# Automatic Control Emerges

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# Automatic Control Emerges

K. J. Åström

1. Introduction
2. The Computing Bottleneck
3. State of the Art around 1940
4. WWII
5. Servomechanisms
6. Summary

*Theme: Unification, theory, and analog computing.*

# Lectures

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# Introduction

Control became established as the first systems field in the period 1940–1960 with a good theoretical base, computational tools and an unusually broad industrial base.

- Solid theoretical base
  - Linear, nonlinear and stochastic systems
- Solid academic base
- Research and education
  - Books and curricula
- Industrial base
- Organizations
- Conferences
- Journals

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# The Computing Bottleneck

Driving force: Transient stability of power networks

General Electric designed a 500 mile transmission line from Canada to New England and New York. Similar situation in Sweden with power generation in the north and consumption in the south.

- Large power networks
- The General Electric Research Laboratory

  Established by Edison
  Charles Proteus Steinmetz

- EE at MIT Dugald Jackson

  Vannevar Bush
  Harold Hazen
  Gordon Brown
  Frederick Terman

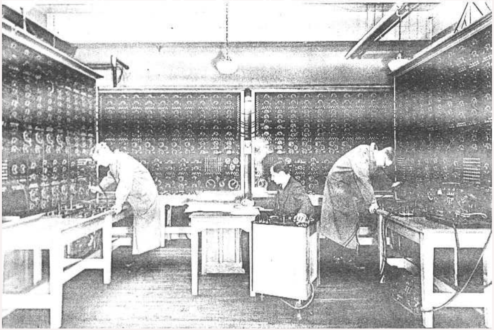
# Vannevar Bush

- PhD Dissertation on Heaviside Calculus 1 year
- Applications to power transmission
- Product Integraph 1925
- Differential Analyzer 1928

- The improved Differential Analyzer
- Course on Heaviside Calculus taken over by Gardner and Barnes who introduced Laplace transforms. Book Gardner Barnes: Transients in Linear Systems 1942.
- Many good students among them Harold Hazen, Frederick Terman, and Harold Edgerton

# MIT Network Analyzer

- Make a physical system that emulates the real system
- Resistors as loads, phase-shifting transformer as generators
- PhD thesis by Hazen and Spencer



# The Computing Bottleneck

- Bush 1927: *Engineering can proceed no faster than the mathematical analysis on which it is based. Formal mathematics is frequently inadequate for numerous problems pressing for solution, and in the absence of radically new mathematics, a mechanical solution offers the most promising and powerful attack wherever a solution in graphical form is adequate for the purpose. This is usually the ease in engineering problems.*
- Melvill Jones 1935: *It is in fact rare for anyone actually engaged upon the design of aeroplanes to make direct use of computations ... In my own opinion it is the difficulty of computation ... .*
- Erik Persson 1950: *At that time, solving the characteristic equation with a mechanical calculator was itself an ordeal*

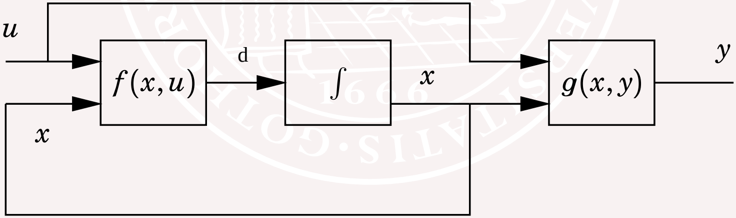
# The Idea of Analog Computing

Create a feedback loop for

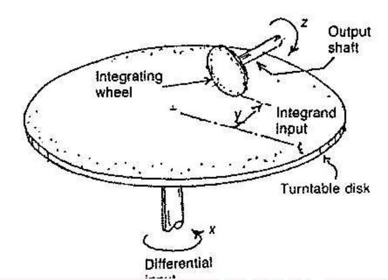
$$\frac{dx}{dt} = f(x,u), \qquad y = g(x,u)$$

