Automatic Control in Lund

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Automatic Control in Lund

1. Introduction
2. System Identification and Adaptive Control
3. Computer Aided Control Engineering
4. Relay Auto-tuning
5. Two Applications
6. Summary

Theme: Building a New Department and Samples of Activities.

Lectures

		1940	1960	2000
1	Introduction			
2	Governors	|	|	|
3	Process Control	|	|	|
4	Feedback Amplifiers	|	|	|
5	Harry Nyquist	|	|	|
6	Aerospace	|	|	|
7	Automatic Control Emerges	←	|	|
8	The Second Phase	←	←	|
9	Automatic Control in Sweden	|	|	|
10	Automatic Control in Lund		|	|
11	The Future of Control			→

Introduction

LTH started in 1961

- A new engineering school close to an old University
- First control course taught by Felix Aasma CTH 1964

KJÅ

- KTH and the TTN Group - Inertial Guidance and Navigation, MIT and Draper Lab
- IBM Research - T. J. Watson Laboratory, San Jose Laboratory
  Bertram, Kalman, Berkeley, Stanford, MIT, Columbia, Lockheed
- IBM Nordic Laboratory
  Papermachine mdeling and control
  System identification
  Minimum variance control
  Computer control
- Professor in 1965

LTH - 1965

- LTH Base Plan (stomplan) and Ragnar Woxen rektor
- Centrally governed
- Faculty of professors (and lecturers) the governing body
  You meet once a month good for interaction
- Budget: positions, material and equipment
- Research funding
  Mainly through the university - Competence for allocation?
  STU (Many changes now Vinnova och SSF)
- Red, blue and green money, July 1st
- Skåne - technically a development region (ett tekniskt uland!) Three exceptions: Kockums, Sydkraft, TetraPak
- Industrial contacts essential

Base Plan (Stomplanen)

Planned resources

- Professor (4h)
- 2 Lecturer (12 h ≈ Associate prof with tenure)
- 4 assistants
- 1 secretary
- 1 technical assistant
- 1 research engineer
- 1 instrument engineer
- 3 lab personel
- Equipment funding 0.8 MSEK ≈ 8 MSEK today

Lack of compentent candidates at many levels. Impossible to attract top people from US. First lecturer Gustaf Olsson 1967. Philosophy: Trade long term gain for short term pain.

Starting a New Department

- Good people
  If you want a 2 meter jumper it is not enough to have two one meter jumpers (Prof Terman Stanford)
- High Quality Education
  Industry needs good engineers
  Student interest
  Good teachers
- High Quality Research
  Compete on the global arena
  Long term research program
  Guest researchers
- A good lab
  Too many professors in automatic control have a platonic love for control systems - they talk a lot about them but they have not touched them.

To Lab or not to Lab

- Clear intention in Base Plan - BUT (Woxen)
- Personal view: Labs are expensive but necessary if we want to educate engineers
- Good resources in the Base Plan
  - Bad details
- European tour
  - Destillation columns
  - Mini rolling mills
- Decision: Industry will be our real lab
  Establish good network, the Swedish advantage
- Simple lab processes for courses
- Personel
  - Competence to develop and run lab processes
  - Competence to participate in experiments in industry
- Goal: Get a computer

Industry Collaboration

- Billerud, IBM ±, Kockums, Sydkraft
- Volvo, Saab, ABB, Ericsson, Vattenfall, Atomenergi, FOA
- Pulp and Paper, Waste Water Treatment, Building Automation
- Trips with students and faculty
- Contact days
- Seminars
- Courses

  Teknologföreningen, LTH, Kockums
  Useful for grad students to interact person-to-person
  Useful contacts for projects
- Personel exchange Billerud/LTH
- Master theses
- Projects

Education

Basic courses

- Introductory Course

  Advice from Helmut Hertz
  Merger of classic control and state space
  Labs
- Advanced Course

  Nonlinear, Computer Control, Stochastic Control
  Inherited Jack Bertrams course on Nonlinear Control from Columbia. Lots of examples, Lyapunov, piecewise constant

PhD courses

- Emulation of US graduate education with limited resources
- Lots of discussions and guest lecturers

  Linear systems, optimal control, algebraic system theory, real time programming, multivarible systems, adaptive control, system identification

Programming Real-Time Systems

- Absolutely essential to Control
- *Real-time programming* James Schoeffler CASE 1971
- *Computers in Control Systems* J, Wieslander PDP15 1972
- *Computers in Control Systems 2*, Hilding Elmqvist 1979
  - LSI-11, Concurrent Pascal, real time kernel
- *Computers in Control Control Systems 1* transfered to Gustaf Olsson who became Professor of IAE 1987
- *Applied Real-Time Programming* IBM PC, Modula 2, 1983
- *Computer Implementation of Control Systems*, VME Motorola 68020 89-93
- *Real-Time Systems*, Karl-Erik Årzén 1993
  - Windows NT, Pentium, InTouch 1996
  - PowerPC, Migration to Java started 1998
  - Java, Linux, PC 2000
  - ATMEL AVR microprocessors 2003
  - Holistic view of computer control 2007

