Early Development of Automatic Control in Sweden

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The 1912 Nobel Prize in Physics



Gustaf Dalén: "for his invention of automatic regulators for use in conjunction with gas accumulators for illuminating lighthouses and buoys".

Source Karl Grandin Fysikaktuellt 4 Dec 2012 20-21

The 1912 Nobel Prize in Physics

- Many candidates: Kammerlingh Onnes (1913), Max Planck (1918), Albert Einstein (1921), Walther Nernst (1920), Henri Poincaré (†), ...
- Unanimous physics committee, chaired by professor Gustaf Granquist Uppsala, proposed Heike Kammerlingh Onnes
- Erik Johan Ljungberg CEO of Stora Kopparberg, member of the class for economic, statistical and social sciences proposed Dahlén, nominated Dahlen
- Discussion November 12 1912, Ljungberg's proposal won the vote 37-28

Some Swedish Industries

- Nordiska Armaturfabriken 1896 (NAF ⇒ Saab ⇒ Alfa Laval Automation ⇒ ABB)
- TA 1897 Hilmer Andersson (+ Tour Agenturer Tour Andersson ⇒ TAC ⇒ Schneider)
- AGA 1904
- Källe Regulator 1921
- ARCA regulatorn GunnAR CArlstedt 1918, Berlin 1922, IVAs guldmedalj 1924
- Billman Regulator 1932 (⇒ Landis and Gyr ⇒ Siemens)
- ElektronLund 1955 (Satt Control, Alfa Laval Automation ⇒ ABB)
- ASEA (⇒ ABB)
- Ericsson, Philips, Kockums, Volvo
- Bofors (⇒ Saab ⇒)
- Saab many different divisions

Automatic Control in Sweden

1. Introduction
2. The Entrepreneurs and their Companies
3. ASEA - Master of Frequency Response
4. Military Projects
5. IBM Nordic Laboratory
6. Academia
7. Summary

Theme: Followed the international pattern.

Nils Gustaf Dalén 1869-1937 and AGA

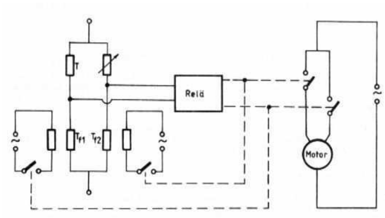
- Chalmers 1896
- One year with Stodola (Hurwitz stability critieron) vid ETH
- Technical director Svenska Karbid och Acetylen 1901
- CEO Svenska Aktiebolaget Gasackumulator (AGA) 1909
- Nobel Prize in Physics 1912
- AGA incorporated in Linde Group 2000

  Scientific recognition, inventor, entrepreneur, businessman
- Hypothetical question on research funding: VR - too few pulications! Vinnova - Strong industrial impact!
- Has he contributed to Chalmers high Shanghai rating?

Billmanregulator 1932-1980 - Stig Billman

- Civ. ing. KTH 1929, MS thesis "Behavior of temperature controllers"
- Birka regulator company automation of oil burners
- Billmanregulator AB March 16, 1932 for constructing and selling oil burners
- Motor-driven valve with thermal feedback
- Pioneering work in temperature control of buildings
- Rapid expansion with strong board from large export companies AGA, Ericsson et al
- Global sales and manufacturing
- Incorporated in Landis & Gyr 1980
- Landis & Gyr acquired by Siemens Building Technology 1998

Billman's Electric Valve

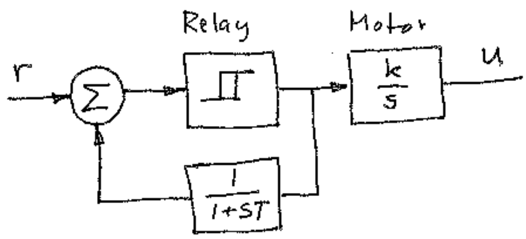


- Use motor with relay as an amplifier
- Thermistors give long time constants for integral control (thermal feedback)

Approximate relay by high gain use voltage balance

$$\frac{1}{1+sT}V = E, \qquad U = \frac{k_v}{s}V = \frac{k_v(1+sT)}{s}E$$

Block Diagram

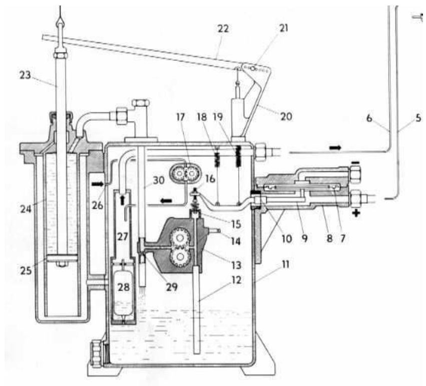


$$G(s) = \frac{k}{s}\frac{k_r}{1+\frac{k_r}{1+sT}} \approx k\frac{1+sT}{s} = kT + \frac{k}{s}$$

