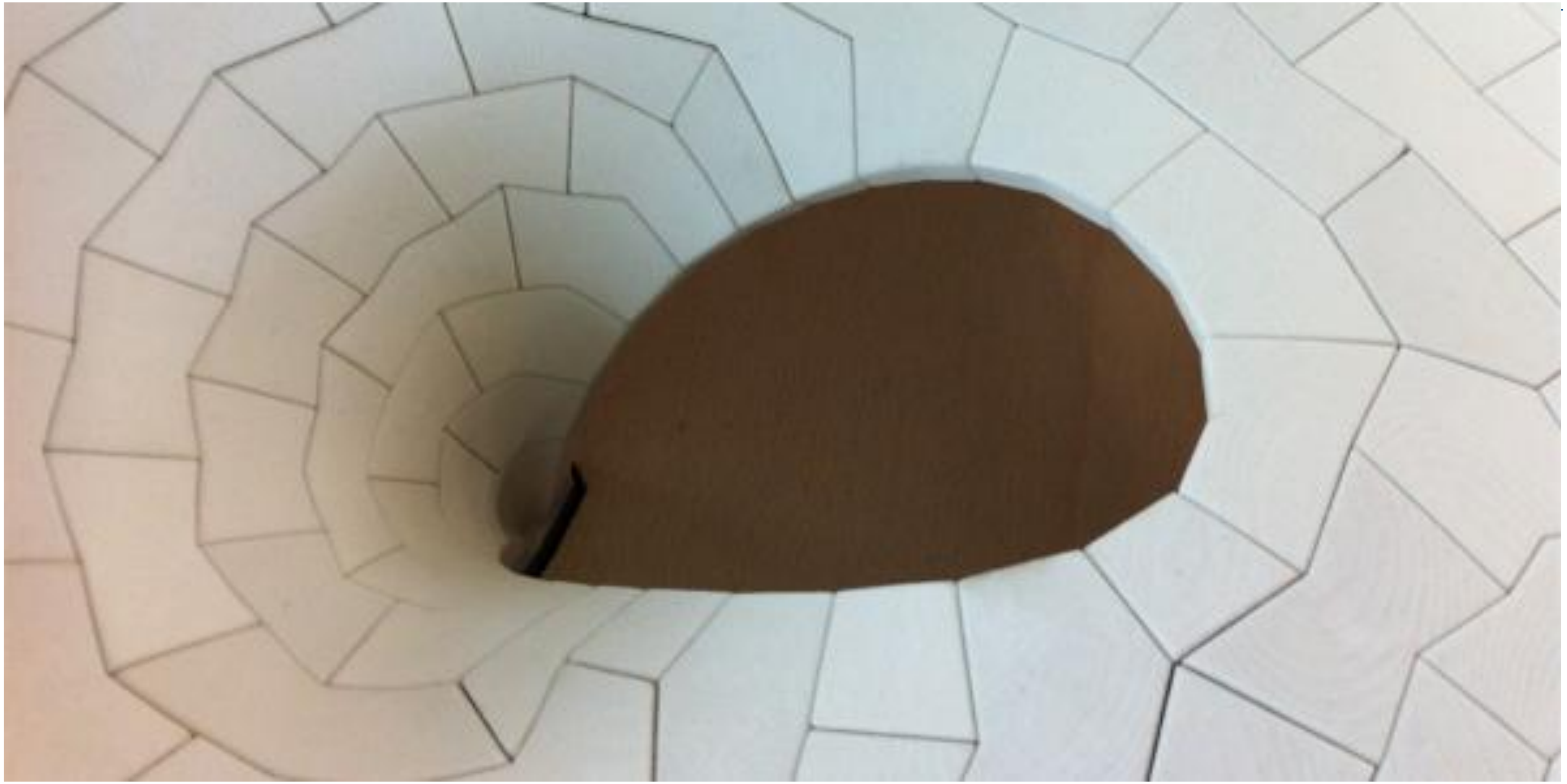


Moseley (1843)

