MVC and MPC

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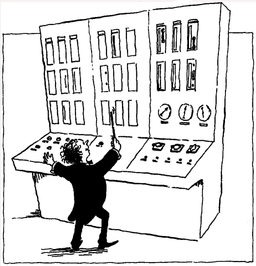
Congratulations to a Stellar Career!

- Points of tangency



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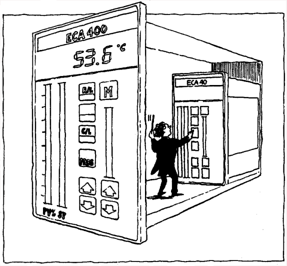


- IFAC Teddington 1964
- IFAC Prague 1967 First Identification Symposium
- Generalized predictive control Automatica 1987
- A memorable semester as Douglas Holder Visiting Fellow Oxford in 1988
- Control is much more than algorithm design; diagnostics, fault detection and reconfiguration are also of prime significance.

Introduction

Minimum Variance Control

- Inspired by practice
- Åström 1966
  (IBM J R&D 1967)
- Model structure MISO
- Explicit disturbance modeling
- Minimize variance
- Identification
- Self-tuning
- Harris index

Model Predictive Control

- Inspired by practice
- Richalet 1976
  (Automatica 1978)
- Cutler DMC
  (ACC 1980)
- Model structure MIMO-FIR
- Reference trajectory
- Captures saturation
- Widely used in industry

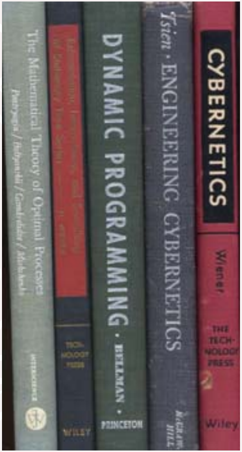
What can we learn?

Outline

- Introduction
- The IBM-Billerud Project
- Modeling
- Minimum Variance Control
- Adaptation
- Reflections

The Scene of 1960

- Servomechanism theory 1945
- IFAC 1956 (50 year jubilee in 2006)
- Widespread education and industrial use of control
- The First IFAC World Congress Moscow 1960
- Exciting new ideas
  - Dynamic Programming Bellman 1957
  - Maximum Principle Pontryagin 1961
  - Kalman Filtering ASME 1960
- Exciting new development
  - The space race (Sputnik 1957)
  - Computer Control Port Arthur 1959
- IBM and 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 12 months.*
- Moore+Goldstine: *A revolution every 10 year!*
- Unfortunately software does keep up with hardware
- Roughly 10 years between MVC and MPC

The Billerud-IBM Project

- Background
    - IBM and Computer Control
    - Billerud and Tryggve Bergek
- Goals
    - Billerud: Exploit computer control to improve quality and profit!
    - IBM: Gain experience in computer control, recover prestige and find a suitable computer architecture!
- 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?
    - Find an architecture of a process control computer!
- Philosophy
    - Cram as much as possible into the system!
- Tasks
    - Production Planning
    - Production Supervision
    - Process Control
    - Quality Control
    - Reporting
- Later 1969
    - Millwide control

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

The Billerud Plant

- 660,000 ADt/year
- Three fiber lines
- Six paper machines

Containerboard
Sack
Kraft
Market pulp

Summary

Industrial

- A successful installation
- Computer achitecture for process control

  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 show-case 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
- Wasted a lot of time on historical data
- Big struggle to do real plant experiments
- Identifications requires a great range of skills

Basis Weight and Moisture Control

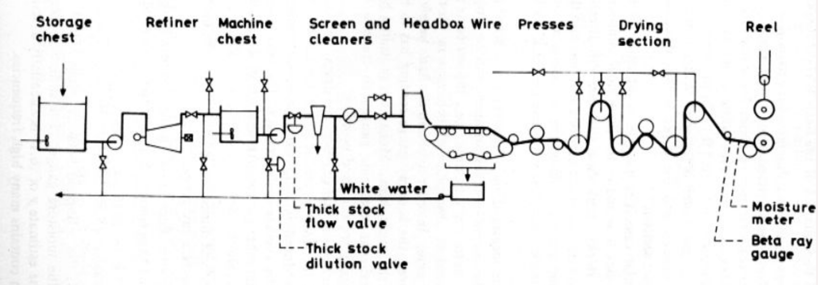


Fig. 6.9. Simplified diagram of a kraft paper machine.

