POLITECNICO DI MILANO





Advanced Aerospace Control

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School of Industrial and Information Engineering

Aeronautical Engineering

- General information on the course.
- Overview of the course programme.

General information

- Marco Lovera
  - Dipartimento di Scienze e Tecnologie Aerospaziali
  - Tel. 02-23993592
  - email marco.lovera@polimi.it

- Meeting hours: Tuesday 14.30-16.30

- Course web page: accessible from

  http://www.aero.polimi.it/lovera

Course schedule

- Schedule:
  - Monday 9.30-11.15 BL27.18
  - Tuesday 11.30-13.15 BL27.11
  - Wednesday 9.30-11.15 BL27.17

- Composition of the course:
  40/45 lecture hours
  10/15 exercises, worked examples and seminars
  for a total of 6 CFU.

Exam

Two options available for the exam:

- oral exam
- a project (more on this later).

There is no mid-semester test.

Prerequisites

“Fondamenti di Automatica” or equivalent introductory course to systems and control and SISO frequency-domain analysis and design.

Key topics on which prior knowledge is assumed:

- Linear systems theory
- Stability of linear systems
- Laplace and Fourier transforms
- Frequency domain analysis of SISO linear systems
- Nyquist and Bode criteria for the stability of SISO feedback systems
- Static and dynamic performance for SISO feedback systems

(we will rapidly revise some of these topics in the first lectures)

Material

Slides – in progress, available on the web

Reference textbooks:

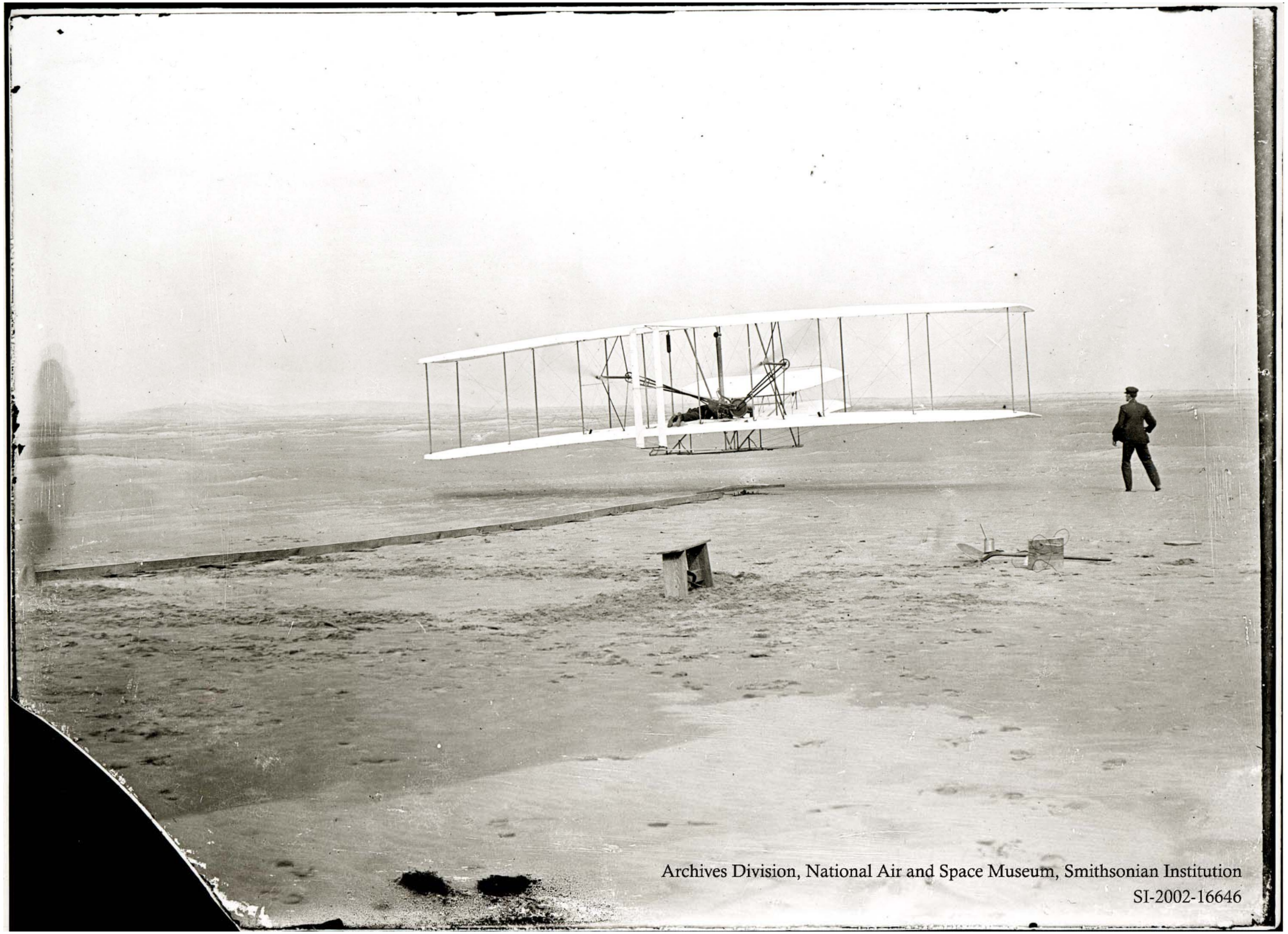
- H. K. Khalil: “Nonlinear Systems”, Prentice Hall, 2001.
- E. Lavretsky, K. Wise: “Robust and Adaptive Control with Aerospace Applications”, Springer.

