The Second Wave

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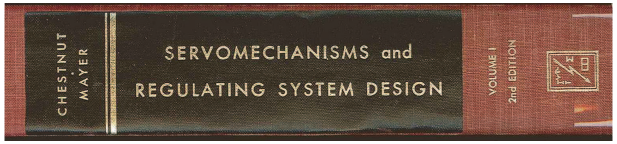
1. Introduction
2. Major Advances
3. Computing
4. Control Everywhere
5. Summary

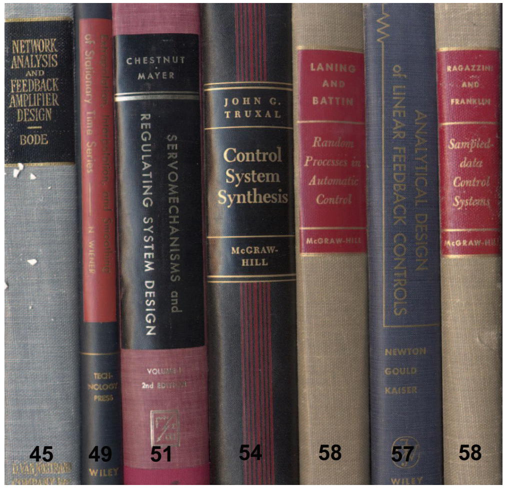
Introduction

- Use of control in widely different areas unified into a single framework by 1960
- Education mushrooming, more than 36 textbooks from 14 countries
- Organizations: IFAC national member organizations
- Conferences IFAC, ACC, CDC, …
- Strong diversified industrial base

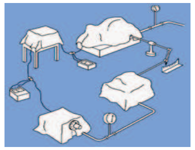


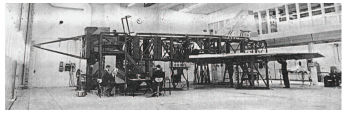
1 The Automatic Control Problem
2 Manipulation of Complex Numbers
3 Solution of Linear Differential Equations
4 Laplace Transform for the Solution of Linear Differential Equations
5 Steady-State Operation with Sinusoidal Driving Functions
6 Methods for Determining System Stability
7 Typical Control Elements and Their Transfer Functions
8 Types of Servomechanisms and Control Systems
9 Complex Plane Representation of Feedback Control System Performance
10 Design Use of Complex Plane Plot to Improve System Performance
11 Attenuation Concepts for Use in Feedback Control System Design
12 Application of Attenuation-Phase Diagrams to Feedback Control Design Prob
13 Application of Root Locus to Feedback Control Design Problems
14 Multi-Loop and Multi-Input Feedback Control Systems
15 Comparison of Steady-State and Transient Performance of Servomechanisms
16 Fundamentals of Analog Computing

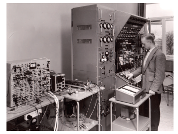
Consolidation



Automatic Control







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

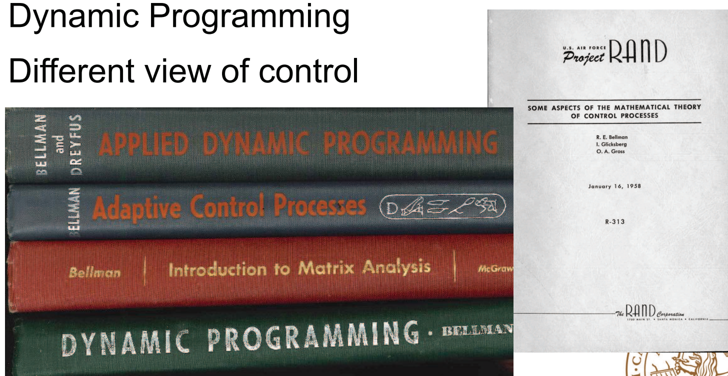
Rand 1945--

- Douglas Aircraft financed by USAF
- Think Tank today ~1700 people
- Herman Kahn *On Thermonuclear war*
- Optimization, game theory, systems analysis, economics
- Richard Bellman, Georg Danzig, von Neumann, Paul Samuelson, (Henry Kissinger, Condolezza Rice, Donald Rumsfeld, Daniel Ellsberg)

http://www.youtube.com/watch?v=ceMgdXahhAY

Richard Bellman

- Los Alamos, Princeton (Lefschetz) Rand, USC
- Dynamic Programming
- Different view of control