PhD Program

- Modeled after USA
- Collaboration with Mathematics Department
- New courses

  Stochastic Control
  System Identification
  Adaptive Control
  Later part of CI program thanks to Per Eriksson
- Ad hoc using visitors
- Independent studies
- Seminars run by the students
- Independent studies based well organized material, tapes, lecture notes, books, self-instruction. Improve material during the course (The box concept)
- Group projects (prof, industry, experienced PhDs and unexperiences PhDs)
- Program formalized in Educational Reform 1975

Formal PhD Program 1975

Goals: Ability to

- add new knowledge
- work independently
- to understand, formulate analyze and solve problems
- understand possibilities and limitations of quantiative methods
- to communicate by talking and writing
- to cooperate in groups on systems problems
- to gather knowledge from different fields and organized in systematically
- to generate new knowledge

Strong foundation in the field of systems science measured by international standards. Good abilities to use computers for off-line problem solving and for on-line control.

Course List 1975

- Introductory Course
- System Theory

  2.1 Finite state systems
  2.2 Linear systems
  2.3 Stochastic systems
  2.4 Nonlinear stochastic systems
  2.5 Infinite dimensional systems
  2.6 Independent study
- Optimization

  3.1 Parametric Optimization
  3.2 Calculus of Variations
  3.3 LQG Theory
  3.4 Optimal Control
  3.5 Independent Study
- Applications

  4.1 Numerical Methods in Control
  4.2 Modeling
  4.3 System Identification
  4.4 Ada[ptive and Learning
  4.5 Hardware and Software for On-line Control
  4.6 Process Control
  4.7 Non-technical Applications
  4.8 Systems Engineering
  4.9 Independent Study

Visitors

- Don't appoint until competent candidates are available, use money for visitors!
- More than 30 visitors 0.5 – 6 months the first 10 years

- Michael Athans MIT
- Richard Bellman USC
- Harald Cramer SU
- Peter Falb Brown
- Y. C. Ho Harvard
- Isaac Horowitz Colorado
- Eliahu Jury Berkeley
- Rudolf Kalman Florida
- David Mayne Imperial
- A. McFarlane Cambridge
- Sanjoy Mitter MIT
- Bob Narendra Yale
- Lucien Polak Berkeley
- H. Rosenbrock UMIST
- Murray Wonham Toronto
- Lotfi Zadeh Berkeley

Research Plan

Goals:

- Research results on high international level
- Researchers on a high international level with a broad knowledge
- Cover a broad range to be able to educate the engineers that Sweden need

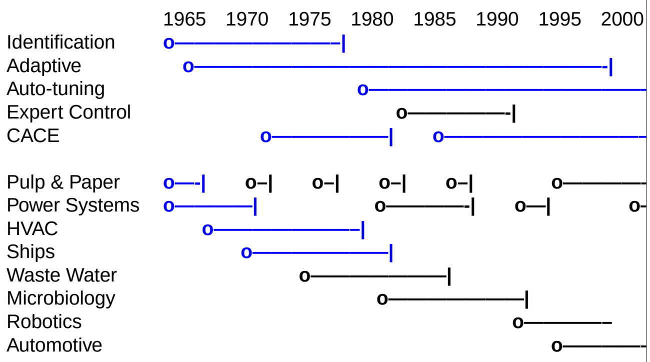
Topics

- System identification
- Adaptiv control
- Computer control
- Computer Aided Control System Design
- Large Systems
- Applications in broad areas in close collaboration with industry

Industrial interaction

- MS theses, projects, experiments

Overview



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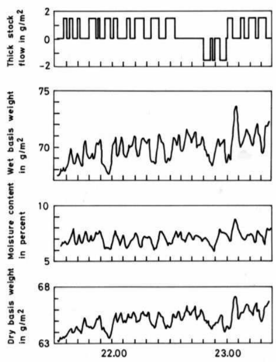
Theme: Building a New Department and Samples of Activities.

Initial Conditions

- IBM experience
- Theory
- Code
- Practical know-how
- Many theoretical questions
- Probability theory
- Statistics
- Experimental conditions
- Recursive computations



Identification and Adaptive Control < 1980

Topics

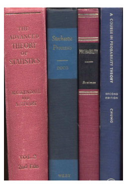
- Algorithms
- Convergence
- Applications
- Software Idpac
- Models with structure
- Non-uniform sampling
- Input design
- Closed loop experiments
- Recursive estimation
- Adaptive control

Students

- Torsten Söderström
- Björn Wittenmark
- Ivar Gustafsson
- Lennart Ljung
- Bo Leden
- Ulf Borisson
- Ulf Borisson
- Jan Sternby
- Jan Holst
- Lars Jensen
- Bo Egardt
- Clas Källström

Subspecialization

- Good start from Billerud-IBM project, much to do
- Deep dive
  Statistics, numerics, probability theory, estimation theory, experiment design
  Lectures book plan
- Hunt for data
  Pulp and Paper, Billerud
  Power systems, Sydkraft
  Ship steering, Sea Swift, Kockums, SSPA