  Accessible online from www.biblio.polimi.it
- S. Skogestad, I. Postlethwaite: “Multivariable Feedback Control: Analysis and Design”, Wiley, 2005.

  First three chapters available online at www.nt.ntnu.no/users/skoge/book/

Aerospace and Control?

Kitty Hawk, December 1903



The main difficulty...

“Men already know how to construct wings or airplanes…

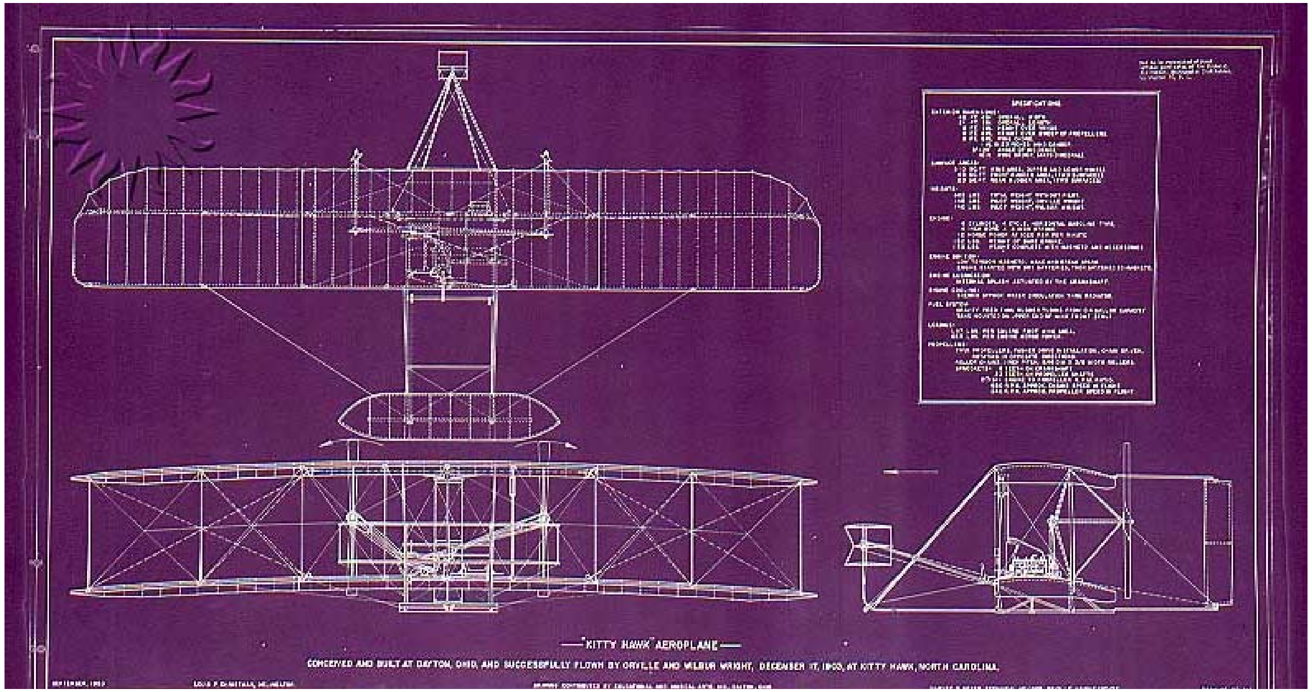
Men also know how to build engines and screws of sufficient lightness and power…