Källe regulator 1921-1969

- Torsten Källe 1893-1975
- Civ ing CTH 1919 worked at Billerud paper mill
- Started Killeregulator AB in Säffle 1921
- The Källe controller - and the carrot consistency sensor
- Gustaf Dalén medal 1955 Chalmers engineering association
- IVA's Gold Medal for *his contribution to automatic control* 1958
- Honorary doctor at Chalmers 1963
- Donation for the professorship in automatic control at Chalmers 1963
- Ekman medal from Svenska Pappers- och Cellulosaingenjörsföreningen 1963
- Acquired by Bonniers renamed EUR-Control

Källe's Controller

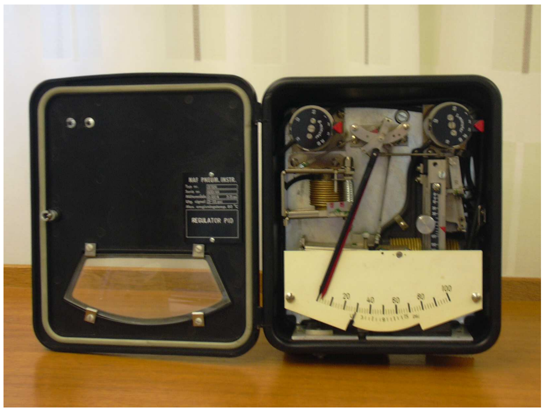


Clever hydraulic actuator integrated with a controller

Nordiska Armaturfabriken NAF

- Founded in Linköping 1899
- Valves, pressure sensors and regulators
- Manufactured valves in Lund
- Flight instruments, gyro horizons, altimeters
- Pneumatic controllers
- DCS system SDM20, SDM 30
- Relay auto-tuning based on KJs and Tore patent
- Development office in Lund Science Park Tore Hägglund worked there 1985-89
- Controller activity sold to Satt Control, Ahlsell, Alfa Laval Automation, ABB
- Valves sold to Flow Serve 2004

NAF's Pneumatic PID Controller



Tour & Andersson - TAC - Schneider

- 1875 A. H. Andersson & Co Christiania valves
- Tour Agenturer, Stockholm RVO valve
- 1952 First electronic controller TE1
- 1962 First transistorized controller TE5
- 1966 Incentive (Wallenberg) buys A. H. Andersson
- 1970 Incentive buys 75% of Tour Agenturer
- 1968-78 Computer Control of Buildings LTH
- 1975 Acquires part of Carl Olin AB DDC-6
- 1975 Computerized system 6000
- 1977 Tour & Andersson (TA) formed
- 1984 TA SYSTEM 7 energy control and building management
- 1995 TA Hydronics and TA Control
- 1996 Head office moves to Malmö
- 2003 Schneider Electric

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Power Systems

- Turbine controller (Ytterberg ABB)
- Strong collaboration between ABB and Swedish State Power Board (Vattenfall)
- Problems with long distance power transmission
- Ivar Herlitz

  Engineer KTH, work at ABB
  Harvard and GE Schenectady
  Riverside Power Co
  Stanford
  PhD KTH. The Stability of Long Transmission Lines. KTH 1928
- Uno Lamm and HVDC
- The nuclear reactors AB Atomenergi
- Asea Atom
- Sydkraft (EON)

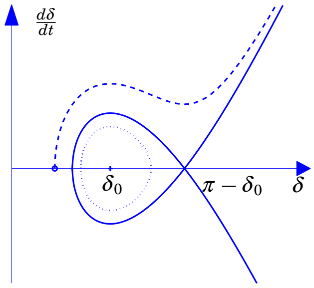
Herlitz Stability Analysis

The swing equation

$$\omega_0 J \frac{d^2\delta}{dt^2} = P_g - P_c \sin\delta, \qquad P_{max} = \frac{V_f V_l}{X}$$

δ angle deviation, V_g generator voltage, V_l line voltage, X line reactance, P_g generated power, P_c consumed power