Operations required

- Integration
- Function generation
- Amplification
- Input and output



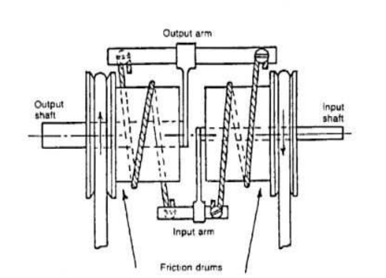
# The Ball and Disk Integrator



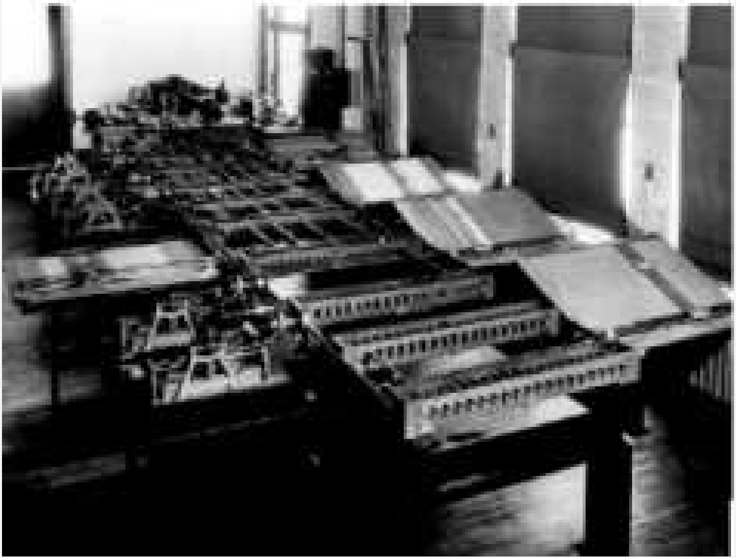

- Differential gear
- Curve readers
- Plotters

# The Torque Amplifier

Idea: $F_2 = e^{\mu\alpha} F_1$

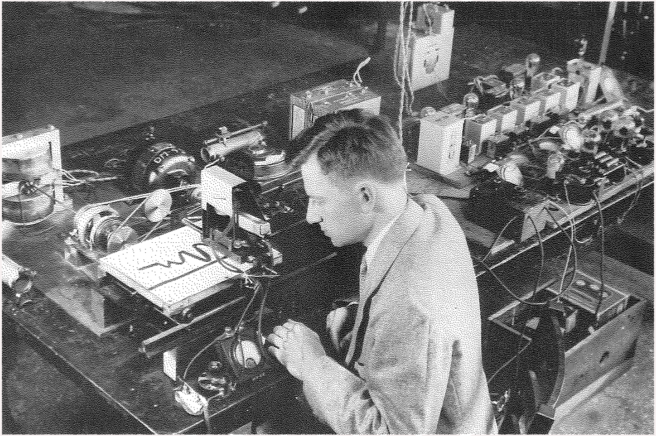



# The First Differential Analyzer 6 ODE



# The First Differential Analyzer

# Hazen's Curve Follower



# The Differential Analyzers

- Kelvin's tidal simulator (ball and disk) 1878
- The power network analyzer 1924
- The Differential Analyzer 1928–
- The Rockefeller Differential Analyzer 1941
- Copies at other institutions

  Moore School University of Pennsylvania 10 integrators
  Ballistics Laboratory Aberdeen MD 10 integrators
  University of Manchester, Hartree and Porter 8 integrators
  Cambridge University, Lennard-Jones 8 integrators
  General Electric Schenectady 14 integrators
  GE and UCLA 14 integrators
  Queens University Belfast, Meccano 1-2 % accuracy
  University of Oslo, Energy Institute Leningrad
  Chalmers Ekelöf 1950 5 integrators

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*Theme: Unification, theory, and analog computing.*

