Ships and Aerospace

Karl Johan Åström

Department of Automatic Control LTH
Lund University

Ships and Aerospace

K. J. Åström

Ships and Aerospace

- Cutting edge technology
- Technology driver
- 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
  - Manoevrability versus stability
  - Human-in-the-loop
  - Integrated process and control design
  - Mission critical applications

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

Aerospace

- Today few dozen companies for civil and military markets
- Commercial jetliners: Boeing 787 ... Airbus 380 ... private jets, military, helicopters, missiles, satellites, UAVs
- Today a 20 billon dollar business (2×10^{10} $),
- Often cutting edge technoloty
  Hardware
  - Airplanes, missiles, satellites, gyros, accelerometers
- Simulation: analog and digital
- Control
  - Rediscovered integral action
  - Optimal control
  - Kalman filtering
- A very strong technology driver
- Very high safety standards
- Model based systems engineering
- Highly selected and skilled operators: pilots and astronauts
- Pilot in the loop
- Hardware in the loop simulation

Torpedos

- Most advanced control systems in the late 1800
- Robert Whitehead demonstrated 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.

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

Ships and Aerospace

K. J. Åström

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)

Missiles

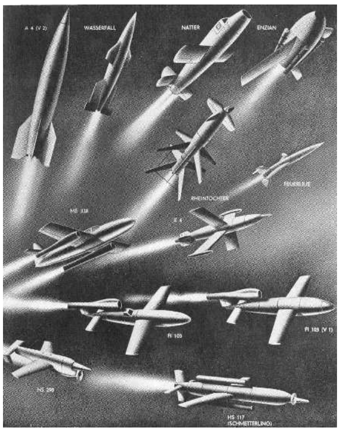
- How to achieve superior spaceflight capability
- Germany 1940-45
  - Cruise missiles V1
  - Ballistic missiles V2
- Sputnik Oct 4 1957
- Juri Gagarins April 12 1961
- Kennedy and NASA
- Apollo 11 July 1969
- Landings on Mars and Ve

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

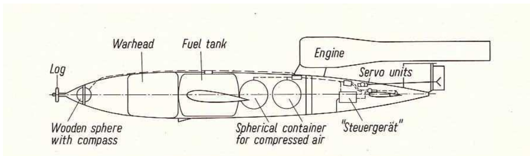
Collection of German Guided Missiles

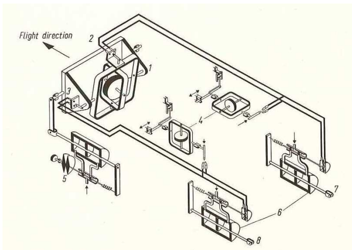


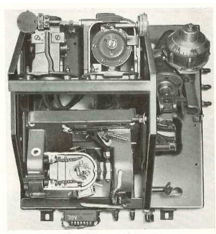
The V1 Cruise Missile

- 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





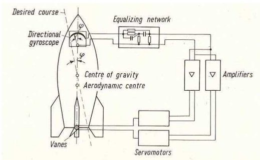


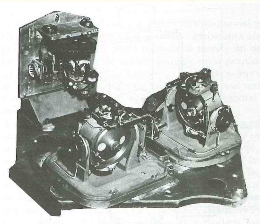
Repövning Gotska Sandön

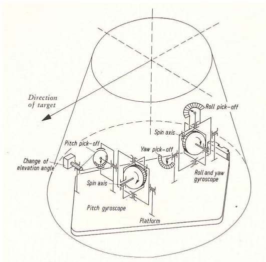
V2 Ballistic Missile

- 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 Wernher 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
- Bäckebobomben - Luthander and Boestad

The V-2 Autopilot



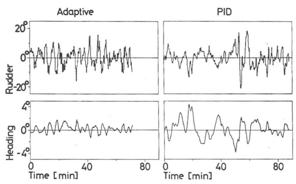




Development after 1945

- Identification of ship steering dynamics LTH
- Adaptive autopilots for ship steering LTH Kockums
- Supersonic flight Chuck Jaeger (The Right Stuff!)
- Inertial navigation IMU and GPS
- Automatic landing
- 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
- Autonomous flight
- Boeing 777 and 787 and Airbus
- Extensive simulation - off line and HIL (hardware in-the-loop)
- Model based systems engineering