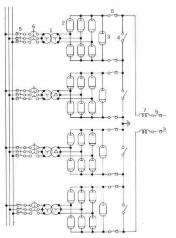
Center at δ_0
Node at $\pi - \delta_0$
Homo-clinic orbit through center



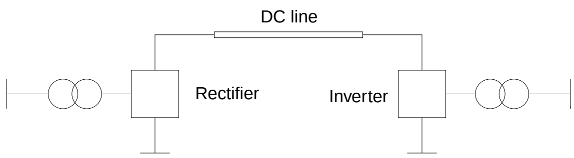
High Voltage DC Transmission

- Uno Lamm ABB

  CI KTH 1927, ABB, PhD KTH 1943
- Cable to Gotland 1954 - mercury arc switches
- An interesting hybrid system
- ASEA achieved global dominance
- Major improvements with thyristor valves
- Hardware and systems principles
- Safety a major concern



HVDC Control Principle



- Direction of power flow can change rapidly
- Find a sound principle to control power transmission (architecture)! The current is

$$I = \frac{V_t - V_r}{R}$$

- Can this relation be used safely?

ASEA - Masters of Frequency Response

- The Central Laboratory
- Aage Garde and Erik Persson
- How control problems were solved
- Impact of Nyquist's stability critierion
- Brave experimentation with Frequency Response
- Interesting design methods
- Active on the international arena CIGRE, IFAC, IEE

  Aage Garde participated in the Cranfield konferensen, member of Swedish IFAC committee
  Participation at the ASME Frequency Response Symposium New York
  Erik Persson IFAC Basel 1963
- At the frontline in the mid 1950s

When the Nyquist Theorem arrived at ASEA

- Nyquist Regeneration Theory Paper 1932
- Control activity at ASEA
  - Central laboratory Aage Garde/Erik Persson
  - Model-Solve Characteristic Equation-Guess-Modify
  - Computational tools - mechanical calculator
  - The Nyquist revolution
  - Garde, A (1948) Frekvensanalytisk behandling av reglersystem. Aseas tidning (Frequency Analysis of Control Systems) 27-33
  - Garde, A and Erik Persson (1960) Automatisk djupstyrning av ubåt. (Automatic Depth Control of Submarines) Aseas tidning 127-131.
- Naval Procurement Agency (Marinförvaltningen)
- Seminars by Garde and Persson in Lund

Impact of the Nyquist Theorem

We had designed controllers by making simplified models, applying intuition and analyzing stability by solving the characteristic equation. (At that time, around 1950, solving the characteristic equation with a mechanical calculator was itself an ordeal.) If the system was unstable we were at a loss, we did not know how to modify the controller to make the system stable. The Nyquist theorem was a revolution for us. By drawing the Nyquist curve we got a very effective way to design the system because we know the frequency range which was critical and we got a good feel for how the controller should be modified to make the system stable. We could either add a compensator or we could use extra sensor.

Erik Persson Free translation from seminar in Lund.

Depth Control of Submarines

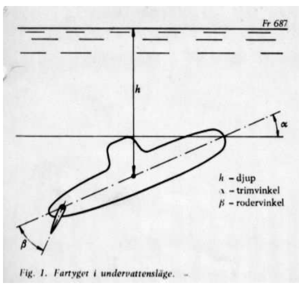


Fig. 1. Fartyget i undervattensläge.

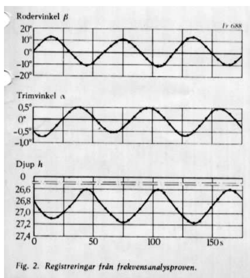
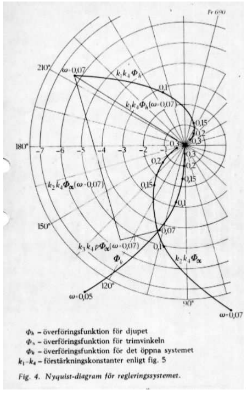
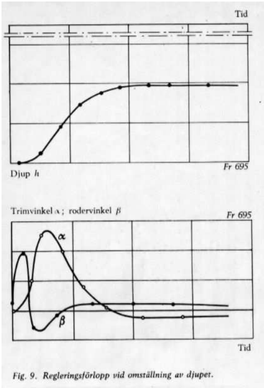


Fig. 2. Registreringar från frekvensanalysproven.

- How to generate sine-waves and how to measure and record depth and trim?