# Overview

- Feedback invented and used in many areas often with revolutionary consequences
  - Governors and electric power generation
    - Thousands of governors: Siemens, Woodward, ABB, ...
  - Process control
    - More than 600 instrument companies in USA by mid 1930
  - Ships and aerospace
    - Thousand gyrocompasses, autopilots, engine controllers, steering engines
  - Telecommunications
    - All long distance communication required lots of amplifiers
- Similarities of different fields not recognized
- A few books
  - Tolle Regelung der Kraftmaschinen, 1905.
  - Zhukovskii Theory of the regulation of the motion of machines, 1909.
  - Trinks Governors and the Governing of Prime Movers. Carnegie Institute of Technology, 1919.

# Interview with Oppelt

But there was no common approach to control problems in the different engineering disciplines. For example in 1937 I gave a conference paper on flight control, which was later published in an aeronautical journal. This was the first systematic study of the topic, and at the end of the paper I also compared flight control with the control of other variables such as pressure and temperature, giving the equivalent mechanical system in each case and comparing systems equations and typical dynamic behavior. This idea of a common ground between entirely different types of control systems was quite new but the paper was not known outside aeronautical circles, owing to its appearance in a specialist journal.

# Research and Education

Industry dominated research

- Siemens, Sperry, Woodward, Honeywell

Strong industrial research laboratories

- General Electric
- AT&T

Some university activity

- St. Petersburg Vyshnegradski
- Stodola ETH
- Zhukovskii Aeronautical Institute 1902
- Max Schuler at Göttingen 1923 Applied Mechanics
- Institute of Automation and Remote Control Moscow 1939
- Kazan Aviation Institute
- Karl Kupfmüller, Oppelt EE TH Darmstadt
- Leonard TH Stuttgardt

# Theory

The mechanical engineering inheritance

- Physical modeling, simplification
- Linearization
- The characteristic equation
- Routh-Hurwitz stability theorem

The electrical engineering inheritance

- The Nyquist stability criterion
- Bode plots
- Gain-phase relations
- The notion of minimum phase
- The ideal cut-off characteristics

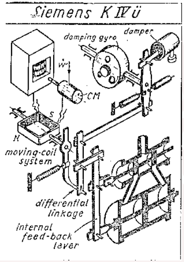
# Organizations

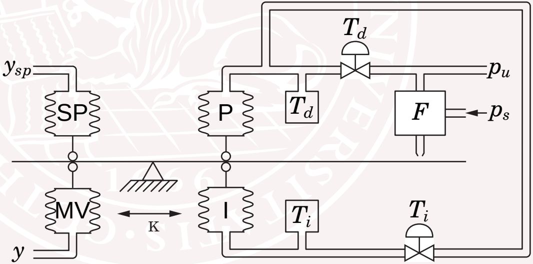
- American Institute of Electrical Engineers 1884
- IEE Institution of Electrical Engineers 1889 $\Rightarrow$ IEEE 1963
- Institution of Radio Engineers 1912 $\Rightarrow$ IEEE 1963
- Royal Aircraft Establishment (RAE) Farnborough 1918
- The Process Industries Division of ASME formed Industrial Instruments and Regulators Committee in 1936.
- VDI/VDE 1938
- Institute of Automation and Remote Control, Moscow 1939
- ISA (Instrument Society of America $\Rightarrow$ International Society for Automation) 1945
- Institute of Measurement and Control, London 1945

# Implementation

- Mechanical
- Pneumatic
- Electric

Extensive use of feedback in sensing, actuation and control.