RIAS 1955-1973

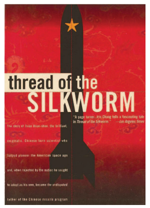
- Research Institute of Advanced Studies Baltimore, New Jersey
- Founded by the Glenn Martin Co
- Apply new ideas of fundamental research in mathematics, electronics, and physics
- Lefschetz (Princeton) and Kalman
- Turned from basic research when Martin Marietta was formed 1963
- Kalman left 1964, a large part of the control group moved to Brown University

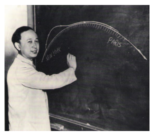
R. E. Kalman 1940--

- BA and MA 1953 MA 1954
- PhD Columbia Ragazzini 1957
- RIAS 1958-64
- Short time IBM and DuPont
- Stanford 1964-71
- University of Florida 1971-92, ETH 73
- IEEE Medal of Honor

H. S. Tsien 1911-2009

- Shanghai Jiao Tong University
- Caltech (von Karman) cofounder of JPL, colonel USAF
- Security clearance revoked, detained for 5 years
- Returned to China 1955 led development of the Silkworm





1. Introduction
2. Method of Laplace transform
3. Input, Output, and Transfer functions
4. Feedback Servomechanism
5. Noninteracting Controls
6. AC Servomechanism and Oscillating Control Servomechanism
7. Sampling Servomechanisms
8. Linear Systems with Time Lag
9. Linear Systems with Stationary Random Inputs
10. Relay Servomechanims (Tsypkin 1955)
11. Nonlinear Systems
12. Linear Systems with Variable Coefficients
13. Control Design by Perturbation Theory
14. Control Design with Specified Criteria
15. Optimalizing Control
16. Filtering of Noise (Wiener 1949, Laning Battin 1956)
17. Ultrastability and Multistability
18. Control of Error

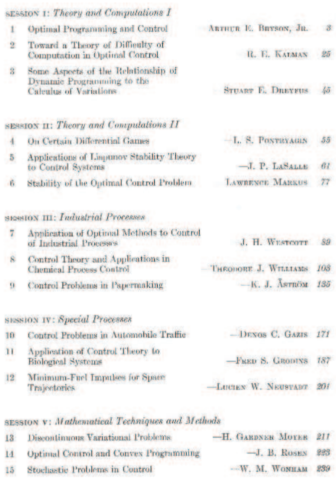
Norbert Wiener 1894-1964

- Child protegee BA math 1909, PhD Harvard 1912
- Cambridge (Bertram Russel, Hardy), Göttingen (Hilbert, Landau)
- Ballistics Aberdeen
- MIT war effort: filtering, information theory, neuropsychology

IBM

- Large commercial opportunities
- T J Watson Research Center Yorktown Heights San Jose CA, Kalman, Bertram
- Advanced development
- Pilot projects
- Acquisition of instrument company?
- IBM 1710, IBM 1800
- IBM Nordic Laboratory 1960-95

IBM Symposium 1964



SESSION I: *Theory and Computations I*

1	Optimal Programming and Control	Arthur E. Bryson, Jr.	*3*
2	Toward a Theory of Difficulty of Computation in Optimal Control	R. E. Kalman	*25*
3	Some Aspects of the Relationship of Dynamic Programming to the Calculus of Variations	Stuart E. Dreyfus	*45*

SESSION II: *Theory and Computations II*

4	On Certain Differential Games	—L. S. Pontryagin	*55*
5	Applications of Liapunov Stability Theory to Control Systems	—J. P. LaSalle	*61*
6	Stability of the Optimal Control Problem	Lawrence Markus	*77*

