Travels in Process Reality

K. J. Åström

Department of Automatic Control, Lund University

Outline

1. Introduction
2. Computer Control
3. Adaptive Control
4. PID Control and Autotuning
5. Reflections

Computer Based Processs Control

- The scene of 1960
    - Using computers for process control
    - Paradigm shift in control theory
- Port Arthur and RW-300 closed loop control March 15 1959
- Process industries saw potential for improved quality and efficiency
- Computer companies projected large potential markets
- Case studies jointly between computer and process companies
- IBM and the Seven Dwarfs (IBM 70 % market share)
    - IBM Research Yorktown Heights Jack Bertram
        - Mathematics Department Rudolf Kalman
        - The DuPont project Kalman moved to DuPont
        - Jack Bertram took over
    - IBM Development San Jose
- IBM Nordic Laboratory 1960-(1983)-1995 (peak > 200 people)

The Billerud Plant - First Real Encounter

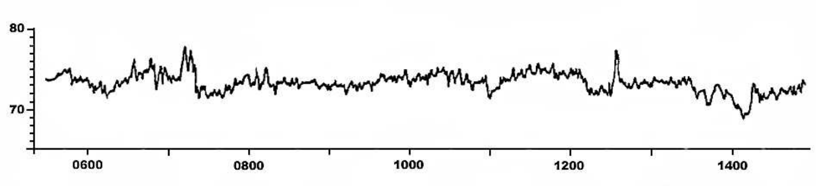
The Billerud-IBM Project 1962-66

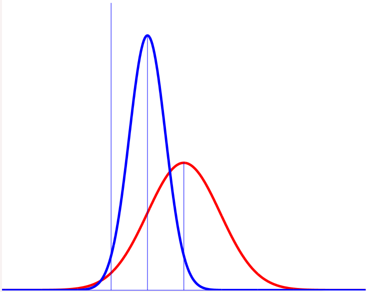
- Background
  - Computer control and IBM
  - Computer control and Billerud Tryggve Bergek and Saab
- Goals
  - Billerud: Exploit computer control for more efficient production
  - IBM: Spectacular case study. Recover prestige!
  - IBM: What is a good computer architecture for process control?
- Tasks - squeeze as much you can into the computer
  - Production Planning
  - Production Supervision
  - Process Control
  - Quality Control
  - Reporting
- 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

Computer System

- 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
- One hardware interrupt (special engineering)
- Home brew operating system
- Fastest sampling rate 3.6 s

Steady State Regulation

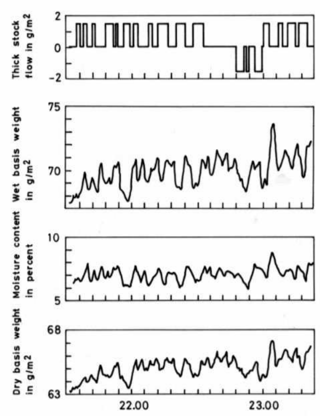




- What can be achieved?
- What are the benefits?
- Small improvements 1% important
- How to model the system
- Physics or experiments
- Stochastic properties important
- Control laws

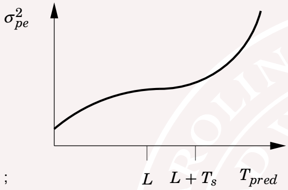
Modeling from Data (Identification)

- Experiments in normal production
- To perturb or not to perturb
- Open or closed loop?
- Maximum Likelihood Method
- Model validation
- 20 min for two-pass compilation of Fortran program!
- Control design
- Skills and experiences

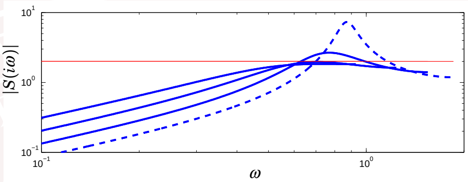


KJÅ and T. Bohlin, Numerical Identification of Linear Dynamic Systems from Normal Operating Records. In Hammond, *Theory of Self-Adaptive Control Systems, Plenum Press, January 1966.*