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# War Pressures

Many politicians recognized that science could have a significant impact on the war effort

- USA
- England
- Soviet Union
- Germany
- Sweden Tage Erlander & Torsten Gustafsson FOA
- Similar efforts in many countries SupAero Pelegrin

Typical problems

- Radar and autopilots
- Fire Control: All navies had good automatic fire control around 1900 but aircraft produced new challenges because of their high speed
- Activities started in many countries around 1930
- Process Control in Los Alamos

# The Fire Control Problem

- All navies had good automatic fire control around 1900
- Aircraft produced new challenges because of their speed
- Activities started in many countries around 1930

  Detection
  Tracking
  Prediction
- Early experiments with radio direction finding 1935
- System in operation when German day time attacks began August 1940
- PPI and sampling
- High frequency generation
- Intense radar development

# The UK Effort

- Experiments with radar in mid 1930
- Admiralty Signals School (ASE)
- Air Defense Experiment Establishment (ADEE)
- Aeronautical Research Council, Royal Air-force Establishment (RAE)
- Churchill, Lindemann and Tizard
- Tizard FRS Rector of Imperial College
- The Tizard Committee for the Scientific Survey of Air Defense 1935
- Unclear Command lines
- The Servo Panel established March 1942 by Ministry of supply

  Hartree and Porter University of Manchester
  A Callender Research Department of ICI?
  Arnold Tustin Metropolitan Vickers (Met-Vic)

# Arnold Tustin

- Metro Vickers (Met-Vic), Sheffield: Control of electric motors
- Gun control for ships
- Professor of EE Birmingham 1948-1955
- Professor Imperial College 1955-1964
- Edited proceedings of Cranfield Conference
- Tustin's method $s = 2(z-1)/h(z+1)$
- The mechanism of economic systems, Heinemann, London 1953

# The US Effort

- National Research Council under National Academy of Sciences
- National Defense Research Committee (NDRC) proposed by

    Karl T. Compton, President MIT
    James B. Conant, President Harvard
    Frank B. Jewett, President Bell Labs and National Academy of Sciences
    Vannevar Bush, President Carnegie Institution, Chairman National Advisory Committee for Aeronautics (NACA)

  Decision taken by Roosevelt, General Marshall and Admiral Stark on June 27 1940.
- Should not replace work done in research labs by Navy and Army nor flight
- NDRC subsumed under Office of Scientific Research and Development (OSDR) under Vannevar Bush
- Clear command lines (Bush held the money bag!)

# Labs at and around MIT

Around MIT

- The Radiation Laboratory
- The Lincoln Laboratory
- The Harvard Electronics Laboratory

At MIT

- The Servomechanisms Laboratory Gordon Brown
- The Instrumentation Laboratory Charles Stark Draper

# The Radiation Laboratory (RadLab) 1940–45

- Not an MIT Lab but a lab at MIT
- Radar research and development - the Rad Lab disguise
- August 16 1940 visit by Tizard commission worked out plans with NRDC (Bush) for lab with civilian and academic staff for radar development
- October 16 DuBridge hired as lab director
- Strong industrial collaboration Bell Labs GE, Westinghouse, Sperry, RCA
- About 4000 people
- Closed Dec 31 1945 reborn as the MIT Research Laboratory for Electronics (RLE)

  Microwave and physical electronics, microwave physics, communications, electronics, computation
- The Radiation Lab Series
- Run by MIT staffed by MIT faculty, Bell Labs, Sperry Gyroscope, GE, Taylor Instruments
- A wide range of people from many branches of industry

# Building 20 at MIT


- The Sata Center: Ray and Maria Sata (founder of Analog Devices)
- Tech Model Railroad Club, cradle of hacking

# The Radiation Lab Series

*MASSACHUSETTS INSTITUTE OF TECHNOLOGY*

## RADIATION LABORATORY SERIES



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## THEORY OF SERVOMECHANISMS

*Edited by*

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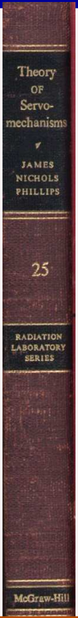
OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
NATIONAL DEFENSE RESEARCH COMMITTEE