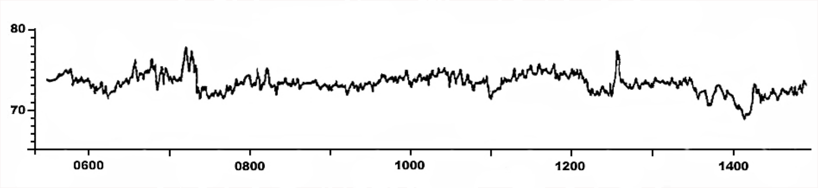
- Two important loops
- Triangular coupling MISO works

Modeling for Control

- Modeling by frequency response key for success of classical 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
- Can we find something similar to frequency response for state space systems?

Typical Fluctuations

First measurement of fluctuations in basis weight 1963



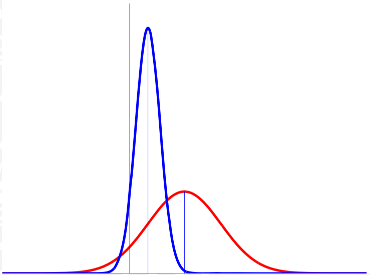
Availability of sensor crucial!
A lot of effort to obtain this curve!

Stochastic Control Theory

Kalman filtering, quadratic control, separation theorem

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

$$\begin{aligned} dx &= Axdt + Budt + dv \\ dy &= Cxdt + de \end{aligned}$$

Much redundancy $z = Tx$ + noise model. The innovation representation reduces redundancy of stochastics and filter gains appear explicitely in the model

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

Canonical form for MISO system removes remaining redundancy, discretization gives (C filter dynamcis)

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

Modeling from Data (Identification)

The Likelihood function (Bayes rule)

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

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

$$Ay(t) = Bu(t) + Ce(t) \qquad C\epsilon(t) = Ay(t) - Bu(t)$$

$$\epsilon = \text{one step ahead prediction error}$$

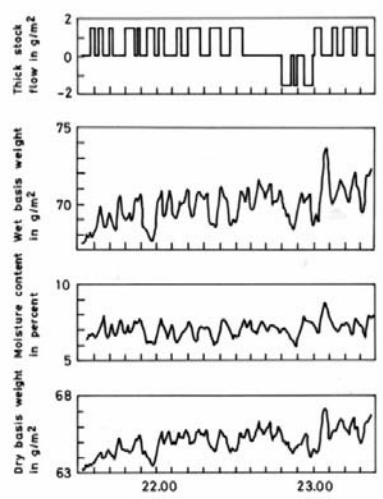
Efficient computations

$$\frac{\partial J}{\partial a_k} = \sum_{1}^{N} \epsilon(t)\frac{\partial \epsilon(t)}{\partial a_k} \qquad C\frac{\partial \epsilon(t)}{\partial a_k} = q_k y(t)$$

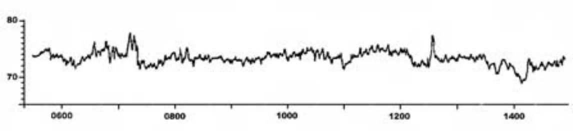
- Estimate has nice properties Åström and Bohlin 1965
- Good match identification and control. Prediction error is minimized in both cases! Cleaned up by Lennart Ljung ...