Minimum Variance Control



;

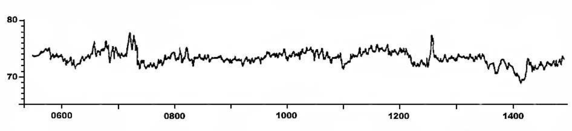


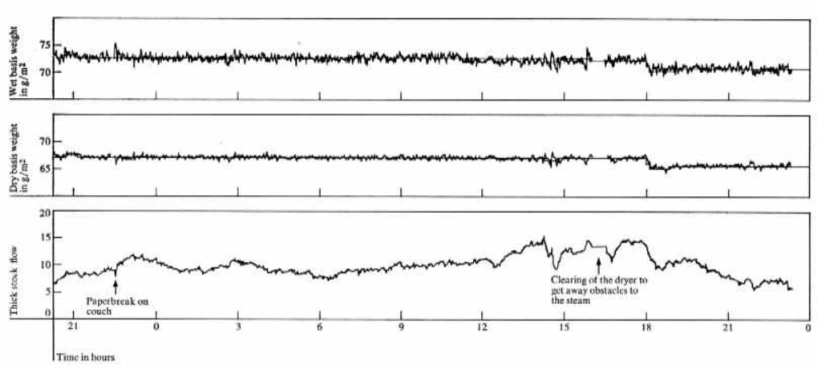
The predition horizon T_{pred} is the key design variable

- Variance increases with increasing $T_{pred} > L$
- Maximum sensitivity increases with increasing $T_{pred} > L$
- Sampling period T_s gives quantization of T_{pred}
- Rule of thumb: no more than 1 - 4 samples per dead time

KJÅ Computer Control of a Paper Machine - An Application of Linear Stochastic Control Theory, IBM J R&D **11** (1967), pp. 389-405

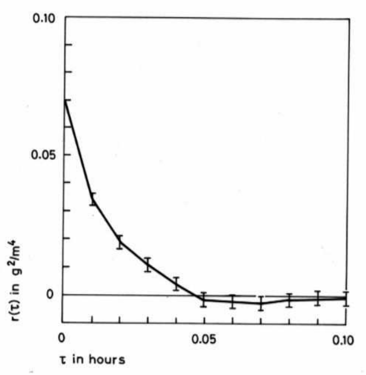
Experiments





Summary

- Regulation can be done effectively by minimum variance control
- Easy to validate - moving average
- Sampling period is the **design variable**!
- Robustness depends critically on the sampling period
- The Harris Index
- Why not adapt?



The self-tuning regulator (STR) automates identification and minimum variance control in 35 lines of FORTRAN code

KJÅ & B. Wittenmark On Self-Tuning Regulators, Automatica **9** (1973),185-199

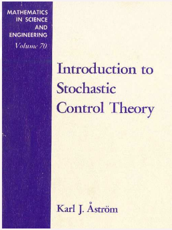
Lessons Learned

- Value of good leadership: goals, freedom and encouragement
- Be brave and challenge
- Value of experiments in industry - Industry will be our Lab!
- Send students to experiment in industry - credibility
- System identification - computer control version of frequency response
- Minimum variance control

  Easy to assess - mean square prediction error - Harris index

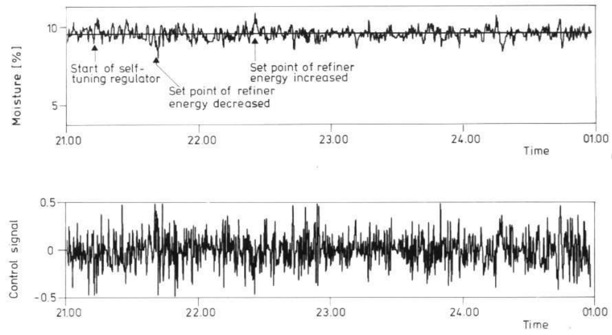
  Easy to test - moving average

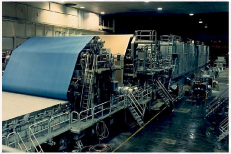
  Prediction horizon T_{pred} is the key design variables
- Importance of embedded computing and software
- Project well documented in IBM reports and a few papers but we should have written a book!
- Richard Bellman: If you have done something worthwhile write a book!