RADIATION LABORATORY · M.I.T. · CAMBRIDGE · MASS · 1940-1945

# James Nichols Phillips

1. Servosystems
2. Mathematical Background
   - Filters
   - The Weighting Function
   - The Frequency-Response Function
   - The Laplace Transform
   - The Transfer Function
   - Systems with Feedback
3. Servo Elements
4. General Design Principles for Servomechanisms
5. Filters and Servo Systems with Pulsed Data
6. Statistical Properties of Time-variable Data
7. RMS-Error Criterion in Servomechanism Design
8. Application of the New Design Method



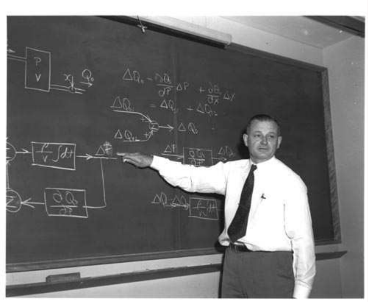
# The Servomechanism Laboratory

- EE at MIT Jackson → Bush → Hazen → Brown
- Hazen's papers on servomechanisms

  Hazen, H. L. Theory of servomechanisms. Journal Franklin Institute 1934
  Hazen, H. L. Design and test of high performance servo-mechanisms. Journal Franklin Institute 1934
- Request from US Navy for a course based on Hazen's 1939 papers
- The Servomechanism laboratory formed in 1940 with strong support from Navy and NRDC
- One of MITs first contracts with NDRC 1940
- The lab spirit: make commitments get things done.
- Brown and Campbell *Servomechanism theory*

# Gordon Brown

- Born in Australia 1907
- Came to US 1922
- BS MIT 1931
- Worked for Bush on the integraph for Sc.D.
- Assistant Professor 1939



- Hazen proposed to start research on servomechanisms
- The Servomechanism Laboratory 1940
- Dean EE 1952-1957

# The Lab Spirit

In the Servo Lab, says Brown, the presiding spirit was a drive to get things done on time. Unlike many other academic laboratories (except for that of Draper, who was pursuing similar lines), this one undertook real engineering development projects on contract, a novel experience even for a school of engineering at that time. Thus, asserts Brown with pride, the faculty and students worked "in an interdisciplinary environment on relatively new and authentic problems that had not been tackled before, in ways whereby they carried responsibility to get them done". In weapons development, he observes, "we'd never seen a hydraulic control system in our lives until we actually had a 40-mm gun control in the lab".

# The Lab Spirit ...

The gun control Brown’s lab developed went to the Army and then out to actual combat operation. Eventually, 40,000 of them were manufactured by American industry. “This was contrary”, Brown continues, “to the academic doctrine that you should never do anything in a rush, you should never have deadlines, you should be allowed to live in an ivory tower world of dabbling”. A fundamental shift of outlook was taking place in the wartime period – a true practicum was biting deeper into engineering training.

# The Servomechanism Laboratory

- Started by Brown 1940
  - Development of Servomechanisms
  - Numerically Controlled machine Tools
  - The computer language APT
  - The flight simulator Jay Forrester.
    - Analog – digital Whirlwind – DEC PDP8
    - The core memory
  - Hybrid analog computing
- RLE $\Rightarrow$ the Electronic Systems Laboratory ESL 1959
  - Newton, Gould, Kaiser, Schweppe
  - Athans, Brockett, Zames, Willems, Mitter, Glover, ...
  - More than 377 degrees (MS and PhD) from 1963 to 1971
  - Michael Athans director 1974, very dynamic leadership
- ESL became an interdepartmental lab in 1978, renamed Laboratory for Information and Decision Systems LIDS
- Sanjoy Mitter director 1981

# The Instrumentation Laboratory

Mission

- Gyros, gun-sights, inertial navigation
- Research and education directly for the military
- Component and system development and manufacturing
- Drapers Club

Accomplishments

- Gun-sight Mark 14 operational 1942

  About 100000 designed by Draper and built by Sperry
- Febe navigation system 1949
- Spire all inertial system 1955
- Polaris inertial navigation system 1950-1964
- Missile guidance: Thor, Titan 1950-1960
- Apollo Command and Lunar Landing Modules 1960