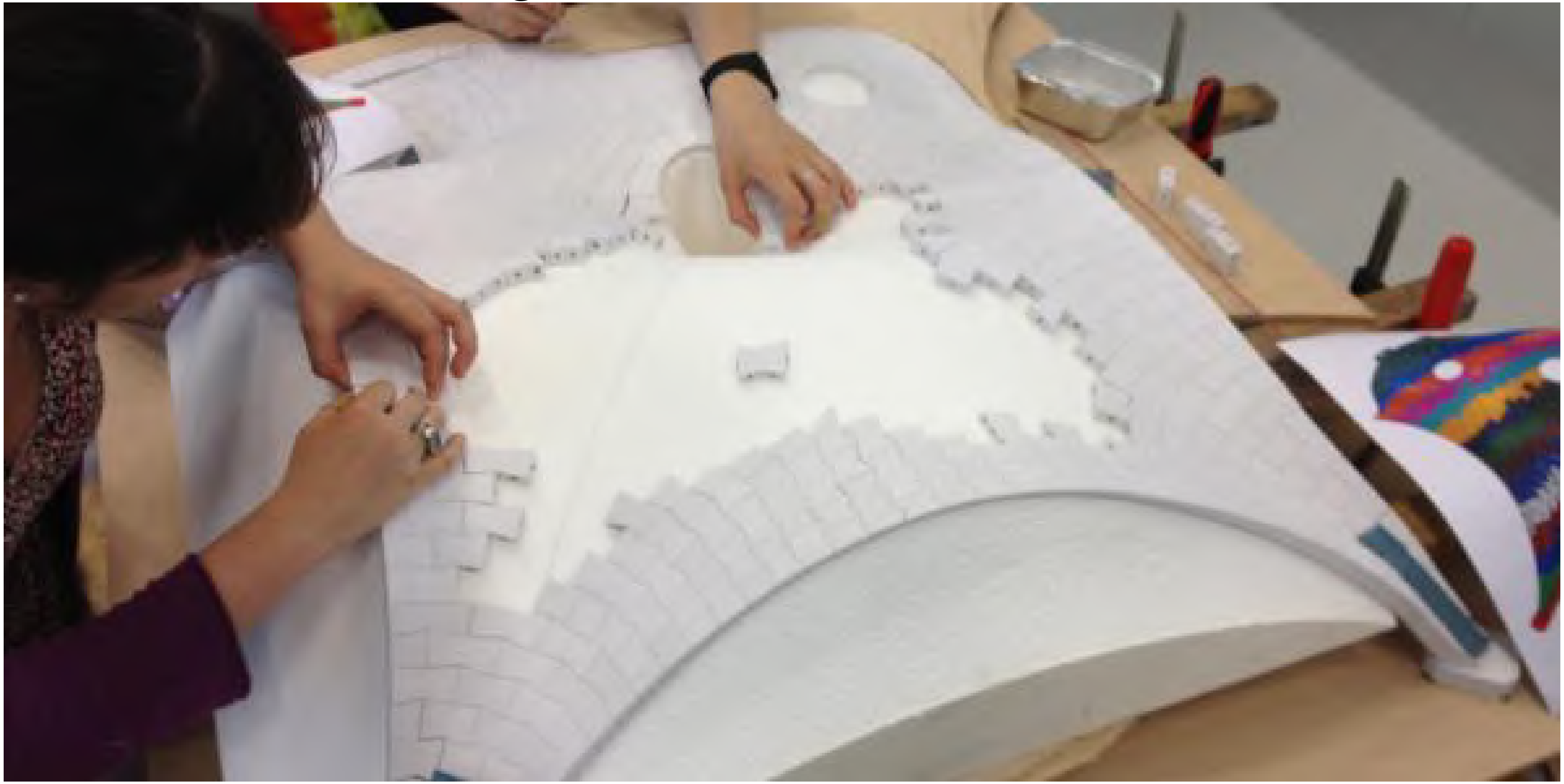


Varignon (1725)

