Introduction to History of Control

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A Broad Picture

There are examples of control from ancient time but control became widely used in the industries that emerged in the 19th and 20th centuries: steam power, electric power, ships, aircrafts, chemicals, telecommunication. Control was sometimes an enabling technology (aircraft, telecom). Similarities between different applications were not recognized.

Control became a separate engineering discipline in the 1940s and it has developed rapidly ever since. Today there are applications expanding everywhere and there are great new research challenges.

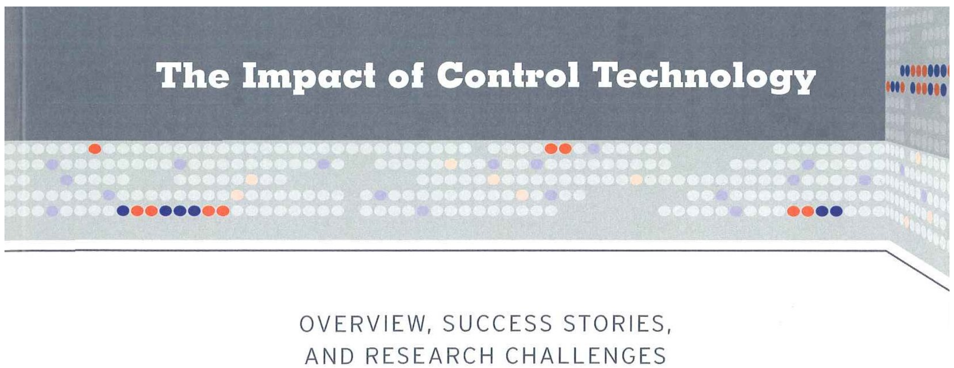
IEEE NAE AFOSR IFAC

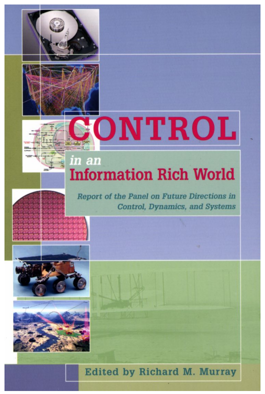
The Impact of Control Technology

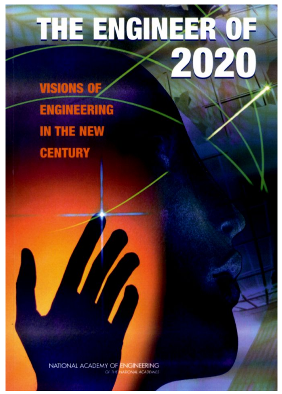
Overview, Success Stories and Research Challenges

Tariq Samad and Anuradha Annaswamy (editors)

http://ieeecss.org/general/impact-control-technology



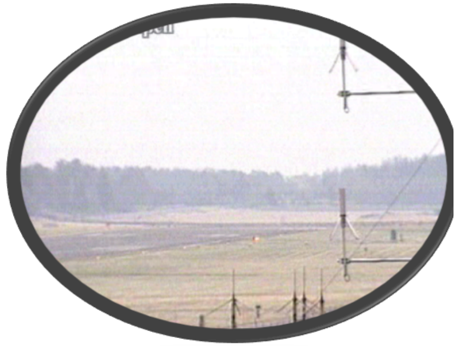




K J Åström: Control – The Hidden Technology Advances in Automatic Control Highlights of the ECC'99, Springer London

The Hidden Technology

- ☺ Widely used
- ☺ Very successful
- ☹ Seldom talked about
- 😐 Except when there is a disaster
- 😐 Why?

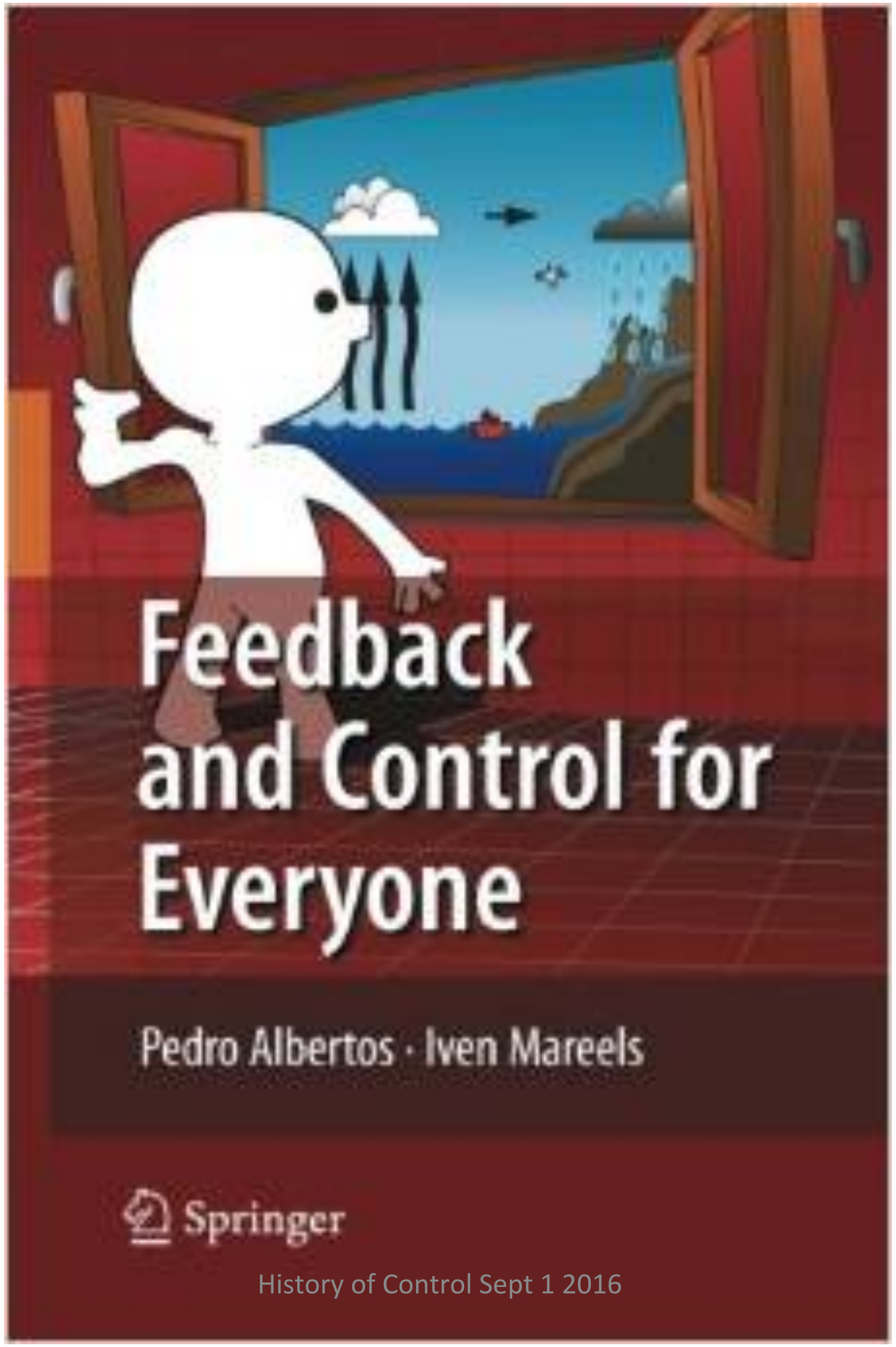


Easier to talk about devices than ideas.

The ideas and accomplishments of control have not been well presented to our collegues in science and to the general public! Control inside!

The Royal Insurance buliding Montreal 1861-1951

Solid foundations has been a hallmark of the control community


Feedback and Control for Everyone
Pedro Albertos · Iven Mareels
Springer

What is Controls?

- Requirements: Specifications
- Architecture: System structure, sensors, actuators, computers, communication, HMI
- Modeling and simulation: Physics and data
- Control Design: Models, algorithms and logic
- Implementation: Verification and validation
- Commissioning and tuning
- Operation: Diagnostics, assessment, fault detection
- Reconfiguration and upgrading

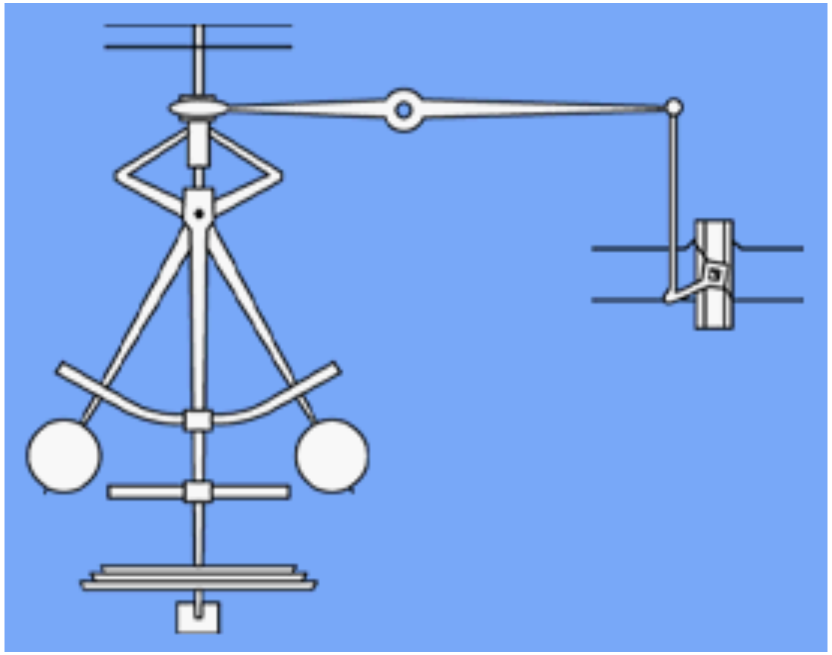
1. Introduction
2. **A Brief History**
3. Accomplishments
4. Challenges
5. Conclusions

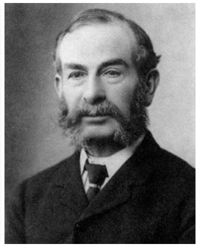
A Brief History

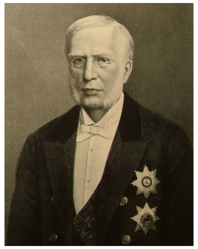
- A young field
- Early use in many fields
  - Governors
  - Process control
  - Vehicle control
  - Communication
- Servomechanism Theory
- Consequences
- The Second Phase
- The Third Phase?

Power Generation

- Problem: Generate AC at constant frequency
- Solution: Turbincontroller
- Side effects: stability theory
- Maxwell and Routh
  Stodola and Hurwitz
  Vyshnegradski, Lyapunov
  Tolle 1905



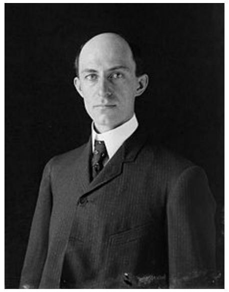
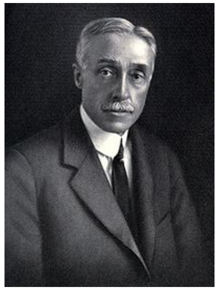




Process Control

- Problem: Keep pressure, temperature and concentration constant
- Solution: The PID controller
- Side effects: Industrial standard system, sensors, valves, controllers, communication.
- Ziegler-Nichols tuning rules 1942

Flight Control

- Problem: How to fly?
- Solution: Understand dynamics. Wright Brothers: Focus on maneuverability, stabilize with manual control
- Side effects: Autopilots, flight dynamics

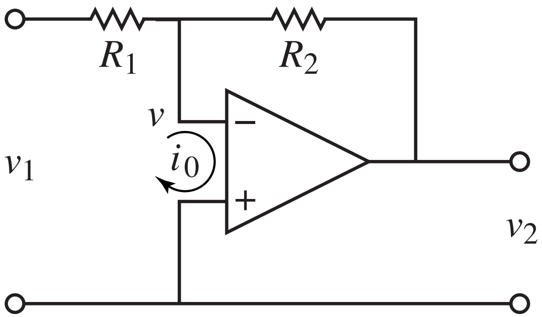




Sperry 1913

Autonomy 1947

Telecommunication

- Problem: Phone communication over long distances? How to make a good amplifier from bad components (vacuum tubes)
- Solution: The feedback amplifier
- Side effects: Stability and design theory (Nyquist, Bode)



$$\frac{v_2}{v_1} = -\frac{kR_2}{R_1 + R_2 + kR_1} \approx -\frac{R_2}{R_1}$$

The Power of Feedback

- Accurate systems from imprecise components
- Reduce effects of disturbances and component variations
- Regulate, stabilize and shape behavior
- Drawbacks
  - Risk of instability
  - Sensor noise is fed into the system