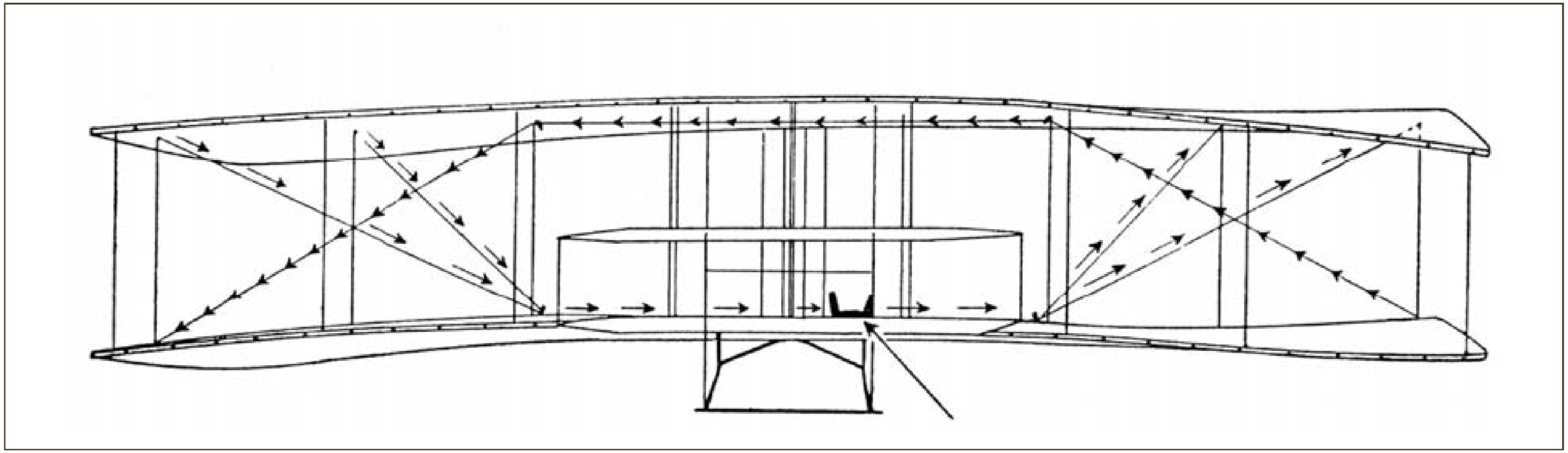
Inability to balance and steer still confronts students of the flying problem…

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, 1901.

