Servomechanism Theory

K. J. Åström

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Introduction

- Feedback invented and used in many areas often with revolutionary consequences
  - Steam engines
  - Electric power
  - Process control
  - Vehicle control
  - Telecommunications
- Similarities of different fields not recognized
- Appropriate tools of abstraction were missing
- Books such as Tolle (1905) Joukowsky (1909) well established in special field
- Little influence from academic
- Max Schuler at Göttingen since 1923 Dept of Applied Mechanics
- Kupfmüller 1220

Interview with Oppelt 1992

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.

EE an MIT

Started as part of Physics Department

- Louis Duncan 1902-1904
- Harry E Clifford 1904-1907
- Dugald C Jackson 1907-1938
- Edward L Moreland 1935-1938
- Harold Hazen 1938-1952
- Gordon Brown 1952-1959

Electrical Power Networks

- Interconnection of power networks
- Transient behavior of power networks
- Superpower ≈ 1920
- The role of Jackson
- 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 case in engineering problems
- Network Analyzers

Vannevar Bush

- PhD Dissertation on Heaviside Calculus
- Took **one year** to complete.
- Applications to power transmission
- Courses that were taken over by Gardner and Barnes who introduced Laplace transforms Transients in Linear Systems 1942
- Many smart students among them Harold Hazen
- The Product Integraph 1925
- The Differential Analyze 1928–
- The improved DA
- Network Analyzers

The MIT Network Analyzer

The Differential Analyzers

- The Product Integraph 1925
- The Differential Analyze 1928–
- The Rockefeller Differential Analyzer 1941
- Following
  - Ballistics Laboratory Aberdeen
  - University of Pennsylvania
  - General Electric Schenectady
  - University of Manchester Hartree and Porter
  - Queens University Massey Belfast
  - Cambridge University Lennard-Jones
  - University of Oslo Rosseland
  - Energy Institute Leningrad
  - Chalmers

The Computing Integraph

Bush , Kershaw, Kear, Hazen, Gardner

The First Differential Analyzer

The Rockefeller Differential Analyzer

Harold Hazen

- PhD with Spencer on the Network Analyzer 1924
- Worked a short while at GE Schenectady
- Returned to MIT 1925 assistant to Bush
- Curve follower for the differential analyzer
- Power gain 10^{11}
- 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

Harold Hazen

Hazen's Paper

- Clear understanding of the role of feedback: For a simple vacuum tube amplifier the linear response was due to to the constancy of the parameters within the amplifier. Any departure from constancy of these parameters affects the relation between input and output directly. For a servomechanism, however, the only function of the servo-amplifier element is to apply sufficient force to the servo output to bring it rapidly to the correspondence of the servo input. Such an amplifier can be a relatively crude affair.
- Blacks work was not published at the time
- Was aware of Nyquist but did not see the connection.
- Relay feedback and continuous feedback
- Relation to other fields Minorsky, Process Control

War Pressures

- Fire Control
- Gun sights
- Aircraft Instruments
- Voltage stabilization for aircraft generators
- Process Control in Los Alamos
- USA NRCD
- UK Servo-Panel
- Germany VDI

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
- High frequency generation
- Intense radar development

The UK Effort

- Experiments with radar in mid 1930
- Admiralty Signals School (ASE)
- Air Defense Experiment Establishment (ADEE)
- Lindemann and Churchill 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
  - Douglas Hartree
  - Porter
  - Arnold Tustin

Arnold Tustin

- Metro Vickers 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 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 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 Bush
- Clear command lines

The Radiation Laboratory 1942-1945

- Not an MIT Lab but a lab at MIT
- Largely staffed by outsiders
- A wide range of people from many branches of science with a focused mission
- Run by MIT
- About 4000 people
- The Radiation Lab Series
- James Nichols Phillips

Radiation Lab Activities

James, Nichols, Phillips

Servomechanism Theory

- A generic way to look at a wide range of problems
- Block diagrams
- Linearization
- Frequency response for identification
- Laplace transforms
- Nyquist stability theory
- Bodes theory
- Graphical design methods
- Hall and Nichols charts
- Experimental validation
- Implementation with analog techniques

Gordon Brown

- Born in Australia 1907
- Came to US 1922
- BS MIT 1931
- Worked on the integraph for Sc.D.
- Assistant Professor 1939
- Hazen proposed to start on servomechanisms
- The Servomechanism Laboratory
- Dean EE 1952-1957

Gordon Brown

The Servomechanism Laboratory

- Hazens course for the Navy
- Gordon Brown
- Dugald Jackson's outlook had worked closely with Bush and Hazen
- Make commitments
- Get things done
- Take industrial contracts
- One of MITs first contracts with NDRC 1940
- Brown and Campbell Servomechanism theory

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".

The Lab Spirit, cont

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 gun control Browns 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

- Development of Servomechanisms
- Reintjes director 1953
- Process Control
- Numerically Controlled machine Tools
- The computer language APT
- The flight simulator
  - Analog – digital Whirlwind – DEC PDP8
  - The core memory
- The Electronics Research Laboratory 1959
  - Newton Gould Kaiser
  - Brockett, Willems
  - Schweppe
  - Athans, Mitter
- More than 377 degrees (MS and PhD) from 1963 to 1971
- LIDS 1971

Other MIT Laboratories

- The Instrumentation Laboratory
- Charles Stark Draper
- Gun sights
- Gyros
- Inertial guidance
- Apollo
- The Draper Lab
- The Lincoln Lab

The Classical Books

- James Nichols Phillips, 1947
- Brown and Campbell Principle of Servomechanisms 1948.
- Oldenburg Sartorius, The Dynamics of Automatic Control, 1949
- Chestnut and Meyer Servomechanisms and Regulating System Design Vol 1 and 2 1951.
- Tsien Engineering Cybernetics, 1952
- Truxal Feedback Theory and Control System Synthesis, 1954

Conclusions

- Driving forces
- Automatic Control had arrived
- Its substance
  - The idea of feedback
  - Modeling identification
  - Analysis
  - Design
  - Implementation
  - Why did this not happen at Bell labs
  - Why did this not happen at the instrumentation companies
- Multidisciplinary research labs
- The role of academia
- The research University
- What happened afterwards at MIT?