The Scene of 1940

Widespread use of control in many fields

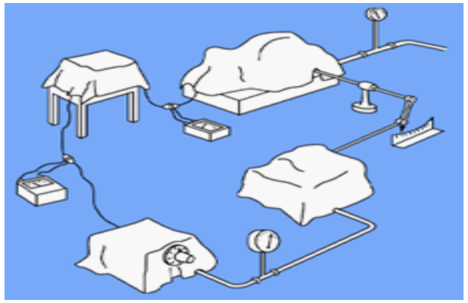
- Power generation and distribution
- Process control
- Autopilots for ships and aircrafts
- Telecommunications

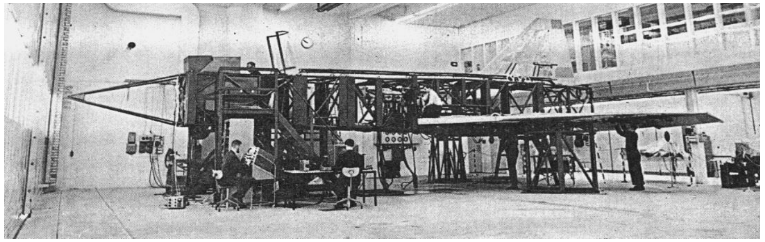
The similarities were not recognized

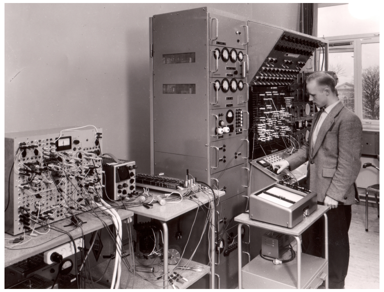
The Discipline Emerges

- Drivers: The war effort, gunsights, radar,..
- Concepts: Feedback, feedforward
- Design tools: Block diagrams, transfer functions
- Simulation: Analog computing
- Implementation: Analog computing
- Holistic view of theory and applications

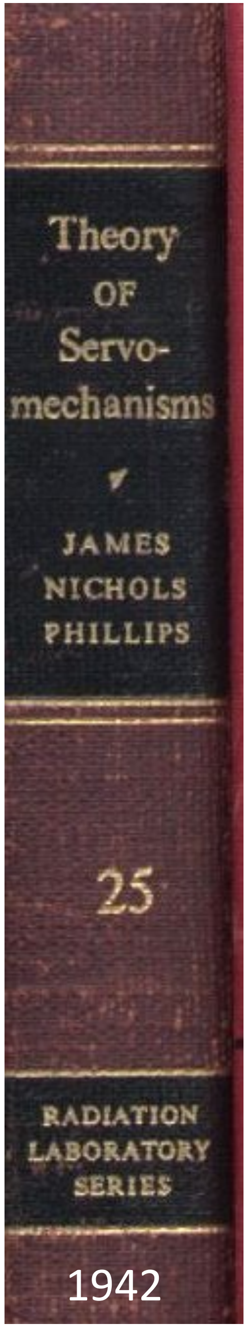
Servomechanisms







- Theory
  - Complex variables
  - Laplace Transforms
- System Concepts
  - Feedback
  - Feedforward
- Design
  - Frequency Response
  - Graphical Methods
- Analog simulation
- Implementation



ServomechanismTheory

Hubert M. James

Professor of Physics Purdue University

Nathaniel B. Nichols

Director of Research Taylor Instrument Companies

Ralph S. Phillips

Associate Professor of Mathematics University of Southern California

Office of Scientific Research and Development

National Defence Research Committee

Consequences

Education

Application

Industrialization

Organisation

Journals

Conferences

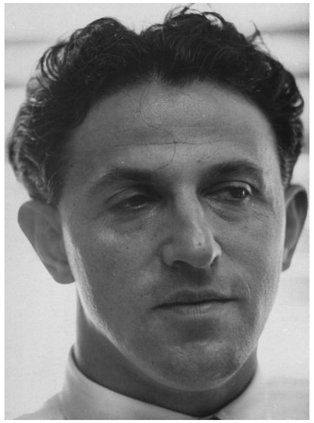
IFAC

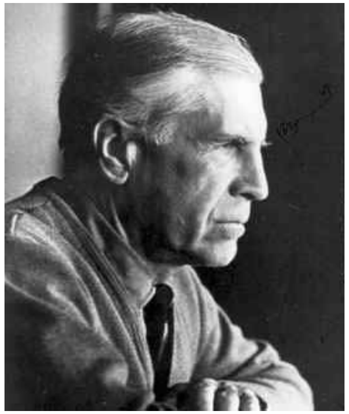
The Golden Age

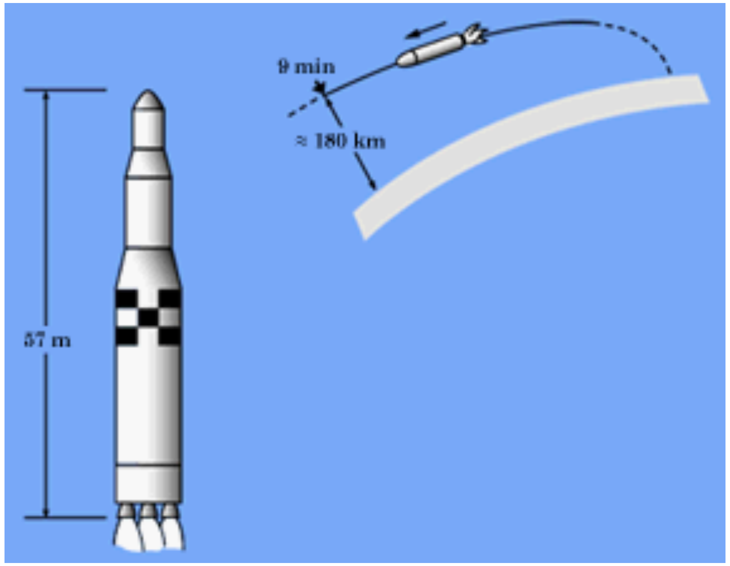
- Drivers: space, computer control, mathematics
- Rapid growth of subspecialities:
- Optimal, stochastic, nonlinear, ...
- Computational tools
- Impressive development of theory
- The holistic view was lost!

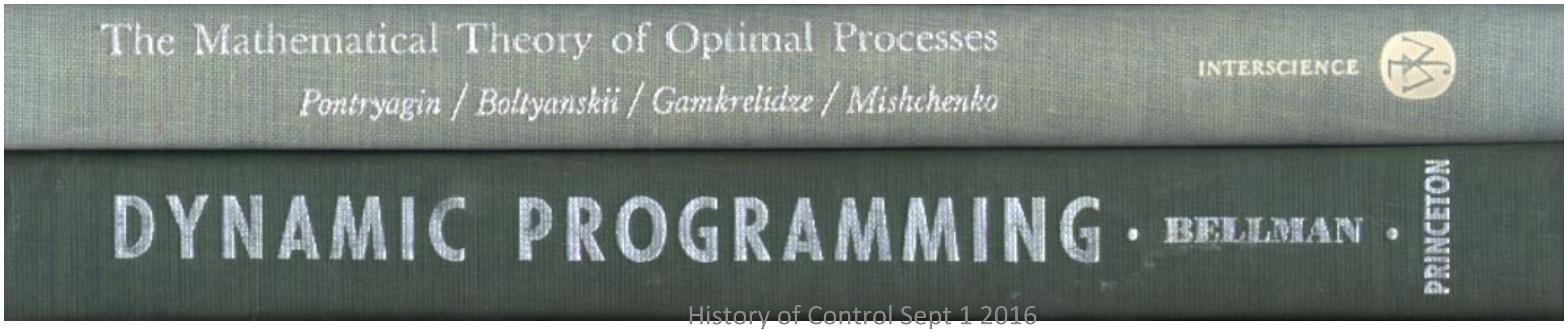
Optimal Control

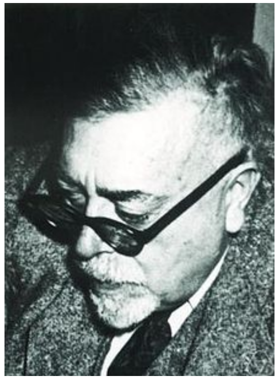
- Hamilton, Jacobi, Bellman 1957
- Euler, Lagrange, Pontryagin 1962
- Model predictive control







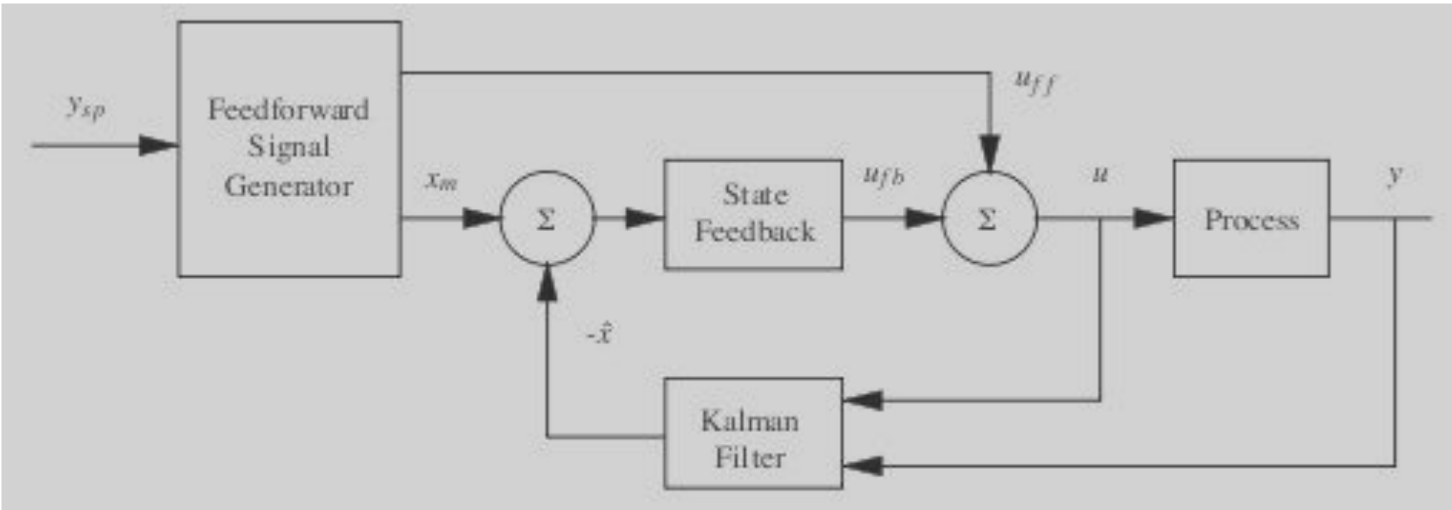




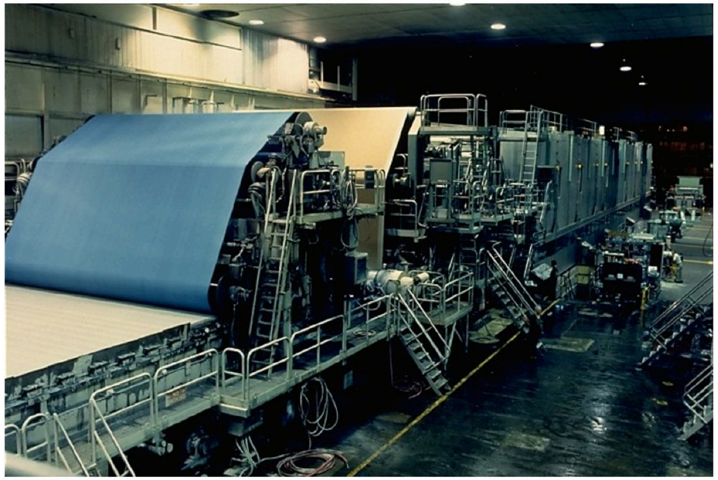
Kalman Filtering

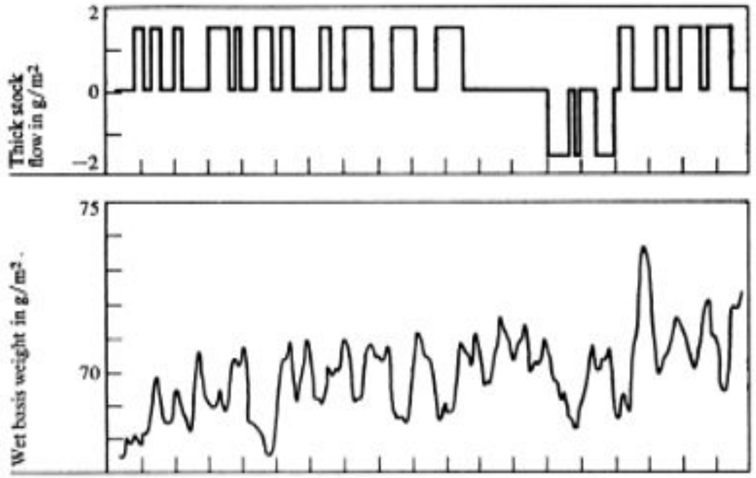
Kalman 1961:

- ➢ Efficient way to filter signals
- ➢ Combine measurements and mathematical model to estimate process state
- ➢ New controller structure based on Kalman filter, state feedback and feedforward generator

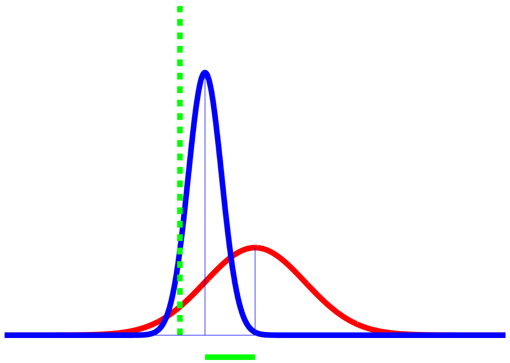


System Identification





Billerud IBM Project 1962-66
Regulation of quality variables



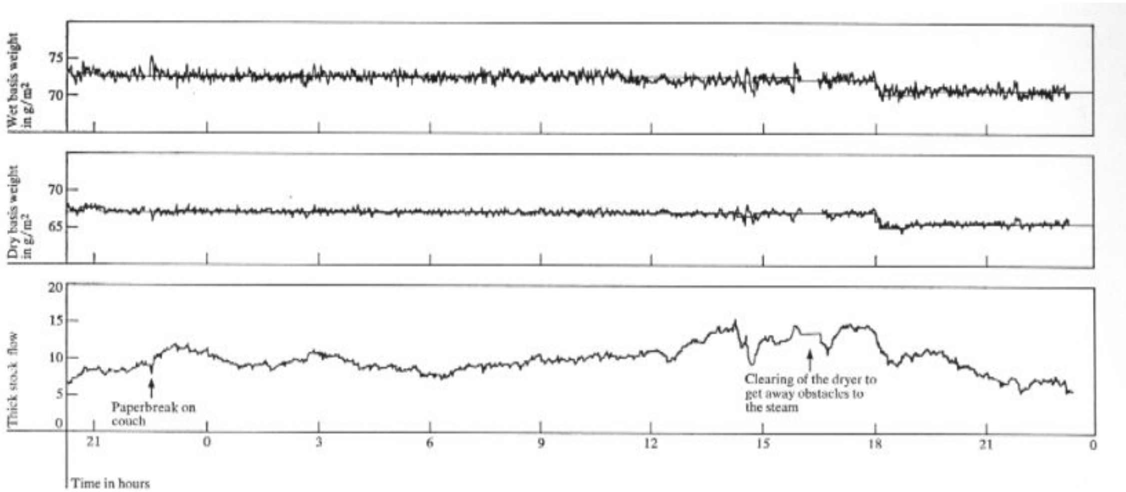
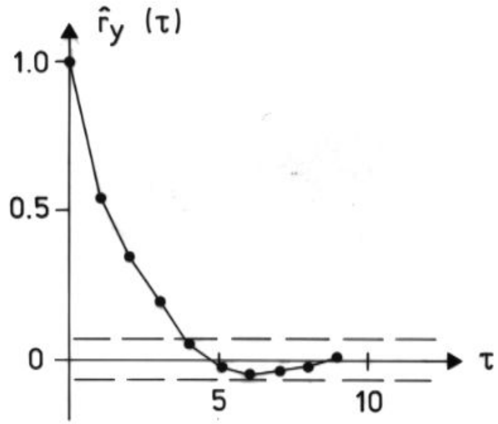
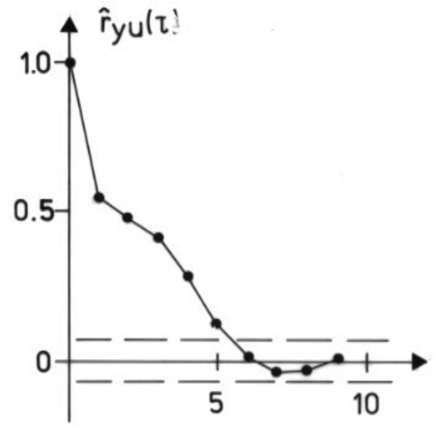


Figure 7 Results of test run with on-line control of basis weight.

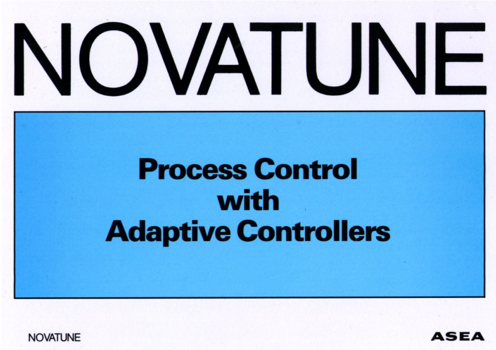
Adaptive Control

- The self-tuning regulator
- Moving average control
- Theory (insight)
- Case studies
- Adaptive feedforward
- Industrial experience
- Harris index



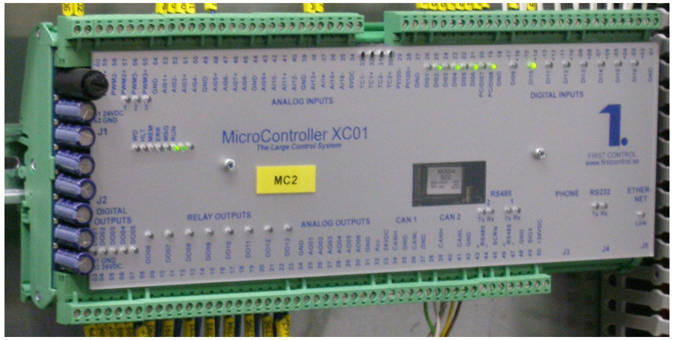


Borisson Syding 1975



Winner of IEEE CSS Control Technology Award

FIRST CONTROL SYSTEMS AB



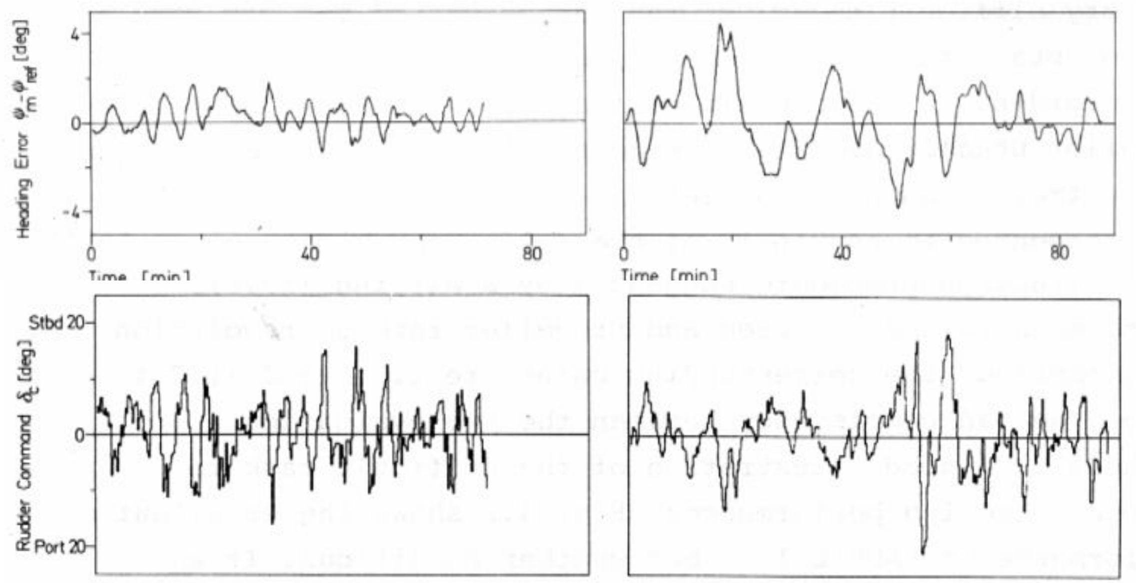
Adaptive Control

Kockumation

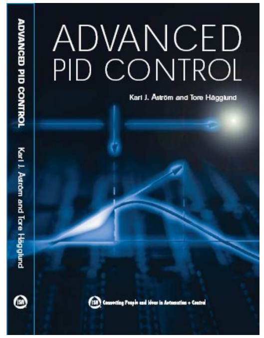
NORTHROP GRUMMAN

DEFINING THE FUTURE

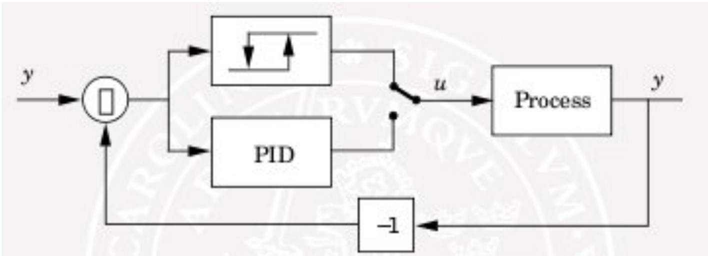
Adaptive PID

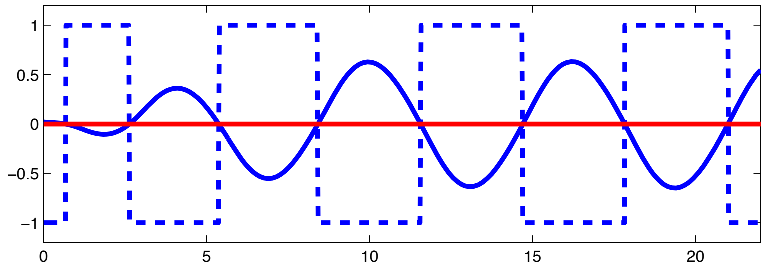


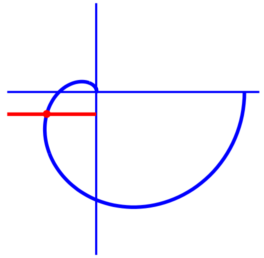
- 3 % reduction in fuel consumption
- Physics based configuration



