Ships and Aerospace

Karl Johan Åström

Department of Automatic Control LTH
Lund University

Ships and Aerospace

K. J. Åström

1. Introduction
2. Ships
3. Early Autopilots for Aircrafts
4. German Autopilots
5. Missiles
6. Later Developments
7. Summary

Theme: Gyroscopes, powerful actuators and mission critical systems.

Lectures

		1940	1960	2000
1	Introduction			
2	Governors	|	|	|
3	Process Control	|	|	|
4	Feedback Amplifiers	|	|	|
5	Harry Nyquist	|	|	|
6	Aerospace	|	|	|
		|		
7	Servomechanisms	←	|	|
8	The Second Phase	←	←	|
9	The Third Phase	←	←	←
10	The Swedish Scene			
11	The Lund Scene			

The Power of Feedback

Feedback has some amazing properties, it can

- make a system insensitive to disturbances,
- make good systems from bad components,
- follow command signals,
- stabilize an unstable system,
- create desired behavior, for example linear behavior from nonlinear components.

The major drawbacks are that

- feedback can cause instabilities
- sensor noise is fed into the system

Introduction

- Driving forces: Emerging technologies such as expanded use of steam power, airplanes, space ships
- New components
  - Actuators
    - Flywheels, Steam servos, Hydraulic servos
  - Sensors
    - Gyroscopes, Pendulums, Accelerometers
- Control principles
  - PID rediscovered
- New elements
  - Integrated process and control design
  - Mission critical applications
  - Man-in-the-loop
- Parallels with governors up to 1910
- Interesting continuation through 1940 and beyond

Ships and Aerospace

K. J. Åström

1. Introduction
2. Ships
3. Early Autopilots for Aircrafts
4. German Autopilots
5. Missiles
6. Later Developments
7. Summary

Theme: Gyroscopes, powerful actuators and mission critical systems.

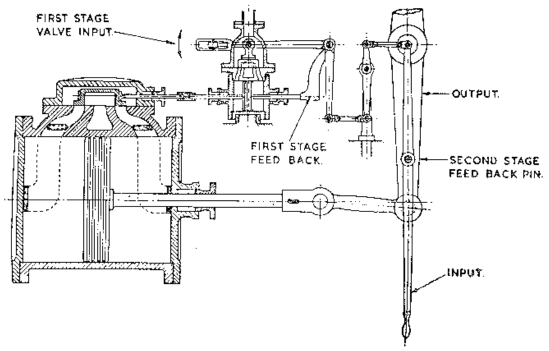
Ships

- Era of large steam ships
  - 1835 Great Western Railway Company
  - 1837 Great Western Bristol-New York
  - 1845 Great Britain
  - 1859 Great Eastern
- Engine control overlap with governors
  - 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
- Servo-moteur 1868 Jean Joseph Farcot
- 1870 A. B. Brown patent on hydraulic servomechanism
- Farcot: Le servo-moteur ou moteur asservi (1873)
- Multi-stage systems
- *A helmsman exerts 30-40 N to operate the rudder which requires loads as high as* 10^5 *N.*
- Could operate large 800 kW engines
- Constant pressure fixed displacement pumps and accumulators
- Variable stroke pumps 1911
- Hele-Shaw and Martineau: Measurement of dynamic input output characteristics

Farcos 2 Stage Servo



Feedback in the actuator

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 a gyroscope for use in torpedo.

Stabilization and Steering of Ships

- Impact of gyros

  Gyro stabilization Schlick 1904
  Anschütz gyro compass 1906 (Max Schuler)
  Sperry gyrocompass 1911
  Sperry 1908 active stabilizer
- 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 James B. Henderson in 1913 with check helm (derivative action), implemented by a rate gyro

Elmer Sperry 1860-1930

- Cornell 1878-79
- Several electric companies Sperry Electric Mining Machine Company, 1888
- Sperry Gyroscope Company 1910

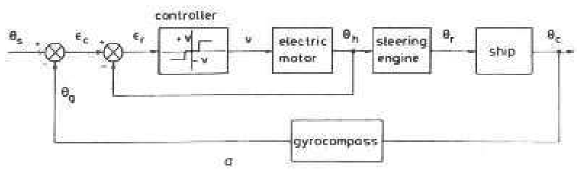
  Gyrocompass, autopilots, bomb-sights, flight control, IP
- London office 1913
  - Major supplier of gyro-compasses to Britain and Russia in competition with Anschütz
- Sperry Rand (Remington Rand) 1955 Univac Computer
- Unisys after merger with Burroughs 1986
- Sperry Marine 1913 now part of Northrup Grumman

Sperry's Gyropilot - Metal Mike

- Sperry's philosophy: "An experienced helmsman 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."