- Torsten Söderström 1969-74 (Lecturer Uppsala)
- Lennart Ljung 1970-76 (Professor Linköping)
- Dropped identification, skipped book, focus on adaptation

Adaptive Control

- Flight control
  Gregory (ed) Proc Self Adaptive Flight Control Symp
  The X15 crash
  Kalman - Columbia - IBM Research - Richard Koepcke
  Adaptation lost to gain scheduling
- Research in system identification drifted away from feedback (late recovery *identification for control*)
- Adaptive Control of Paper machines
  Identification is a tedious procedure that requires skills
  Why not adapt?
  First goal adaptive Minimum Variance Controller
- The Self-Tuning Regulator
- Analysis, industrial validation

Minimum Variance (Moving Average Control)

Process model

$$Ay(t) = Bu(t) + Ce(t)$$

Factor $B = B^+B^-$, solve (minimum degree solution)

$$A{\color{red}F} + B^-{\color{red}G} = C$$

$$Cy = CFe + B^-(Ru + Sy), \qquad S = G \qquad R = FB^+$$

Control law and controlled output are

$$Ru(t) = -Sy(t), \qquad y(t) = Fe(t)$$

where $\deg F \geq$ pole excess of B/A

Make it adaptive!

The Self-Tuning Controller

Make an adaptive minimum variance controller

$$Ay(t) = Bu(t) + Ce(t), \qquad \deg A - \deg B = k$$

Estimate parameters in the model

$$y(t+k) = r_0\Big(u(t) + ...r_m u(t-l) + s_0 y(t) + ...s_n y(t-m)\Big)$$

by recursive least squares and use the control law

$$u(t) + r_1 u(t-1) + ...r_k u(t-l) = -s_0 y(t) - s_1 y(t-1) - ... - s_n y(t-m)$$

If parameters converge then

$$E\big(y(t+\tau)y(t)\big) = 0, \qquad \tau = k, k+1, ..k+l$$
$$E\big(y(t+\tau)u(t)\big) = 0, \qquad \tau = k, k+1, ..k+m$$

If l and m sufficiently large then parameters converge to MVC.

The Self-tuning Regulator Björn Wittenmark

On Self Tuning Regulators*
Sur les Régulateurs Auto-Syntonisants
Über selbsteinstellende Regler
О самонастраивающихся регуляторах

K. J. ÅSTRÖM and B. WITTENMARK

Control laws obtained by combining a least squares parameter estimator and a minimum variance strategy based on the estimated parameters have asymptotically optimal performance.

Automatica **9** (1973) 185-189

- Known time delay
- $B(z)$: no zeros outside unit disc, sign of b_0 known
- Degrees of R and S sufficiently large
- Integral action and anti-windup

Convergence Analysis Lennart Ljung

Analysis of Recursive Stochastic Algorithms

LENNART LJUNG, MEMBER, IEEE

IEEE Trans AC-22 (1977) 551–575

Markov processes and differential equations

$$dx = f(x)dt + g(x)dw, \qquad \frac{\partial p}{\partial t} = -\frac{\partial p}{\partial x}\left(\frac{\partial f p}{\partial x}\right) + \frac{1}{2}\frac{\partial^2}{\partial x^2} g^2 f = 0$$

Lennarts idea

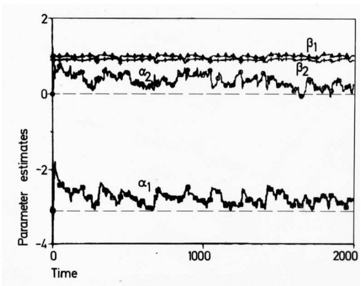
$$\theta_{t+1} = \theta_t + \gamma_t \varphi e, \qquad \frac{d\theta}{d\tau} = f(\theta) = E\varphi e$$

Convergence of recursive algorithms and STR (Ay=Bu+Ce)
Counterexample
Jan Holst: Local stability if real $\mathrm{C}(\mathrm{z_k}) > 0, \mathrm{B}(\mathrm{z_k}) = 0$

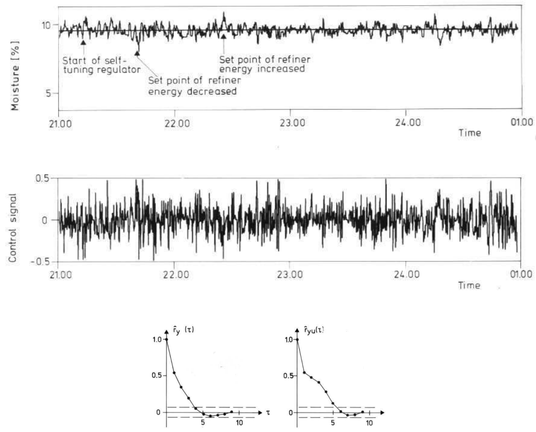
STR Counter Example

$$B(z) = z^2 + z + 0.9, \qquad C(q) = z^2 + 1.5z + 0.75$$
$$z_k = -0.5 + 0.806\,i, \qquad C(z_k) = -0.4 + 0.403\,i$$

