Ships, Aircrafts and Space Vehicles

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3. Airplanes
4. Space
5. Simulation
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Introduction

- Driving forces: Emerging technologies such as expanded use of steam power, airplanes, space ships
- New components
  - Actuators
    - Flywheels
    - Steam servos
    - Hydraulic servos
  - Sensors
    - Gyros
    - Pendulums
    - Accelerometers
- Control principles
  - PID rediscovered
- New elements
  - Integrated process and control design
  - Mission critical applications
  - Man-in-the-loop

Ships

- Era of large steam ships
  - 1835 Great Western Railway Company
  - 1837 Great Western Bristol-New York
  - 1845 Great Britain
  - 1859 Great Eastern
- Engine control
  - Open loop Augusta 1855
  - Closed loop steam servo Great Eastern
- Steering
- Servo motor (Servomoteur)
- Roll stabilization
- Gun-turrets
- Torpedos
- Submarines

Hydraulic Steering Engines

- Drawback of steam
- 1870 A. B. Brown patent on hydraulic servomechanism
- Servo-moteur 1868 Jean Joseph Farcot
- Farcot: Le servo-moteur ou moteur asservi (1873)
- Multi-stage systems
- “A helmsman exerts 3-4 kg go operate the rudder which requires loads as high as 10000 kg.
- Could operate large 800kW engines
- Constant pressure fixed displacement pumps and accumulators
- Variable stroke pumps 1911
- Hele-Shaw and Martineau: Measurement of dynamic input output characteristics

Picture of Farcos 2 Stage Servo

Torpedos

- Most advanced control systems in the late 1800
- Robert Whitehead showed a torpedo driven by pneumatic engine at Fiume for Austrian Navy in 1869
- Great interest from England
- Whitehead torpedos built for the Admiralty
- Depth control
  - The secret - proportional feedback from depth and attitude
- In the US the Howell torpedo driven by heavy flywheel (10000 rpm). Depth control by mechanical servo powered from flywheel. Flywheel acted as a gyro, roll tendency compensated for by feedback.
- 1895 Ludwig Obry of the Austrian Navy invented gyroscope for use in torpedo.

Stabilization and Steering of Ships

- Impact of gyros
  - Gyrostabilization Schlick 1904
  - Anschütz gyro compass 1906
  - Sperry 1908 active stablilizer
  - Brown gyrocompass in UK 1916
- Automatic steering
- Werner Siemens automatic steering of torpedo boats 1872-74. Rudder operated by electric motor, relays, connected to magnetic needle.
- Connect steering engine to gyrocompass
- Brown failed with proportional control
- Similar problems encountered with torpedoes
- Problem was fixed by Sir James B. Henderson in 1913 with ‘check helm’ (derivative action), obtained by a rate gyro

Sperry’s Gyropilot - Metal Mike

- Work started 1912
- Sperry’s philosophy: "An experienced helms man should ‘meet’ the helm, that is, back off the helm and put it over the other way to prevent the angular momentum of the ship carrying it past the desired heading."
- Compare with Fuzzy control
- Patent on anticipator applied 1914
- Patent granted 1920
- Trials April and October 1922
- ‘The metal-Mike behaved like an experienced helmsman.’
- By 1932 more than 400 systems installed
- How to understand Sperry’s scheme?

Block Diagram of Metal Mike

Minorsky

- Born 1885 in Karcheva
- Imperial Technical School St. Petersburg
- Joined Russian Navy 1917
- Emigrated USA 1918
- Assistant to Steimetz at GE Research
- Experiments with US Navy 1922 PID
- Successful but never pursued
- Patents given to Bendix 1930

Minorsky

Directional stability of automatically steered bodies J. Am. Soc. Naval Eng. 34 (1922) 284-

Model

$$J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} = K\delta + M_d$$

Systematic exploration of different controller structures

$$\delta = -k_1\theta - k_2\frac{d\theta}{dt} - k_3\frac{d^2\theta}{dt^2}$$

$$\frac{\delta}{dt} = -k_1\theta - k_2\frac{d\theta}{dt} - k_3\frac{d^2\theta}{dt^2}$$

$$\frac{d\delta}{dt} = -k_1\theta - k_2\frac{d\theta}{dt} - k_3\frac{d^2\theta}{dt^2}$$

$$\frac{d^2\delta}{dt^2} = -k_1\theta - k_2\frac{d\theta}{dt} - k_3\frac{d^2\theta}{dt^2}$$

First class, second class, third class etc.