Relay Autotuning





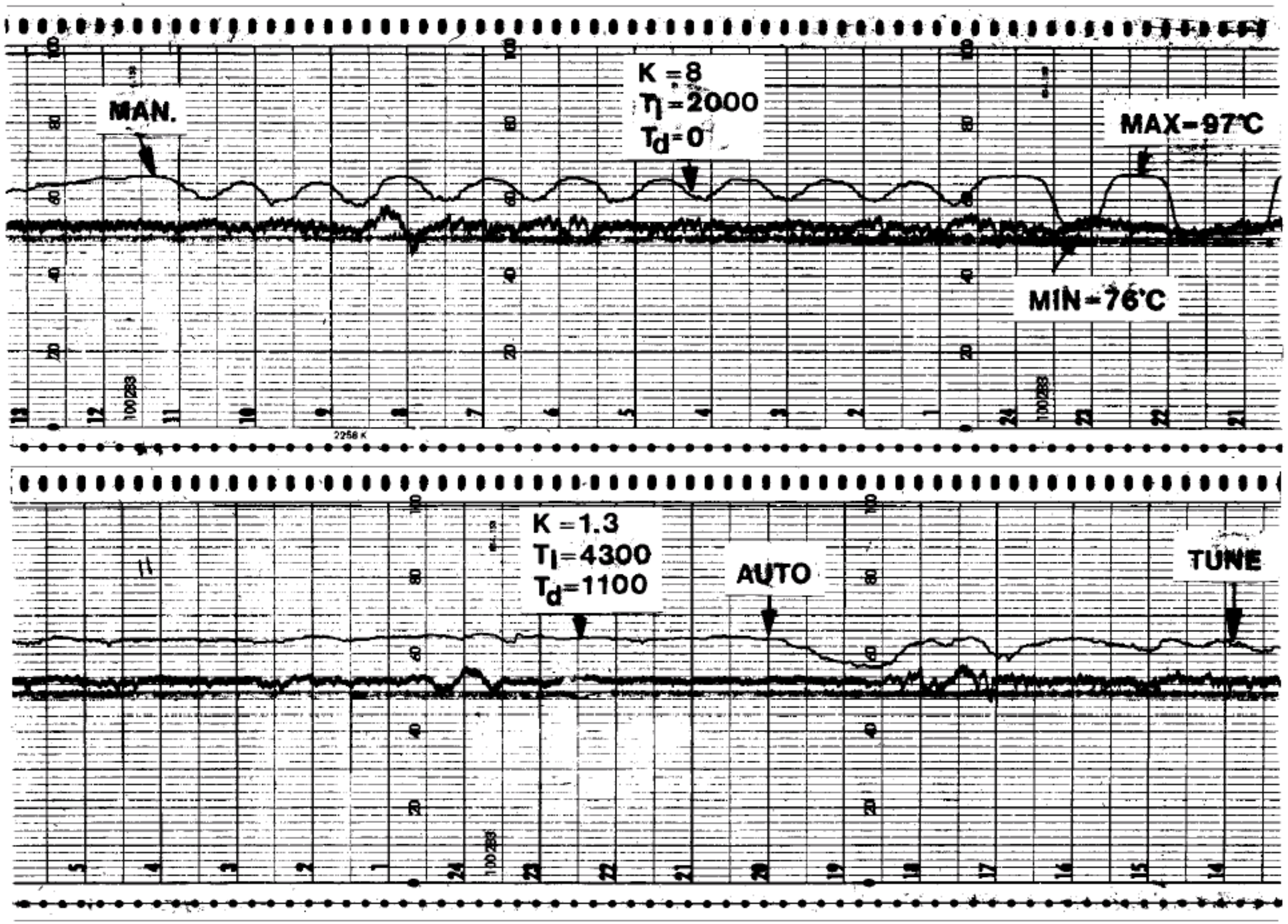


- Robust and easy to use
  - Well adapted to users
  - One-button tuning
  - Automatic generation of
    - gain schedules + adaptation
- Many versions
  - Stand alone, DCS, PLC
- Large numbers
- Excellent industrial experience

ABB

EMERSON
Process Management

NATIONAL INSTRUMENTS™

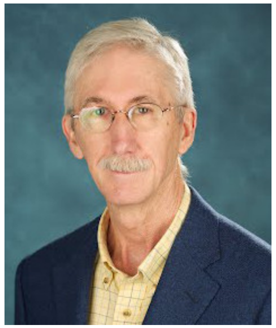


All controllers should have facilities for automatic tuning!

Robust Control

- Classic Bode: non-minimum phase is important
- State space: reachability and observabilty
  Robustness of state feedback $g_m = \infty$, $p_m = 60^o$
  Non-robustness of output feedback
- Robust Control: Youla, Zames, 4 author paper:
  Doyle, Glover, Khargonekar, Francis
- Fundamental limitations (back to Bode)
  Delays and RHP poles are important





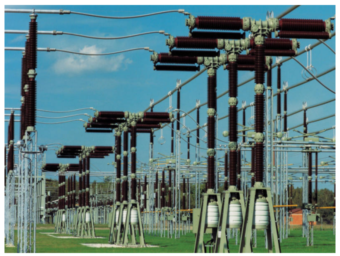
1. Introduction
2. A Brief History
3. **Control Everywhere**
4. Challenges
5. Conclusions

Applications

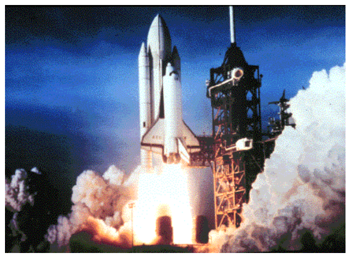
Traditional fields expanding and new fields emerging

- Power Systems
- Process Control
- Aerospace
- Automotive
- Buildings
- Robotics

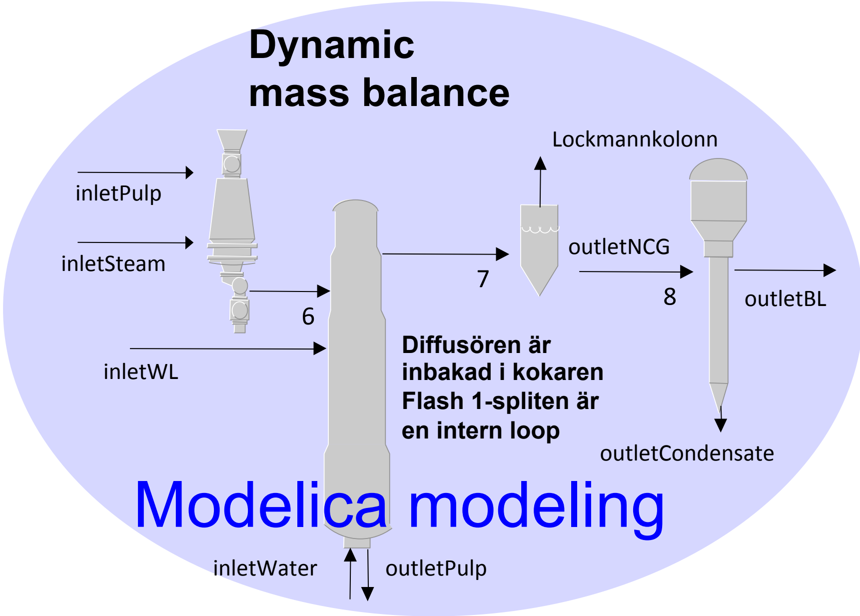
- Computer Systems
- Global enterprise control
- Advertising
- Mobile phones
- Art and games
- Physics and Biology



