The Future of Control

Some personal reflections

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NAE, AFOSR, IEEE, IFAC

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

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 disciplines were not recognized.

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

The Hidden Technology

☺ Widely used
☺ Very successful
☹ Seldom talked about
😐 Except when there is a disaster
😐 Why?
Easier to talk about devices than ideas.
We have not presented our ideas well to collegues in science and to broader audiences

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. Control Everywhere
4. Challenges
5. Conclusions

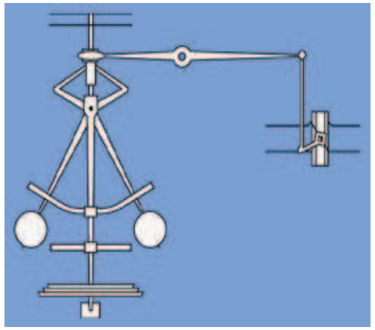
A Brief History

- Early use in many fields
  - Power systems
  - 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, Tolle 1905
  Maxwell and Routh
  Lyapunov



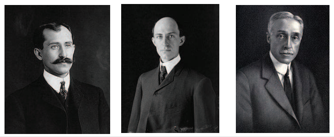
Process Control

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

Flight Control

- Problem: How to fly?
- Solution: Understand dynamics.

  Wright Brothers: Build maneuverable but unstable aircraft stabilize with manual control
- Side effects: Autopilots, flight dynamics

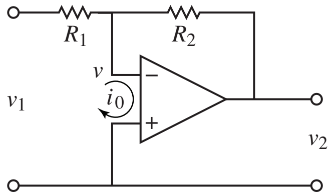


Sperry 1913

Autonomy 1947

Telecommunication

- Problem: How to phone 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

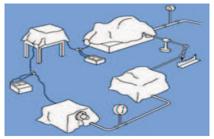
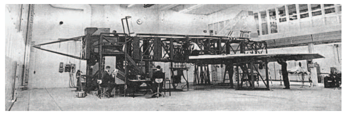
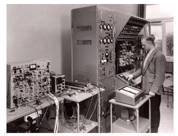
- Power generation and distribution
- Process control
- Autopilots for ships and aircrafts
- Telecommunications

The similarities were not recognized

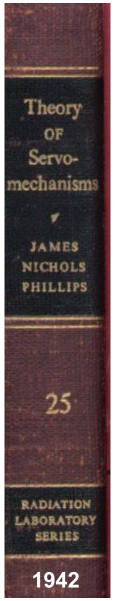
The Discipline Emerges

- Drivers: The war effort, gun sights, 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
- Design
  Frequency Response
  Graphical Methods
- System Concepts
  Feedback
  Feedforward
- 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

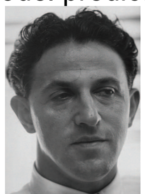
Education	Organisation
Application	Journals
Industrialization	Conferences

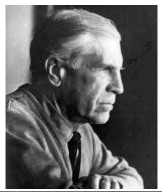
The Second Phase

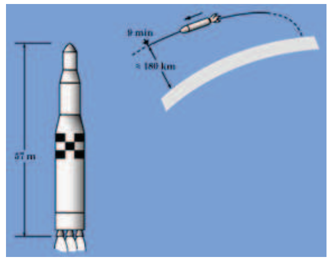
- Drivers: space, computer control, mathematics
- Rapid growth of sub-specialities: Optimal, stochastic, nonlinear, ...
- Computational tools
- Impressive development of theory
- The holistic view was lost!