Ship with First Class Controller

Ship

$$J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} = K\delta + M_d$$

Controller

$$\delta = -k_1\theta - k_2\frac{d\theta}{dt} - k_3\frac{d^2\theta}{dt^2}$$

Closed loop system

$$(J + Kk_3)\frac{d^2\theta}{dt^2} + (D + Kk_2)\frac{d\theta}{dt} + k_1\theta = M_D$$

The control system provides virtual inertia, virtual damping and virtual spring.

Compare with our servo lab!

Ship with Second Class Controller

Ship

$$J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} = K\delta + M_d$$

Controller

$$\frac{d\delta}{dt} = -k_1\theta - k_2\frac{d\theta}{dt} - k_3\frac{d^2\theta}{dt^2}$$

Closed loop system

$$J\frac{d^3\theta}{dt^3} + (D + Kk_3)\frac{d^2\theta}{dt^2} + Kk_2\frac{d\theta}{dt} + Kk_1\theta = \frac{dM_d}{dt}$$

A constant disturbance torque will not give any steady state heading deviation! Integral action!

Controller can influence all terms of characteristic equation, hence complete freedom!

Refers to Blondel (1919) and Hurwitz for stability analysis.

$$(D + Kk_3) + Kk_1 > JKk_1$$

Practical Experiments

Sea trials battleship USS New Mexico 1923.

First controller

$$\delta = -k_1\theta - k_2\frac{d\theta}{dt}$$

Deviation and check helm!

Deviations around $6°$ Confusion because of integrating action i rudder engine. Increasing k_2 reduced fluctuations to $2°$.

When acceleration term was added fluctuations were down to $1/6°$

Considerable practical problems in implementation, sensors and controllers.

Minorsky's work had little impact compared with Sperry and Anschütz who had lots of practical experience and skilled engineers. Sperry had 400 autopilots in operation by 1932.

Minorsky gave up his patents to Bendix in 1930.

Summary of Ship Steering

- Large ships required steering engines
- The birth of the servo motor
- Uppfinnar-Jocke vs Professor Kalkyl
- Sperry's autopilots very successful
- Minorskys work interesting but little practical impact
- Much interesting work on torpedos

Flight Control

- Driving forces: Emergence of a new technology. Air travel and air warfare.
- Technology
  - Sensors Gyros Pendulums Accelerometers Compass
  - Actuators
  - Signal processing
- Theory versus practice
- Some new elements
  - Integrated process and control design
  - Man-in-the-loop
  - Simulation
  - Mission critical
- Flight control
- Automatic guidance
- Navigation
- Guidance

Some Dates

- 1905 Kitty Hawk
- 1912 Sperry's demonstration
- 1930-40 Mass Production of autopilots
- 1947 Robert E Lee
- 1957 Sputnik
- 19xx Apollo

The Wright Brothers

Early experimenters, Cayley, Lilienthal and Langley tried to make stable aircrafts

Wilbur Wright Western Society of Engineers 1901: Men already know how to construct wings or airplanes, which when driven through the air at sufficient speed, will not only sustain the weight of the wings themselves, but also that of the engine, and of the engineer as well. Men also know how to build engines and screws of sufficient lightness and power to drive these planes at sustaining speed ... Inability to balance an steer still confronts students of the flying problem. ... When this one feature has been worked out, the age of flying will have arrived, for all other difficulties are of minor importance.

The Robert E Lee Story

- September 23, 1947 C-54
- Sperry A-12 autopilot
- Bendix automatic throttle control
- IBM punch card equipment for course
- No human touched the controls from start until landing
- Selection of radio station, course, speed, flap setting, landing gear, final application of wheel brakes.

New York Times Sept 23, 1947

Flight Dynamics

- G. H. Bryan Stability in Aviation, Mc Millan London. 1911. Linearization, separation of longitudinal and lateral, coined "stability derivative".
- 1911 Bairstow and Melvill Jones measured stability derivatives and calculated motions of practical airplanes.
- 1924 Gates, Garner and Cowley assumed that controls moved according to certain "control laws" and calculated motion of aircraft. Garner mand provision for lag in application of control (actuator dynamics!).
- 1935 Melvill Jones: Dynamics of the Airplane, in W. Durand, editor Aerodynamic Theory, Durand Reprinting Committee, Pasadena, CA. Practical experiments that verified theory is applicable

The Role of Theory

- Routh's stability conditions known and used
- Melvill Jones: "In spite .. of the completeness of the experimental an theoretical structure ... it is undoubtedly true that, at the time of writing, calculations of this kind are very little used by any but a few research workers. It is in fact rare for anyone actually engaged upon the design of aeroplanes to make direct use of computations ..., or even to be familiar with the methods by which they are made. ... In my own opinion it is the difficulty of computation ... which as prevented designers of aeroplanes from making use of the methods. ..."

