Adventures in System Identification

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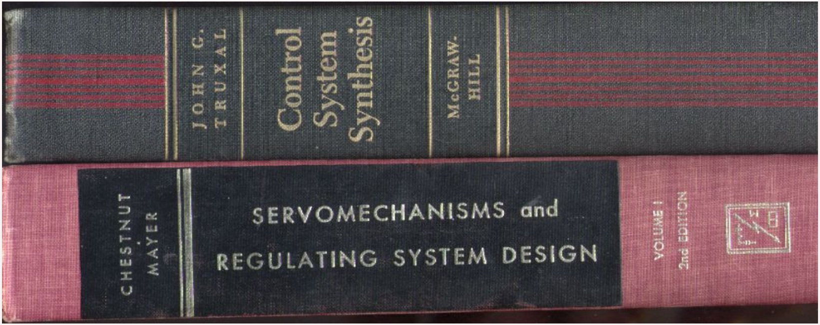
Control in 1960

Birth of Automatic Control ≈ 1945

- World War II
- Education (KTH 49/50 Professur 1959, CTH 1962, LTH 1965)
- Organization IFAC 1956 (50 year jubilee last week)
- The First IFAC World Congress Moscow 1960



The Spirit of the 1960's

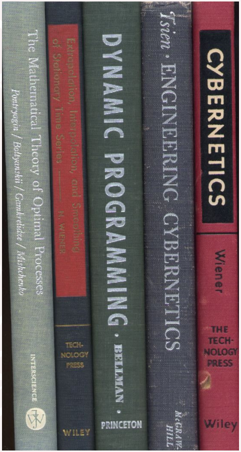
Exciting Theory

- Dynamic Programming Bellman 1957
- The Maximum Principle Pontryagin 1961
- Kalman Bol. Soc. Mexicana 1960
- Kalman Filtering ASME 1960
- The Separation Theorem Joseph and Tou 1961

Challenging Applications

- The space race (Sputnik 1957)
- Computer Control Port Arthur Refinery 1959

IBM The Computer Giant
The IBM Nordic Laboratory 1961



The Role of Computing

- Vannevar Bush 1927. *Engineering can proceed 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 approximately every 18 months.*
- Moore+Goldstine: *A revolution every 10 year!*
- Unfortunately software does keep up with hardware

Outline

- Introduction
- The IBM-Billerud Project
- Modeling and Control
- Back to the Future
- Reflections

The Billerud-IBM Project

- Background
  - IBM and Computer Control
  - Billerud and Tryggve Bergek
- Goals
  - Billerud: Exploit computer control
  - IBM: Experience in computer control. Recover prestige!
- Schedule
  - Start April 1963
  - Computer Installed December 1964
  - System identification and on-line control March 1965
  - Full operation September 1966
  - 40 many-ears effort in about 3 years

Goals and Tasks

- Goals
  - What can be achieved by computer control?
  - What should a good process control computer look like?
- Philosophy
  - Cram as much as possible into the system!
- Tasks
  - Production Planning
  - Production Supervision
  - Process Control
  - Quality Control
  - Reporting

Computer Resources

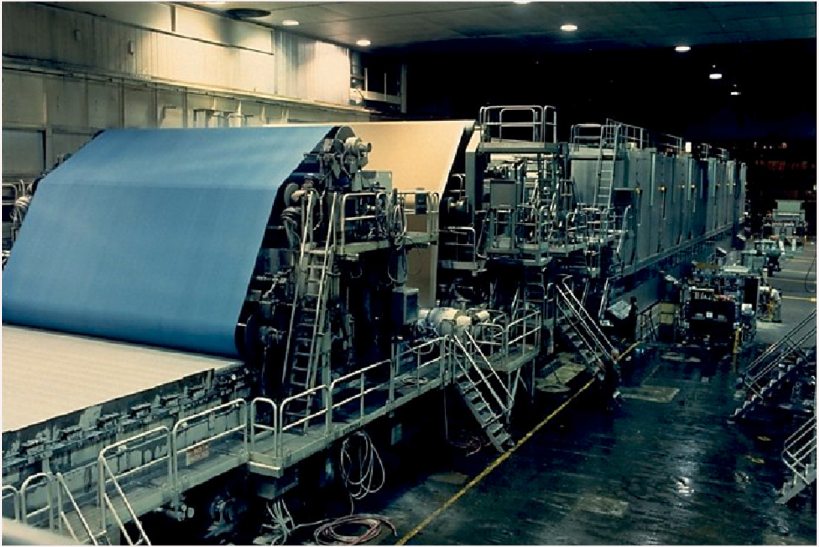
- IBM 1720 (special version of 1620 decimal architecture)
- Core Memory 40k words (decimal digits)
- Disk 2 M decimal digits
- 80 Analog Inputs
- 22 Pulse Counts
- 100 Digital Inputs
- 45 Analog Outputs (Pulse width)
- 14 Digital Outputs
- Fastest sampling rate 3.6 s
- One hardware interrupt (special engineering)
- Home brew operating system