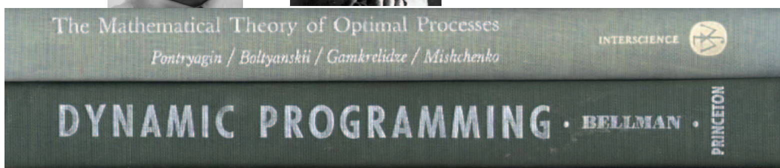
Optimal Control

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



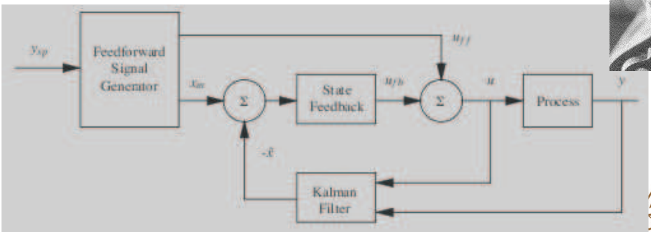






Kalman Filtering

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



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

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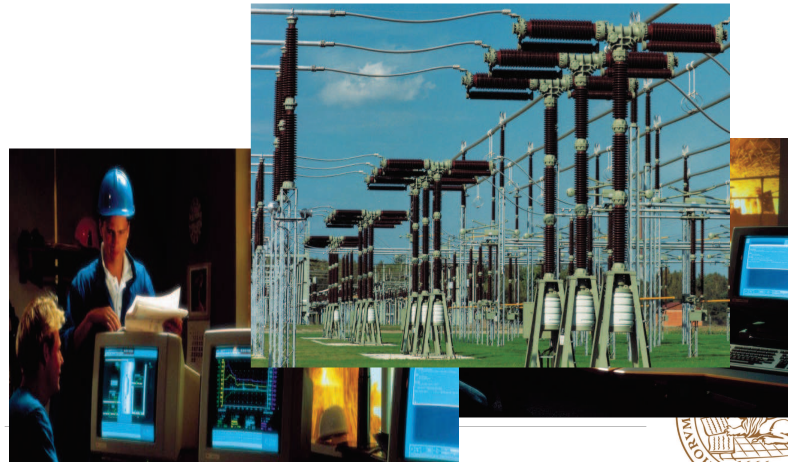
Power Generation and Distribution Smart Grids



Process Control

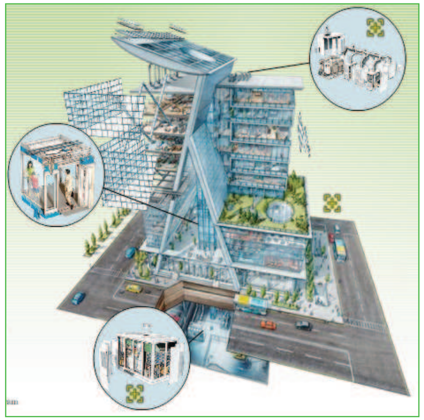
Buildings

Design &
Energy Analysis

Windows &
Lighting

Natural
Ventilation

Indoor
Environment



Elevators

Safety

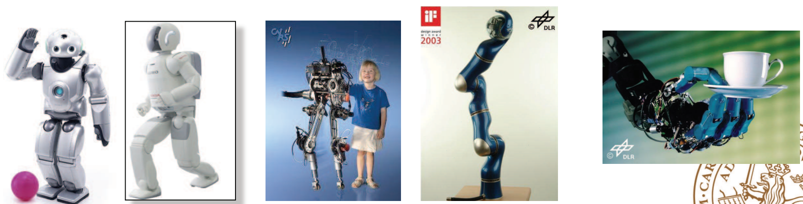
HVAC

Vibration
damping

Sensors, Networks,Communications, Controls

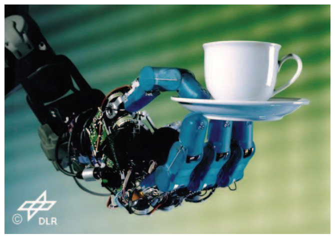
Slide from UTRC

Manufacturing robotics



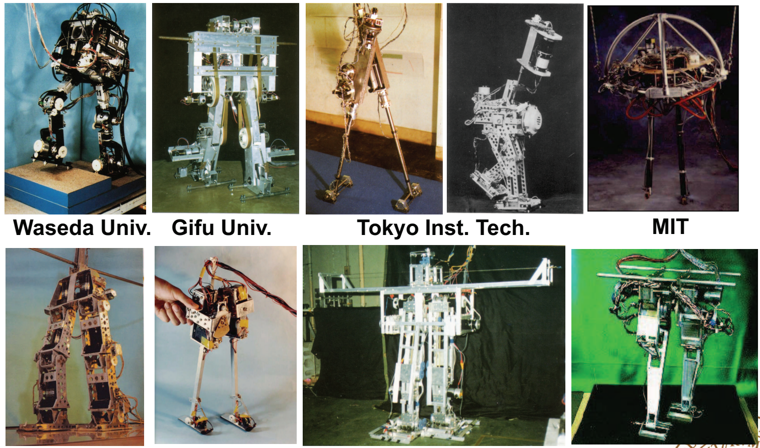
DLR Robots and Hands

LWR III: 7 joints weight/load ~ 1
150 W, 3 cables
Hand II: 13 joints 3 kg finger force



Gerd Hirzinger DLR

Historical biped robots in 1980s and early 90s



HONDA Shock!