Ship Steering - Kockums



Physics based initialization 3 % fuel reduction

C. Källström, KJÅ, N. E. Thorell, J. Eriksson, L. Sten, Adaptive Autopilots for Tankers, Automatica, **15** 1979, 241-254

System now marketed by Northrup-Grumman

Optimal Control 1

- John Bernoulli: The brachistochrone problem 1696
- Let a particle slide along a frictionless curve. Find the curve that takes the particle from A to B in the shortest time.

$$J(y) = \int_A^B \frac{\sqrt{1+y'^2}}{\sqrt{2gy}} dx = \int_A^B g(y, y') dx$$

- Solved by: John and James Bernoulli, Newton, l'Hospital
- Euler: Isoperimetric problems. Example largest area with given circumference.
- Functionals: Curve $\rightarrow R$
- Functional analysis

Optimal Control 2

The Golden Era of calculus of variations 1930-39: Department of Mathematics at Univeristy of Chicago was the leading place

- Refine, polish, streamline

Emerging interest in control

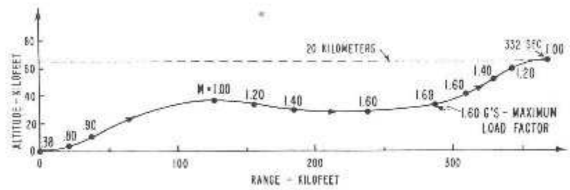
- The space race (Sputnik 1957)
- Dynamic programming, Bellman 1957 - key idea recursion
- Pontryagin's maximum principle, 1962 - key idea new perturbation
- LaSalle's bang-bang principle
- Numerical solutions
- A classical field became energized

Later developments

- Growth of computing power, numerical methods for optimzation, model predictive control MPC

Bryson's Flight ≈ 1965

Bryson (Professor at Harvard) made major computations. A nice test was on an airplane



Twice as fast as with standard procedure!
Traditional analysis prdicts that the plane cannot reach 20 km!

Ships and Aerospace

K. J. Åström

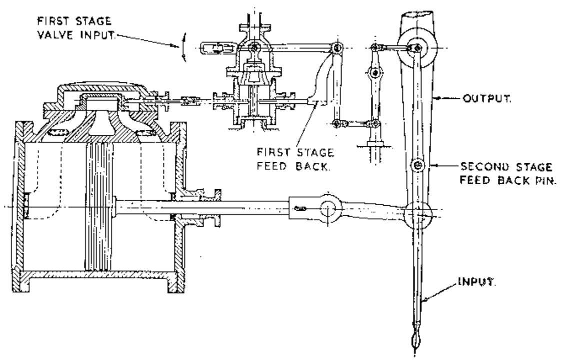
1. Introduction
2. A Little History
3. Sensing and actuation
4. Stability and Manoevrability
5. Autopilots
6. Dynamic Modeling Ships
7. Dynamic Modeling Aircrafts
8. Summary

Many Technology Issues

A continuous struggle with actuation and sensing resulted in a strong development of products and emergence of new companies

- How to generate sufficient force to steer a ship
- Load as high as 10^5 N required
- Gears necessary for humans
- Many technologies: mechanical, electrical, hydraulic
- Servo-moteur 1868 Joseph Farcot
- Brown 1870 patent on hydraulic steering engine
- Multi-stage systems