Human Resources

- Extremely good and farsighted management
  - Kai Kinberg IBM Nordic Laboratory
  - Tryggve Bergek Billerud
- Good resources
- Competent and interested participants
- Good mix of people
- Many short term participants
- Open atmosphere with pressure on dead-lines and results
- A great learning experience

The Billerud Plant

Drying Section



Summary

Short range

- A successful installation
- Strawman for computer achitecture (IBM 1800, IBM 360)

Methodology

- Method for identification of stochastic models
- Basic theory, consistency, efficiency, persistent excitation
- Minimum variance control

What we misssed

- Project was well documented in IBM reports and a few papers but we should have written a book

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Process Modeling

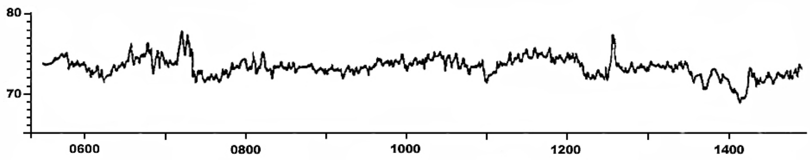
- Process understanding and modifications (mixing tanks)
- Physical modeling
- Logging difficulties
- Drastic change in attitude when computer was installed
- Good support from management Kai Kinberg:

  “This is a showcase project! Don’t hesitate to do something new if you believe that you can pull it off and finish it on time.”
- The beginning of system identification

Modeling for Control

- Stochastic control theory is a natural formulation of industrial regulation problems
- State space models for process dynamics and disturbances
- Physical models may give dynamics
- Process data necessary to model disturbances
- Modeling by frequency response crucial for application of classical control
- Can we find something similar for state space systems?

Typical Fluctuations



A lot of effort to obtain this curve!

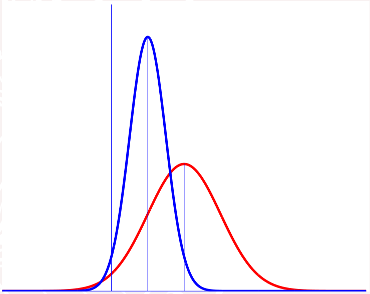
Stochastic Control Theory

Process model

$$dx = Axdt + Budt + dv$$
$$dy = Cxdt + de$$

Controller

$$d\hat{x} = A\hat{x} + Bu + K(dy - C\hat{x}dt)$$
$$u = L(x_m - \hat{x}) + u_{ff}$$



A natural approach for regulation of industrial processes.

Model Structures

Process model

$$dx = Axdt + Budt + dv$$
$$dy = Cxdt + de$$

Innovations representation

$$\begin{aligned} dx &= Axdt + Budt + Kd\epsilon \\ &= (A - KC)xdt + Budt + Kdy \\ dy &= Cxdt + d\epsilon \end{aligned}$$

Canonical form and discretization

$$A(q^{-1})y(t) = B(q^{-1})u(t) + C(q^{-1})e(t)$$

Modeling from Data (Identification)

The Likelihood function (Bayes rule)

$$p(\mathcal{Y}_t,\theta) = p(y(t)|\mathcal{Y}_{t-1},\theta) = \cdots = -\frac{1}{2}\sum_1^N \frac{\epsilon^2(t)}{\sigma^2} - \frac{N}{2}\log 2\pi\sigma^2$$

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

$$C\epsilon(t) = Ay(t) - Bu(t)$$

$$\theta = (a_1,\dots,a_n,b_1,\dots,b_n,c_1,\dots,c_n,\epsilon(1),..$$

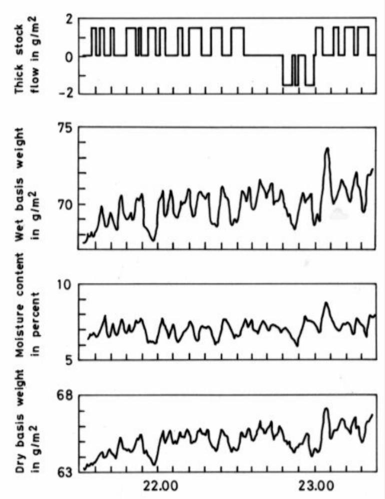
Efficient computations

$$\frac{\partial J}{\partial a_k} = \sum_1^N \epsilon(t)\frac{\partial \epsilon(t)}{\partial a_k} \qquad C\frac{\partial \epsilon(t)}{\partial a_k} = q_k y(t)$$

- Estimate has nice properties Åström and Bohlin 1965
- Good match identification and control. Prediction error is minimized in both cases!