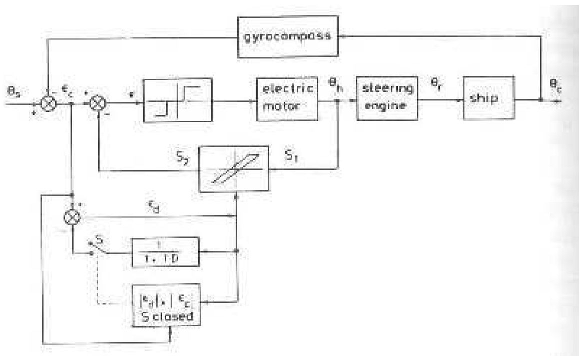
- Work started 1912
- Compare with Fuzzy control
- Patent on anticipator applied 1914, granted 1920
- Trials April and October 1922
- *The metal-Mike behaved like an experienced helmsman.*
- More than 400 systems installed by 1932

Block Diagram of Metal Mike



- Notice actuation with an electric motor, with relay as an amplifier.
- Feedback makes the combination behave as a linear system.
- Nice example of how feedback can be used to shape linear behavior from nonlinear components. See Billman regulator later.

Metal Mike 2



The Autopilot - From Sperry Manual

Controller parameters

- Rudder ratio (proportional gain $k_p = 1, 2, 3, 4$)
- Rate sensitivity (derivative gain $k_d = 0 - 135$)
- Rate signal filtering ($T_f = 0, 5, 10, 15$ factory chosen)
- Rudder bias (integral gain $k_i \approx 0.001$
- Weather adjust (dead zone max $3°$)

Under practical seaway conditions, ships are always subject to some yawing and this can create large rudder swings through the rate channel action. Such rudder swings may not contribute to course regulation of the ship since the ship's response is not fast enough, and these useless rudder swings are classified as 'rudder activity'. Rudder activity must be avoided since it induces additional drag on the ship and wear of the steering system. The solution is to filter the derivative. This filtering can be very effective, but the filter constants must be prudently chosen.

Nicholas Minorsky 1885-

- Born 1885 in Karcheva
- Imperial Technical School St. Petersburg (Vyshnegradski?)
- Joined Russian Navy 1917
- Emigrated USA 1918
- Assistant to Steimetz at GE Research
- Experiments with US Navy 1922 PID
- Successful but never pursued
- Competed with Sperry
- Patents sold to Bendix 1930
- Professor at Stanford

Minorsky 1885

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

$$\delta = -k_1\theta - k_2\frac{d\theta}{dt} - k_3\frac{d^2\theta}{dt^2} \qquad \text{first class controller}$$

$$\frac{d\delta}{dt} = -k_1\theta - k_2\frac{d\theta}{dt} - k_3\frac{d^2\theta}{dt^2} \qquad \text{second class controller}$$

$$\frac{d^2\delta}{dt^2} = -k_1\theta - k_2\frac{d\theta}{dt} - k_3\frac{d^2\theta}{dt^2} \qquad \text{third class controller}$$

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! Stability condition by Hurwitz

$$(D + Kk_3)Kk_2 > JKk_1$$

Practical Experiments

Sea trials battleship USS New Mexico 1923.

First controller

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

Deviation (proportional) and check helm (derivative)!

Deviations around 6° Confusion because of integrating action i rudder engine. Increasing k_2 reduced fluctuations to 2°. Reduced to $1/6$° when acceleration feedback was added.

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.

Lesson learned: Theory is not enough!