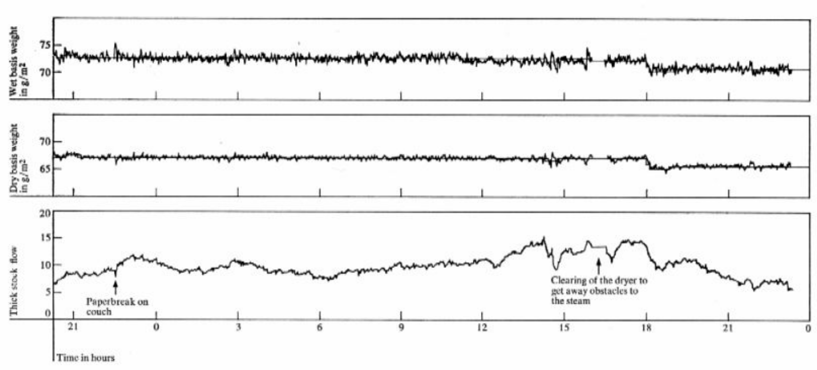
Practical Issues

- 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



Results


80
70
0600
0800
1000
1200
1400


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

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Control

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

Minimum Variance (Moving Average Control)

Process model

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

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

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

$$Cy = AFy+B^-Gy = F(Bu+Ce)+B^-Gy = CFe+B^-(B^+Fu+Gy)$$

Control law and output are given by

$$B^+Fu(t) = -Gy(t), \qquad y(t) = Fe(t)$$

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

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

Properties of Minimum Variance Control

- The output is a moving average

$$y = Fe, \qquad \deg F \le \deg A - \deg B^+.$$

Easy to validate!

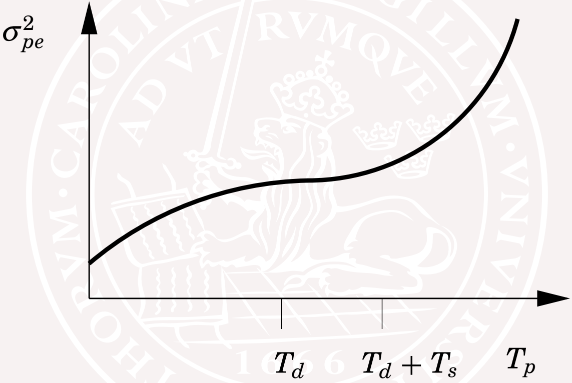
- Interpretation for $B^- = 1$ (all process zeros canceled), y is a moving average of degree $n_{pz} = \deg A - \deg B$. It is equal to the error in predictiong the output n_{pz} step ahead.
- Closed loop characteristic polynomial is

$$B^+ C z^{\deg A - \deg B^+} = B^+ C z^{\deg A - \deg B + \deg B^-}.$$

- The sampling period an important design variable!
- Sampled zeros depend on sampling period. For a stable system all zeros are stable for sufficiently long sampling periods.

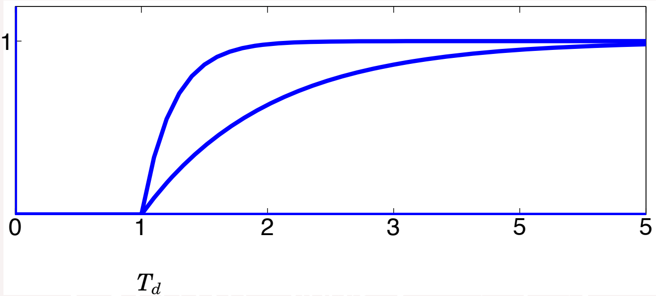
Performance ($B^- = 1$) and Sampling Period

Plot prediction error as a function of prediction horizon T_p



T_d is the time delay and T_s is the sampling period. Decreasing T_s reduces the variance but decreases the response time.

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.

Robustness Analysis

Consider a system with time delay T_d design for a closed loop time constantT_{cl}. The main system functions are:

$$G_t(s) = \frac{e^{-sT_d}}{1+sT_{cl}}$$

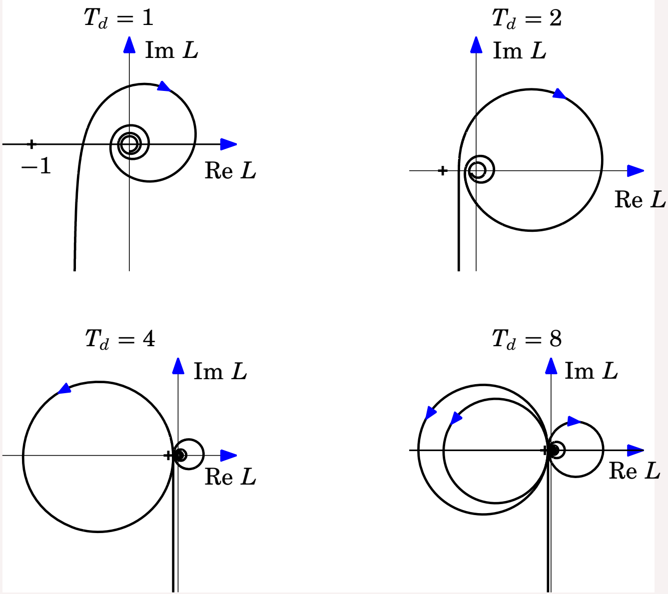
$$G_s(s) = 1 - G_{cl}(s) = 1 - \frac{e^{-sT_d}}{1+sT_{cl}}$$

$$G_\ell(s) = \frac{e^{-sT_d}}{1+sT_{cl} - e^{-sT_d}}$$

Sensitivity and complementary sensitivity functions are always less than 2! So things look good!

BUT Look at the delay margins!

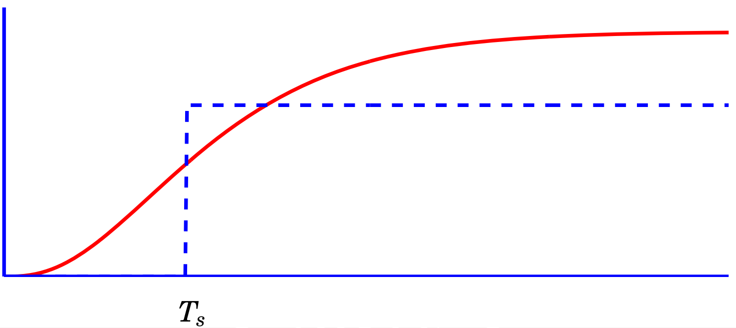
Nyquist Plots for Smith Predictors $T_{cl} = 1$



Another Robustness Result

A simple digital controller for systems with **monotone** step response (design based on the model $y(k+1) = bu(k)$)

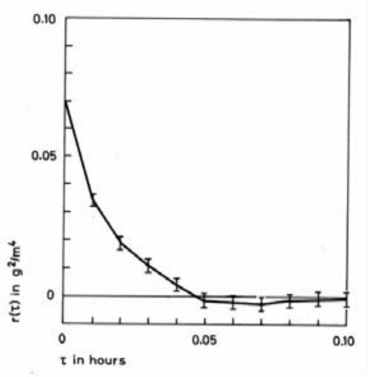
$$u_k = k(y_{sp} - y_k) + u_{k-1}, \qquad k < \frac{2}{g(\infty)}$$



Stable if $g(T_s) > \dfrac{g(\infty)}{2}$ kjå: Automatica **16** 1980, pp 313–315.

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 and related criteria
- OK to assess but why not adapt?



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Drawbacks with System Identification

- Experiment planning requires prior knowledge
- Process perturbations required
- Time consuming
- Requires competence
- Adaptation is an alternative

The Self-tuning Regulator

- Process model: $Ay(t) = Bu(t-k) + B_{ff}u_{ff}(t) + Ce(t)$
- Select sampling period and time delay k, rules for stable systems
- Estimate parameters in the model

$$y(t+k) = Sy(t) + Ru(t) + R_{ff}u_{ff}(t)$$

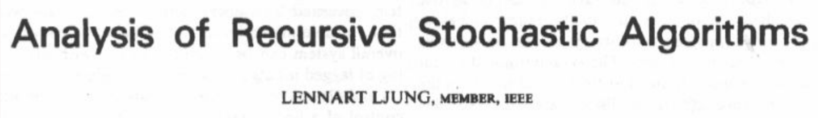
- If estimate converge

$$r_y(\tau) = 0, \tau = k, k+1, \cdots k + \deg(S)$$
$$r_{yu}(\tau) = 0, \tau = k, k+1, \cdots k + \deg(R)$$