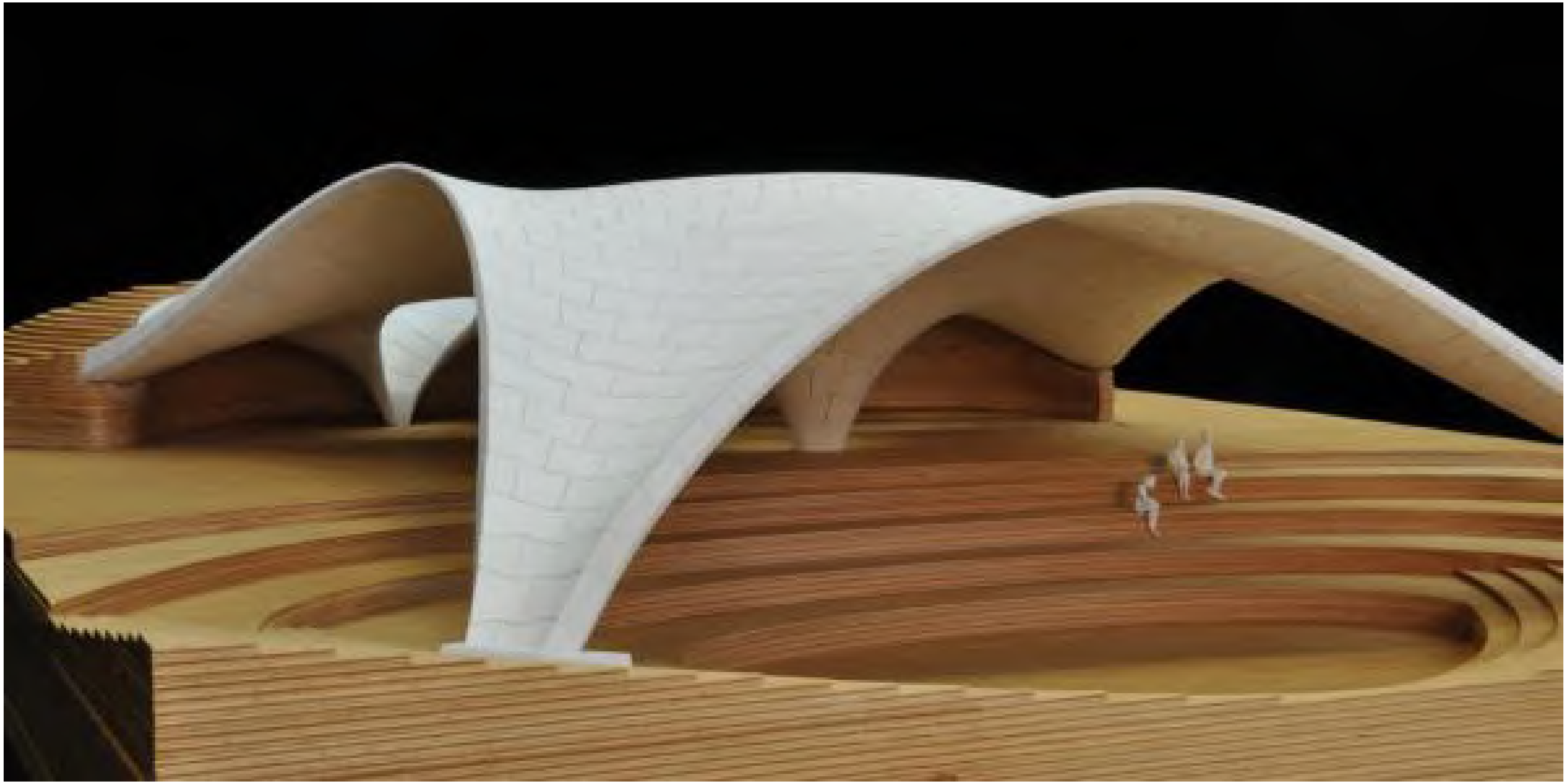




NCCR Digital Fabrication
Advanced Building Processes in Architecture



MLK Jr. Park Stone Vault, Chestnut Plaza, Austin



"Texas Cream" Limestone
Average block size of 3 x 2 x 0.9 m, 13 tons