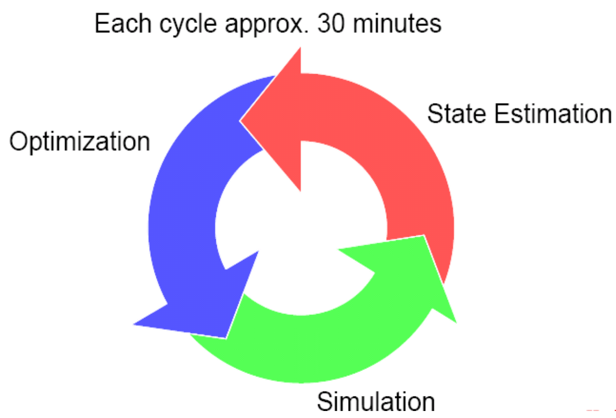





Mill Wide Control

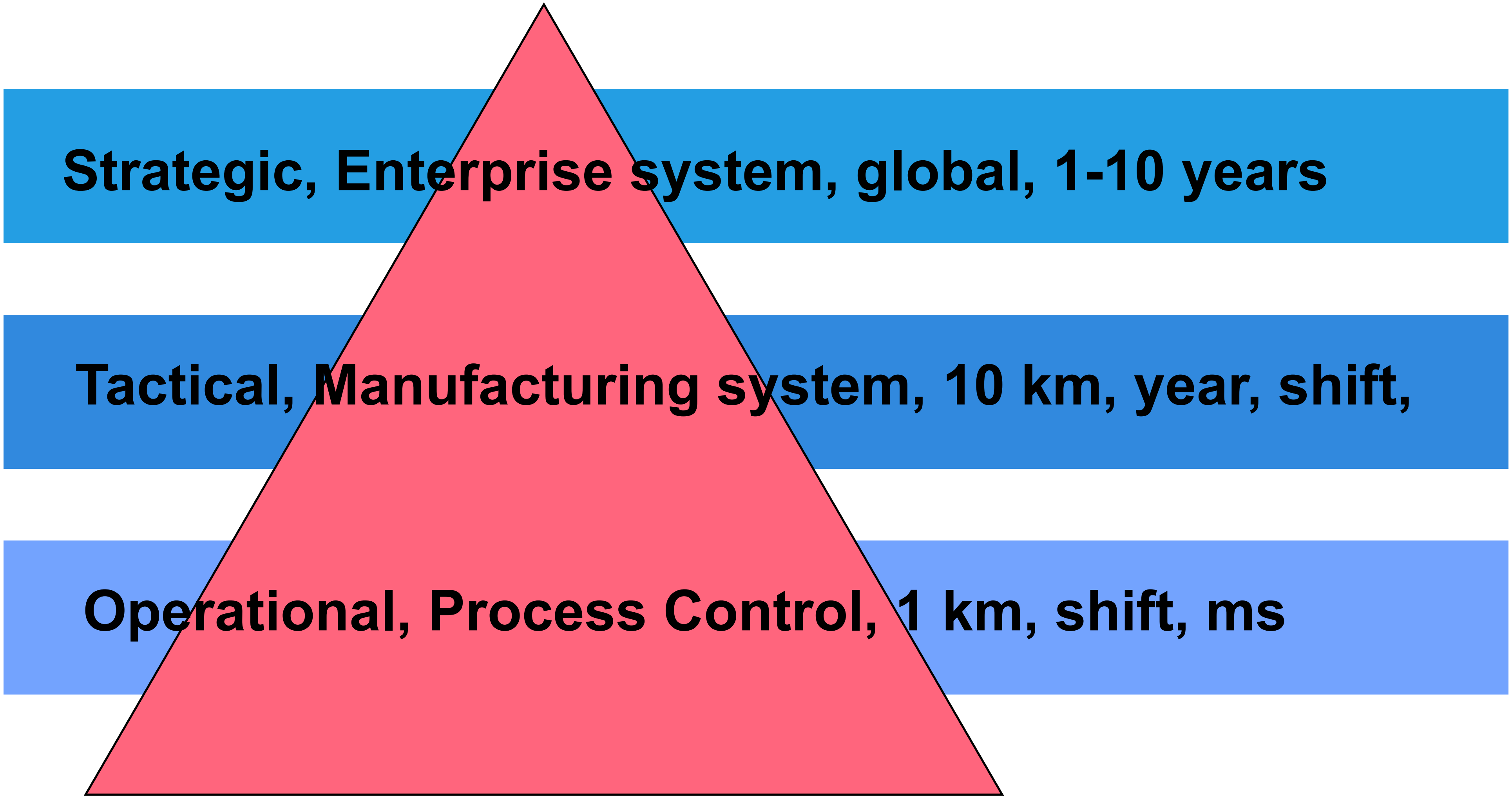


25 Production units
38 Buffer tanks
250 Streams
250 Measurements
2500 Variables

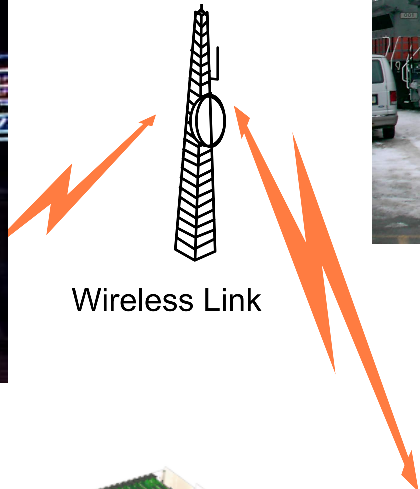


Slide from Alf Isaksson ABB

Global Enterprise Control

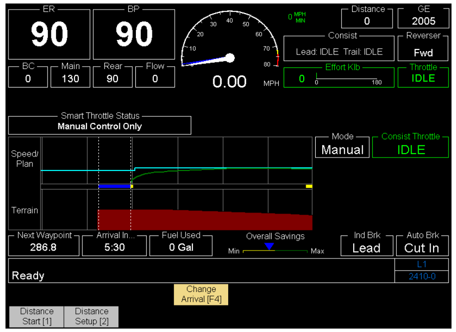


Trip Optimizer

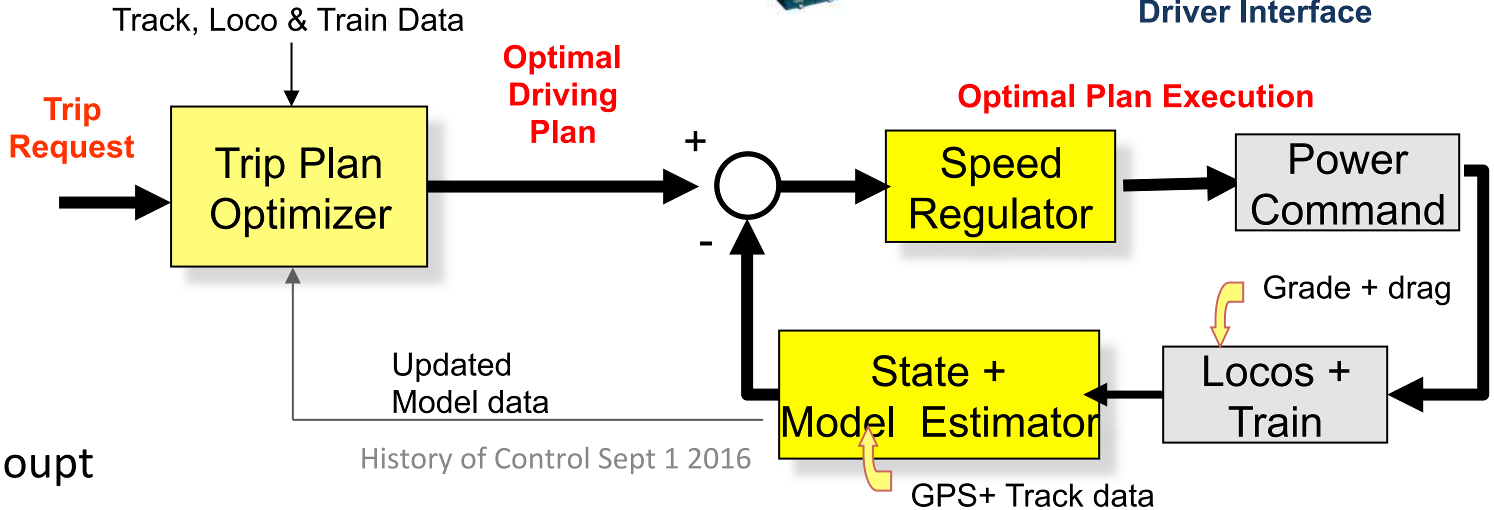


- Thousands of decision variables
- Thousands of constraints
- 10-30 second update rate
- 8-20% fuel saving

On Board Computer



Driver Interface



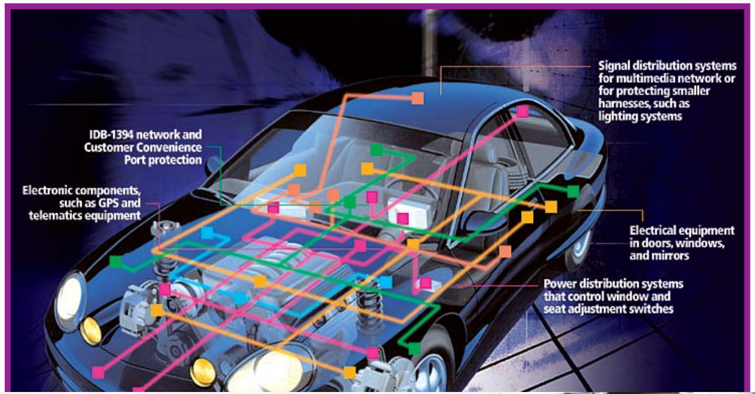
Courtesy of Paul Houpt

Automotive

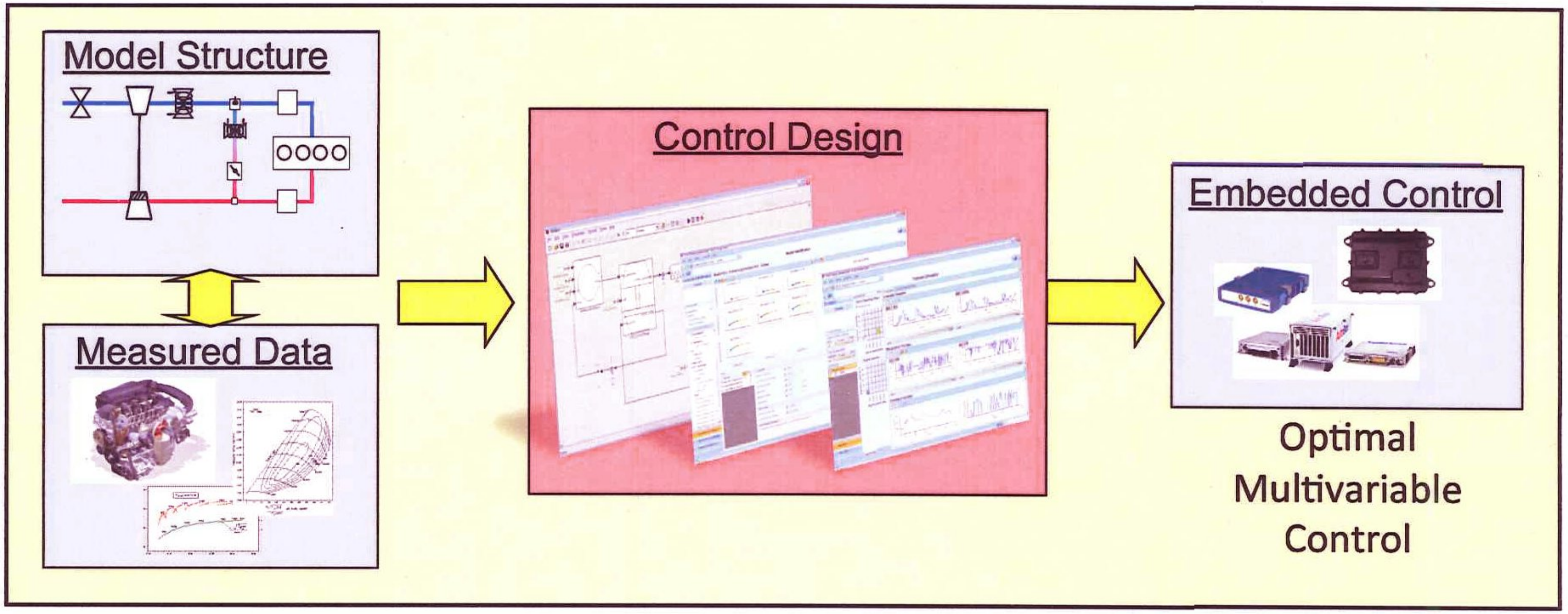
- Strong technology driver

  Microcontroller, Autosar

- Power trains
- Adaptive cruise control
- Collision avoidance
- Traction control
- Lane guidance assistance
- Traffic flow control
- Platooning



Automotive Powertrain Control



- Explicit MPC control (Morari, Borelli)
- Robust to engine variability and aging
- Automatic generation of models and code for embedded systems
- Human-machine interface tailored to skill set of users

Courtesy of Honeywell OnRAMP team

Honeywell

Mobile Phones – Billions of Loops

1980

Ericsson Hotline 900 Pocket
Price: 5000 $
Weight: 4kg resp 630 g
Talk time: 30 min
Affordable for few

2010

Vodafone150
Price: 700 rupies ~ 13 $
Weight: 60g
Talk time: 5hours
Affordable for most

10 control loops * 10^9phones/year = 10^{10} loops

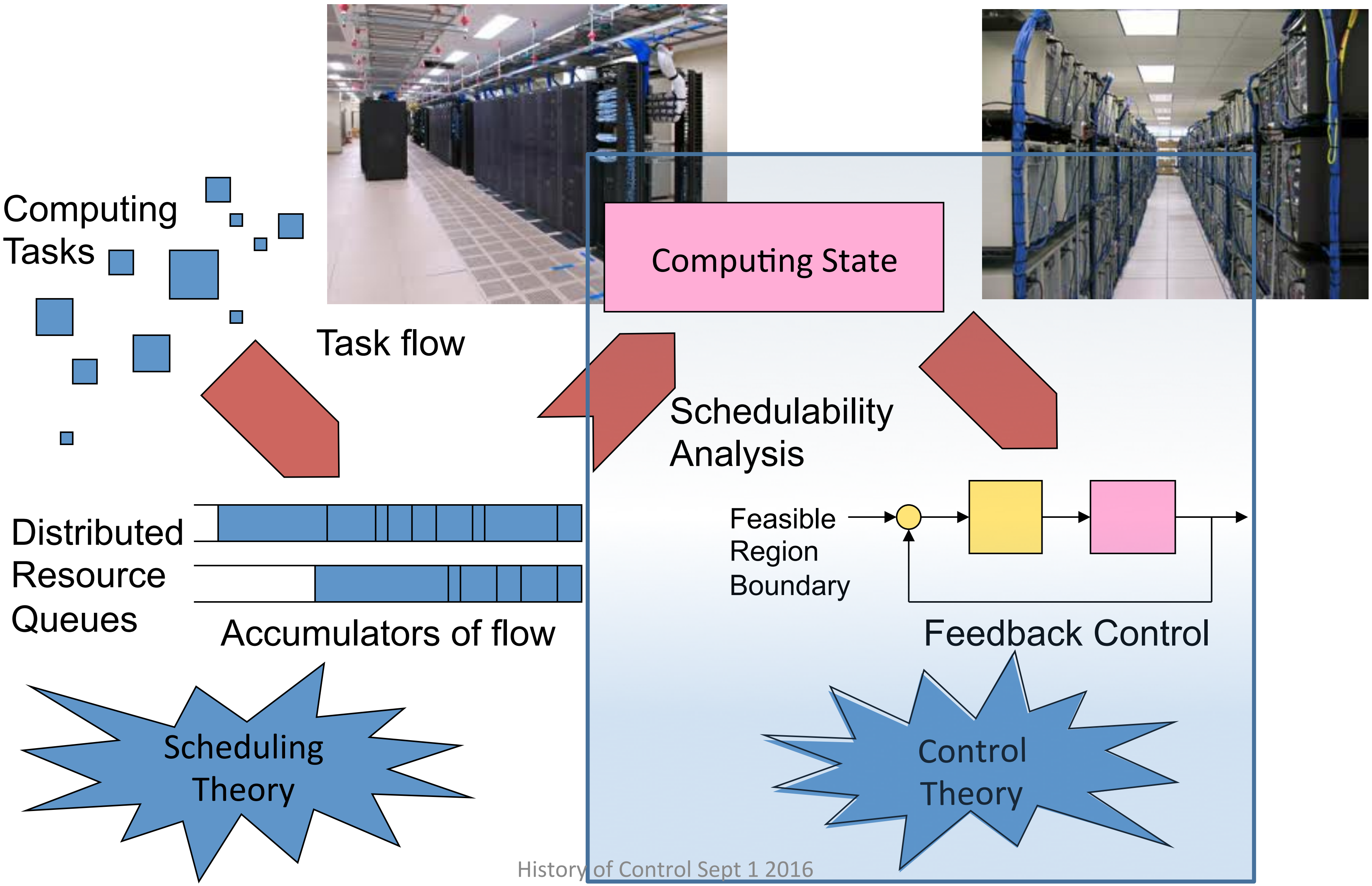
Frequency control – temperature, voltage, aging, Doppler effect
Without feedback: frequency error ~ 10 parts per million
With feedback: frequency error ~ 0.01 parts per million => 1000 times improvement

Power control and gain control – components with large dynamic range are costly
Receive power range 10^{-14}W – 10^{-5}W
Transmit power range 10^{-8}W – 1W (compare lamp versus nuclear power plant)