SESSION III: *Industrial Processes*

7	Application of Optimal Methods to Control of Industrial Processes	J. H. Westcott	*89*
8	Control Theory and Applications in Chemical Process Control	—Theodore J. Williams	*103*
9	Control Problems in Papermaking	—K. J. Åström	*135*

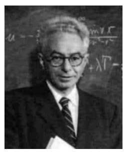
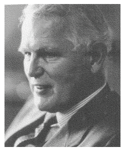
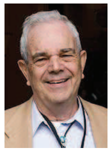
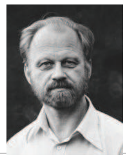
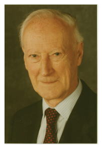
SESSION IV: *Special Processes*

10	Control Problems in Automobile Traffic	—Denos C. Gazis	*171*
11	Application of Control Theory to Biological Systems	—Fred S. Grodins	*187*
12	Minimum-Fuel Impulses for Space Trajectories	—Lucien W. Neustadt	*201*

SESSION V: *Mathematical Techniques and Methods*

13	Discontinuous Variational Problems	—H. Gardner Moyer	*211*
14	Optimal Control and Convex Programming	—J. B. Rosen	*223*
15	Stochastic Problems in Control	—W. M. Wonham	*239*



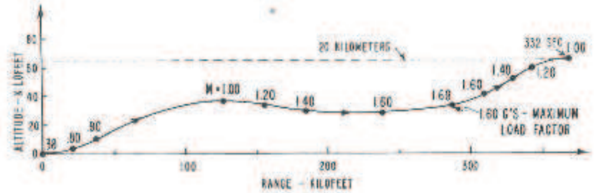
1. Introduction
2. **Major Advances**
3. Computing
4. Control Everywhere
5. Summary

The Space Race

- ➢ Both US and USSR imported missile technology from Germany (V2 Wernher von Braun) and started development
- ➢ Sputnik 1957
- ➢ Weak missiles and optimal control
- ➢ Optimization and control essential
- ➢ Computer technology

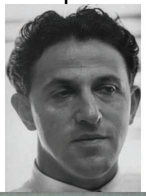
Optimal Control

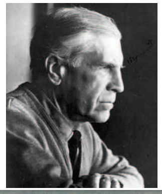
- ➢ Heavy satellites weak rockets
- ➢ Optimization with constraints abs(F) < 1
- ➢ Computational methods
- ➢ Bryson's calculations USAF experiment

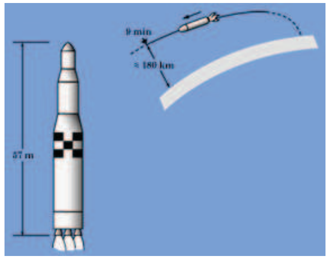


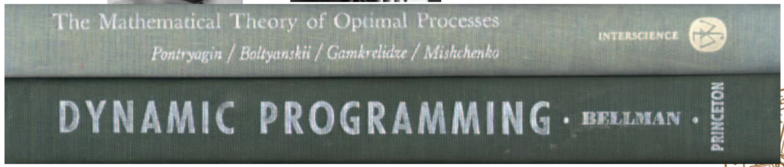
Optimal Control

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



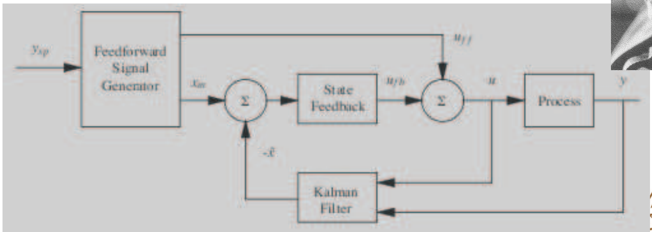






Kalman Filtering

Kalman 1961:
- ➢ Efficient recursive filtering of signals
- ➢ Combine measurements and mathematical model to estimate process state
- ➢ New controller structure based on Kalman filter, state feedback and feedforward generator