Flight Control in Germany

Driving forces:

- Regular Lufthansa flights to Moscow, London, Paris and Rome in the 1920s. Interest to keep schedules under all meteorological conditions. Instruments such as turn indicators, magnetic compass, air speed indicators used. Desire to control direction automatically.
- The Versailles Peace Treaty of June 28, 1919 prohibited Germany to have air force, tanks and heavy artillery

Major actors:

- Siemens
- Askania
- Möller-Patin
- Air Ministry
- The Army Ordinance Department

Askania

Had experience in airplane instrumentation, altimeter, air-driven turn-indicator, magnetic compass with pneumatic pickoff, airspeed indicator. Also experience with jet-tube based industrial controllers.

The course controller was based on compass, turn indicator and pneumatic actuator, a rate-gyro was added later.

First unit tested 1927 on airship "Zeppelin LZ 127". Installed by Lufthansa on Junkers W33 and Ju52 and many other planes. Result not very satisfactory because of the poor heading signal. Much improved results when a Sperry directional gyro (manufactured under license from Sperry) was used.

Mickey Mouse Picture of Askania's Autopilot

Boykow's Autopilot

Siemens Central-Laboratories. Had just finished work on radio control of target ship "Zähringen". Received order for remote controlled airplane 1927. Collaboration with Capt. Johann Maria Boykov who coined the term "Automatischer Pilot". Two free gyros (Trägheits-Rahmen" and clutch operated electric servo motors.

J. M. Boykow "Der Automatische Pilot für Flugzeuge Illustrierte Flugwoche Dez. 1938.

Flight test in Junkers W33 plane with radio control from Junkers G24. Automatic takeoff and landing was also planned.

System has hardware difficulties.

Siemens Activities

Siemens decided to go their own way under Edward Fischel, head of Labs since 1930. Good engineer with theoretical knowledge. Wanted to base the design on proven standard components (from steam-turbine Controllers.

Siemens registered the name Autopilot as a trade-mark.

Electro-hydraulic servo with rate gyro and magnetic compass later augmented by directional gyro. Lateral control was based on pendulum, airspeed indicator and barometric altimeter. Successfully tests of of three axis autopilot in 1932. Autopilot worked well for slow airplanes. Five systems built, some exported.

Air Ministry decides to go for electro-hydraulic directional control and not a three axis autopilot. A new gyro and improved electro-hydraulic servos developed. More than 100 000 gyros and 35 000 directional controllers K1Vü were manufactured up to end of WWII.

Mickey Mouse Picture of Siemens Autopilot and Directional Gyro

Askania

Compressible air had no chance against incompressible oil i servo systems for airplanes.

Askania contacted hydraulic specialist Hans Thoma. Developed a controllable three-wheel pump with slide valves. Compare with Källe!

A very small effective servo-unit 6.7 kg including oil. No problem with friction because of slide-valves. Gyros and signal transmission still pneumatic.

Intensive flight testing on Deutsche Lufthansa Focker-Wulf FW200 and Dornier Do 26 across the Atlantic with excellent results but no orders. Siemens mass production was sufficient.

Mickey Mouse Picture of Askania Hydraulic Servo

The Möller-Patin Autopilot

Möller had worked for Askania but left in 1934. Two goals:

- Pure electric control
- Match the controllers dynamic behavior to the pilot

Innovations

- Use actuator as a pure integrating device
- Added feedback from angular acceleration

Test in mid 1930 gave surprisingly good results that could not be explained (complex zeros!). Operation was very smooth because of integrator.

Later additional improvements due to simplicity of electric signal processing.

Mass Production ordered by Air Ministry.

Mickey Mouse Picture of Möller-Patin Electric Autopilot

Advances in Theory

W. Oppelt: "A general theory of flight control did not exist at that time. it was unknown that all control problems followed the same rules. In every application-filed an own "control-philosophy" arose and led sometimes to very curious ideas. Since the basis for an objective proof was available, the different opinions were presented with persistence according to the temperament of the individual."

Works by Stodola and Tolle well known.

Karl Küpfmüller "Über die Dynamik der selbstättigen Verstärkungsregler" ENT Vol 5 1928, signal flow circuits. Stability from step responses with an interesting mathematical model.

Teaching by Max Schuler, head of the Institute of Applied Mechanics in Göttingen since 1923. "Einführung in die Theorie der selbstättigen regeler." Leipzig 1956.