PI(D) , anti-windup, feedforward, scheduling

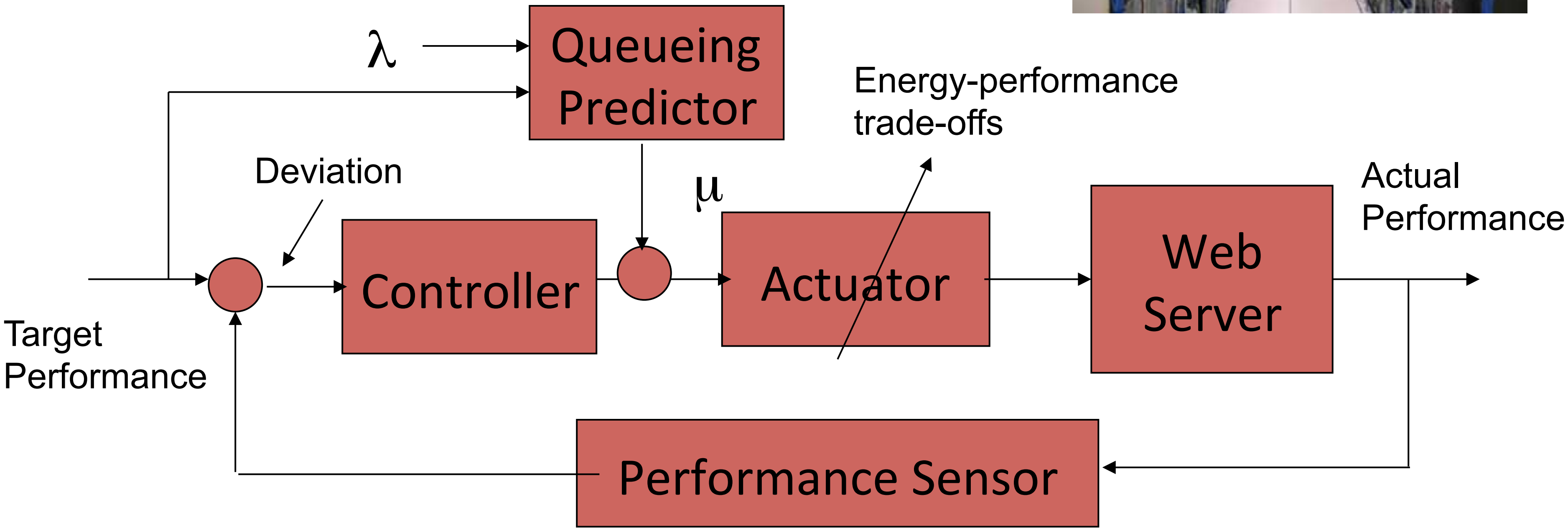
Thanks to Bo Bernhardsson

Control of Computing Systems
(Data centers, Server clusters, Data fusion)

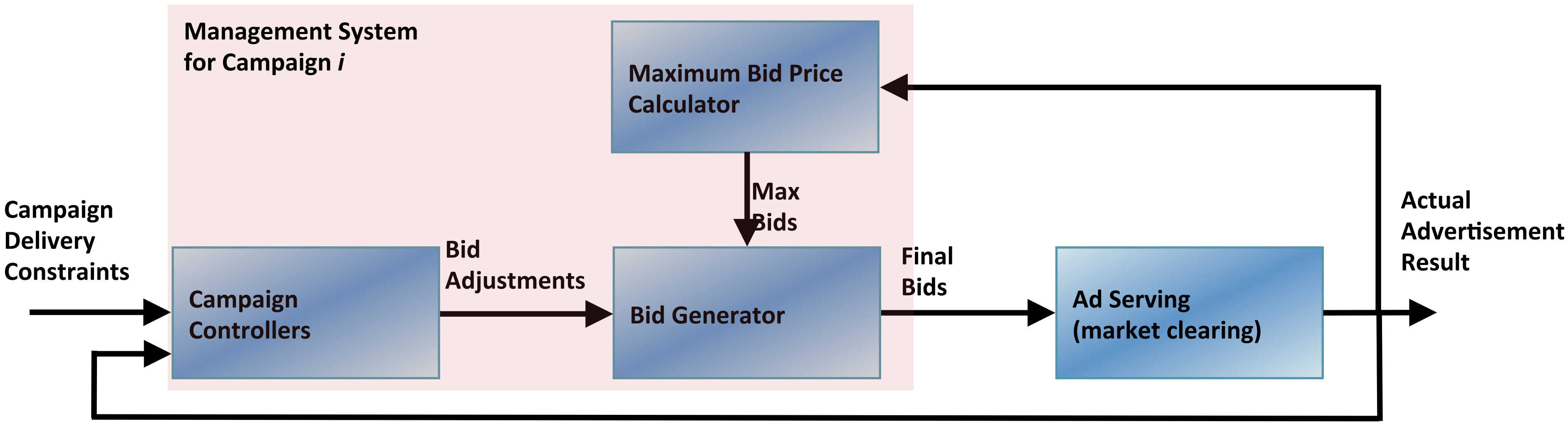


Energy Management in Data Centers

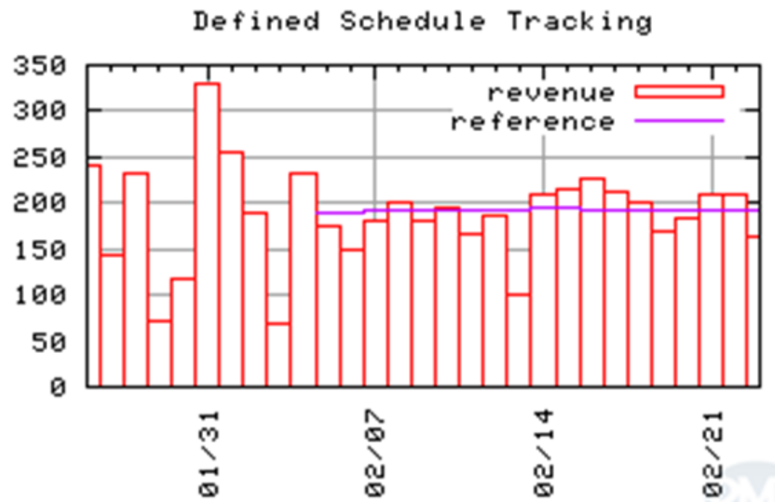
- Total consumption: 2% of energy spent (US EPA estimate)
- Energy bill 20-50% of total profit
- Energy-performance trade-offs managed by optimization and feedback



Internet Advertisement



- Decentralized control
- Auction bidding



Courtesy of Niklas Karlsson

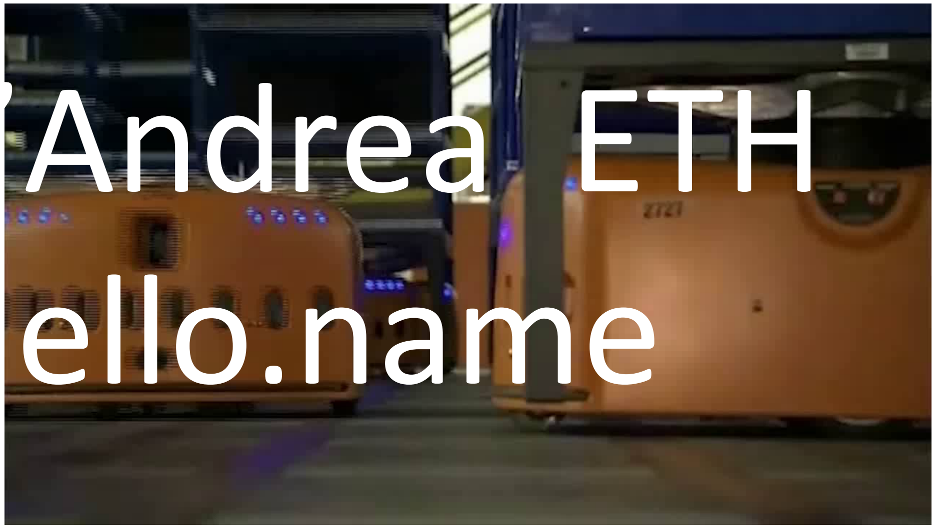
Art and Games ++

Robotic Chair

RoboCup

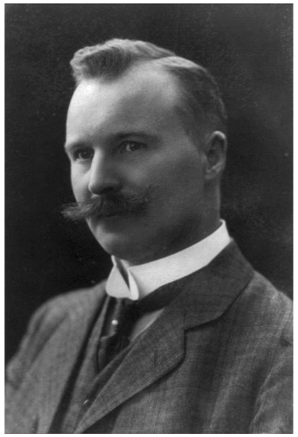
Flight Assembled Architecture

Kiva Systems



Raffaello D'Andrea ETH

http://raffaello.name



Physics

- Nobel prizes in physics

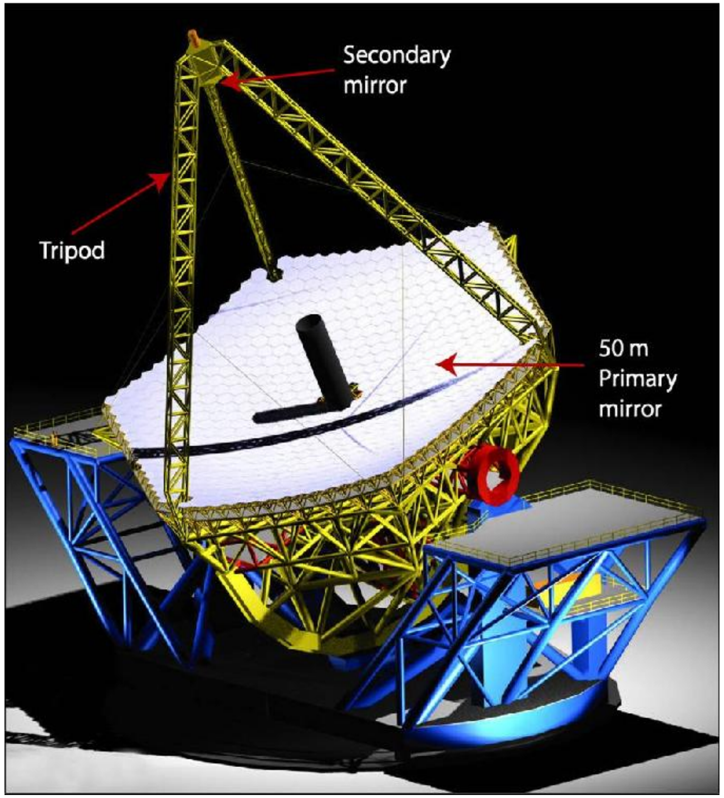
  Gustaf Dalén 1912

  Simon van der Meer 1984

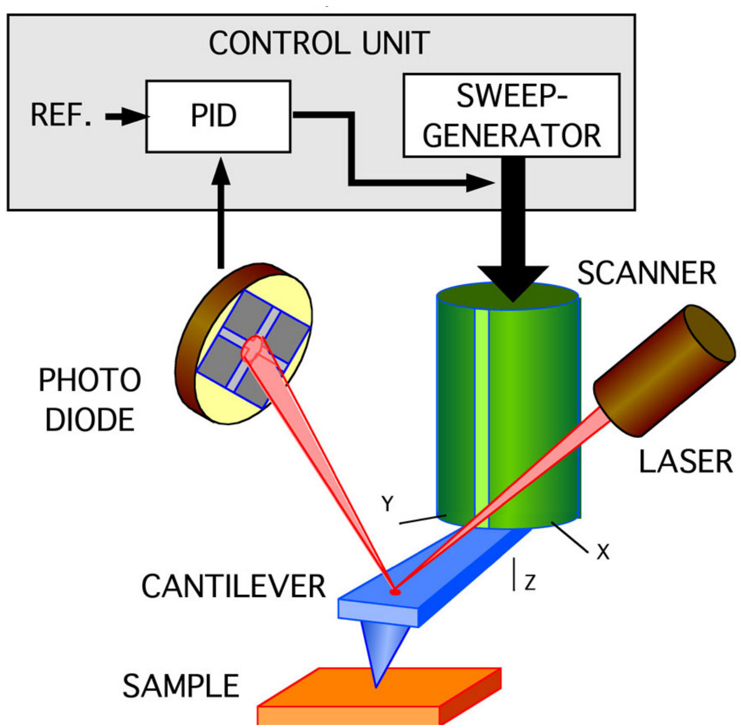
  (stochastic cooling)
- Quantum and molecular systems
- Shear flow turbulence (gain not instability)

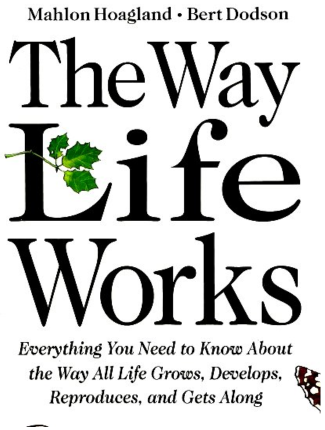
Instruments Giga to Nano

Adaptive Optics

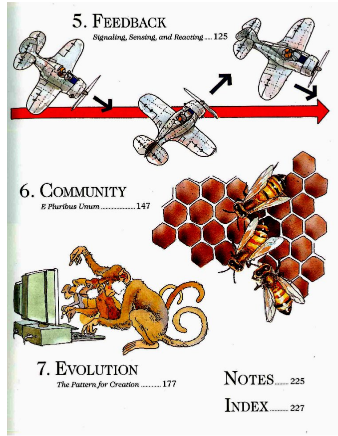


Atomic Force Microscope





Biology



Feedback is a central feature of life. The process of feedback governs how we grow, respond to stress and challenge, and regulate factors such as body temperature, blood pressure, and cholesterol level.