# Charles Stark Draper - The Draper Lab

- Born Winsor MI 1901
- BS Psychology Stanford 1922
- SB Electrochemical Engineering MIT 1926
- Army Air Corps Texas 1927
- MS MIT 1928
- PhD Physics MIT 1938
- Founded Instrumentation Laboratory 1938
- Laboratory spun off as the Draper Lab 1973
- The Draper Medal NAE

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# Harold Hazen

- PhD thesis with Spencer on the Network Analyzer 1924
- Worked am short while at GE Schenectady
- Returned to MIT 1925 assistant to Bush
- Curve follower for the differential analyzer
- Theory of Servomechanisms (1934) J. of Franklin Institute
- Design and Test of a High Performance Servo (1934) J. Franklin Institute
- Connection of servos to many other areas
- Course on Servomechanism to US Navy 1939 Bush, Hazen, Brown
- Brown started Laboratory at MIT

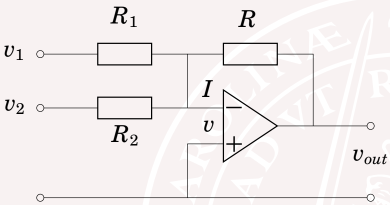
# Automatic Control Emerges

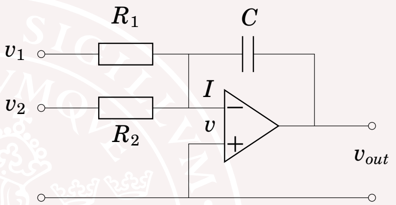
- A generic way to look at a wide range of problems
    - Block diagrams
- Linear theory
    - Laplace transforms, transfer functions, Nyquist's criterion
- Frequency response for identification
- Nonlinear theory
    - Describing functions, phase plane
- Stochastic theory
    - Wiener filtering and min square design
- Sampled data systems
- Graphics based design methods
    - Bode, Nyquist and Nichols plots
    - Root locus
- Analog techniques
    - Simulation, implementation, HIL verification

# The Operational Amplifier

- Amplifier as a component
- Schwartzel Bell Labs 1941
- Ragazzini Colombia 1943
- George Philbrick
  - Experiments with electronics at Foxboro
  - NRDC panel
  - Philbrick Research Inc. 1947
- Burr Brown Arizona 1956
- National Semiconductors 1959
- Analog Devices 1965
- Field Programmable Analog Array (FPAA)