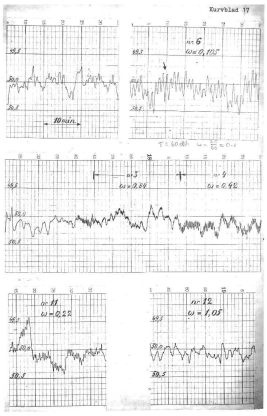
State Feedback using Nyquist Plots



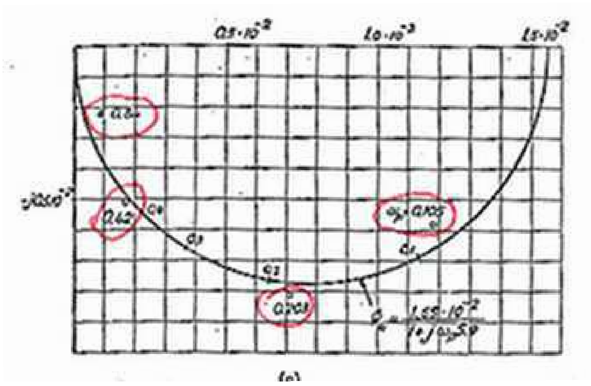


Dynamics of the Swedish Power Network

- Frequency response from power to frequency for Swedish power network
- Experiments Feb 25 - March 1 1949
- Oja, Persson, Almström
- Inject sinusoidal perturbations by changing a 50 MVA alternator
- Noisy signals correlations used to extract sinusoid
- Dynamics changes with time $P(s) = b/(s + a)$



Swedish Power Network 2



Summary

- Knowledge about the Nyquist theorem changed control at ASEA from trial and error to design
- Group of critical size at the Central Laboratory in Västerås
- A systematic way to obtain models from experimental data
- A nice design method, notice multi-variable aspects
- Fearless use of frequency response for modeling
- Many applications
- Group very active internationally CIGRE, ASME, IFAC
- Missed the paradigm shift in 1960, optimal control, computer control and Kalman filtering
- Unfortunate influence on the Chair of Control at KTH

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Theme: Followed the international pattern.

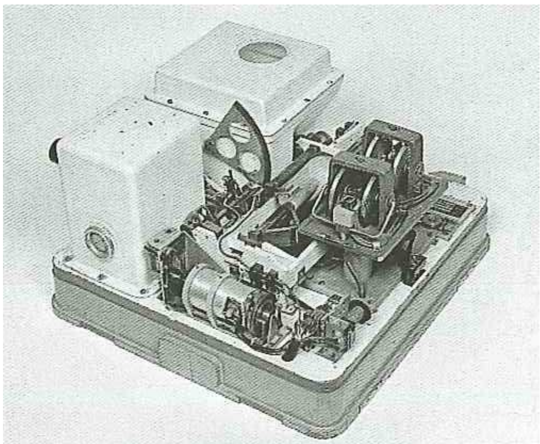
The Defense Industry - The Large Projects

- *Alliansfri i fred och neutral i krig - Non-aligned in peace neutral in war*
- FOA 1945
  - Chemistry, Physics Electronics, Operations research
  - Bäckebobomben (Boestad, Luthander)
  - TTN Gruppen Bengt Joel Andersson
- Stril 60, JA37 Viggen, (Gripen)
- Aeronautics KTH Prof Luthander
- The Army, Navy and Air Force Procurement Agencies (Arme-, flyg- och marinförvaltningarna)
  - Avionics Bureau
  - Missile Bureau
- Saab
- Bofors - Gun-sights
- Volvo Flygmotor
- The Electronics Industry
  - AGA, Arenco, Ericsson, Philips, TUAB

Gun Sights

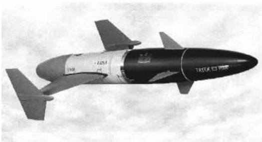
- Draper and Sperry
- Wilkinson Saab
- Gun-sight for dive bombing
  - Air-driven gyroscope, electro-mechanical analog computer, nonlinear function generator in the form of an asymmetrical rotating body. Gyro manufactured by NAF, function generator by Arenco (Tändsticksbolaget)
- Made in large numbers in the US by licensing
- Wilkinson E. Dive Bombing. PhD thesis, Royal Institute of Technology, Stockholm, Sweden, June 20, 1947

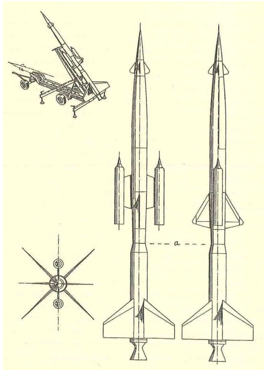
Wilkinson's Gun Sight



Missile Guidance

- The threat
- Viggen
- KTH Flygteknik Prof Sten Luthander
- Bäckebobomben 19440613
- Gustav Boestad KTH
- Saab R-System
- The TTN Group