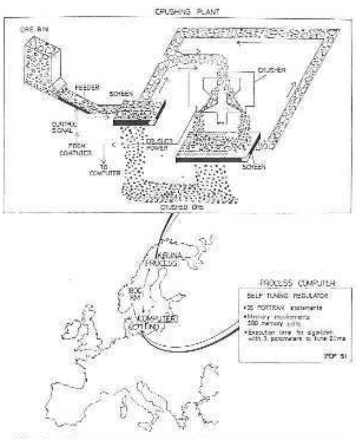
Simulation with $A(z) = z^3 - 1.6z^2 + 0.75z$



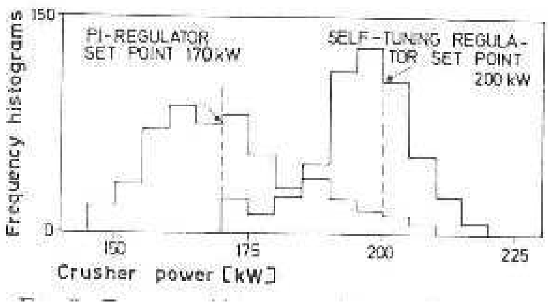
Paper Machine Control BW and UB



Ore Crusher Borisson Syding 1975



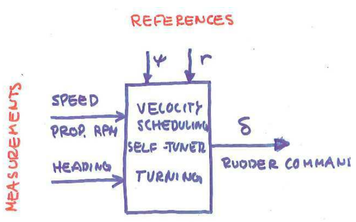
Ore Crusher 2

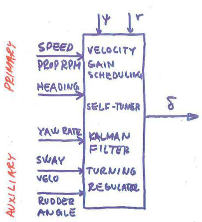


10% increase of production!

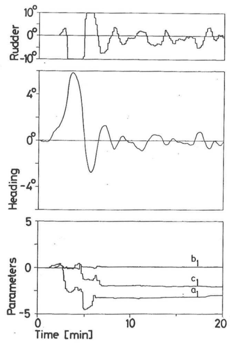
Ship Steering Claes Källström

- Major applications projects with Kockums and SSPA
- Structured system identification and adaptive control
- Claes Källström moved to SSPA after PhD

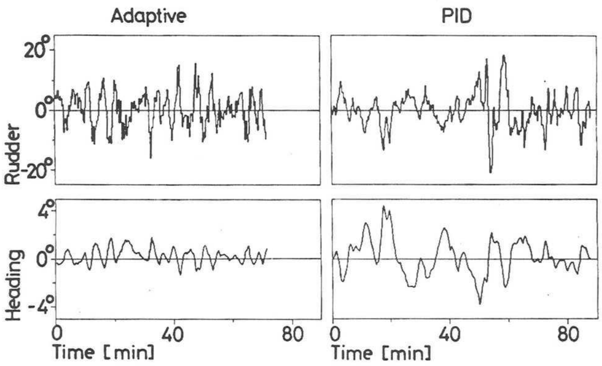




Initialization of Adaptive Auto-pilot



Performance at Sea



3% energy saving compared to PID

Product Still on the Market

NORTHROP GRUMMAN
DEFINING THE FUTURE

Novatune and First Control

- The Novatune experience
  - Projects 73-74
  - Bengtsson rolling mill 1979
  - ASEA Innovation 1981
  - 30 persons 50M
  - Transfer to ASEA Master
- Tuning of feedforward very successful
- First Control
  - Rolling mills
  - Semiconductor manufacturing
- Why not a standard?
  - Not PhD free?

Winner of IEEE CSS Control Technology Award
FIRST CONTROL SYSTEMS AB
Ångsgärdsg.4, S-721 30 Västerås, Sweden Ph +46 21 417880 Fax +46 21 412810

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Theme: Building a New Department and Samples of Activities.

The Role of Computing

- Computing changes what we mean by a solution!
- Gordon Moore Intel 1965: *The number of transistors per square inch on integrated circuits has doubled approximately every 18 months.*
- Moore+Goldstine: *A revolution every 10 years!*
- Difficult to realize the consequences of the dramatic changes and exploit the possibilities
- Tempting to implement old ideas in new technology

Computing and CACE

The scene of 1965: Computing centers, long turn around time

- Good base funding 800k
- Smil, (IBM 7090), Univac
- Allocation of computing resources - taking over computer center at night

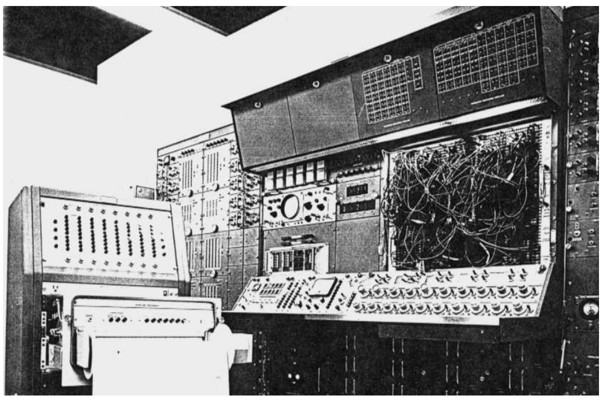
Simulation

- EAI 231R - Bureucracy and a stroke of luck 1966
- Work horse for simulation for education and research: courses, thesis projects, nonlinear control
- Sampled data controllers by switching