…and the main contribution: controllability





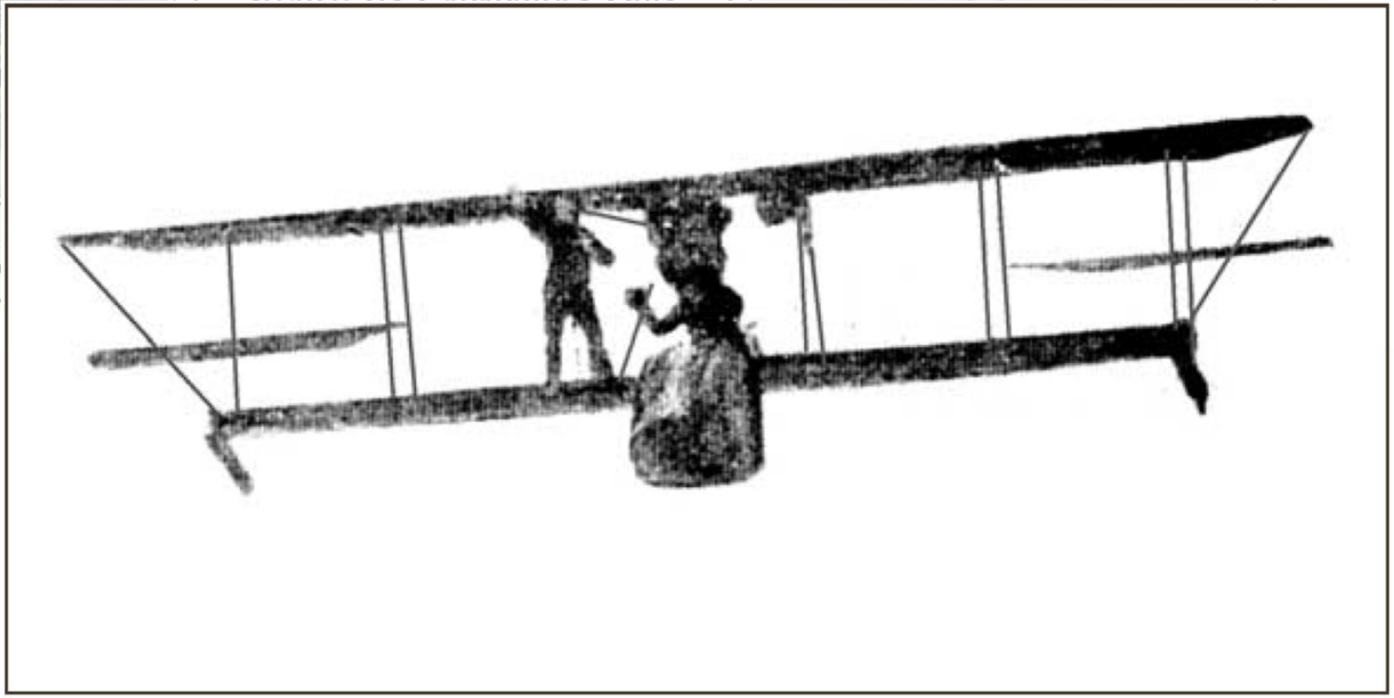
Paris, June 1914


96 SCIENTIFIC AMERICAN August 8, 1914

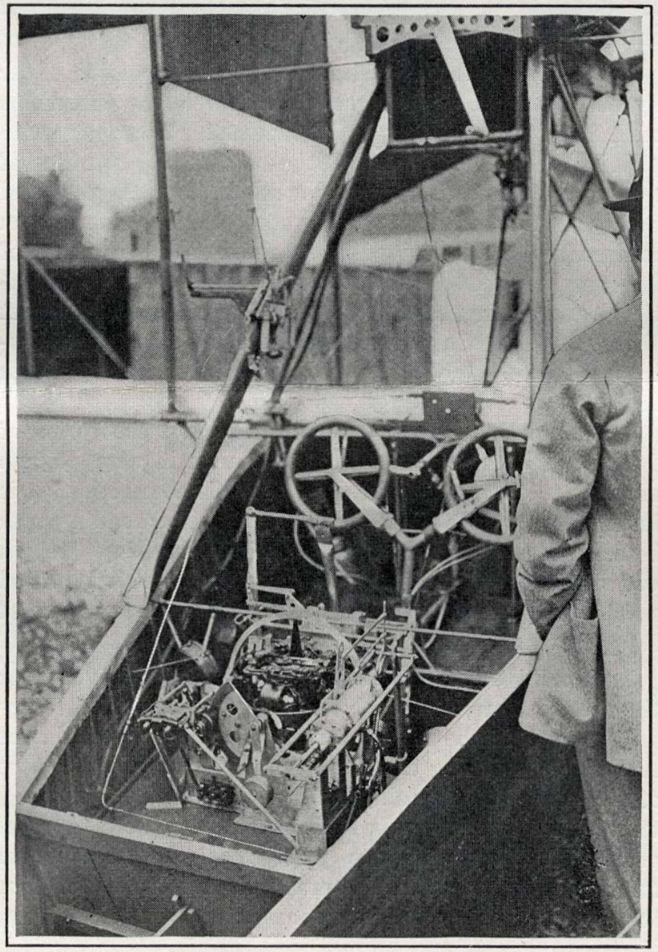
The Sperry Gyroscopic Stabilizer

How It is Constructed, How It Operates, and How It Demonstrated Its Capabilities Dur-