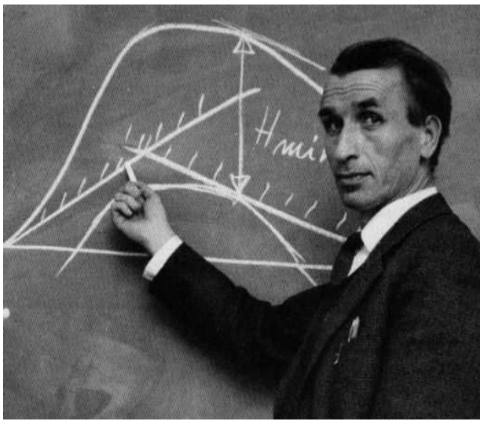




Saab R-System

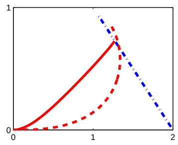
- Airplanes changed from carriers of black boxes to systems
- Formed 1954, inspired by Rand Corporation 1945
- Hans Olov Palme - aeronautical engineer KTH
  Enthusiastic, charismatic, visionary leader
- Recruited a fantastic talent pool 75 persons in 1955
  Strong creativity, broad range and deep knowledge
  Tore Gullstrand, Bengt Gunnar Magnusson, Gösta Hellgren, Gösta Lindberg, Lars Erik Zachrisson, Viggo Wentzel
- Three groups: Systems, avionics, special projects
- Airborne computers, missile guidance, inertial navigation, simulation, operations analysis, Datasaab
- Electronics industry formed TUAB to compete

Lars Erik Zachrisson



Lars Erik Zachrisson 1919-1980

- Engineering Physics KTH 1945
- FOA 1947-57 missile guidance
- Proportional navigation 1946.
  Control principle for guidance
  Patent and analysis



- Markov Games 1955 (Isaac's 1965)
  A tank duel with game theoretic implications, 1955, 1957
  Markov games. In advances of Game Theory. Princeton University Press 1964. Isaacs bok 1965.
- Saab R-system 1957-63
- Docent in Automatic Control KTH 1959
- Optimization and System Theory KTH
- Professor System Theory and Optimization KTH 1963 (69)
- Anders Lindquist 1972 (Z:s first PhD student)

FOA

Missile guidance

- Thorvald Persson
  Lars Erik Zachrisson
  proportional navigation
- Inertial navigation
  Philips, AGA, Saab
  MIT Draper

Analog computing

- Jonas Agerberg
  SAMS 1959
  ADA

Radar, computers, Besk

Brodin, Persson och Jahnberg

RB 04 early air-to-sea missile

TTN Gruppen

- Goal: Understand inertial navigation and guidance
- Structure
  FFV: Torsten Bergens
  FOA: Thorvald Persson
  KTH: Bengt Joel Anderson, Svante Jahnberg, Åslund, KJÅ
  Aga, Philips, Saab, Servomechanism

- Free-wheeling, chaotic
  FOA's ball gyro, . . .
- Free access to Besk (The only Swedish Computer)
- The MIT connection
- Fantastic learning experience BUT many constraints

Vertical, Vertical, Who's got the Vertical?

Longitudinal position error with constant gyro drift

$$\ddot{e}_x = g\psi, \qquad \psi = \omega_0 t, \qquad e = \frac{g\omega_0}{6}t^3$$

Azimuth error

$$\dot{e}_a = U_0\omega_0 t, \qquad e_a = \frac{U_0\omega_0}{2}t^2$$

Assume $\omega_0 = 1°/s = 4.85 \times 10^{-6}$ [rad/s] $u_0 = 300$ m/s $t = 3600$ gives $e_x = 370$ km and $e_a = 9$ km.

Drift rates must be brought down to $0.01°$/h. Azimuth gyro drift less important.