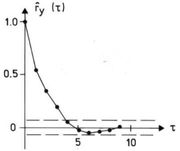


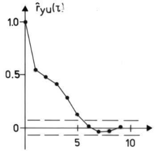
Outline

Paper Machine Control









U. Borisson and B. Wittenmark An Industrial Application of a Self-Tuning Regulator, 4th IFAC/IFIP Symposium on Digital Computer Applications to Process Control 1974

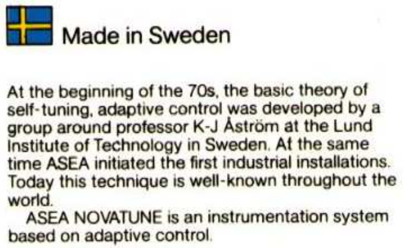
ABB

ASEA Novatune G Bengtsson

- ASEA Innovation 1981
- DCS system with STR
- Grew quickly to 30 people and 50 MSEK (internal price) in 1984
- Worked very well because of good people

Incorporated in ABB Master 1984 and later in ABB 800xA

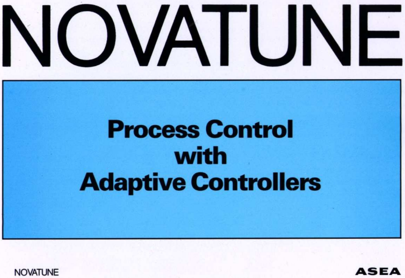
- Difficult to transfer to standard sales and commision workforce (sampling period and prediction horizon)



Made in Sweden

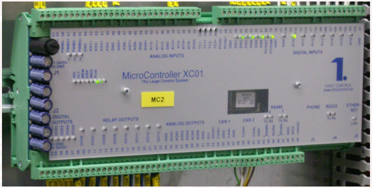
At the beginning of the 70s, the basic theory of self-tuning, adaptive control was developed by a group around professor K-J Åström at the Lund Institute of Technology in Sweden. At the same time ASEA initiated the first industrial installations. Today this technique is well-known throughout the world.

ASEA NOVATUNE is an instrumentation system based on adaptive control.



Industrial Applications

- A number of applications in special areas
- Paper machine control
- Ship steering Kockums
- Rolling mills
- Ore grinding
- Semiconductor manufacturing
- Novatune G Bengtsson
- Tuning of feedforward very successful
- First Control
- Process diagnostics Harris and similar indices