December, 1996
Press release of a humanoid robot P2, from HONDA
Height 2m, Weight 200kg

Self contained humanoid robot which can perform beautiful dynamic biped walk surprised robot researchers all over the world!

HRP-3（2007）

Height	1.6 m
Weight	68 kg (with batteries)
DoF	42 (Arm 7×2, Leg 6×2, Waist 2, Neck 2, Finger 5×2)
Sensors	CCD Camera ×3 (stereo vision) CCD Camera ×2 (remote control) IMU, 6-axis force sensors for wrists and ankles

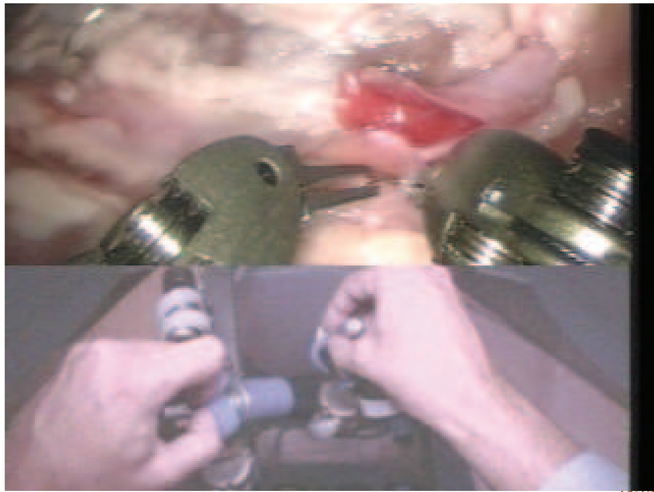
- Sponsor: NEDO
- Water dust proof（IEC IP52)
- Cover Design: Yutaka Izubuchi
- Basic Design: AIST
- Design & Manufacture: Kawada Industries Inc.

Humanoids

Hiroshi Ishiguro

Biomedical

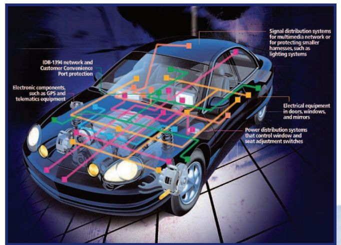
Video to follow curtesy of: Intuitive Surgical, Inc. and Dr. Magnus Annerstedt, Lund University



Vehicles

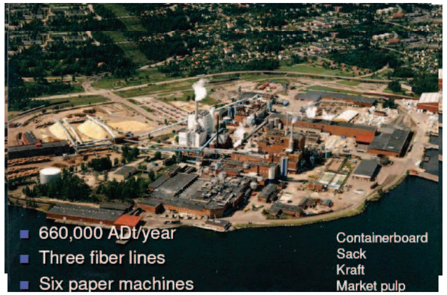
Automotive

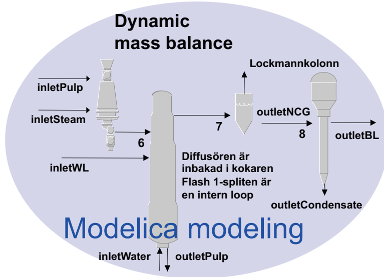
- Strong technology driver
- Engine control
- Power trains
- Adaptive cruise control
- Collision avoidance
- Traction control
- Lane guidance assistance
- Traffic flow control