- Strong scepticism from George Gamov and others
- Drapers coup: Classified Conference
  Gamov invited, did not come

The Idea

Make a pendulum and increase its apparent moment of inertia with acceleration feedback

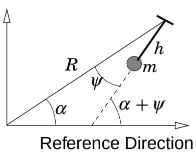
- Avoid closing the Schuler loop through the gimbals
- A single axis gyro can measure angular acceleration

Equations of motion:

$$J\frac{d^2\theta}{dt^2} = -mgh\psi + mRh\frac{d^2\alpha}{dt^2} + u$$

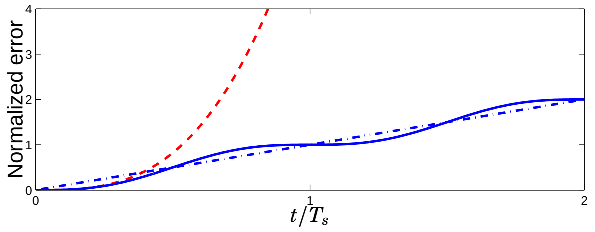
$$u = -k\frac{d^2\theta}{dt^2}$$

$$(J+k)\frac{d^2\theta}{dt^2} = -mgh\psi + mRh\frac{d^2\alpha}{dt^2} + u$$



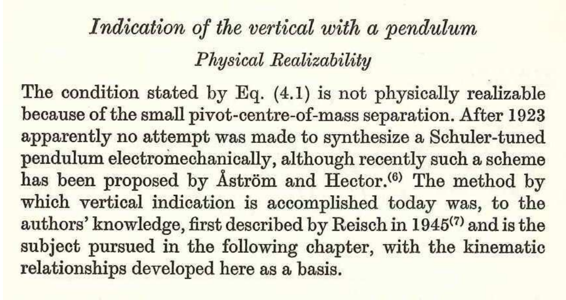
$$(J+k)\frac{d^2\psi}{dt^2} + mgh\psi = (mRh - J - k)\frac{d^2\alpha}{dt^2}$$

Schuler Tuning - Error Growth



$$e(t) = \frac{g\omega_0}{6}t^3, \quad e(t) = R\omega_0\left(t - \frac{1}{\omega_s}\sin(\omega_s t)\right), \quad \omega_s = \sqrt{g/R}\text{(84min)}$$

Recognition from MIT



Indication of the vertical with a pendulum

Physical Realizability

The condition stated by Eq. (4.1) is not physically realizable because of the small pivot-centre-of-mass separation. After 1923 apparently no attempt was made to synthesize a Schuler-tuned pendulum electromechanically, although recently such a scheme has been proposed by Åström and Hector.[6] The method by which vertical indication is accomplished today was, to the authors' knowledge, first described by Reisch in 1945[7] and is the subject pursued in the following chapter, with the kinematic relationships developed here as a basis.

W. R. Markey and J. Hovorka *The Mechanics of Intertial Position and Heading Indication*, Wiley, New York 1961

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IBM Nordic Laboratories 1960-1995

Euforia about computer control in the process industry

- Three tasks
  - Develop technology for computer control
  - Execute good demonstration projects
  - Computer architecture for process control
- The Billerud project 1962-67
  - Experimental determination of models for control of paper machine dynamics inspired the maximum likelihood method for system identification by Torsten Bohlin and KJÅ
  - Minimum variance control KJÅ
  - Excellent project, unfortunately no book
- IBM abandoned plans to buy an instrument company
- Impact on Academia
  - K. J. Åström professor in control at LTH 1965
  - Torsten Bohlin professor professor in control at KTH 1971
  - Jorma Rissanen professor i control LiTH 1975
  - Hans Andersin professor in computer science Helsinki
  - Dines Bjorner professor in computer science DTU 1976

The Billerud-IBM Project

- Background
  - IBM and Computer Control
  - Billerud Tryggve Bergek and Saab
- Goals
  - Billerud: Exploit computer control
  - IBM: Experience in computer control. Recover prestige!
  - What should a good process control computer look like?
  - Cram as much as possible into the system!
    - On-line process control, production planning, production supervision, quality control, reporting
- Schedule
  - Start April 1963
  - Computer Installed December 1964
  - System identification and on-line control March 1965
  - Full operation September 1966
  - 40 man-years effort in about 3 years