Winner of IEEE CSS Control Technology Award

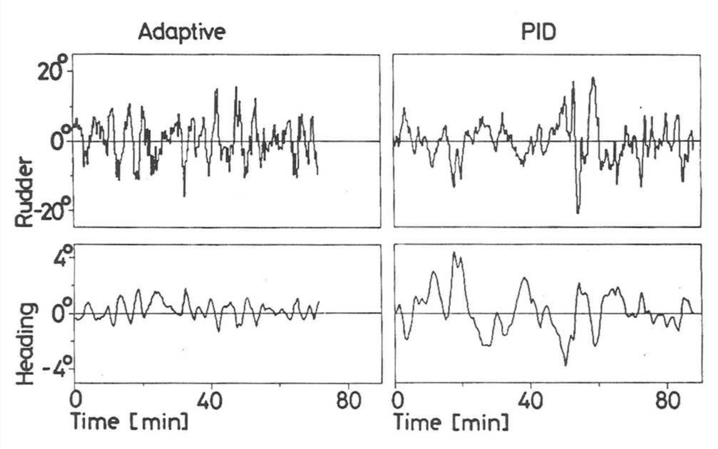
FIRST CONTROL SYSTEMS AB

Ängsgärdsg.4, S-721 30 Västerås, Sweden Ph +46 21 417880 Fax +46 21 412810

NORTHROP GRUMMAN

DEFINING THE FUTURE

Ship Steering



Physics based initialization, 3 % fuel reduction

C. Källström, KJÅ, N. E. Thorell, J. Eriksson, L. Sten, Adaptive Autopilots for Tankers, Automatica, **15** 1979, 241-254

Control over Networks

- IBM Stockholm - Sandviken 1962 Are you still talking?
- Borisson Syding 1973

  Adaptive control of ore crusher

  Lund Kiruna 1400 km

  Home made modems

  Supervision over phone

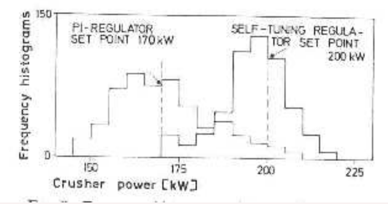
  Samplig period 20 s
- Lars Jensen 1973-78

  Control of HVDC systems

  Extensive experiments with networked on-line control

  Interactive Process Control Language

  TAC => Schneider



Lessons Learned

- Important issues: initialization, excitation, forgetting
- STR very successful in restricted domains

  Papermachines, rolling mills, ship steering, ore crushers, ...
- Tuning the STR requires insight of computer control, identification and adaptive control
- Novatune was very successful when manufactured, sold and commissioned by a highly competent small team but was not successfully transfered to a large organization
- Never easy to introduce new concepts
- Match system to background and experiences of users
- Important to explain how a system works to the users
- PhD free control
- The magic black box (STR) is still a pipe dream!

Outline

1. Introduction
2. Computer Control
3. Adaptive Control
4. PID Control and Autotuning
5. Reflections

PID Control - The Lund Experience

- Snobbishness and hybris: PID why bother?
- Telemetric Axel Westrenius 1979
- Mike Sommerfeld and Eurotherm 1979

  Windup, bumpless transitions, testbatch
- PID really useful but largely neglected in academia
- Auto-tuning with Tore Hägglund

  Ziegler-Nichols tuning: good idea but bad execution, too little process information only two parameters, bad tuning rule quarter amplitude damping

  What information is required for PID tuning? How should it be done?
- NAF: S. Larsson, patents, products and books
- Comments from collegues in academia: Why work on such trivial problems as the PID?

PID Control - Predictions and Facts

1982: The ASEA Novatune Team: *PID Control will soon be obsolete*

1989: Conference on Model Predictive Control: *Using a PI controller is like driving a car only looking at the rear view mirror: It will soon be replaced by Model Predictive Control.*

1993: Bill Bialkowski Entech pulp and paper: *Average paper mill has 3000-5000 loops, 97% use PI the remaining 3% are PID, adaptive etc. Investment 25 k$ per loop: 4000*25 k$=100M$*

- 50% works well
- 25% ineffective
- 25% dysfunctional

2002: Desborough and Miller (Honeywell) *Based on a survey of over 11000 controllers in the refining, chemicals and pulp and paper industries, 98% of regulatory controllers utilise PID feedback*

2016: Sun Li and Lee *Survey of 100 boiler-turbine units in the Guangdong Province in China showed: 94.4% PI, 3.7% PID and 1.9% advanced controllers*

PID Tuning

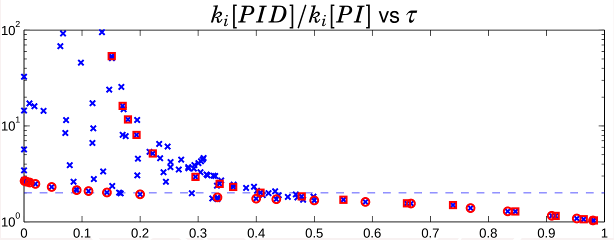
- What process information is required?
- How can the information be obtained?
- Tuning criteria

  Load disturbance attenuation
  Measurement noise
  Robustness
  Set point following - set point weighting
- Testbatch
- Can we find correlations to process parameters?
- What are the parameters?