Some Kalman Papers

Kalman, R. E. Contributions to the theory of optimal control. Bol. Soc. Mat. Mexicana 5 (1960) 102-119

Kalman, R. E. Bucy, R. S. New relults in linear filtering and prediction theory. ASME J Basic Engineering 83D (1961)

Kalman, R.E. New methods and results ibn linear prediction and filtering Theory. RIAS Report 61-1 February 135 pp

Kalman, R. E. When is a linear control system optimal? Trans ASME J Basic Engineering, 86D (1964) 51-60

Kalman, R.E. Englar, T.S. Users Manual for the Automatic Synthesis program. Martin Marietta June 1996

LQG Control

- Linear quadratic control and the Riccati equation
- Infinite gain margin p_m =60^o
- Kalman Filtering and noise
- The Separation principle
- Numerical methods
- Matlab

Stability Margins

The LQ controller with state feedback has amazing stability margins

Kalman 1964

Critique: Horowitz, Rosenbrook, McMorran: Good, bad or optimal? IEEE-AC 1971

Safonov and Athans 1977

What about output feedback?

A new kid on the block

Honeywell Interoffice Correspondence

Date: August 23, 1977
To: C. A. Harvey
From: J. C. Doyle
Location: S&RC, Research

cc: L. Q. Gaussian
J. A. Hauge
A. P. Kizilos
A. F. Konar
E. E. Yore
N. R. Zagalsky
Systems and Control Technology

Subject: "Guaranteed Margins for LQG Regulators"

ABSTRACT

There aren't any.

All engineers who have been using LQG methodology may pick up their Nichols charts from the supply room.

Robust Control

- LQG/ Singular values not eigenvalues are what matters

- LTR Stein, Athans
- Hinfty control Zames ,…,
- Doyle, Glover, Khargonekar, Francis 1989

  Two Riccati equations
- Structured uncertainty mu

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




Subspecialities

- Optimal Control
- Nonlinear Control
- Stochastic Control
- System Identification
- Adaptive Control
- Sampled data systems
- Hybrid systems …
- Robotics, automotive, …

Subspecialties

- Initiative shifted to academia
- Understanding and learning new math
- Building groups of critical size
- Explore many details
- Development of books and courses
- The academic publication and education culture drives specialization
- Difficult to keep breadth

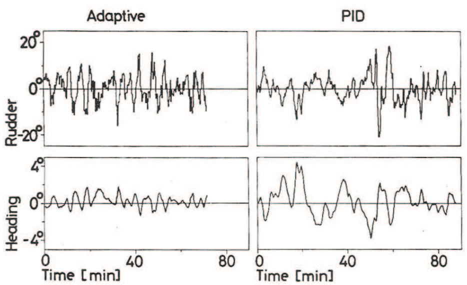
System Identification

- Direct measurement of transfer functions a major factor for the success of classical control
- How to find similar methods for state space based control
- The IFAC identification symposia, starting in Prag 1967
- More details in Swedish Scene

Adaptive Control

- Driving force: Supersonic aircrafts
- The Brave Era
- Gain Scheduling
- Model Reference Control
- The Self-tuning Regulator
- Recent developments
- More in the Swedish Scene

Ship Stering Autpilots



NORTHROP GRUMMAN

Nonlinear Control

- Functional analysis, circle criterion, small gain theorem, Popov, Kalman-Yakubovich
- Differential geometry: Brocket, Isidori, Byrnes, …
- The Royal Society Workshop

The Second Wave

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

1. Introduction
2. Major Advances
3. **Computing**
4. Control Everywhere
5. Summary

Computer Control

- Drawbacks of analog technology: drift, calibration, programming
- Poor computer performance
- Supervisory control
- Slow computers required slow sampling rates
- Development driven by computer and process companies