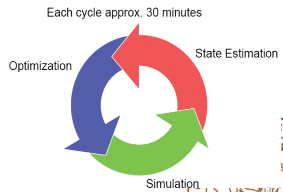
Consumer Electronics

Mill Wide Control



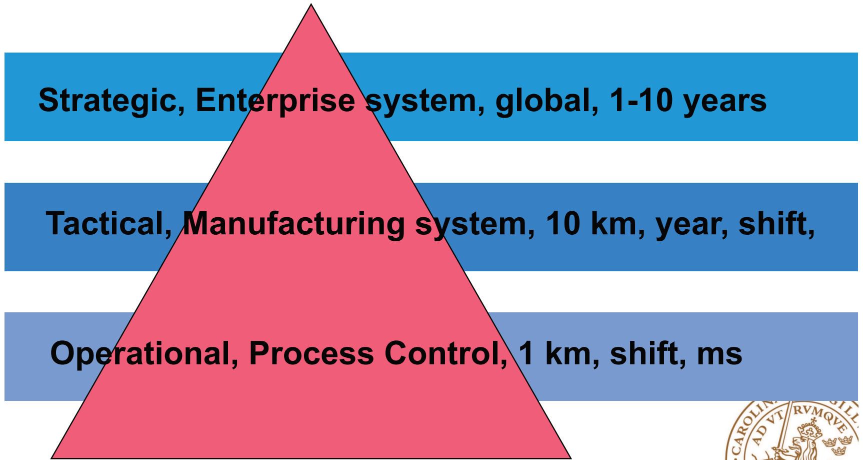


25	Production units
38	Buffer tanks
250	Streams
250	Measurements
2500	Variables



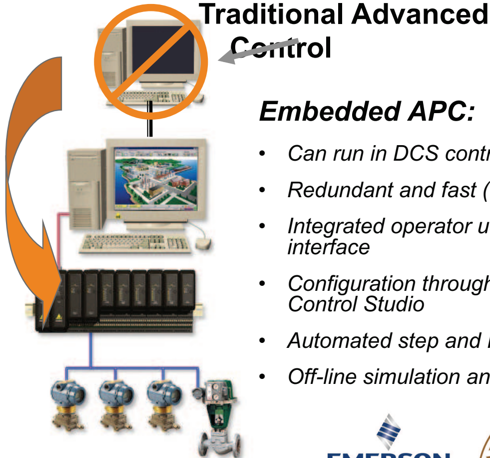
Slide from Alf Isaksson ABB

Global Enterprise Control



Embedded APC

- NO extra databases
- NO database synchronization issues
- NO watchdog timers
- NO fail/shed logic design
- NO custom DCS programming
- NO interface programming
- NO operator interface development



Embedded APC:

- *Can run in DCS controllers*
- *Redundant and fast (1/sec)*
- *Integrated operator user interface*
- *Configuration through standard Control Studio*
- *Automated step and Model ID*
- *Off-line simulation and training*

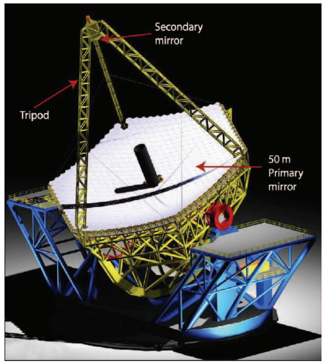
EMERSON Process Management

Physics

➢ The causality issue
➢ Nobel prizes in physics
  Gustaf Dalén 1912
  Simon van der Meer 1984
  (stochastic cooling)
➢ Quantum and molecular systems
➢ Turbulence

Instruments Giga to Nano

Adaptive Optics



Atomic Force Microscope

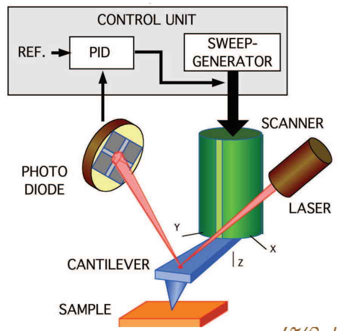
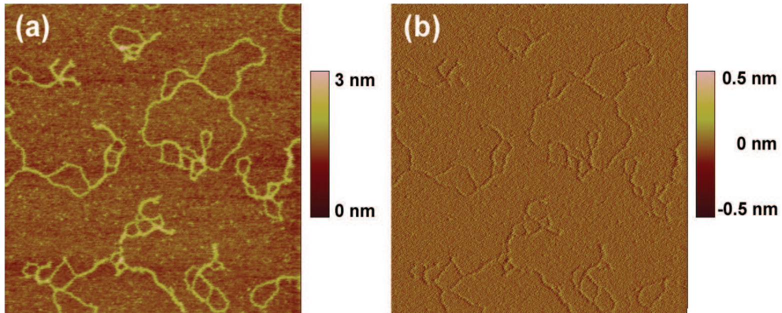
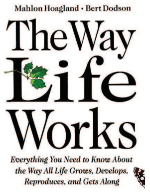