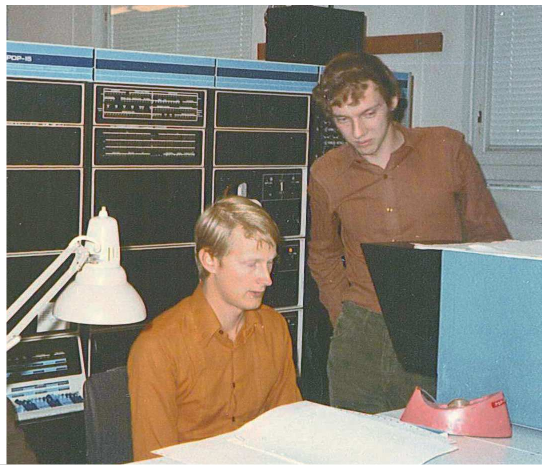
Computers

- PDP15 16k core 256 k disk July 1970
  Tektronics display, inkjet printer
- Vax 11/780 0.5MB 2× 28MB disk 8 terminals Sept 1980
  1982: 2.5 MB 256 MB disk 32 terminals

Analog Computer EAI 231



Johan, Hilding and PDP15



Computer Aided Control Engineering 1970-81

- Driver: Efficient computational tools for applied projects
- Background: Interpretive computing: BASIC, APL
- Key contributors: Johan Wieslander, Ivar Gustavsson, Hilding Elmqvist. Two programmers Tommy Essebo, Tomas Schöntal
- Collection of tools for identification, analysis, simulation and design
- Standard tools for the department for many years
- STU requirements:
  - Should be useful for industry
  - Not allowed to put it in the public domain
- Many licences
- Basis for sound economy for many years

CACE Programs Johan Wieslander

- INTRAC - Interaction module: command interpreter with macro facility common to all programs
  `MLPAR <- DATA N`
- IDPAC - System identification
  `OPTFB L CLSYS <- LOSS SYS`
  Ivar Gustafsson demo at SYSID'73
- MODPAC - Model transformation
- SYNPAC - Control system synthesis
- POLPAC - Polynomial design

Tools for modeling and simulation

- SIMNON - Simulation of continous and sampled systems
- Dymola - Object oriented physical modeling
- Modelica - Modeling of large physical systems

IDPAC

Identification

- `LS, ML` – Least squares and maximum likelihood identification
- `SQR, STRUC` – LS data reduction and structure def

Simulation and model analysis

- `DETER, DSIM, FILT, RANPA, RESID, SPTRF`

Timeseries operations

- `ACOF CCOF` - Auto and cross correlations
- `CONC CUT PICK INSI` – Concatenate, cut, pick, generate
- `SCLOP VECOP SLIDE` – Scalar and vector operations,
- `STAT TREND` – Statistics and tred

Frequency response

- `ASPEC, CSPEC, DFT, IDFT, FROP` – Auto and cross spectrum frequency operations

Example of Design

Assume a continuous sytem `A, B, C` with noise covariances `R1, R12, R2` and loss function `Q1, Q12, Q2` explore changes of 33 element of `Q1` for designs with different sampling rates

```
MACRO DESIGN alpha
ALTER Q1 33 alpha
FOR H=0.5 TO 2.5 STEP 0.5
SAMP dsys <- csys h
TRANS Q <- csys Q
OPTFB L <- dsys
KALFI K <- dsys
CONNECT clsys <- dsys K L
SIMU x y <- clsys uref
PLOT x(1) x(7) x(8) xe(1) xe(8) u
NEXT h
END MACRO
```

SIMNON

- We needed a nonlinear simulator for validation
- CSMP (IBM San Jose) poor structure and poor interaction
- Hilding Elmqvist's Masters Thesis Project 1972
  Interaction principles teletype and oscilloscope
  Formal syntax Backus-Naur standard form
  Compile to p-code, interprete p-code
  FORTRAN
- Strong industrial interest – one year support from ITM
- Licensing to Swedish industry: FFA, FOA, Gambro, Kockumation, Philips, Saab, SSPA, STFI, Studsvik, Sydkraft, Vattenfall, Volvo Flygmotor and many universities
- Many external courses
- Porting to PC 1986
- Mathworks agent in the US for a short time
- Transfer to SSPA 1989

System Descriptions

```
CONTINUOUS SYSTEM proc
Input u
Output y
State x
Der dx
dx=sat(u,0.1)
END

CONNECTING SYSTEM
yr(reg)=1;
y(reg)=y(proc)
u(proc)=u(reg)
```

```
DISCRETE SYSTEM reg
Input yr y
Output u
State I
New nI
Tsamp ts
v=k*e+I
u=sat(v.0.1)
nI=I+k*h*e/Ti+u-v
ts=t+h
k:1
h:0.1
a=1
```

Simulation Commands

Six basic commands

```
SYST - Activate sytems
PAR - Change parameters
INIT - Initial conditions
SIMU - Simulate a system
PLOT - Choose variables to be plotted
AXES - Draw axes
```