Design of PID Controllers

Insight into design of PID controllers

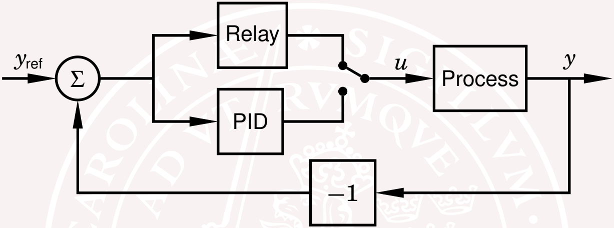
- Role of FOTD model $P(s) = \frac{K}{1+sT}\, e^{-sL}$ and test batch
- The normalized time delay: $\tau = \frac{L}{L+T}$
- Lag and delay dominated dynamics

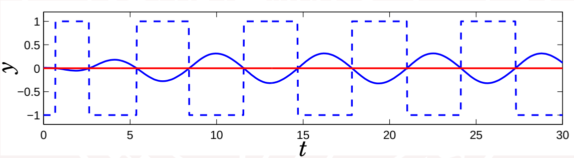


Observations

- $\tau > 0.5$ FOTD model and PI control is sufficient
- $\tau < 0.5$ Better modeling and derivative action can be significant

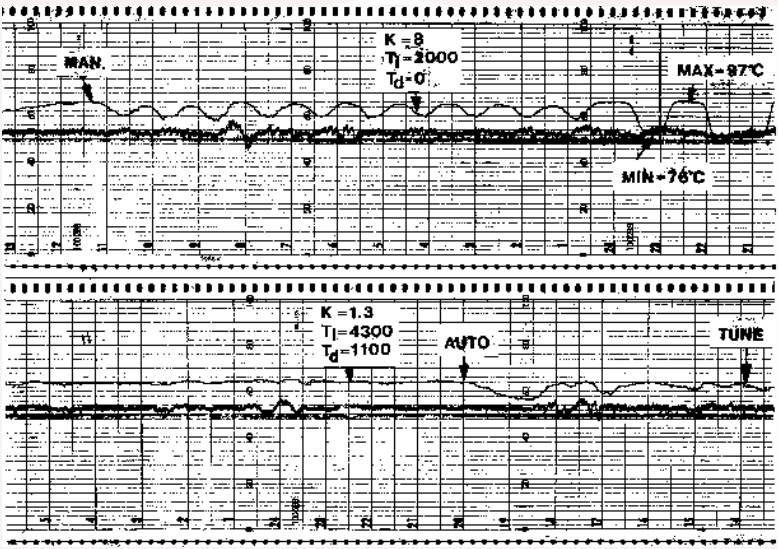
Relay Auto-tuning





KJÅ and Tore Hägglund: Patents, Automatic tuning of simple regulators with specifications on phase and amplitude margins, Automatica 20 (5), **1984**, 645-651

Temperature Control of Distillation Column



Commercial Auto-Tuners

- One-button tuning
- Automatic generation of gain schedules
- Adaptation of feedback and feedforward gains
- Many versions
  - Single loop controllers
  - DCS systems
- Robust
- Excellent industrial experience
- Large numbers

Industrial Systems

Functions

- Automatic tuning AT
- Automatic generation of gain scheduling GC
- Adaptive feedback AFB and adaptive feedforward AFF