Image of DNA String

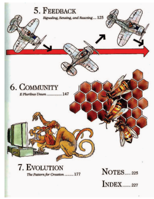


A Phycicists View

The obvious places to learn about control theory – introductory engineering textbooks ... - are not very satisfactory places for a phycisist to start. They are long - 800 pages is typical - with the relevant information often scattered in different sections. ... They often cloak concepts familiar to the physicist inunfamiliar language and notation. ... The main alternative, more mathematical texts, ..., are terse but assume that the reader already has an intuitive understanding of the subject. John Beckhoefer Rev. Mod. Phys. July 2005



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

Systems Biology

Leading biologists have recognized that new systems-level knowledge is urgently required in order to conceptualize an organize the revolutionary developments taking place in the biological sciences, and new academic departments and educational programs are being established at major universities, particularly in Europe and in the United States

Eduardo Sontag 2006

Charles Darwin

It is not the strongest of the species that survive, nor the most intelligent, it is the one that is most adaptable to change.

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

Challenges

Increased use in engineering

- Networks and complex systems
- Autonomous systems
- Learning, reasoning and cognition

Natural science

- Devices and ideas in physics
- Strong systems orientation in biology
- Many previous attempts. Will it work this time?

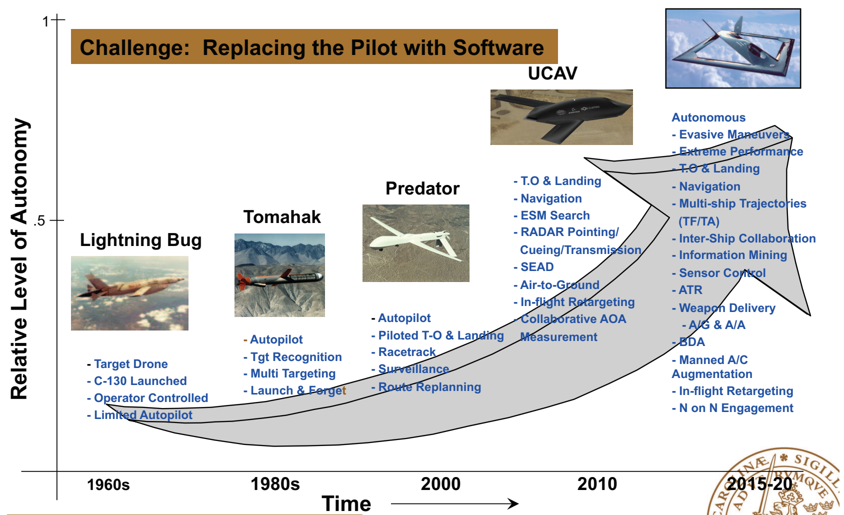
Autonomous Systems

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

Darpa Grand Challenge

Dickmanns 1995 - 95% autonomi

Autonomy UAVs

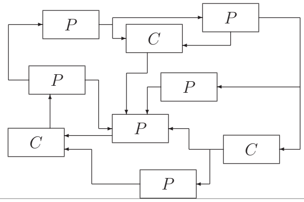


Siva Banda U.S. Air Force Research Lab

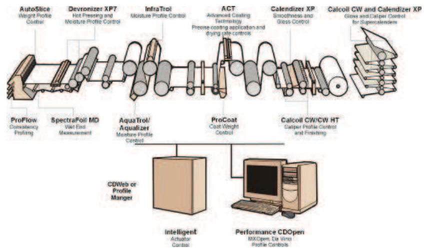
Cognition

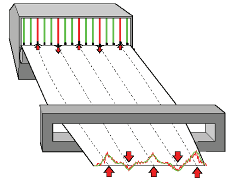
New Problems

- ➢ Complex networked systems
- ➢ Sensor rich control
- ➢ Actuator rich control
- ➢ High level control principles
- ➢ Safe design of embedded systems



Cross Direction Control





Several hundred sensors and actuators, millisecond operation, controlling paper thickness to within microns!

Honeywell Laboratories

A Third Phase?

- ➢ Drivers: embedded systems, networks, biology, physics, economy ...
- ➢ Autonomous distributed systems
- ➢ Sensor and actuator rich systems
- ➢ Provable safe design and reconfiguration
- ➢ Can the holistic view be recovered?