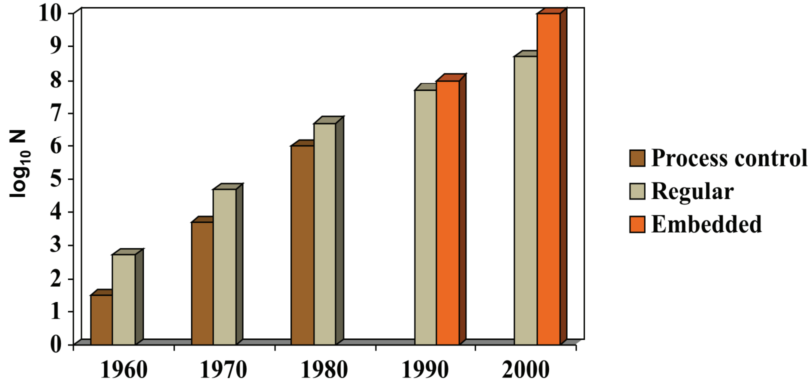
The Whirlwind Computer

- Flight trainer-analyzer 1944-56
- MIT Servomechanism Laboratory Forrester 1944
- From analog to digital computing
- Core memory 1953
- Ken Olsen and Digital Equipment
- PDP 8 1965

Computer Control

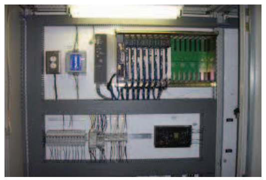
- TRW and Texaco March 12, 1959
- Billerud project 1962-66
- Minicomputers 1967-
- Microcomputers 1972 -
- Distributed control 1990 -
- Sampled data system
- Real time systems

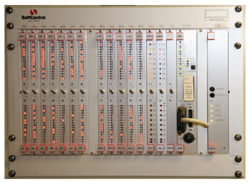
Computer Control



Control, Logic & Sequencing

- Logic for safety shut off, sequencing for start and stop
- Control algorithms for regulation
- Traditionally control and relay cabinets
- Relay cabinets became PLCs and control algorithms added, control cabinets became DCS and logic was added
- International standards emerged





Control Logic & Sequencing

- GM Spec and Bedford Associates1968, Modicon > Gould > AEG > Schneider
- Claes Ahlerup, Göran Sigfridsson Xjobb spring 72 LTH: ElektronLund (Göran Andersson) PBS 1973 > SattControl (AEG) 1977 > Alfa Laval > ABB
- Mini- and microcomputer based PLCs
- Programming, ladder logic, Boolean, GrafCet, GrafChart
- All control systems contain logic and sequencing. We should pay more attention to this in our courses!

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!

CACE

- Numerical mathematics: Numerical linear algebra, Lyapunov and Riccati equations
- Subroutine libraries
- Use computers to package theory
- Early experiments 1970-1985: IDPAC, SYNPAC, Simnon, Dymola
- Matlab 1981

Matlab

- Linpac, Cleve Moler 1980: MATLAB – An Interactive Matrix Laboratory, Symposium in Lund Sept 1980
- Systems Control Inc CTRL-C – Control Extensions
- Integrated Systems Inc (ISI), Matrix-X 1982, SystemBuild 1984, Code generation
- John Little MathWorks1984, PC Matlab, Simulink, Toolboxes
- Scilab, Octave, SysQuake (interactive)
- Comsol FemLab (PDE modeling) 2000