Practical Issues

- Sampling period
- To perturb or not to perturb
- Open or closed loop experiments
- Model validation
- 20 min for two-pass compilation of Fortran program!
- Control design
- Skills and experiences



Control

- Time delay and stochastic disturbances
- Mild coupling
- Conventional PI(D) at lower level
- Simple digital control for non-critical loops
- Minimum variance control and moving average control
- Limited computational capacities
- Robustness performance trade-offs

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

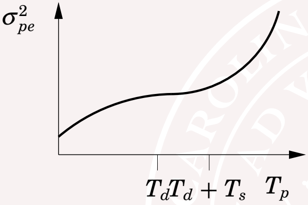
$$Ru(t) = -Sy(t), \qquad y(t) = Fe(t)$$

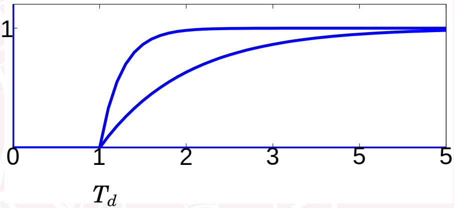
where $\deg F \geq$ pole excess of B/A

Sampling period is design variable!

True minimum variance control $V = E\frac{1}{T}\int_0^T y^2(t)dt$

Performance and Robustness



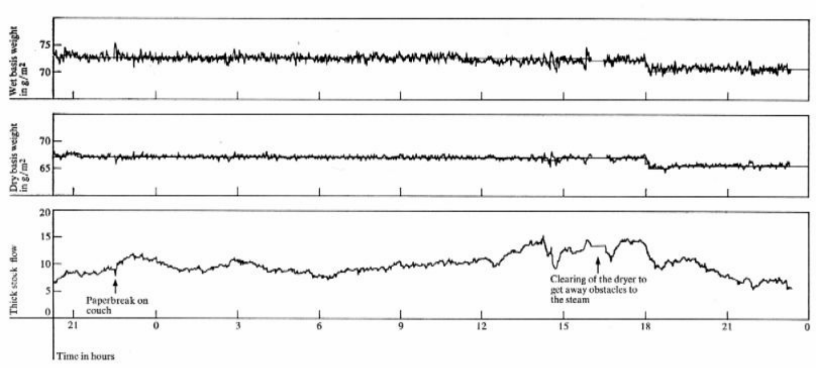


- Strong similarity between all controller for systems with time delays, minimum variance, moving average and Smith predictor.

  It is dangerous to be greedy!

- Rule of thumb: no more than 1-4 samples per dead time motivated by simulation.

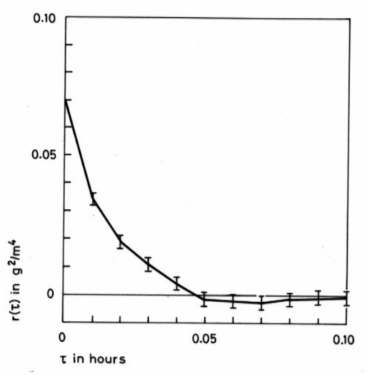
Results



Wet basis weight in g/m²
75
70
Dry basis weight in g/m²
70
65
Thick stock flow
20
15
10
5
0
Paperbreak on couch
Clearing of the dryer to get away obstacles to the steam
21
0
3
6
9
12
15
18
21
0
Time in hours

Summary

- Regulation can be done effectively by minimum variance control
- Easy to validate
- Sampling period is the **design variable**!
- Robustness depends critically on the sampling period
- The Harris Index
- OK to assess but why not adapt



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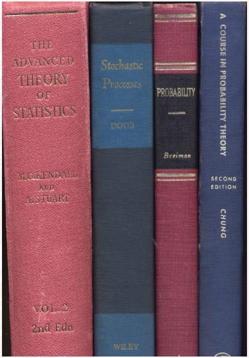
Academia Calls

- Inspiration experiences from the Billerud-IBM project
  - Lots of ideas
  - Lots of unsolved problems
  - Many industrial contacts
- A research program
  - Identification, Adaptive Control, Optimization, CACE
- Digging Deep
- Good potential for academic jobs
- Torsten Söderström 1969-74, Lennart Ljung 1970-76



Themes and Researchers

- Algorithms for identification
- Applications to a wide range of industrial systems
- Software Idpac
- Analysis of algorithms
- Recursive estimation
- Adaptive control
- Identification in closed loop
- Input design

- Torsten Söderström
- Björn Wittenmark
- Ivar Gustafsson
- Lennart Ljung
- Johan Wieslander
- Bo Leden
- Ulf Borisson
- Jan Sternby
- Jan Holst

A Great Group

Convergence Analysis

Analysis of Recursive Stochastic Algorithms

LENNART LJUNG, MEMBER, IEEE

IEEE Trans AC-22 (1977) 551–575

Markov processes and differential equations

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

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)

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Experiences

- Applied industrial projects can inspire research, provided that they have enlightened management
- Challenges are very important
- Necessarey to look deeper and to fill in the gaps, even if it takes a lot of effort and a lot of time - a long range view is necessary to get real insight
- Contact with real problems is very healthy for research in engineering
- Useful for a project to change environment and people
- Important to give young researchers a playing field

Congratulations Lennart

May your hands always be busy,
May your feet always be swift,
May you have a strong foundation,
When the winds of changes shift.
May your heart always be joyful,
May your song always be sung,
May you stay forever Ljung,
Forever Ljung, forever Ljung,
May you stay forever Ljung.

Acknowledgements to Bob Dylan Forever Young 1974

Thank you for a very stimulating time in Lund 1970-76
and many interactions after that!