The Holistic View

- ➢ 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

The Systems Perspective

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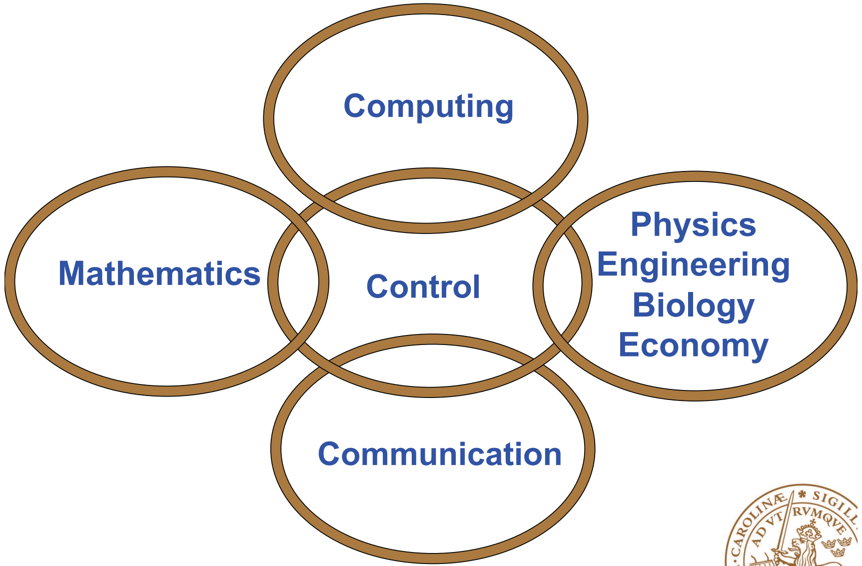
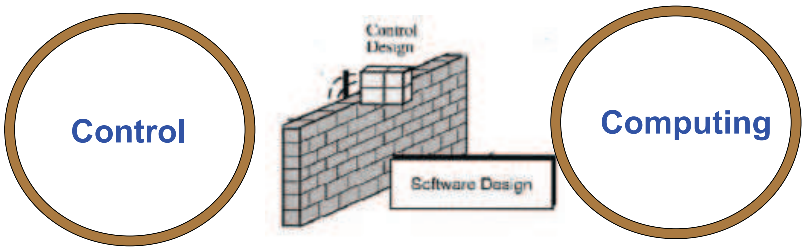