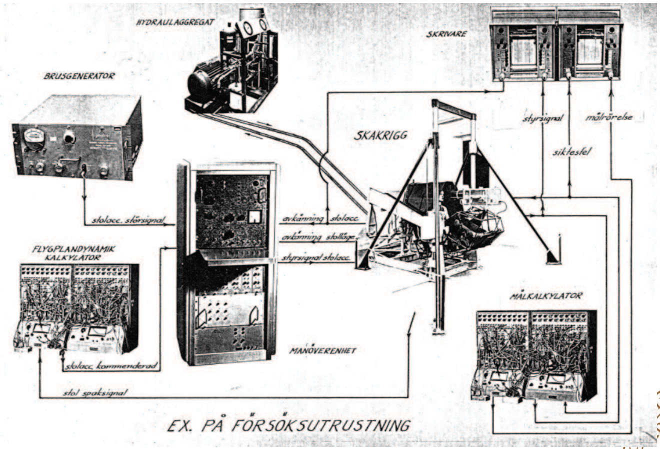
Simulation

- Analog simulation 1928 - 1970
  - Integrators and amplifiers
  - Mechanic and electronic
  - Ordinary differential equations ODE
  - Strong synergies analog between computing and control
- Digital simulation 1955 -
  - Mimic analog computing CSSL 1967, EasyV, CSMP 1967 Simnon 1972, SystemBuild 1984, LabView 1986, Simulink 1991
- Modeling Languages and Numerics 1978 -
  - Differential Algebraic Equations,
  - Domain specific, Adams, Spice
  - Dymola Elmqvist LTH 1978
- Modelica 1996 -
  - Differential Algebraic Equations Gear, Petzold
  - Computer algebra, PC

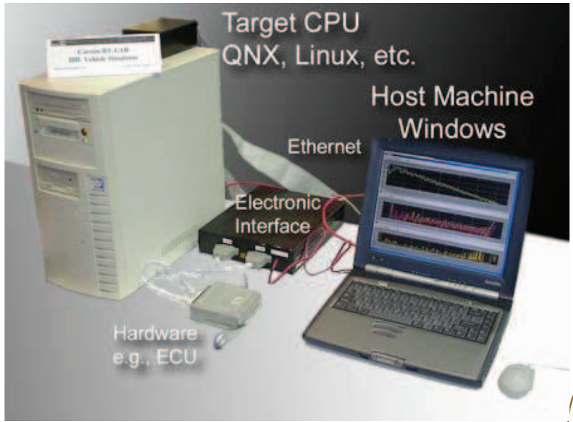
Digital Emulators

- ➢ Selfridge 1955
- ➢ MIMIC Wright-Patterson 1965
- ➢ CSSL Simulation Council 1967
- ➢ ACSL Gauthier and Mitchell 1975
- ➢ Simnon, Elmqvist 1975
- ➢ System Build 1984, Simulink, Vissim 1990

Component testing by hardware in the Loop Simulation 1950

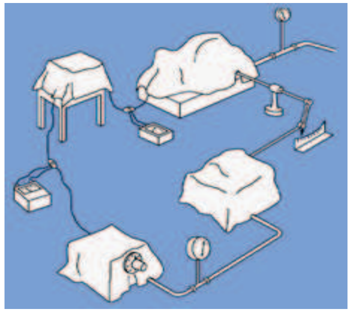


HILS 2000



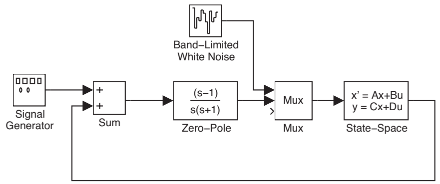
Block Diagram Modeling

- ➢ Information hiding
- ➢ Focus on input & output
- ➢ Many tools
- ➢ SystemBuild MatrixX 1985
- ➢ LabView 1986
- ➢ Simulink Matlab 1991
- ➢ VisSim
- ➢ Scilab



Block Diagram Tools

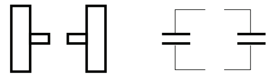
- Mimics the analog computer
- Each block a state model



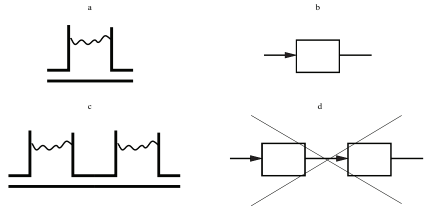
- Matlab-Simulink
- Granularity and Structuring
- Graphical aggregation and disaggregation
- Much manual manipulation from physics to blocks