Basis Weight and Moisture Control

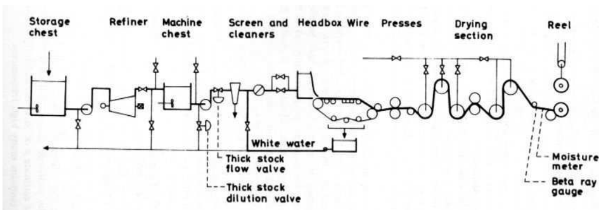
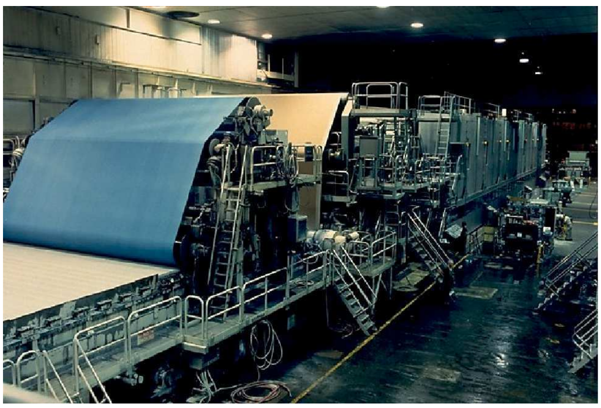


Fig. 6.9. Simplified diagram of a kraft paper machine.

- Two important loops
- Triangular coupling MISO works

The Drying Section



Computer Resources

- IBM 1720 (special version of 1620 decimal architecture)
- Core Memory 40k words (decimal digits variable word length)
- 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 real time operating system

Modeling and Control

- Good support from management Kai Kinberg:

  This is a showcase project! Don't hesitate to do something new and spectacular if you believe that you can pull it off and finish on time.
- Process understanding, data logging and modifications (mixing tanks)
- Modeling by frequency response key for success of classical control
- Physical models may give dynamics but not disturbances
- Stochastic control theory is a natural formulation of industrial regulation problems
- Can we find something similar for state space systems?
- Big struggle to do real plant experiments
- Wasted a lot of time on historical data

Modeling from Data (Identification)

Process model

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

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

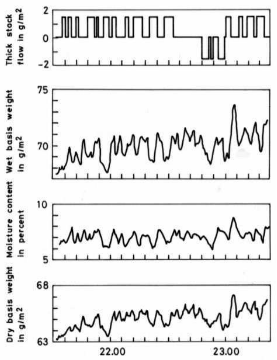
$$\begin{aligned} dx &= A\hat{x}dt + Budt + K(dy - C\hat{x}dt) \\ &= (A - KC)\hat{x}dt + Budt + Kd\epsilon \\ dy &= C\hat{x}dt + d\epsilon \end{aligned}$$

Canonical form for MISO system removes remaining redundancy, discretization gives (C Kalman filter dynamics) ARX

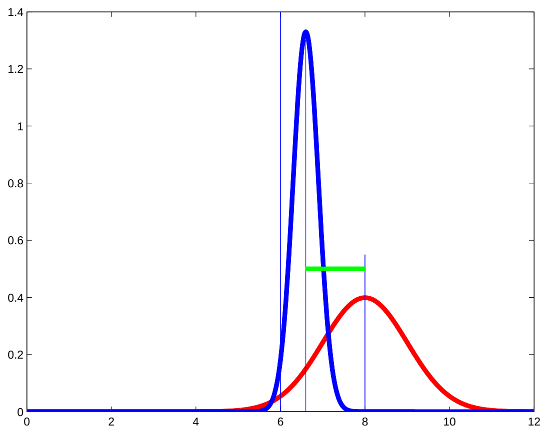
$$A(q)y(t) = B(q)u(t) + C(q)e(t)$$

Practical Issues

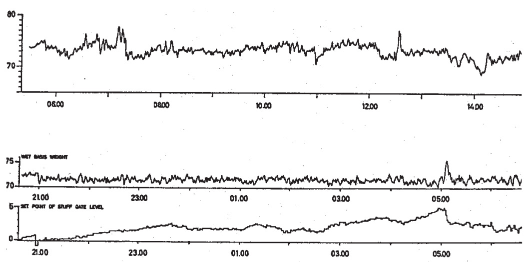
- Sampling period
- To perturb or not to perturb
- Open or closed loop experiments
- Normal or perturbed operation
- Model validation
- 20 min for two-pass compilation of Fortran program!
- Skills and experiences



Minimum Variance Control



Results

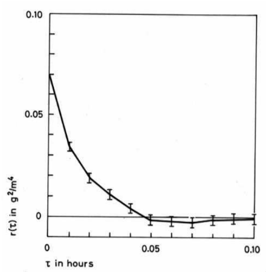


Controller removes the low frequency component

Summary of Minimum Variance Control

- Regulation can be done effectively by minimum variance control
- Easy to validate

  $r(t) = 0, \quad t \geq k$
- Prediction horizon is the **design variable**!
- Robustness depends critically on the sampling period
- The Harris Index
- OK to assess but why not adapt?