The CS Barrier



Feedback,Stability, ODE, PDE
Moderate complexity
Robustness

Logic, languages, DES,FSM
High complexity, abstractions
Architecture

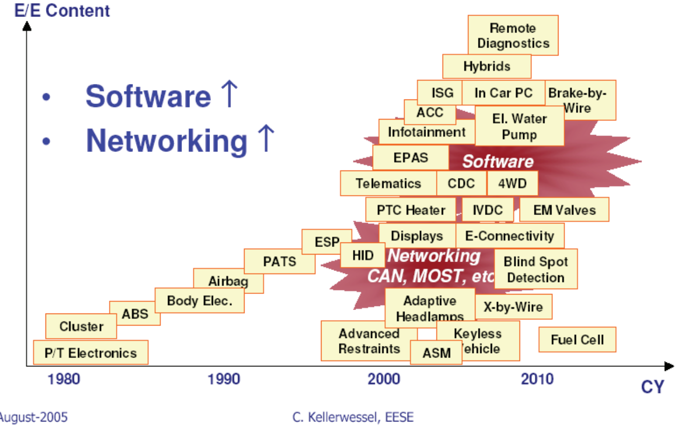
The controller

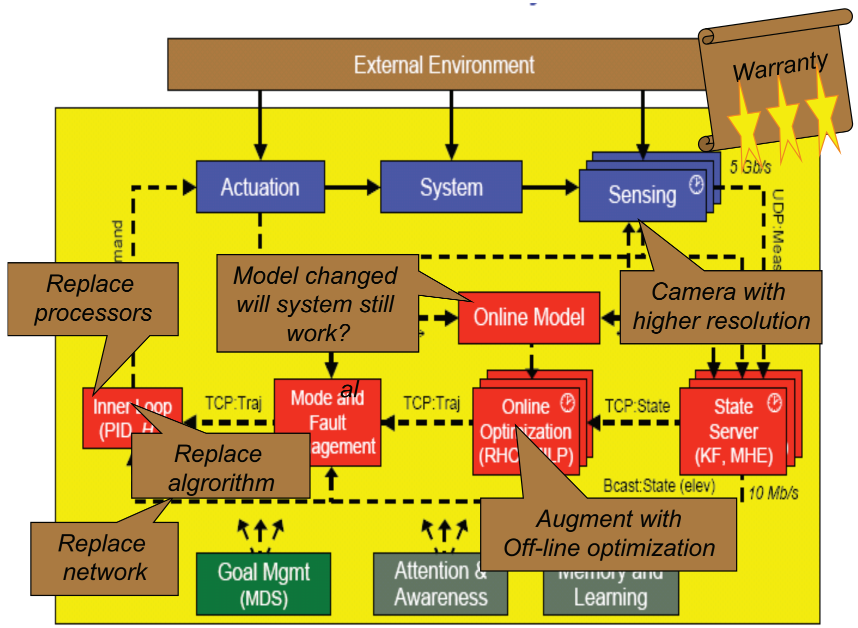
Computing

- 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!

Complexity Increases

- Software ↑
- Networking ↑

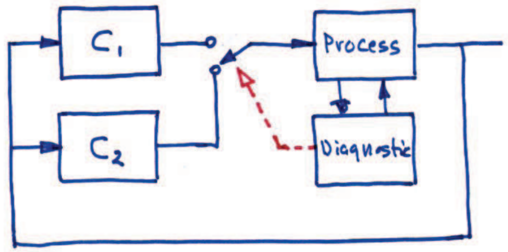




Safe Design

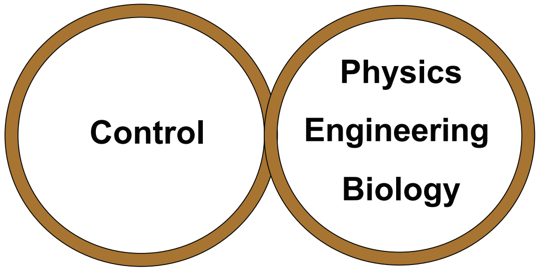
- Much more than automatic code generation
- System architecture
- Modeling
- Integration of subsystems
- Modification, upgrade
- Formal specification, design, verification, validation

Lui Sha's Simplex Algorithm



- Safe on-line testing of new algorithms
- C_1 Safe simple proven algorithm
- C_2 High performance algorithm

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.

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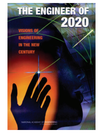
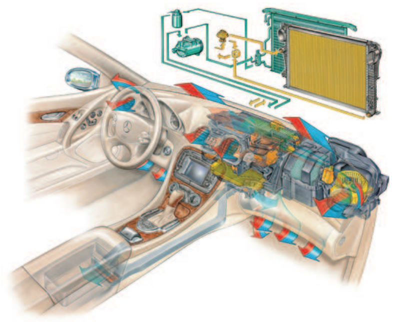


Modelica

- Component-based, multi-domain, modeling language
- Behavior-based, (declarative DAE), object oriented
- Extensive symbolic manipulation, automatic inversion, ...
- Efficient real-time code generation
- Libraries and reuse
- Elmqvist Dymola 1978, Dynsim 1992, Modelica 1996
- Åkesson Jmodelica Optimica

MODELICA

Automotive Climate Control



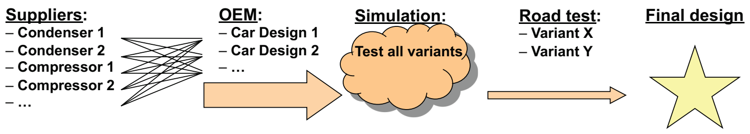
- *Audi, BMW, DaimlerCrysler, Ford, Volvo, Volkswagen and their suppliers have standardized on Modelica*
- *Suppliers provide components and validated Modelica models based on the AirConditioning library from Modelon*
- *Car manufacturers evaluate complete system by simulation*
- *IP protected by extensive encryption*

Picture courtesy of Behr GmbH & Co.

Modelon

Customer Value

- Automotive OEM customers:
  Daimler, BMW, AUDI, VW, Ford, Volvo, …
- Automotive supplier customers:
  Visteon, Valeo, Denso, Behrgroup, Modine, Showa Denko
- Calibrated models by suppliers mandatory in bid for hardware contract
- Substantial reduction of road & climate chamber testing



Successful model-based development process based on exchange of component and system models between suppliers and OEM

Slide from Modelon

Educational Challenges

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

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Conclusions

- Control is a vital dynamic field
- Networked embedded systems
- Autonomy and safety
- The educational challenge
- Recover the holistic view