Summary of Ship Steering

- Similar to governors but one major difference: stronger actuators needed
- The birth of the servo motor
- Tinkering (Sperry) vs theory (Minorsky)
- Sperry's autopilots very successful
- Minorskys work interesting but marginal practical impact
- Also interesting work on torpedos
- Marginal theory development

Ships and Aerospace

K. J. Åström

1. Introduction
2. Ships
3. Early Autopilots for Aircrafts
4. German Autopilots
5. Missiles
6. Later Developments
7. Summary

Theme: Gyroscopes, powerful actuators and systems.

Flight Control Summary

- Driving forces: Emergence of a new technology. Air travel and air warfare.
- Technology

  Sensors: Gyros Pendulums Accelerometers Compass
  Actuators: Hydraulic, electric on Boeing 787
  Signal processing
- Theory versus practice
- Some new elements

  Integrated process and control design
  Man-in-the-loop
  Later Developments
  Mission critical
- Flight control
- Navigation, guidance, automatic landing

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 Wright Flyer flew in 1905

Draper on Wright

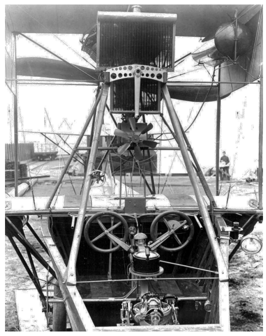
Draper Head of Department of Aeronautical Engineering and founding Director of the Instrumentation Laboratory at MIT

The 43rd Wilbur Wright Memorial Lecture before the Royal Aeronautical Society, May 19 1955.

The Wright Brothers rejected the principle that aircraft should be made inherently so stable that the human pilot would only have to steer the vehicle, playing no part in stabilization. Instead they deliberately made their airplane with negative stability and depended on the human pilot to operate the movable surface controls so that the flying system - pilot and machine - would be stable. This resulted in and increase in manoeuvrability and controllability.

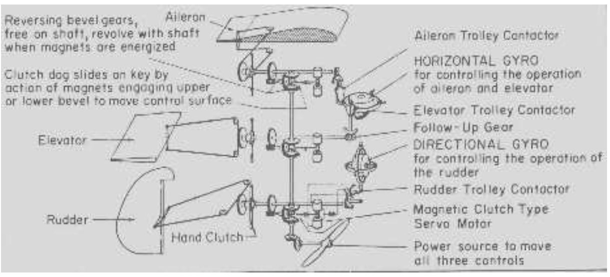
Sperry Autopilot 1914

Air Club of France: Le Concours de la Securité en Aeroplane.



Curtis Flying Boat

Sperry Autopilot 1914



- Directional and horizontal gyros
- Propeller driven air-turbine
- Solenoid clutches

The Role of Theory

- The Royal Aircraft Establishment RAE in Great Britain
- Strong applied mathematics tradition
- 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 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 made 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

Ships and Aerospace

K. J. Åström

1. Introduction
2. Ships
3. Early Autopilots for Aircrafts
4. German Autopilots
5. Missiles
6. Later Developments
7. Summary

Theme: Gyroscopes, powerful actuators and systems.

Flight Control in Germany

Driving forces:

- The Versailles Peace Treaty of June 28, 1919 prohibited Germany to have air force, tanks and heavy artillery.
- Development civil aviation, rockets and missiles
- Requirements and specifications for flight-control systems from Lufthansa who made regular 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.
- Instrument flight tedious, one person keeps the course by looking at the compass, the other holds speed and altitude. Instruments were important.

Major actors:

- Air Ministry, The Army Ordinance Department
- Industry: Anschütz, Siemens, Askania, Möller-Patin

Winfried Oppelt 1912-1999

- Dipl. ing. Technische Physik, Technische Hochschule Darmstadt 1934
- Deutsche Versuchsanstalt für Luftfahrt Berlin 1934-37
- Anschütz Kiel 1937-42
- Siemens Luftfahrtgerätewerk Berlin 1942-45
- PhD Darmstadt 1943
- TH Braunschweig 1943-47, Hartmann und Braun 1947-57
- Built a premier control department in Darmstadt
- Lecturer in EE TH Darmstadt 1952-57
- Professor TH Darmstadt 1957-77
- Kleines Handbuch technischer Regelvorgänge, 1954.
- A Historical Review of Autopilot Development, Research and Theory in Germany. ASME J. Dynamics Systems, Measurement and Control **98:3**(1976) 215-222.

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 not available, the different opinions were presented with persistence according to the temperament of the individual."