  If degrees sufficiently large $r_y(\tau) = 0, \forall \tau \geq k$
- Convergence conditions

KJÅ+BW Automatica **9**(1973),185-199

Convergence Analysis



Analysis of Recursive Stochastic Algorithms

LENNART LJUNG, MEMBER, IEEE

IEEE Trans AC-22 (1977) 551–575

Markov processes and differential equations

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

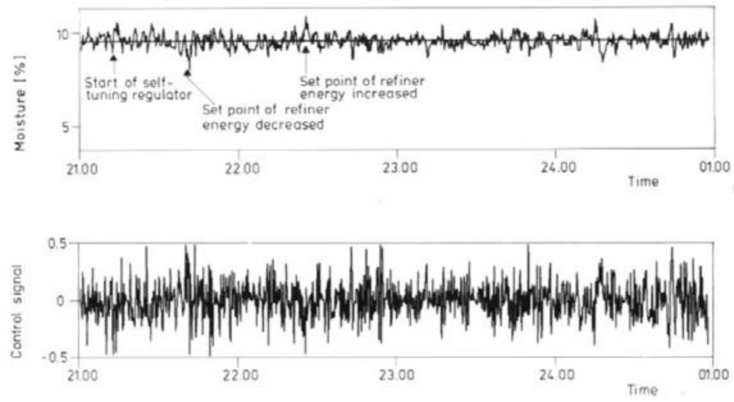
Lennarts idea

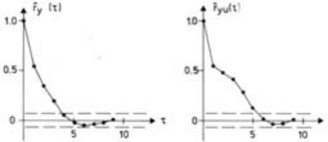
$$\theta_{t+1} = \theta_t + \gamma_t \varphi e, \qquad \frac{d\theta}{d\tau} = f(\theta) = E\varphi e$$

Convergence of recursive algorithms and STR (Ay=Bu+Ce)

Jan Holst: ODE locally stable if $\mathrm{Re} C(z_k) > 0$ for $B(z_k) = 0$

Paper Machine Control





Industrial Applications

- A number of applications in special areas
- Paper machine control
- Ship steering
- Rolling mills
- Semiconductor manufacturing
- Tuning of feedforward very successful
- The Novatune
- Process diagnostics Harris and similar indices

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Winner of IEEE CSS Control Technology Award

FIRST CONTROL SYSTEMS AB

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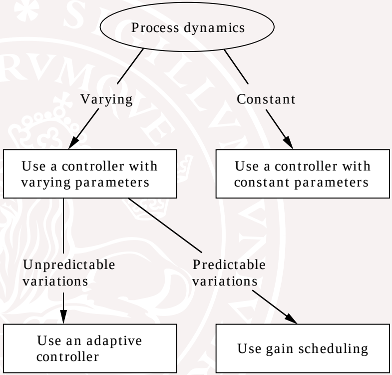
Tuning and Adaptation

- Categories

  Automatic Tuning
  Gain Scheduling
  Adaptive feedback
  Adaptive feedfoward
- Products

  Tuning tools
  PID controllers
  Tool boxes
  Special purpose systems built into instruments