The mechanisms operate at every level, from the interaction of proteins in cells to the interaction of organisms in complex ecologies.

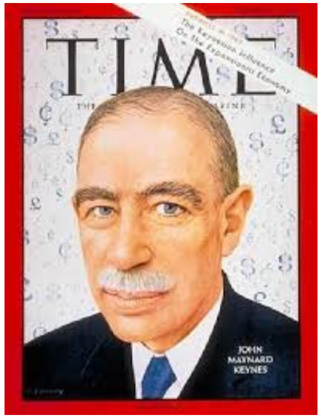
Mahlon B Hoagland and B Dodson The Way Life Works Three Rivers Press 1998

Birds

advantages of instability

The earliest birds pterosaurs, and flying insects were stable. This is believed to be because in the absence of a highly evolved sensory and nervous system they would have been unable to fly if they were not. To a flying animal there are great advantages to be gained by instability. Among the most obvious is manoeuvrability. it is of equal importance to an animal which catches its food in the air and to the animals upon which it preys. It appears that in the birds and at least in some insects the evolution of the sensory and nervous systems rendered the stability found in earlier forms no longer necessary.

John Maynard Smith The Importance of the nervous sytem in the evolution of aimal flight.
Evolution, 6 ,(1952) 127-9.



Economics

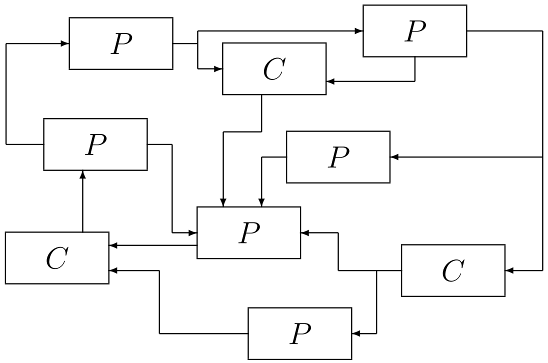
We have magneto trouble, said John Maynard Keynes at the start of the Great Depression: most of the economic engine was in good shape, but a crucial component, the financial system, wasn't working. He also said this "We have involved ourselves in a collossal muddle, having blundered in the control of a delicate machine, the working of which we do not understand" Both statements are as true now as they were then

Paul Krugman The Return of Depression Economics. Penguin 2008

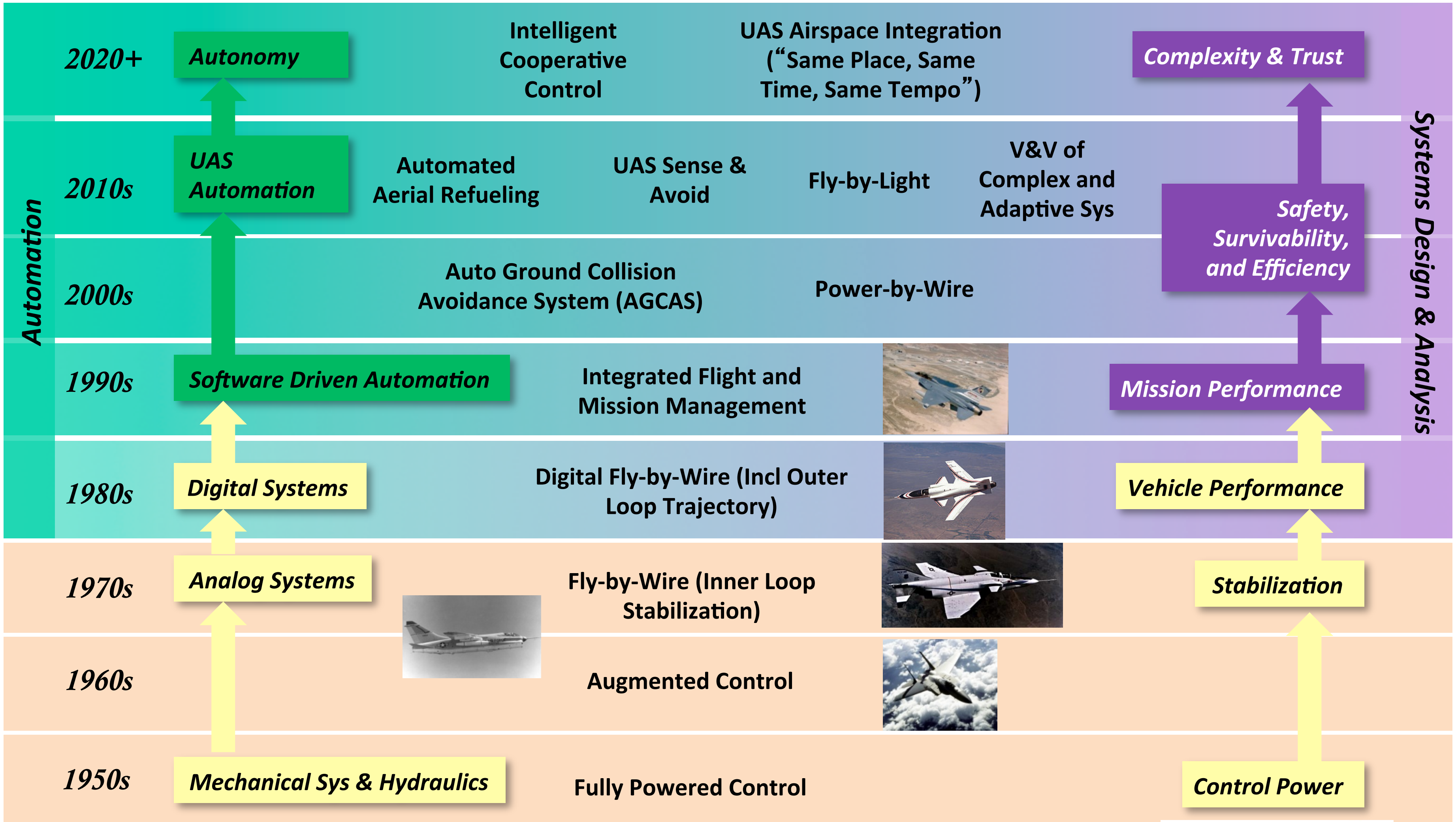
1. Introduction
2. A Brief History
3. Control Everywhere
4. **Challenges**
5. Conclusions

Challenges

- Complex networked systems
- Sensor and actuator rich systems
- Safe design of embedded systems
- Autonomy
- Adaptation, learning, reasoning,cognition
- High level control principles
- Biology



Flight Control – An Evolution of Automation
To Enable Greater Air Vehicle Capability



Autonomous Systems

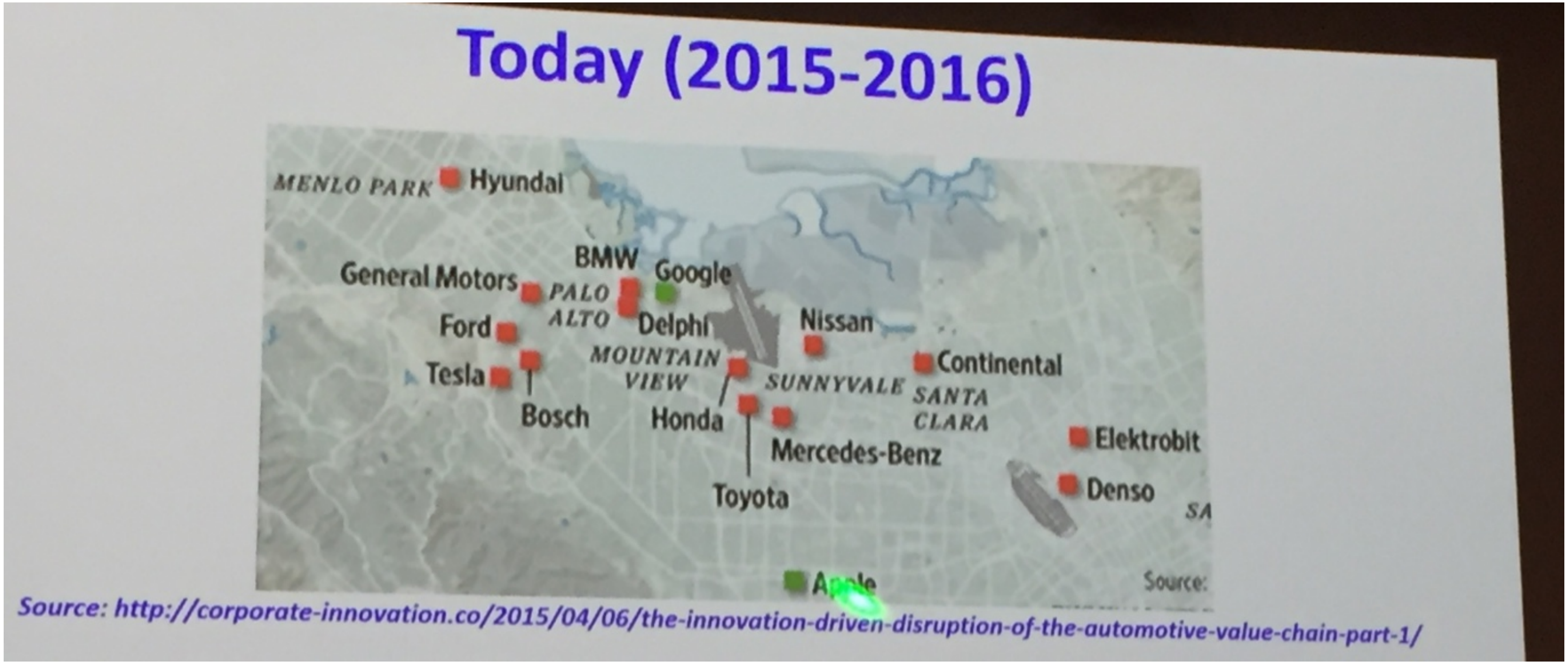
- Adaptation
- Learning
- Cognition
- Safety
- Diagnostics
- Maintenance
- Reconfiguration

Darpa Urban Challenge

Dickmanns 1995 - 95% autonomi

Google driverless car

Autonomous Car Activity in Silicon Valley



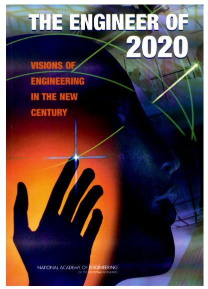
A Third Phase?