Summary

- Extremely good and farsighted management

  Kai Kinberg IBM Nordic Laboratory, Tryggve Bergek Billerud
- Good resources with competent and interested participants
- Good mix of people with many short term participants
- Open atmosphere with pressure on dead-lines and results
- A successful flagship installation
- Straw-man for computer architecture for process control

  IBM 1800, IBM 360
- Method for identification of stochastic models

  Basic theory: consistency, efficiency, persistent excitation
  Engineering practice: input design, execution of experiments
- Minimum variance control
- Project well documented in IBM reports and a few papers but we should have written a book (Bellman's advice)

Automatic Control in Sweden

1. Introduction
2. The Entrepreneurs and their Companies
3. ASEA - Master of Frequency Response
4. Military Projects
5. IBM Nordic Laboratory
6. Academia
7. Summary

Theme: Followed the international pattern.

Teknologföreningen and IVA

- Svenska Teknologföreningen (Sveriges Ingenjörer, Association of Swedish Graduate Engineers)
  - The Club Brunkebergsgatan Stockholm
  - Discussions and networking
  - Courses

    Extensive course activity 1940-70
    Donald Campbell from Gordon Brown's Servomechanism Laboratory at MIT gave the first course in servo-systems in 1948 invited by Teknologföreningen (Invitation initiated by Bertil Palme Philips Teleindustries)
- Royal Swedish Academy of Engineering IVA
  - Scholarships

    Computers: IAS Princeton and Besk
    Control: Qvarnström (Bofors), Åslund (KTH), Sandblad (ASEA)
  - National committee for IFAC
  - Instrument tekniska föreningen ITF 1961

KTH

- Donald Campbell MIT Servomechanisms Lab lecture 1948
- First lectures 1949/50

  Laszlo von Hamos adjunct teacher from the Air-force Missile Bureau (robotvapenbyrån FMV) Gunnar Attebo Källeregulator and Bengt Sjöberg FMV as assistants
- von Hamos signed IFAC deklaration for Sweden in Heidelberg Sept 1956.
- Laszlo von Hamos appointed professor 1959
- FOA sponsored Dept of System theory and Optimization for Lars Erik Zachrisson 1963-69. Regular Chair 1969.
- Torsten Bohlin 1971
- Bo Wahlberg 1991, Håkan Hjalmarsson, Elling Jacobssen, Mikael Johansson, Karl Henrik Johansson

CTH

- Stig Ekelöf professor in electrical engineering - built a differential analyzer initiated
- Henry Wallman gave course for electrical engineers 1953-55

  Wallman came from the Radiation Laboratory MIT
- Robert Magnusson Control for Telecommunication 1959

  Charlie Davidson, ...
- Professorship partially financed by Torsten Källe 1962 Birger Qvarnström appointed 1963

  Qvarnström: KTH Aeronatutics analog computing, Bofors Åke Blomqvist, hydraulic servos for gun pointing, Dial 1958, IVA scholarship , Träforskningsinstitutet STFI
- Separate courses in control for EE and other engineers continued for a long time
- Bo Egardt 1989, Bengt Lennartsson, Clas Breitholtz, Jonas Sjöberg, Martin Fabian, Eriok Coelingh

LTH, LiTH, Uppsala, Luleå

- Lund

  KJÅ1965, Björn Wittenmark 1989, Per Hagander, Tore Hägglund, Rolf Johansson, Anders Rantzer, Anders Robertsson, Karl-Erik Årzén
- Linköping

  Jorma Rissanen 1975 Lennart Ljung 1976
  Torkel Glad 1988, Lars Nielsen 1992, Fredrik Gustafsson 1999, Mille Milnert 2000, Anders Hansson 2001, Svante Gunnarsson 2002
- Uppsala

  Torsten Söderström, 1974, Peter Stoica 1998, Anders Ahlén, Mikael Sternad
- Luleå Thomas Gustafsson

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Summary

- Early development driven by inventors: sensors, actuators and controllers
- Later development driven by large companies and military projects
- Common practice to send engineers abroad Dalén, ASEA, Philips, and to collaborate with universities even if there were no control departments
- IVA acted as CTOs of Sweden
- Academic development relatively late
- Analog computing was a good meeting ground SAMS (Skadinaviska Analogi Maskin Sällskapet replaced by Reglermötet
- Collaboration with the instrument society did not happen even if they they were both hosted by IVA, very different development in Norway NFA 1958 and Finland RF 1953
- Much has happened after 1965