Seven auxiliary commands

```
STORE - Select variables to be stored
SHOW - Plot stored variables
DISP - Display parameters
SPLIT - Split display area
HCOPY - Print displayed curves
ALGOR - Choose integration algorithm
ERROR - Error bound
```

Dymola

- Strong pressure for extensions of Simnon (ITM, STU)
  Matrices and hierarchical systems
- Extending Simnon not good PhD topic, too low I/T ratio
- Fundamental look at modeling of physical systems
  Equations and symbolic manipulation DAE
  Inspiration from circuits and SPICE,
- Hilding Elmqvist: A Structured Model Language for Large Continuous Systems. PhD thesis May 1978
  Formal syntax, Equation based, Object Oriented
  The Acid Test: Sture Lindahl - Thermal boiler and generator
  Implemented in Simula - only OO software available
- Francois Cellier ETH made a Pascal version
- Great ideas but premature

Why did we stop?

+ Useful design and analysis tools
+ Extensive licensing:
  - Swedish industry: FFA, FOA, Gambro, Kockums, Philips, Saab, SSPA, STFI, Studsvik, Sydkraft, Vattenfall, Volvo
  - Universities world wide
  - General Electric licensed all software and transfered to many departments via the Research Department
+ Many external courses
– Did not want to be a software house
– FORTRAN not suitable for large software
- Workshop on Numerical Methods for Control Lund 1980
– Cleve Molers Matlab first installation in Europe
- Interactive computating project ended 1981
- Some documentation continued

`Activity report 93-94 www.control.lth.se`

Omola - Omsim - Modelica - JModelica

- New research program 1986: workstations, graphics, C++
  Sven Erik Mattson 1984, Mats Andersson 1994,
  Bernt Nilsson 1993, Jan-Eric Larsson 1993
  Jonas Eborn 2001, Hubertus Tummescheit 2002
  Programmers: DagBrück, Essebo, Schöntal
- Dynasim 1992 and DLR
- **The 1996 COSY workshop TFRT 7551**
- Migration to Dynasim: Dag Brück 1993 Sven Erik aug 1998
- Jonas Eborn. On Model Libraries for Thermo-hydraulic Applications Jonas Eborn. March 2001
- Hubertus Tummescheit. Design and Implementation of Object-Oriented Model Libraries Using Modelica. Aug 2002
- Johan Åkesson Languages and Tools for Optimization of Large-Scale Systems. Nov 2007

`Activity report 1998 www.control.lth.se`

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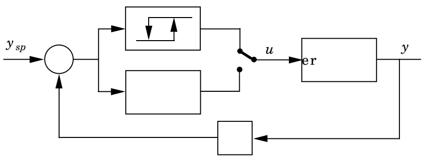
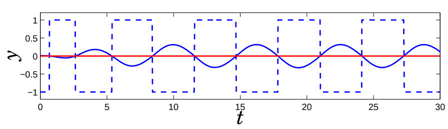
Relay Auto-Tuning 1980 –

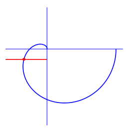
- Telemetric, Eurotherm Manchester: Mike Sommerville
- The importance of PID control! Do simple things first!
- Integral windup and tuning connections to the self-tuning regulator
- Need for automatic tuning
- Why the self-tuning regulator failed
- Push from STU to patent, collaboration with Tore, NAF or TAC
- Patent 1983 with Tore collaboration with NAF
- NAF, Sune Larsson, SDM10 and SDM20, Lund Science park
- Tore Hägglund 1985-1989
- Fisher Controls (Now Emerson) 1989

Relay Auto-tuning



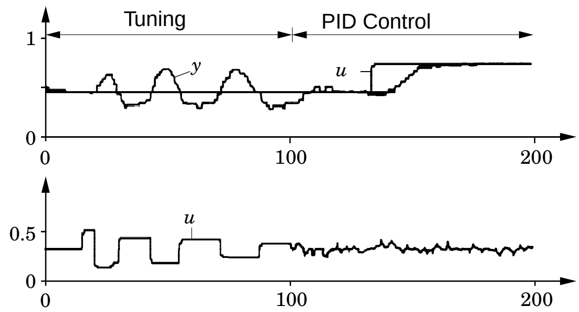
What happens when relay feedback is applied to a system with dynamics? Think about a thermostat?



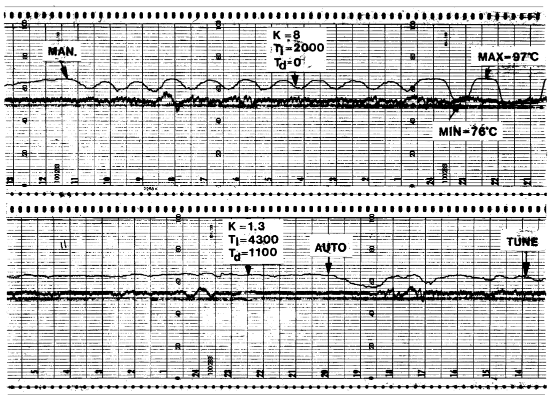


Automatic generation of good excitation signal

The First Experiment - Apple II Implementation



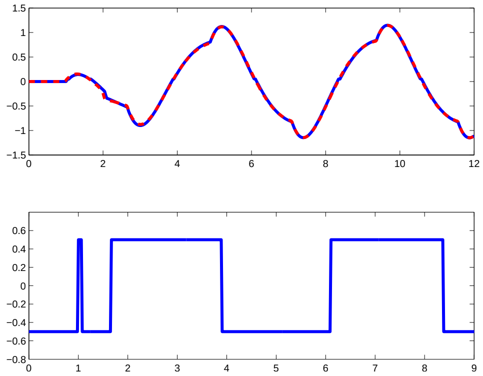
Temperature Control of Distillation Column