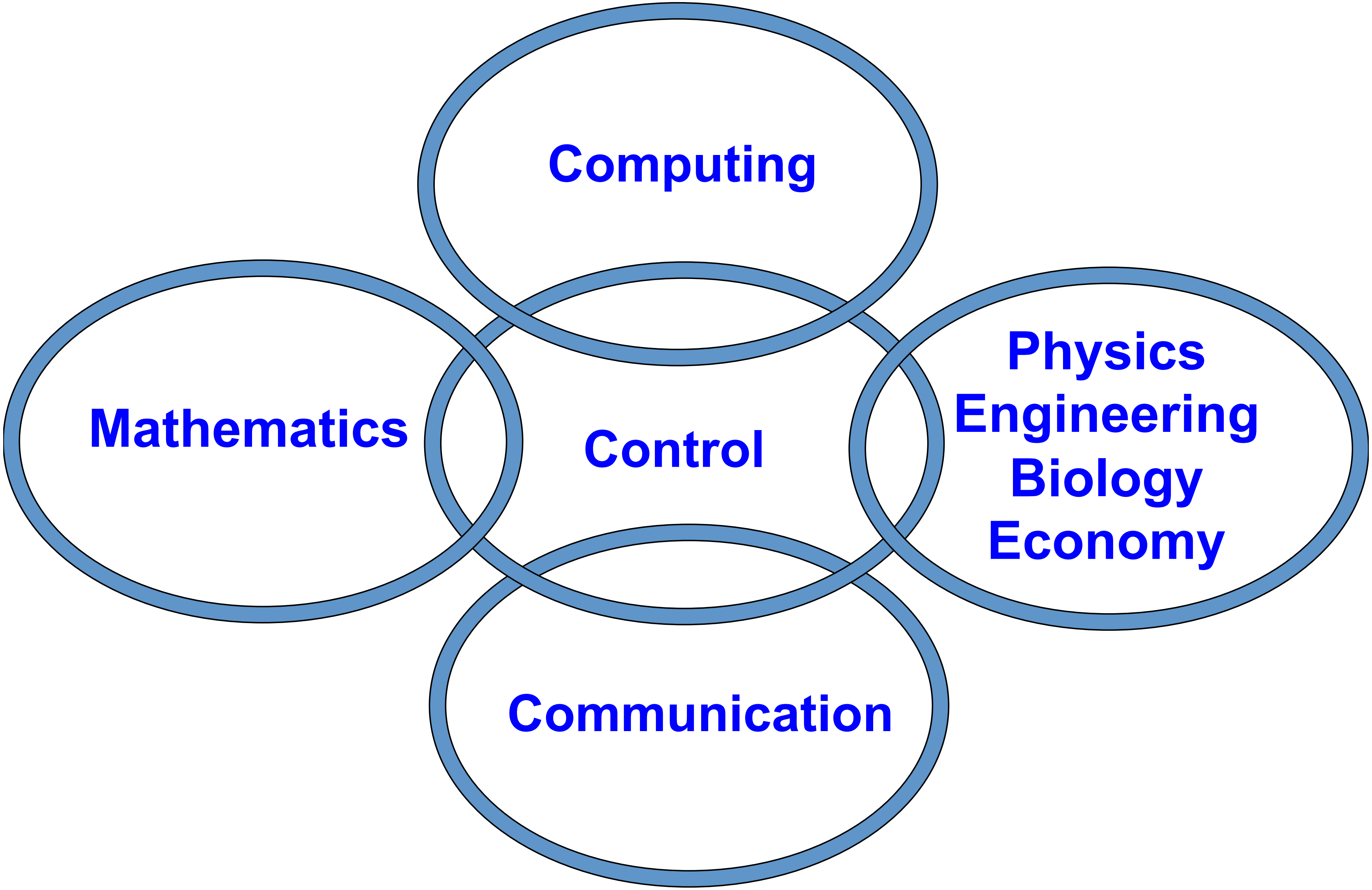
- Drivers: Complex networked systems, physics and biology
- Autonomy (Adaptation, Learning, Cognition)
- Sensor and actuator rich systems
- Provable safe design and reconfiguration
- Recover the holistic view

The Systems Perspective

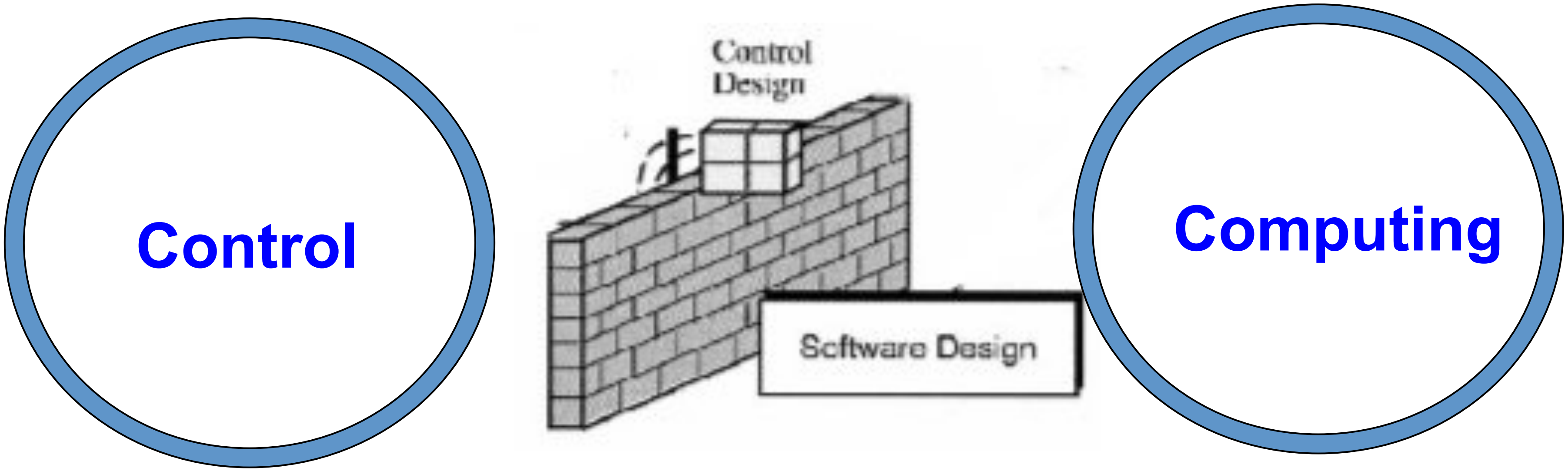
In the past steady increases in knowledge has spawned new microdisciplines within engineering. However, contemporary challenges – from biomedical devices to complex manufacturing designs to large systems of networked devices – increasingly require a systems perspective

NAE The Engineer of 2020




Computing
Mathematics
Control
Physics
Engineering
Biology
Economy
Communication

The CS Barrier



Feedback,Stability, ODE, PDE
Moderate complexity
Robustness

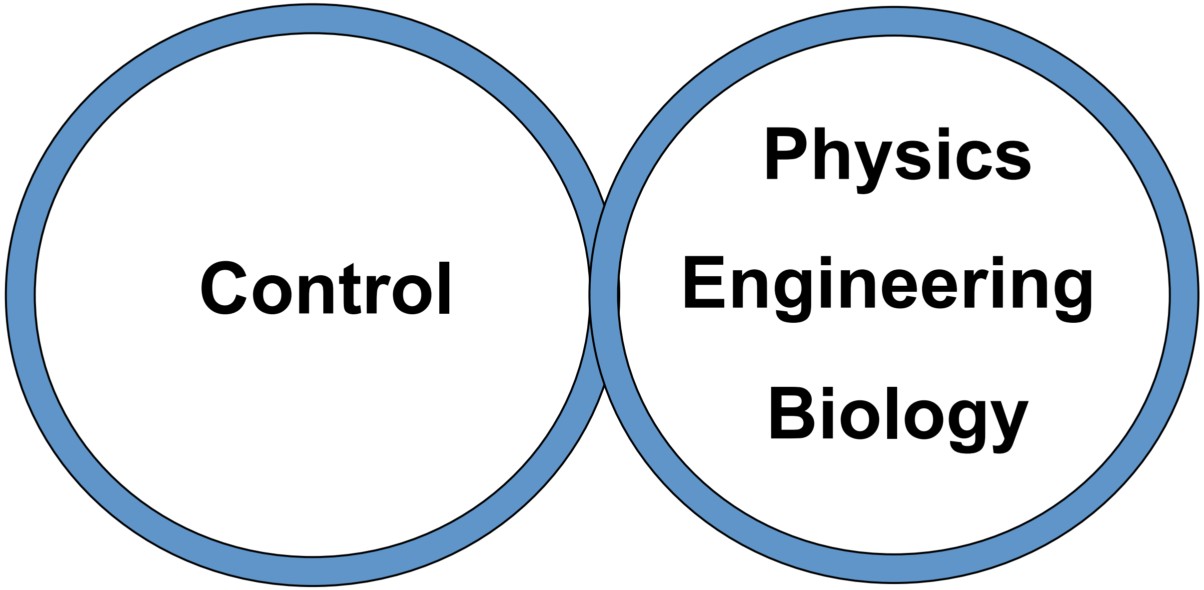
Logic, languages, DES,FSM
Formal methods, abstractions
Architecture

The controller

Computing

- Vannevar Bush 1927. Engineering can progress no faster than the mathematical analysis on which it is based. Formal mathematics is frequently inadequate for numerous problems, a mechanical solution offers the most promise.
- Herman Goldstine 1962. When things change by two orders of magnitude it is revolution not evolution.
- Gordon Moore 1965: The number of transistors per square inch on integrated circuits has doubled in approximately 18 months. A revolution every 10 years!
- Strong potential, but so far algorithms and software have not delivered corresponding productivity increases!

The Physics Barrier



Blockdiagrams ODEs

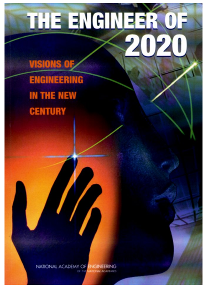
Mass, energy, momentum

Block diagrams unsuitable for serious physical modeling

Modeling for control

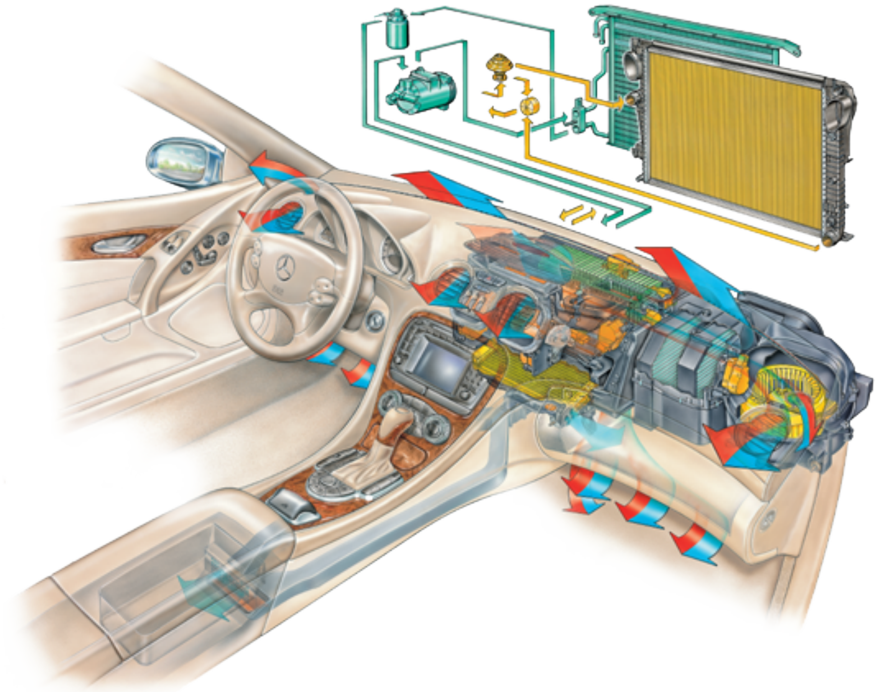
Modeling and Simulation

There will be growth in areas of simulation and modeling around the creation of new engineering “structures”. Computer-based design-build engineering ... will become the norm for most product designs, accelerating the creation of complex structures for which multiple subsystems combine to form a final product.



NAE The Engineer of 2020

Automotive Climate Control



- *Audi, BMW, Daimler, Ford, Volvo, VW and their suppliers have standardized MBD based on Modelica*
- *Suppliers provide components and validated Modelica*
- *Car manufacturers evaluate complete system by simulation*
- *IP protected by extensive encryption*
- *Substantial reduction of road & climate chamber testing*

Picture courtesy of Behr GmbH & Co.

Modelon

Educational Challenges

- Educating the future engineers
- Education of physicists and biologist
- The dilemma of emerging fields
- Filter out the fundamentals and exploit advances in computing
- Deep knowledge in specific areas
- Broad knowledge of neighboring fields
- Ability to communicate and to work in teams

1. Introduction
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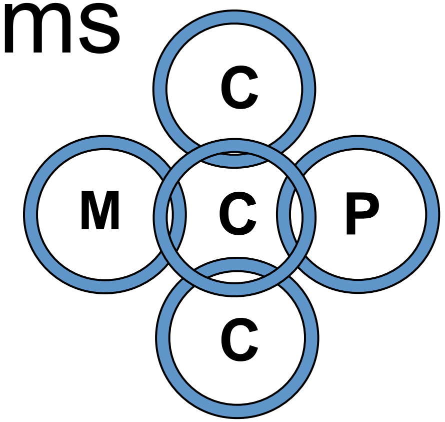
Conclusions

- Control is a vital dynamic field
- Networked embedded systems
- Autonomy and safety
- The educational challenge
- Continue to take care of the foundations and develop the holistic view



What is Controls?

- Requirements: Specifications
- Architecture: System structure, sensors, actuators, computers, communication, HMI
- Modeling and simulation: Physics and data
- Control Design: Models, algorithms and logic
- Implementation: Verification and validation
- Commissioning and tuning
- Operation: Diagnostics, assessment, fault detection
- Reconfiguration and upgrading