Commandant Barres and Lawrenc
conclusion of a fligh

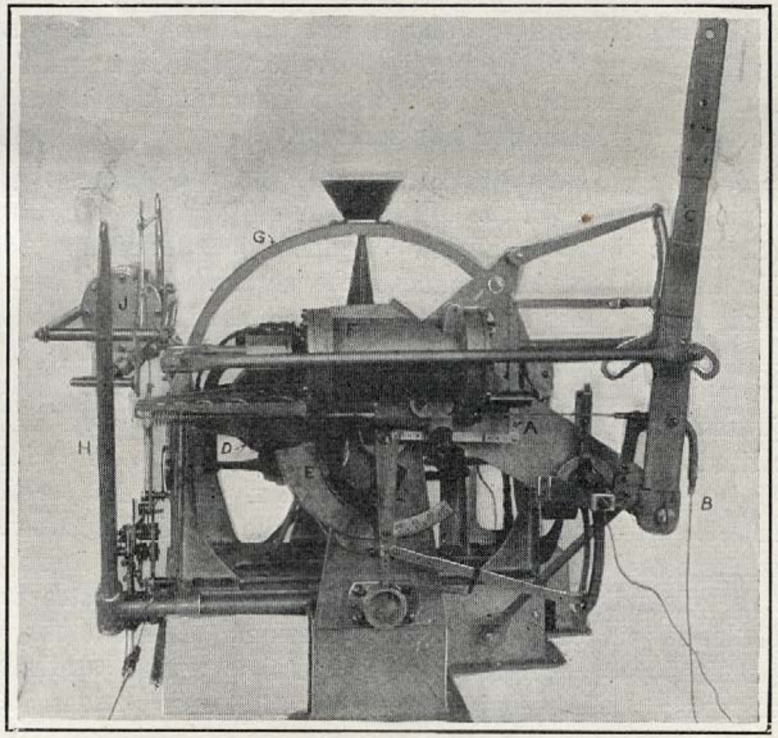


The first autopilot: entirely electro-mechanical and designed empirically



Front view of Sperry stabilizer.

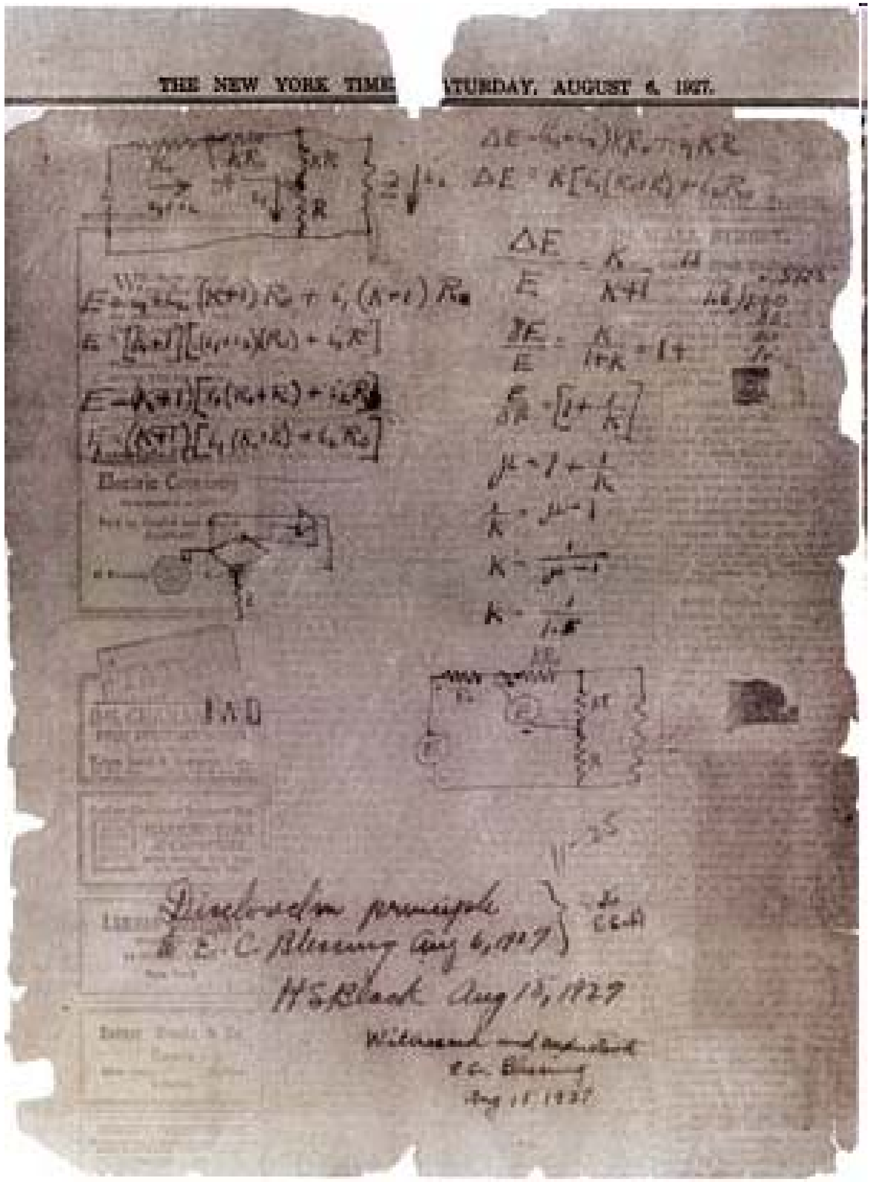
Showing servo-motor at right and rear of gyroscopic group; regulator in front to the left; anemometer above attached to engine strut.