# Analog Computing II



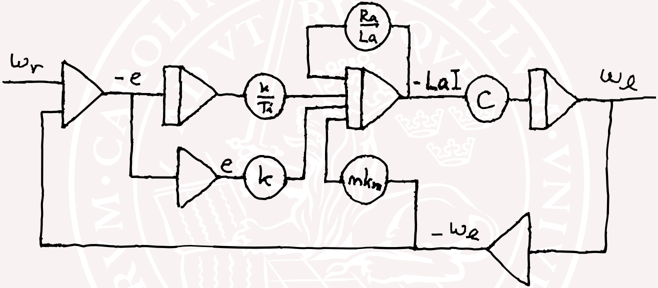




$$v_{out} = -\frac{R}{R_1} v_1 - \frac{R}{R_2} v_2$$

$$v_{out} = -\frac{1}{R_1 C} \int v_1 dt - \frac{1}{R_2 C} \int v_2 dt$$

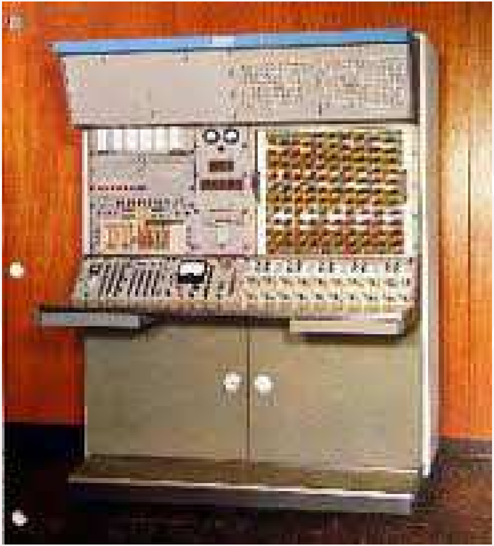
- Standard way to implement controllers
- The Electronic Differential Analyzer 1950
- EAI, Applied Dynamics, Telefunken
- Home brews
- Widespread use of analog computing

# Graphic Representation




Operations: pot set, initial, operate

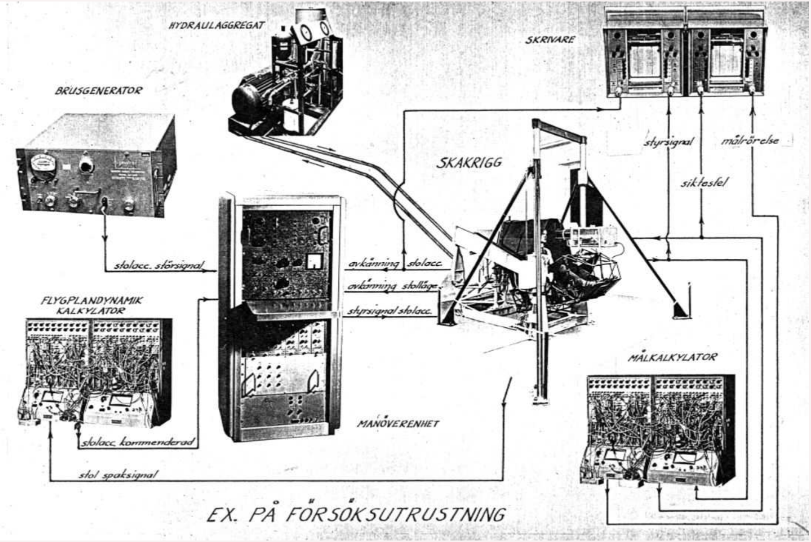
# EAI 231



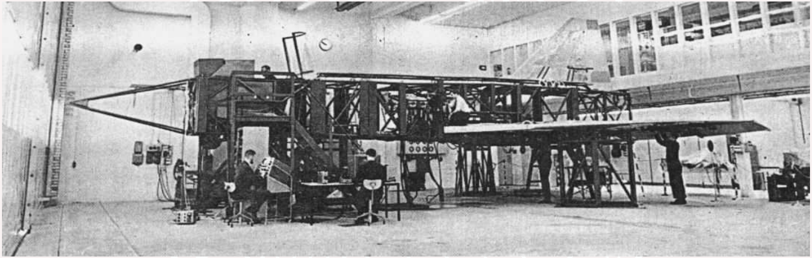
# Analog Computing

+ Closeness to the problem, scaling and amplifier overload indication
+ Man-machine interface
+ Fast solution inherently parallel
+ Repetitive operation
- Granularity, integration, addition, multiplication, function generation
- Structuring
- Time consuming
- Nonlinearities
- Documentation, birds nests and pot lists
- Cost

# Hardware in the Loop Simulation



# Iron Bird



# Consequences

- Education in control spread like wildfire all over the world
- Conferences
- A strong organizational base was created

  Industrial Instruments and Regulator Committee of the Process industries Division of ASME 1936 (transformed in several stages to Dynamic Systems, Measurement and Control Division 1978)

  IRE Professional Group on Automatic Control PGAC October 5, 1954 (transformed to the IEEE Control Systems Society 1984)

  International Federation of Automatic Control IFAC 1956
- Books
- Industrialization

# Conferences

- The Cranfield Conference. July 31 1951. Department of Scientific and Industrial Research, IEE and IMechE UK.