Commercial Auto-Tuners

- Easy to use
  - One-button tuning
  - Semi-automatic generation of gain schedules
  - Adaptation of feedback and feedforward gains
- Robust
- Many versions
  - Stand alone
  - DCS systems
- Large numbers
- Excellent industrial experience - PhD free

Fitting Better Models



Early systems computing limited 2 kB Kristians current work

Properties of Relay Auto-tuning

- Safe for stable systems - The M$ question
- Close to industrial practice
  - Compare manual Ziegler-Nichols tuning
  - Easy to explain
- Little prior information. Relay amplitude
- One-button tuning
- Automatic generation of test signal
  - Automatically injects much energy at ω_{180} without for knowing ω_{180} apriori
- Good for pre-tuning of adaptive algorithms
- Good industrial experience for more than 25 years. Basic patents are running out.

ABB EMERSON Process Management NATIONAL INSTRUMENTS

Automatic Control in Lund

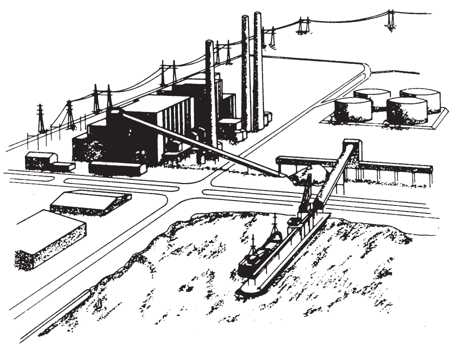
1. Introduction
2. System Identification and Adaptive Control
3. Computer Aided Control Engineering
4. Relay Auto-tuning
5. Two Applications
6. Summary

Theme: Building a New Department and Samples of Activities.

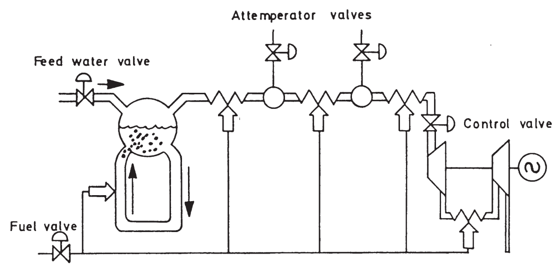
Boiler Modeling and Control 1965 –

- Karl Eklund, the first assistant, was in LTH when I arrived
- Strong support from Sydkraft AB on many levels
- Looking for applications of identification
- Experiments at Öresundsverket – a stroke of luck
  - Remove all controllers perturb many variables log data
- First principles physical modeling of a complex system
  - Many components
  - Large physical dimensions
  - Complicated physics, many domains, PDEs
  - Two phase flow
  - Interesting behavior (Shrink and swell)
- Strong inspiration for research
- Many PhDs and masters projects
- Many projects from Sydkraft

Öresundsverket



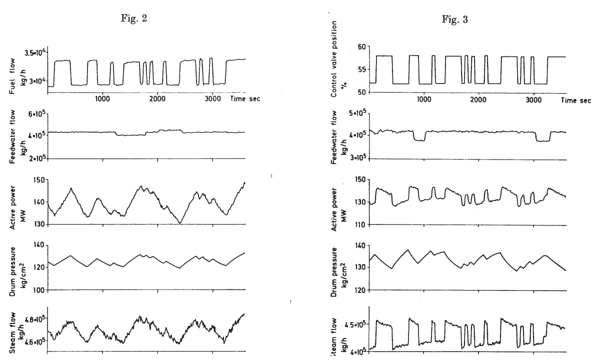
A Schematic Diagram



Schematic diagram of the boiler-turbine unit.

- Control variables: fuel flow, feedwater flow, steam flow
- Interesting variables: drum pressure, drum level, power

Experimental Data 2



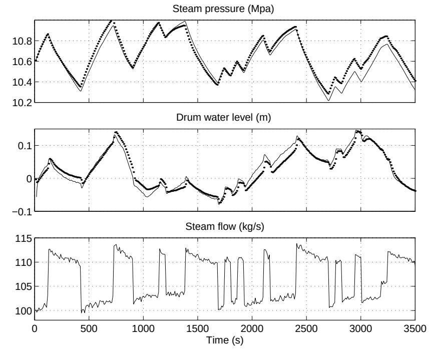
The Low Order Mystery

- System identification of MISO models indicate models orders 4 to 5.
- Even simple physical models gives much higher order
  - Three natural subsystems: drum, downcomers, risers
  - Two phases: steam and water
  - Balance of mass, energy and momentum
  - Crude capturing of storage: 18 states
  - Only water in downcomers: 15 states
  - Momentum dynamics fast: 10 states
- How to reconcile physics and system identification?
- Almost trivial in retrospect but it took a much time and effort
- Very efficient heat transfer in steam-water mixtures
- Pressure in all parts in contact with the steam change in the same way