Leonhard 1944, Michailov 1938

Sovjet Contributions

- Vyshnegradskii
- Lyapunov
- Nikolai Egorovich Zhukovskii (Joukowsky) Theory of regulation of the motion of machines, 1909. Equivalent of Tolle's book. Remained in circulation for a long time revised edition 1933 Kotelnikov and Smirnov.
- 1934 Automation and Remote Control became a special section of the Academy of Sciences. The journal Avtomatica i Telemechanica started.
- First specialized meeting 1940
- Eletrotechnical Institute, Moscow: Solodownikov
- Boiler and Turbine
- Power Engineering
- Michailov stability criterion

Some Centers

- Alexandr Aleksandrovich Andronov 1901-1952
- In the 1930s Two centers:
  - Moscow group
  - Kiev Krylov Bogolyubov
- Kazan Aviation Institute
  - Chetaev 1946
  - Malkin 1952
- Andronovs Seminar Started 1944
  - Lurje
  - Aizerman
- Tsypkin

Confluence of Theory and Practice

- 1947-48 The Northrum YB-49 Flying Wing
- Control configured vehicle
- Hydraulic actuators
- Quasi fly-by-wire, artificial feel
- Stability augmentation (series system) of Dutch roll
- Could fly in unstable loading conditions
- Started damping fashion: yaw, short period, roll, side-slip
- 1950 Bollay Lecture
- BuAer-Northrop Volumes

The Quest for Reliability

- Mission Critical: A new responsibility for automatic control
- Analog, transistors, printed circuit boards not very reliable.
- Safety rather than reliability, hard over failures. Dual channel with force summation and limited authority
- Reliability of hardware, software and the whole development process
- From single string analog to massively parallel digital
- Designs based on sophisticated combination of control theory and simulation, Examples: F-106A, Vickers Armstrong VC-10, automatic landing systems
- Boeing 777 Full fly-by-wire

Flight Control

The Graham Mc Ruer tree

Flight Control Summary

- Integrated Process and Control Design
- Implication of being mission critical: Performance and reliability
- Man in the loop
- Reliable systems

Space Flight

- Jules Verne
- Meshcherskii late 1800
- Tsiolkovskii late 1800
- Goddard 1910-30
- Oberth 1920
- Werner van Braun V-2
- Sputnik 1957
- Apollo
- JPL and unmanned space crafts Gemini

The German Guided Missile Program

A very extensive program

- Rocket technology
- V-1
- V-2
- Radio guidance
- TV guidance
- IR guidance
- Technology: Sensors, actuators, controls
- Strong impact on future US and USSR programs

Picture of German Guided Missiles

V-2

- Work begun in 1929 because of restrictions on long-range artillery
- Create a mobile, effective weapon to strengthen a small army
- Rocket development in Kummersdorf General Dornberger and Werner von Braun started by Army Ordinance Department
- First successful shot October 3, 1942
- Military use started September 8, 1944
- 1115 V2 launched against England 2050 against Brussels, Antwerp and Liege

The V-2 Autopilot

The V-1

- Originally proposed by Air Ministry Technical Office at beginning of war. Turned down by General Staff
- Project reestablished June 10, 1942
- Development, testing, troop training and production very fast 2 years and 3 days
- Military operations began June 13, 1944 with 5000 systems
- 8000 missiles launched against London, 2000 lost immediately, about 2400 reached the target

The V-1 Autopilot

Simulation

- 1620 The slide rule
- 1790 Integrating controller
- 1850 The planimeter
- 1876 Kelvin Brothers tidal simulator
  - Ball and disk integrator
  - Proposal for general purpose analog computer
- 1929-31 The Differential Analyzer
  - Vannevar Bush, Hazen
  - The torque amplifier
  - 6 integrators
  - Copies in Manchester, Cambridge, Oslo
- The Electronic Differential Analyzer
  - The operational amplifier
  - George Philbrick, Ragazzini, EAI
- Homebrews
- 1955 SAMS

How to Simulate

- Define the purpose
- Modeling
- Transform equations to state form
- Scale the variables
- Make simulation diagrams and connect
- Set the potentiometers
- Run
- Document

Analog Computing

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

Digital Simulation

1955 Selfridge

1957 JPL, Lockheed

1958 Dial Bofors Qvarnström

1962 Dynasar General Electric

1962 MIDAS Wright Patterson

1965 MIMIC Wright Patterson

1967 CSSL Simulation Council

1967 CSMP IBM

1969 DARE Korn U of Arizona

1975 ACSL Gauthier and Michell

1975 Simnon Hilding Elmqvist

1978 Dymola Hilding Elmqvist

Discrete Event Simulation

1965 GPSS Gordon IBM

1967 Simula, Dahl

1968 Simscript Kiviat

1974 GASP Pritsker

1979 SLAM Pritsker

Conclusions

- Driving forces: Emergence of new technologies: ships, airplanes, space crafts
- Control becomes mission critical
- Integrated system design
- Confluence of theory and practice
- The role of simulation
- Ultra reliable systems
- Man in the loop
- Question: What technologies are emerging now?