Drawbacks

States may disappear – warning algebraic loop



Composition does not work



Block diagrams not suitable for physical modeling

Domain Specific Tools

- Circuit theory
  - Two ports systems
  - Spice Peterson Berkeley
  - Differential algebraic systems DAE Gear & Petzold
  - Essentially limited to circuits
- Multi-body systems
  - Adams, SolidWorks, ….
- Bond Graphs
  - Henry Paynter MIT
  - Excellent if there is one dominating balance equation. Difficult to deal with many balances.
- Chemical Engineering
  - Complex plants, no dynamics, optimization

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Power Generation and Distribution Smart Grids

Process Control

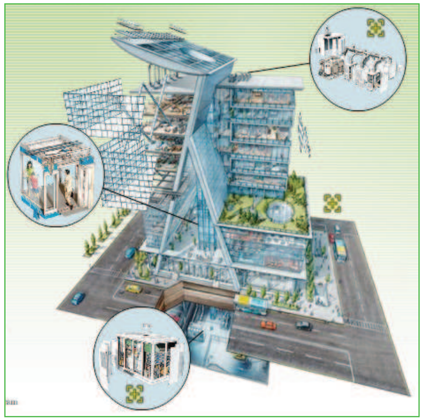
Buildings

Design & Energy Analysis

Windows & Lighting

Natural Ventilation

Indoor Environment



Elevators

Safety

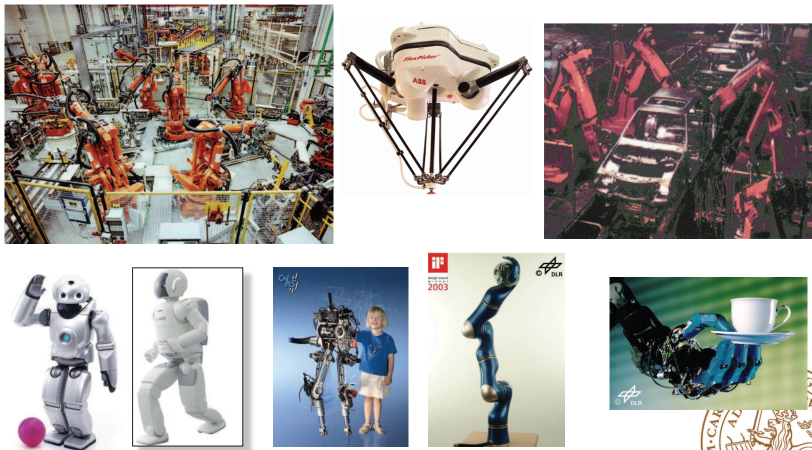
HVAC

Vibration damping

Sensors, Networks,Communications, Controls

Slide from UTRC

Manufacturing robotics



Vehicles

Automotive

- Strong technology driver
- Large quantities, low price
- Microcontrollers
- Cheap sensors and actuators
- Software and systems
- Standardization
- Autosar

Automotive

Strong technology driver

Engine control

Power trains

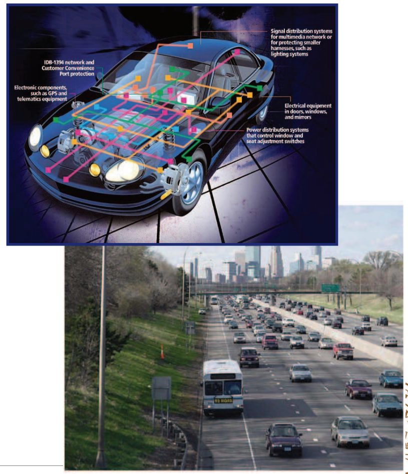
Adaptive cruise control

Collision avoidance

Traction control

Lane guidance assistance

Traffic flow control



Consumer Electronics

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Summary

- Huge advances by applying a wide range of mathematics
- Huge advances in computing: Simulation moved from computer centers to desk tops, Matlab-Simulink. Online control at kHz
- Sub-specialization: From 6 IFAC Technical Committees in 1960 to 34 in 1999
- Holistic view was lost, fragmentation of the community (the IEEE Robotics Society)