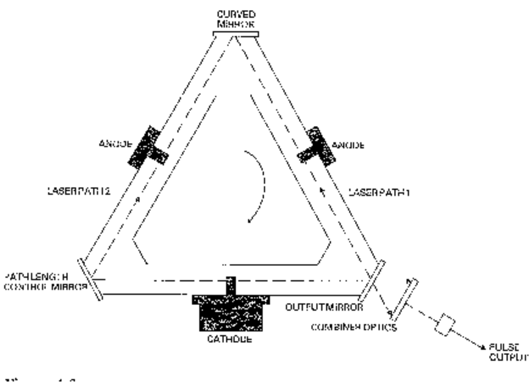
Multi-stage Servo



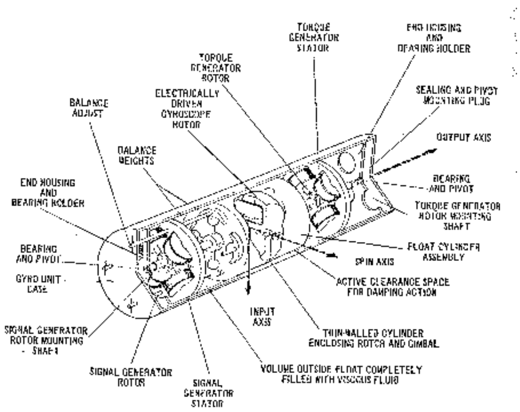
Sensing

- Position
- Gyrocompass
- Angular orientation
- Angular veloctiy
- Gyroculture

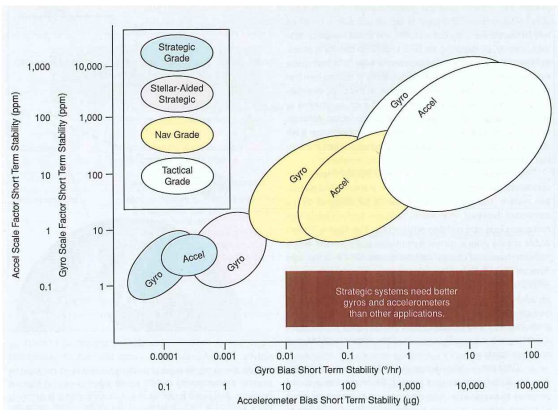
Laser Gyro



Draper Gyro



Gyro Survey



Gyro Compass

- Force the motion of a gyroscope to horisontal rotation by hanging it on a pendulum
- The gyroscope then oscillates around the north-south direction
- Disturbances due to vehicle motion
- Can be eliminated by making the pendulum having the period 84 min (Schuler tuning)

Ships and Aerospace

K. J. Åström

1. Introduction
2. A Little History
3. Sensing and actuation
4. Stability and Manoevrability
5. Autopilots
6. Dynamic Modeling Ships
7. Dynamic Modeling Aircrafts
8. Summary

Stable or Unstable Systems

- Codesign of process and controllers offer many possibilities
- Should we design processes to be stable or unstable?
  - Birds - how nature does it
  - The Wright Brothers
  - Early auto-pilots
  - Understanding of flight dynamics
  - Stable airplanes
  - High performance military aircrafts

Birds

John Maynard Smith, *The Importance of the nervous system in the evolution of animal flight.* **Evolution**, 6 (1952) 127-129.

The earliest birds pterosaurs, and flying insects were stable. This is believed to be because in the absence of a highly evolved sensory and nervous system they would have been unable to fly if they were not. To a flying animal there are great advantages to be gained by instability. Among the most obvious is manoeuvrability, it is of equal importance to an animal which catches its food in the air and to the animals upon which it preys. It appears that in the birds and at least in some insects the evolution of the sensory and nervous systems rendered the stability found in earlier forms no longer necessary.

Wilbur Wright 1901



We know how to construct airplanes. Men also know how to build engines. Inability to balance and 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

Wilbur Wright Western Society of Engineers 1901

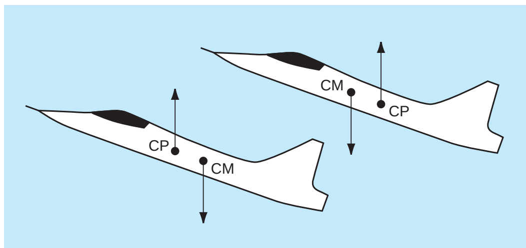
Draper on Wright



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 increased manoeuvrability and controllability.