  A. Tustin (editor) Automatic and Manual Control - Proceedings of the 1951 Cranfield Conference. Butterworth, London 1952.
- The Frequency Response Symposium. New York Dec 1-2, 1943. Part of ASME annual meeting.
  - Rufus Oldenburger (editor) Frequency Response. MacMillan, New York 1955. The volume was dedicated to Nyquist.
- Regelungstechnik - Moderne Theorien und ihre Verwendbarkeit. Heidelberg Sept 25-26 1956. VDI/VDE-Fachgruppe Regelungstechnik (founded 1938). Provisional committee for formation of IFAC with National memberships signed by 30 participants.
- The First IFAC World Congress. Moscow 1960.

# Some Classic Books

- L. A. MacColl, Fundamental Theory of Servomechanisms 1945
- James Nichols Phillips, Theory of Servomechanisms 1947
- G. Evangelisti and N. Z. Editore La Regolazione delle Turbine Idrauliche, 1947
- G. S. Brown and D. P. Campbell Principle of Servomechanisms 1948
- N. Wiener Cybernetics: Or Control and Communication in the Animal and the Machine, 1948
- Wiener Extrapolation, Interpolation and Smoothing of Stationary Time Series, 1949 (Printed version of the Yellow Peril)
- Oldenburg Sartorius, The Dynamics of Automatic Control, 1949
- A. Porter, Introduction to Servomechanisms, 1950
- A. Colino Teoria des Servomecanismos, 1950

# Some Classic Books ...

- Chestnut and Meyer Servomechanisms and Regulating System Design Vol 1 and 2 1951.
- G. A. Korn and T. M. Korn Electronic Analog Computers, 1952
- Tsien Engineering Cybernetics, 1952
- A. W. Porter, Introduction to Servomechanisms, 1953
- J. C. West, Textbook of Servomechanisms, 1953
- A. A. Voronov, Elements of the Theory of Automatic Regulation, 1954
- W. R. Evans, Control System Dynamics, 1954
- Oppelt Kleines Handbuch technischer Regelvorgänge 1954
- Truxal Feedback Theory and Control System Synthesis, 1954

# Some Classic Books ...

- V. V. Solodovnikov Foundations of automatic regulation: theory, 1954
- Newton, Gould and Kaiser Analytical Design of Linear Feedback Controls, 1957
- J. H. Laning and R. H. Battin, Random Processes in Automatic Control, 1958
- Wiener Nonlinear Problems in Random Theory, 1958
- Ragazzini and Franklin, Sampled-Data Control Systems, 1958
- M. A. Aizerman Lectures on the theory of automatic control, 1958
- Gille, Pelegrin and Decaulne Feedback Control Systems - Analysis, Synthesis and Design 1959

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# Summary

- Creation of Automatic Control was driven by War effort
- Coherent theory and basic design methods

  Linear, nonlinear, stochastic
  Identification by frequency response
- Dramatically better technology for implementation by electronic analog computers
- Simulation tools based on analog computing
- Text books

  By 1960 there were at lease 36 textbooks in 14 countries
  USA, Soviet Union and Germany $\geq 5$.
  Education in practically all engineering schools
- Strong national and international organization IFAC
- Mass production of fire control systems and autopilots

# Reflections

- Control – the first systems field
- Why did it not happen at Bell Labs, the instrumentation companies, the process industry and their suppliers?
- Role of multidisciplinary research groups of critical size
- Terminating the Radiation Laboratory

  Wise move to publish!
- What happened afterwards at MIT?

  LIDS still a premier research group

  Draper lab a not-for-profit research and development laboratory with 1400+ employees
- The role of academia

# References


- David A. Mindell, Between Human and Machine - Feedback, Control and Computing before Cybernetics. The John Hopkins Press 2002
- Donald MacKenzie, Inventing Accuracy - A Historical Sociology of Nuclear Missile Guidance. MIT Press 1990