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

Karl Küpfmüller (1897-1977) Prof Darmstadt 1928. "Über die Dynamik der selbstättigen Verstärkungsregeler" ENT Vol 5 1928, circuit theory, stability, block diagrams. Stability from step responses with an interesting mathematical model.

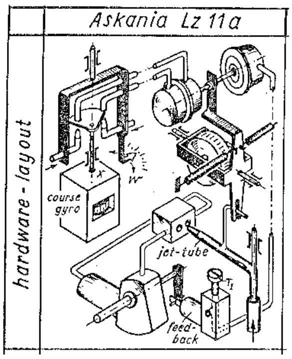
Prof Adolf Leonhard Stuttgart 1936 (1899-1995)

Askania 1927

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

- Askania
- Sensors: Altimeter, turn indicator, magnetic compass, air-speed indicator (all pneumatic)
- Actuator: pneumatic jet tube
- Test flights in 1927 airship Zeppelin LZ 127
- Production unit tested on Junkers W32 and Ju 52
- Disappointing results
- Only mean value of magnetic compass could be used for feedback, gyroscope was needed for good results
- Great improvement with gyroscope licensed from Sperry

Askania's Autopilot



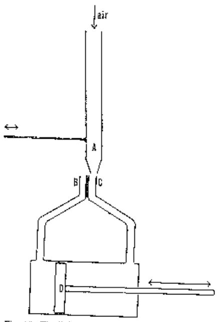


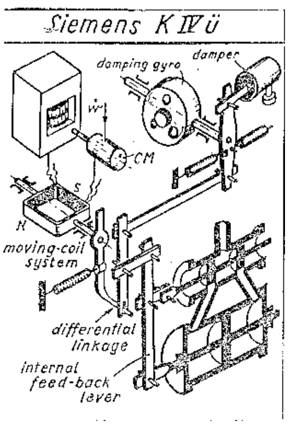
Fig. 16. The Principle of the Askania Jet Device.

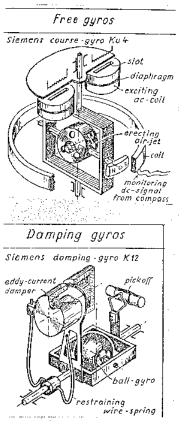
Siemens - Three axis Autopilot

Siemens Central-Laboratories had finished work on radio control of target ship "Zähringen". Collaboration with Bykov. Received order for remote controlled airplane 1927.

- Stabilization with Siemens radio- and command-link.
- Experiments with automatic take-off and landing.
- Autopilot not satisfactory, hardware problems.
- New design 1930 under Fishel.
  - Sensors: magnetic compass, rate gyro, later also directional. gyro, pendulum, airspeed, barometric altimeter.
  - Actuation: Hydraulic with internal feedback.
- Successful test 1932. Air Ministry decides to have electro-hydraulic directional control, not a three axis autopilot. New gyro and improved electro-hydraulic servos.
- Successful design used in nearly all types of airplanes.
- More than 100 000 gyros and 35 000. directional controllers K1Vü were manufactured up to end of WWII.

Siemens K IV ü





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.

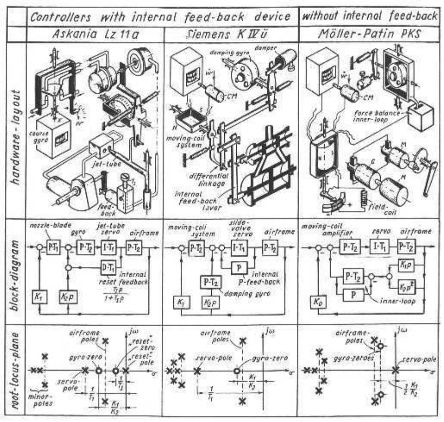
Later additional improvements due to simplicity of electric signal processing.

Mass Production ordered by Air Ministry.

Three German Autopilots

Left to right

- Askania 1927–
- Siemens 1927-
- Möller-Patin 1935



Ships and Aerospace

K. J. Åström

1. Introduction
2. Ships
3. Early Autopilots for Aircrafts
4. German Autopilots
5. Missiles
6. Later Developments
7. Summary

Theme: Gyroscopes, powerful actuators and systems.