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

JAS Gripen



- Advantages of unstable aircraft
- Unstable operating conditions
- Rate saturation due to hydraulics

Ships and Aerospace

K. J. Åström

1. Introduction
2. A Little History
3. Sensing and actuation
4. Stability and Manoevrability
5. Autopilots
   - Human in the Loop
   - Sperry and Minorsky
   - Three German Autopilots
6. Dynamic Modeling Ships
7. Dynamic Modeling Aircrafts
8. Summary

Flight Control


Lockheed Constellation 1943 - 5 person crew

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

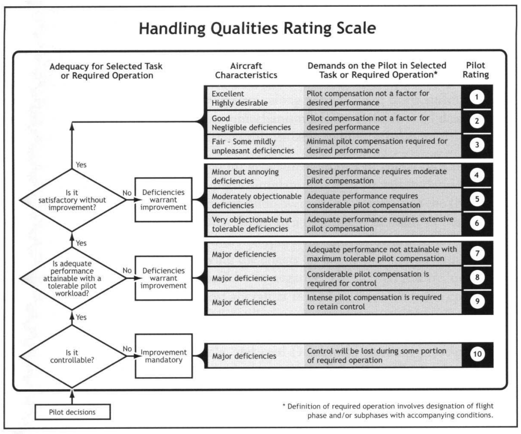
Boeing 777 1995 - 2 person crew

- pilot, copilot

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



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 — A[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.

Elmer Sperry 1860-1930

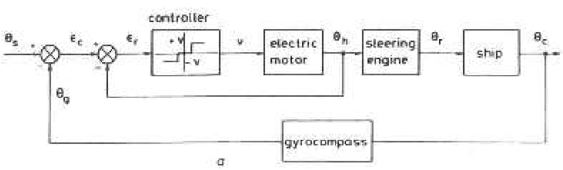
- Cornell 1878-79
- Several electric companies Sperry Electric Mining Machine Company, 1888
- Sperry Gyroscope Company 1910
  - Gyrocompass, autopilots, bomb-sights, flight control, IP
- London office 1913
  - Major supplier of gyro-compasses to Britain and Russia in competition with Anschütz
- Sperry 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."

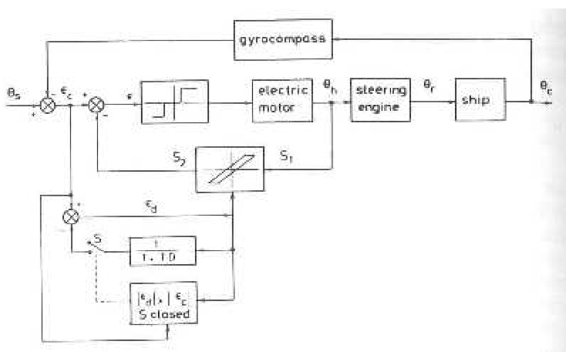
- Work started 1912
- Compare with Fuzzy control
- Patent on anticipator applied 1914, granted 1920
- Trials April and October 1922
- *The metal-Mike behaved like an experienced helmsman.*
- More than 400 systems installed by 1932

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!