Rear view of Sperry stabilizer.

A, automatic lateral lever pivoted on valve control crank; *B*, wire leading to supplementary control lever; *C*, control lever (lateral); *D*, gyroscope; *E*, inclinometer; *F*, cylinder of servo-motor; *G*, suspension ring; *H*, control lever (longitudinal); *J*, longitudinal control cylinder.

New York, August 1927…

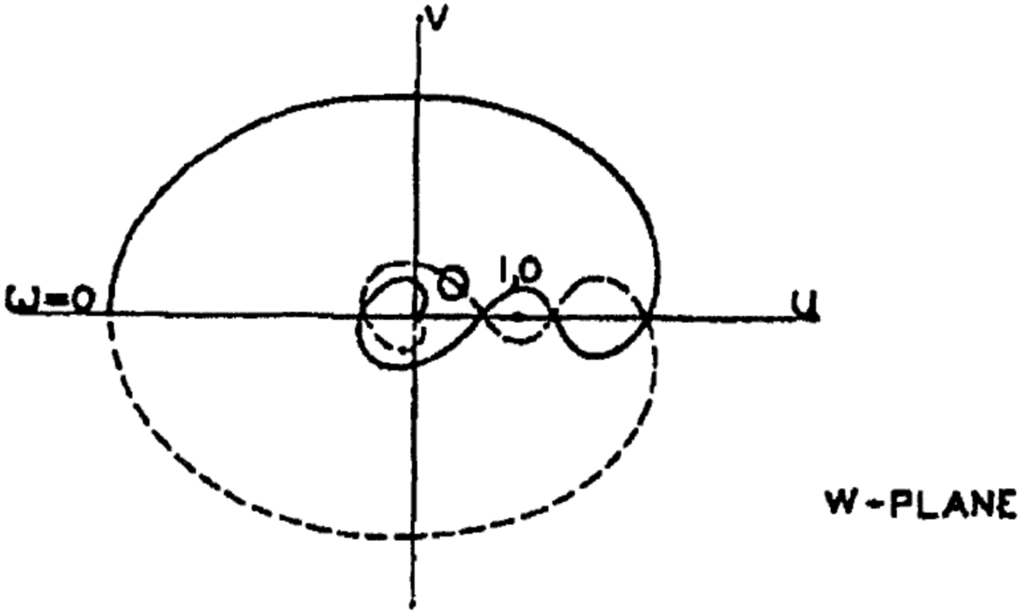


… and November 1932: the foundations of control theory

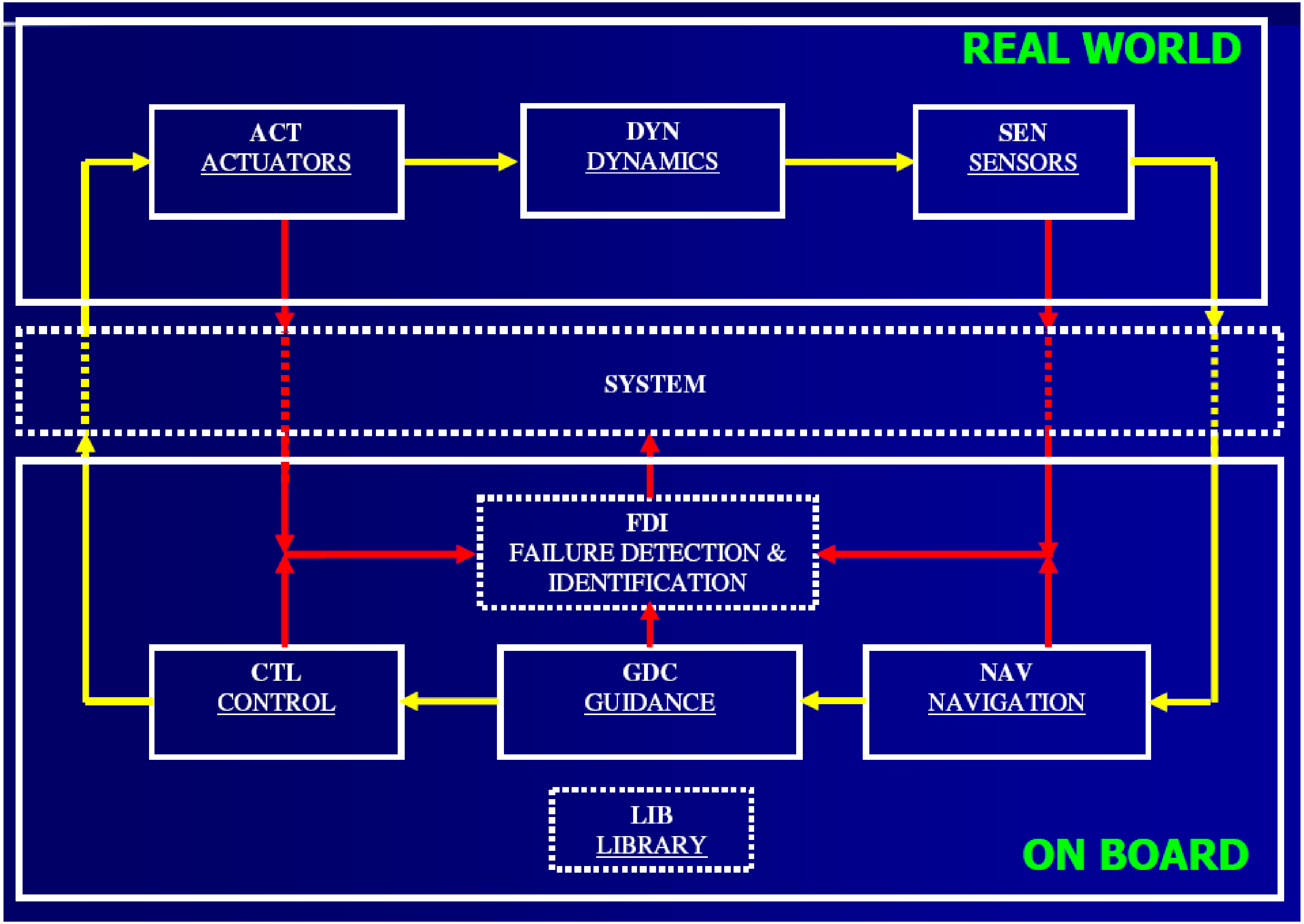
Regeneration Theory

By H. NYQUIST

Regeneration or feed-back is of considerable importance in many applications of vacuum tubes. The most obvious example is that of vacuum tube oscillators, where the feed-back is carried beyond the singing point. Another application is the 21-circuit test of balance, in which the current due to the unbalance between two impedances is fed back, the gain being increased until singing occurs. Still other applications are cases where portions of the output current of amplifiers are fed back to the input either unintentionally or by design. For the purpose of investigating the stability of such devices they may be looked on as amplifiers whose output is connected to the input through a transducer. This paper deals with the theory of stability of such systems.



XXI century: a generic control scheme for an aerospace vehicle



- Automatic control systems play an increasingly important role in aerospace engineering
  - in view of the higher level of automation expected from flight vehicles
  - and of the recent emergence of unmanned vehicles.