Rockets and Missiles

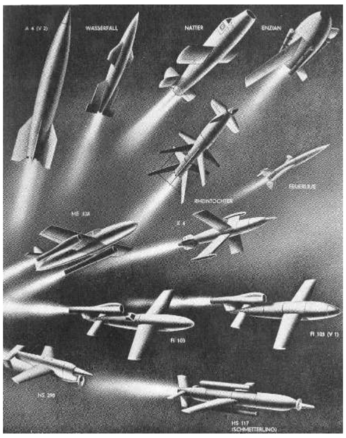
- Jules Verne
- Meshcherskii late 1800
- Tsiolkovskii late 1800
- Goddard 1910-30
- Oberth 1920
- Werner van Braun V2 (A4)
- Sputnik 1957
- Apollo
- JPL and unmanned space crafts Gemini

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

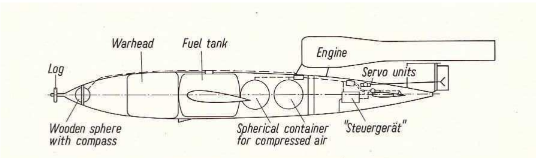
Collection of German Guided Missiles

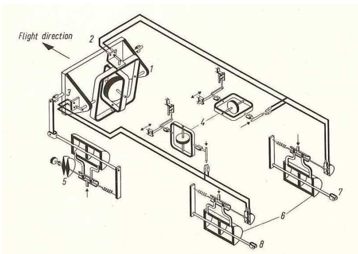


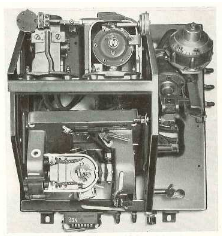
The V1 Cruise Missile

- 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 V1 Cruise Missile





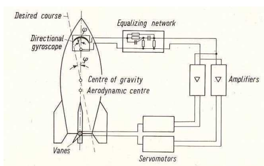


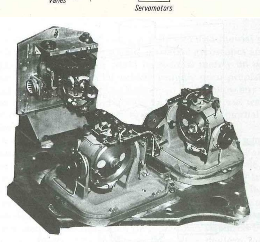
Repövning Gotska Sandön

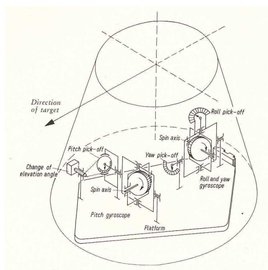
V2 Ballistic Missile

- 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
- Over 1000 V2 launched against England and more than 2000 against Brussels, Antwerp and Liege

The V-2 Autopilot







Ships and Aerospace

K. J. Åström

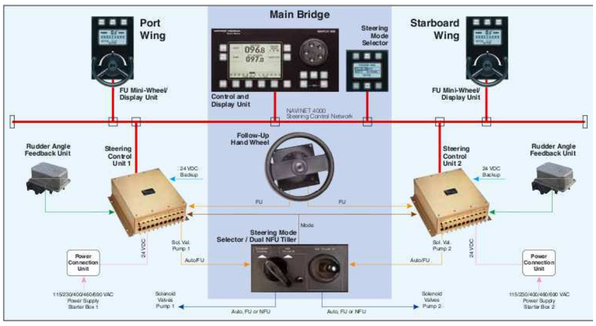
1. Introduction
2. Ships
3. Early Autopilots for Aircrafts
4. German Autopilots
5. Missiles
6. Later Developments
7. Summary

Theme: Gyroscopes, powerful actuators and systems.

An Amazing Development after 1945

- Identification of ship steering dynamics LTH
- Adaptive autopilots LTH Kockums
- Supersonic flight
- Boeing 777 and 787 and Airbus
- Extensive simulation - off line and HIL (hardware in-the-loop)
- Inertial navigation IMU and GPS
- Automatic landing
- Autonomous flight
- Space flight
  - Sputnik 1957 - The space race
  - Apollo. Kennedy speech May 25 1961. Apollo 11 landed on the moon on July 20, 1969
  - Mariner interplanetary flights 1962 to 1973