Three German Autopilots

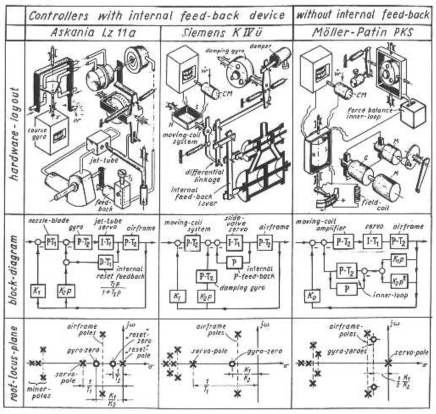
Left to right

- Askania

  1927–
- Siemens

  1927-
- Möller-Patin

  1935

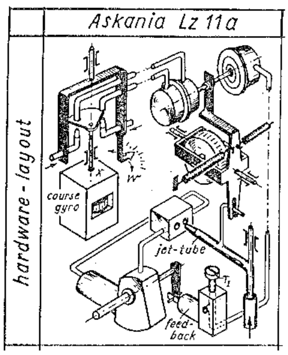


Askania 1927

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



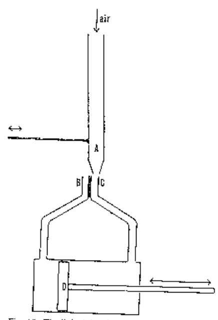


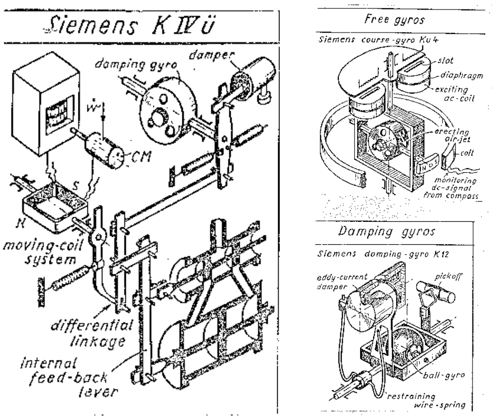
Fig. 16. The Principle of the Askania Jet Device.

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.

Ships and Aerospace

K. J. Åström

Dynamic Modeling of Ships

- Dynamics
- Wind and Waves

Equations of Motion

Mass and momentum balances

$$
\begin{aligned}
m\Big(\frac{du}{dt} - rv - y_g\frac{dr}{dt} - x_g r^2\Big) &= X && \text{surge equation}\\
m\Big(\frac{dv}{dt} + ru - x_g\frac{dr}{dt} - x_g r^2\Big) &= X && \text{sway equation}\\
J\frac{dr}{dt} + m\Big(x_g\big(\frac{dv}{dt} + ur\big) - y_g\big(\frac{du}{dt} - rv\big)\Big) &= M && \text{yaw equation}
\end{aligned}
$$

The hydrodynamic forces have the form

$$Y = Y(u, v, r, \dot u, \dot v, \dot r, \ddot u, \ddot v, \ddot r)$$

which can create nonlinear behavior.

Also notice the dependence on the second derivatives $\ddot u, \ddot v, \ddot r$. These terms are called added mass and added momentum, they are caused by the necessity to accelerate part of the water surrounding the ship.

Added Mass

The added mass can be computed by analysing the flow aroudnthe ship. For a sperical ship in an infinite flued it can be shown that the added mass is

$$\ddot Y = \frac{1}{2}\rho V$$

where V is the volume of the sphere and ρ the density of the surrounding liquid.

Scaling

The equations of motion are conveniently scaled. Introducing L length of ship, V velocity, ρ density, Δ volume displacemetn

Prime A system ρ, L, V
Prime B system ρ, L, T and V
Bis system L, ρ, g, μ, Δ

The scaled systems are surprisingly similar for many different ships

Parameters

- L length of ship
- B breadth of ship
- TF draft front
- TA draft aft
- x_g x-coordinate of center of gravity
- y_g y-coordinate of center of gravity
- RI radius of inertia
- V velocity

Two Ships

Kockums 350 000 ton Tanker

$$A = \begin{bmatrix} -0.419(-0.344) & -0.262(-0.351) \\ -2.59(-0.179) & -2.29(-1.55) \end{bmatrix}$$

$$B = \begin{bmatrix} 0.0912(0.139) \\ -0.745(-1.167) \end{bmatrix}$$

Small cargo ship 65000 ton

$$A = \begin{bmatrix} -0.505 & -0.46 \\ -2.30 & -2.28 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.122 \\ -0.955 \end{bmatrix}$$

Summary of Ship Steering

- 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
- Today reasonable models can be obtained from construction data

Ships and Aerospace

K. J. Åström

1. Introduction
2. A Little History
3. Sensing and actuation
4. Stability and Manoevrability
5. Autopilots
6. Dynamic Modeling Ships
7. Dynamic Modeling Aircrafts
8. Summary