Process dynamics

Varying

Constant

Use a controller with varying parameters

Use a controller with constant parameters

Unpredictable variations

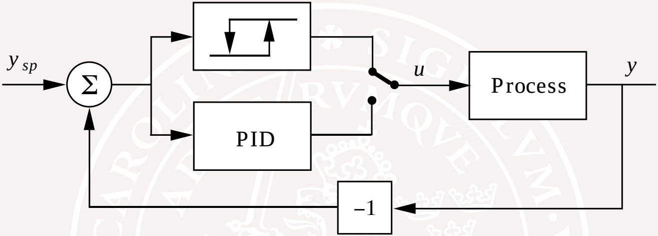
Predictable variations

Use an adaptive controller

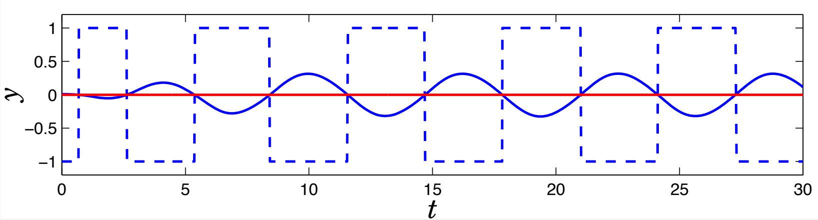
Use gain scheduling

Åström Hägglund Advanced PID Control, 2004

Relay Auto-tuning

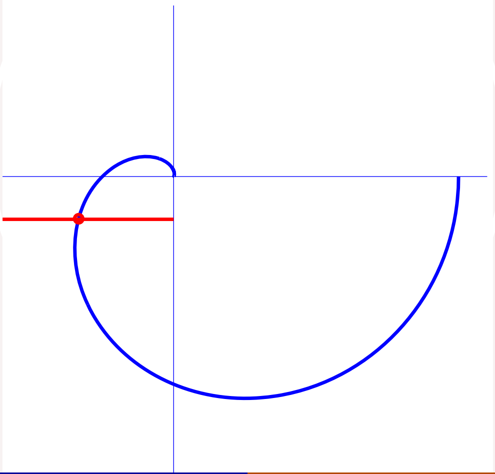


What happens when relay feedback is applied to a system with dynamics? Think about a thermostat?

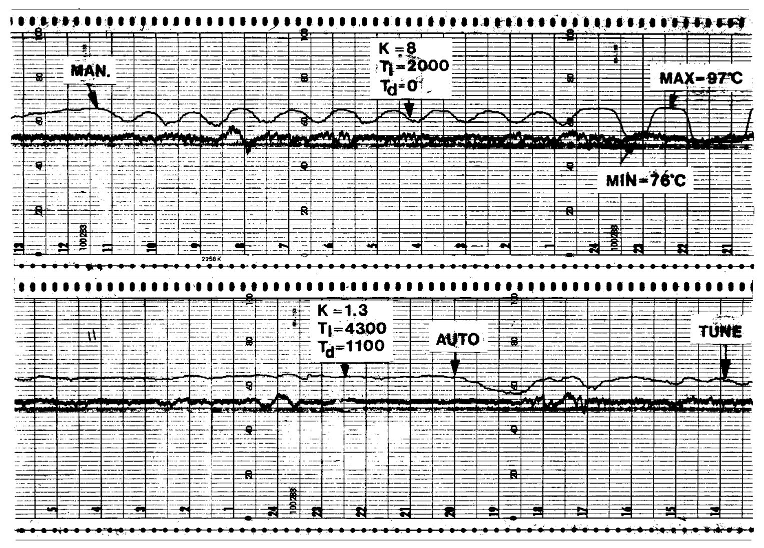


The Excitation Signal

- Relay feedback automatically generates an excitation signal with good frequency content!
- The transient is also useful



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

Properties of Relay Auto-tuning

- Safe for stable systems
- 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™

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Interaction with Industry

- Contact with real problems is very healthy for research in engineering
- Both MVC and MPC emerged in this way
- Applied industrial projects can inspire research, provided that they have enlightened management
- New problems may appear
- Challenges with publications; importance of good Editors
- Necessary 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
- Useful for a project to exchange people between academia and industry
- The Oxford model, the SupAero model, the Lund model

The Knowledge Gap

- Richalet Automatica 1963: MPC requires technical staff with training in:
    - modeling, identification, digital control,...
- The Novatune experience
    - Projects 73-74
    - Bengtsson Cold rolling 79
    - ASEA Innovation 81
    - 30 persons 50M
    - Transfer to ASEA Master

NOVATUNE

Process Control
with
Adaptive Controllers

NOVATUNE

ASEA

- Relay auto-tuning Hägglund kjå 1981
    - One button tuning
- Can relay auto-tuning be useful for MPC modeling?