Adaptive Autopilot - Kockums SteerMaster

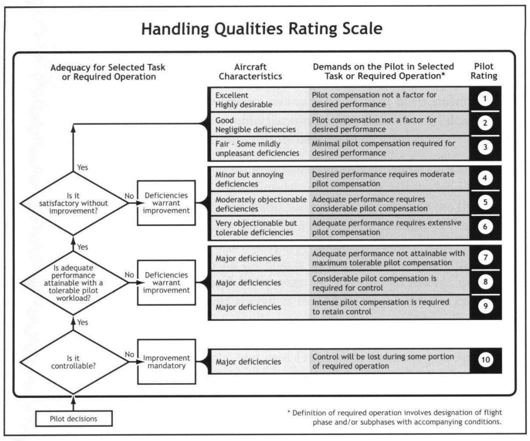


NORTHROP GRUMMAN

Human in and out of the Loop

- Behavior of humans in feedback loops
  - Humans important elements of ships and aircrafts
  - Analysis of human behavior in tracking loops
  - Measurement of the human transfer function
- The Cooper-Harper rating
  - A scale for handling quality used by test pilots and flight test engineers to evaluate the handling qualities of aircraft during flight test. The scale ranges from 1 to 10, with 1 indicating the best handling characteristics and 10 the worst. The criteria are evaluative and thus the scale is considered subjective.

Cooper-Harper Pilot Ratings



Flight Control

Lockheed Constellation 1943 - 5 person crew

- pilot, copilot, flight engineer, navigator, radio operator

Boeing 777 1995 - 2 person crew

- pilot, copilot

Autonomy

Robot-Piloted Plane Makes Safe Crossing of Atlantic

No Hand on Controls From Newfoundland to Oxfordshire—Take-Off, Flight and Landing Are Fully Automatic

By ANTHONY LEVIERO
Special to The New York Times.

WASHINGTON, Sept. 22 — Air Force spokesmen said. Two ships

The Robert E Lee Story

- September 23, 1947 C-54
- Sperry A-12 autopilot
- Bendix automatic throttle control
- IBM punch card equipment provided input to autopilots
- No human touched the controls from start until landing
- Selection of radio station, course, speed, flap setting, landing gear position, final application of wheel brakes all accomplished from program stored on punch cards.

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
- Elliott duplicate self-monitored autopilot for Vickers Armstrong VC-10. Automatic landing single failure survival. Cross connection and cross comparison. Concorde one of the lastes dual monitored auto-pilots
- Smith and De havilland UK more than 50000 automatic landings by 1980
- Boeing 777 Full fly-by-wire
- Boeing 787 Full electric

Ships and Aerospace

K. J. Åström

1. Introduction
2. Ships
3. Early Autopilots for Aircrafts
4. German Autopilots
5. Missiles
6. Later Developments
7. Summary

Theme: Gyroscopes, powerful actuators and systems.

Summary

- Driving forces: Emergence of new technologies: ships, torpedos, airplanes, missiles
- New sensors: gyroscopes
- Actuation: pneumatic, hydraulic, electric
- Control becomes mission critical
- Human in the loop
- Integrated system design
- The role of simulation
- Flight control system enabled the worlds first solo flight (115 hours) by Wiley Post in Winnie Mae July 1933
- Autonomous crossing of the Atlantic 1947
- Thousands of autopilots manufactured during WWII

References

G. H. Bryan Stability in Aviation, Mc Millan London. 1911.

L. Bairstow, B. Melvill Jones and B. A. Thompson, Investigation into the Stability of an Airplane. Aeronautical Research Council (Britain) ARC R&M 77, 1913

S. Bennett, A history of Control Engineering 1800-1930, Peter Peregrinus, IEE 1979.

S. Bennett, A history of Control Engineering 1930-1955, Peter Peregrinus, IEE 1993.

T. H. Hughes Elmer Sperry Inventor and Engineer. John Hopkins Press, Baltimore 1971.

W. Oppelt A Historical Review of Autopilot Development, Research, and Theory in Germany. Trans. ASME Journal of Dynamic Systems, Measurements, and Control. **98:3** (1976) 215–223.

D. McRuer, I. Ashkenas, D. Graham, Aircraft Dynamics and Automatic Control. Princeton 1973.

Th Beneke and A. W.Quick History of German Guided Missile Development. AGARD, Munich 1957