Modeling of Flight Dynamics

Mass and momentum balances, customary to separate motions in the xz (longitudinal)

$$m\left(\frac{du}{dt} + wq - rv\right) = X$$

$$m\left(\frac{dw}{dt} + vp - wp\right) = Y$$

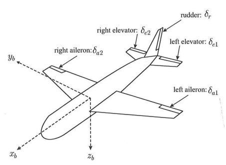
$$J_y\left(\frac{dq}{dt}\right) = M$$

and xy (lateral) planes

$$m\left(\frac{du}{dt} + qw - rv\right) = X$$

$$m\left(\frac{dv}{dt} + rv - qw\right) = Z$$

$$J_z\left(\frac{dr}{dt}\right) = N$$



Coordinates	$x\ y\ z$
Velocities	$u\ v\ w$
Angles	$\psi\ \theta\ \phi$
Angle of attack	α
Angular rates	$p\ q\ r$

Longitudinal Dynamics - Example

The linearized longitudinal dynamics for a four engine jet transport flying straight at 40000 ft with a velocity of 600 ft/sec we have

$$13.78\frac{du}{dt} + 0.088u - 0.392\alpha + 0.74\theta = 0$$

$$1.48u + 13.78\frac{d\alpha}{dt} - 13.78\frac{d\theta}{dt} + 4.46\alpha = -0.246\delta_e$$

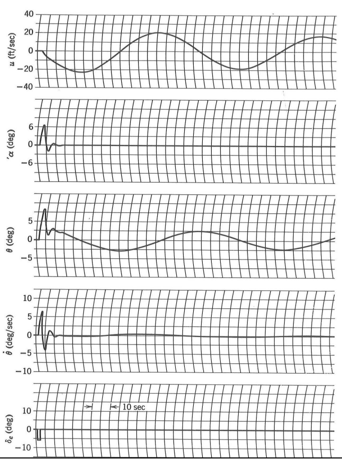
$$0.514\frac{d^2\theta}{dt^2} + 0.192\frac{d\theta}{dt} + 0.0552\frac{d\alpha}{dt} + 0.619\alpha = -0.710\delta_e$$

States: u forward velocity, α angle of attack, θ tilt angle (rotation around y-axis)

Eigenvalues: $\omega_s = 1.145$ rad/s, $\zeta_s = 0.352$ short period oscillation

$\omega_{ph} = 0.073$ rad/s, $\zeta_{ph} = 0.0734$ phugoid oscillation

Longitudinal Dynamics - Example



Lateral Dynamics

The linearized longitudinal dynamics for a four engine jet transport flying straight at 40000 ft with a velocity of 600 ft/sec we have

$$0.02725\frac{d^2\phi}{dt^2} + 0.0553\frac{d\phi}{dt} - 0.0128\frac{d\psi}{dt} + 0.057\beta = 0.0131\delta_r + 0.6\delta_a$$

$$0.585\frac{d^2\psi}{dt^2} + 0.00338\frac{d\phi}{dt} + 0.158\frac{d\psi}{dt} - 0.096\beta = 0.08\delta_r - 0.01\delta_a$$

$$4.71\frac{d\psi}{dt} + 4.71\frac{d\beta}{dt} - 0.344\phi + 0.6\beta = 0.171\delta_r$$

Eigenvalues:

$$\lambda = 0.004,\ \lambda = -2.09,\ \omega_{dr} = 1.345,\ \zeta_{dr} = 0.14$$

The oscillatory mode is called Dutch roll - an out-of-phase combination of "tail-wagging" (yaw) and rocking from side to side (roll) - like a Dutch skater

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

Ships and Aerospace

K. J. Åström

1. Introduction
2. A Little History
3. Sensing and actuation
4. Stability and Manoevrability
5. Autopilots
6. Dynamic Modeling Ships
7. Dynamic Modeling Aircrafts
8. Summary

Summary

- Many similarities between ship and flight dynamics, added mass is a major difference
- Good models can be obtained by physics, validated by tank and flight tests