Drum Level Control - Sydkraft Rod Bell

- 30% of emergency shut downs of French nuclear reactors attributable to level control problems in steam generators
- EDF Benchmark at IFAC Beijing 1999
- The Swedish situation
- Model based control
- Modeling groups
  - Stuttgardt: Quazza, Welfonder
  - ETH: Profos
  - Milan: Quazza, Maffezoni
  - Philadelphia Electric: Harry Kwatny
  - Australia: Rodney Bell

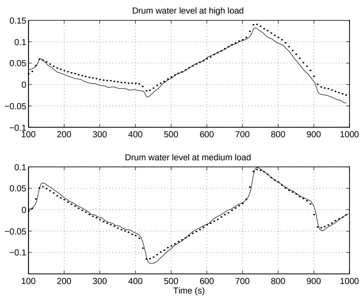
Step in Steam Flow Rate at High Load



Open loop simulation - not prediction models

Response in Drum Level to Steam Flow

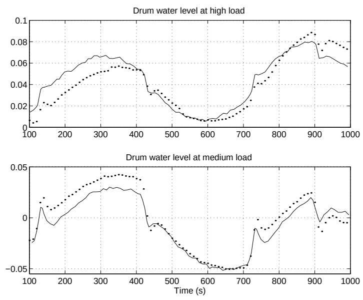
High Load Top Low Load Bottom



Open loop simulation - not prediction models

Response in Drum Level to Fuel Flow

High Load Top Low Load Bottom



Open loop simulation - not prediction models

Computer Control of Buildings 1968-78

- Insight through meetings, courses, MS projects
- Fitted well for the System Identification Project
- Looking for good application of computer control
- Good professor in Department of Energy and Building Design (Bo Adamson)
- Good funding opportunities (Byggforskningsrådet)
- Good project for Karl Eklund in case he wanted to stay

  Kalle left to the Axel Jonson Research Institute
- Good timing for the 1973 oil crisis (pure luck)
- Possibility to have real impact

  Industry situation: poor control, Installation practice, difficulties with tuning due to seasonal variations
  Slow systems

Interesting Factors

Industry structure

- Builders and the building code
- Control companies

  Billmanregulator, Honeywell, Landis & Gyr, Tour Andersson
- Consultants

  Orrje & Co, Skandiakonsult, Theorells, ÅF

System characteristics

- Low cost, simple actuators and sensors
- PI control
- Nonlinearities, friction, backlash, hysteresis
- Seasonal variations
- Installation and operating practice
- Tedious to tune because of long timeconstants

Experiments

- Computer control at its infancy
- Portable small computer or remote control over phone lines
- Remote experimentation with identification and control
- Originally PDP 15 at the department with HP Coupler/Controller and modems
- Reading analog input 2.6 s set analog or logic signals 0.7s
- Experiments with ÅF and Malmö hospital
- Physical modeling and identification of components and subsystems
- Experiments with on-line control
- The Interactive Process Control Language IPCL
- More than 1000 hours of experiments

Lars Jensens PhD Thesis

- Introduction
- Experimental Equipment
- Modeling
- Examples of Modeling
- Controller design

  Conventional
  Simple self-tuners
  Quotient controller
  Computer control
- Examples of on-line control
- A Process Control Language

Technology Transfer

- Carl Olin Elektronik AB Lund
- Data General NOVA 32kbyte, 100AI, 100DI
- Lars Jensen on leave for a year
- IPCL crucial
- First computer control system for buildings?
- Successful installation in commercial buildings
- TA acquired Carl Olin 1975-78
- TA markets DDC6 1978
- Schneider acquires TAC
- May students work at Schneider

Why We Quit?

- Lars Jensen became Professor of Installationsteknik
  - Natural to transfer project
  - Good rule don't compete with your students
- Department philosophy: useful to switch application areas
- Building code and industry culture
- Results transfered to industry
- Many students at TAC/Schneider
- Stora Energipriset to Lars Jensen and KJ 1993

Lessons Learned

Control is not only

- Modeling
- Analysis and Simulation
- Control design
- Implementation

But also

- Validation and testing
- Commissioning and tuning
- Operation and modification

Impact of IPCL

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Summary

- Things ain't what they used to be (Andra tider nu)
- Useful to make plans even if you don't follow them. Even more important to adapt
  - Process control computer — CACE
  - Relay auto-tuning was not planned
- Good idea with experiments in industry instead of running large operations at the department
- Useful to rotate department chairmanship and courses
- Useful to include CS and numerics
  - Real-time computing, language design, IPCL, CACE
- Useful to realize that projects should have an end
- Save well documented models and data
  - Eklunds boiler data, Lindahls power systems model