Sample of products

- NAF Controls SDM 20 - 1984 DCS: AT, GS, A
- SattControl ECA 40 - 1986 SLC: AT, GS
- Satt Control ECA 04 - 1988 SLC: AT
- Alfa Laval Automation Alert 50 - 1988 DCS: AT, GS
- Satt Control SattCon31 - 1988 PLC: AT, GS
- Satt Control ECA 400 -1988 2LC: AT, GS, A
- Fisher Control DPR 900 - 1988 SLC: AT, GS, A
- Satt Control SattLine - 1989 DCS: AT, GS, A
- Fisher Control Provox -1993 DCS: AT, GS, A
- Emerson Delta V - 1999 DCS: AT, GS, A
- ABB 800xA - 2004 DCS: AT, GS, A

Emerson Experience

- Tuner can be used by the production technicians on shift with complete control over what is going on.
- Operator is aware of the tuning process and has complete control.
- The user-friendly operator interface is consistent with other DCS applications so technicians are comfortable with it. It can be taught and become useful in less than half an hour.
- The single most important factor is that operators and technicians take ownership of control loop performance. This results in more loops being tuned, retuned or fine-tuned, tighter operating conditions and more consistent operations, resulting in more consistent quality and lower costs.

McMillan, Wojsznis, Meyer: Easy Tuner for DCS ISA'93

Lessons Learned

- The wide range of applications is a challenge for control research
  - Number of loops
  - Character of users
  - Resources and design efforts
  - From aerospace to process control
- Picking relevant problems
  - Small wounds and poor friends should not be despised.
- Insights about PID control
  - Fundamental limitation, time delay
  - Information needed for control design
  - FOTD model and its limitations
  - Design methods
    - Load disturbance attenuation: minimize IAE= $\int_0^\infty |e(t)|dt$
    - Robustness: limit maximum sensitivities M_s, M_t
    - Measurement noise injection: bound noise gain $||G_{un}||_2$
    - Command response (set point weighting)
  - Computations: algorithms, complexity and localization box, DCS, networks and cloud

Outline

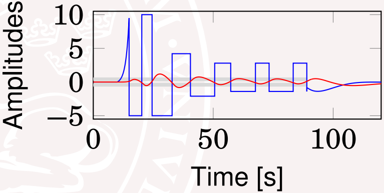
1. Introduction
2. Computer Control
3. Adaptive Control
4. PID Control and Autotuning
5. Reflections

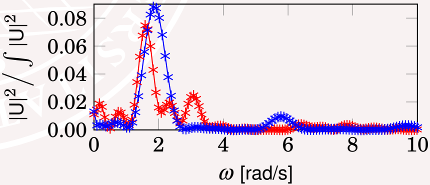
The Role of Computing

- 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!*
- Productivity has not kept up with these advances because software has not kept up

What is Next?

- Next generation relay autotuners
  - Josefin Berner's thesis
  - Asymmetric relay
  - Extra excitation (chirp)?
  - System identification
  - Multivariable
- Recover the STR?
- Diagnostics (Tore)
  - Oscillation detection
  - Idle index
  - Valve friction
- Autonomous process control
  - Exploit computing & cloud
  - Performance assessment
  - Loop assessment
  - Learning





Impact of Process Reality

- Close contact with reality is a necessity for good research
- Testing and commissioning extremely valuable experiences
- Software for modeling and design

  Computer Aided Control Engineering: IDPAC ⇒ Ljung: System Identification Toolbox, SYNPAC, MODPAC, SIMNON, Elmqvist: Dymola ⇒ Modelica

  Startups: DynaSim AB (Dassault Systèmes), Modelon AB
- Software for embedded systems

  We have taught hard real time programming since 1970 (too important to leave to computer science)

  Classical control and analog computing

  Computer control and embedded systems

  Elmqvist SattLine ABB
- Industry should remain to be our lab!

  Increases credibility - a win-win situation

  Confront teachers and students with reality

  Exchange people between academia and industry

  Useful to leave the comfort zone