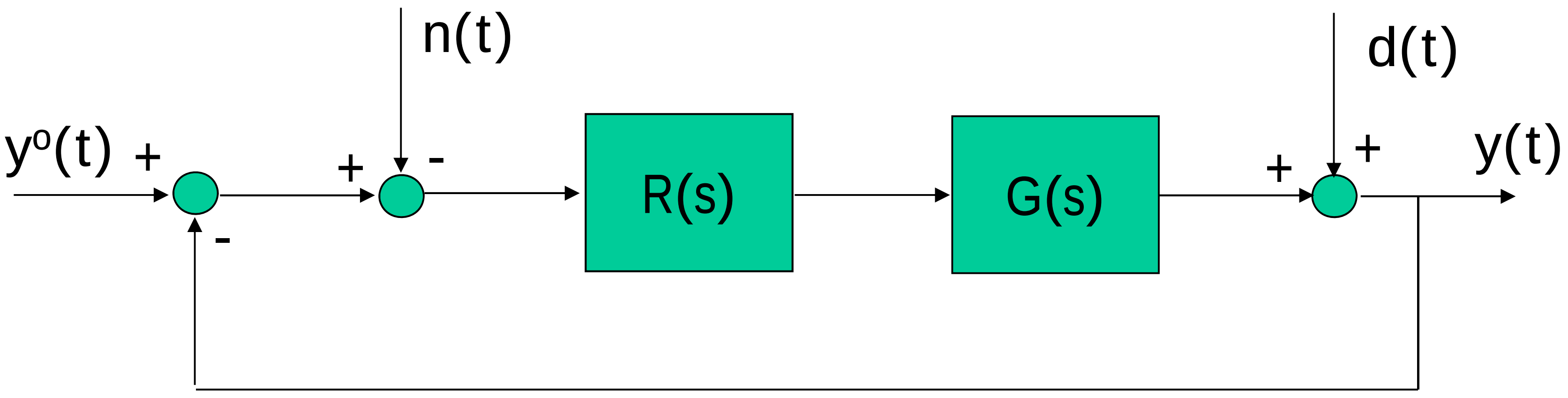
- Aerospace control systems design problems are intrinsically multivariable, nonlinear, often associated with large model uncertainty and unstable dynamics.

- These are the main reasons why advanced methods for analysis and synthesis are frequently adopted in aerospace applications.

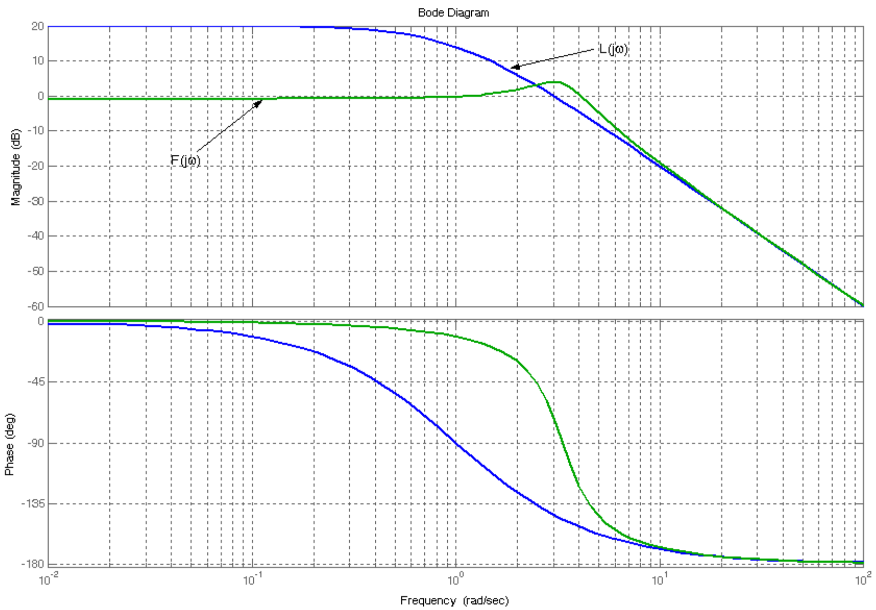
In view of the above, the course aims at the following goals:

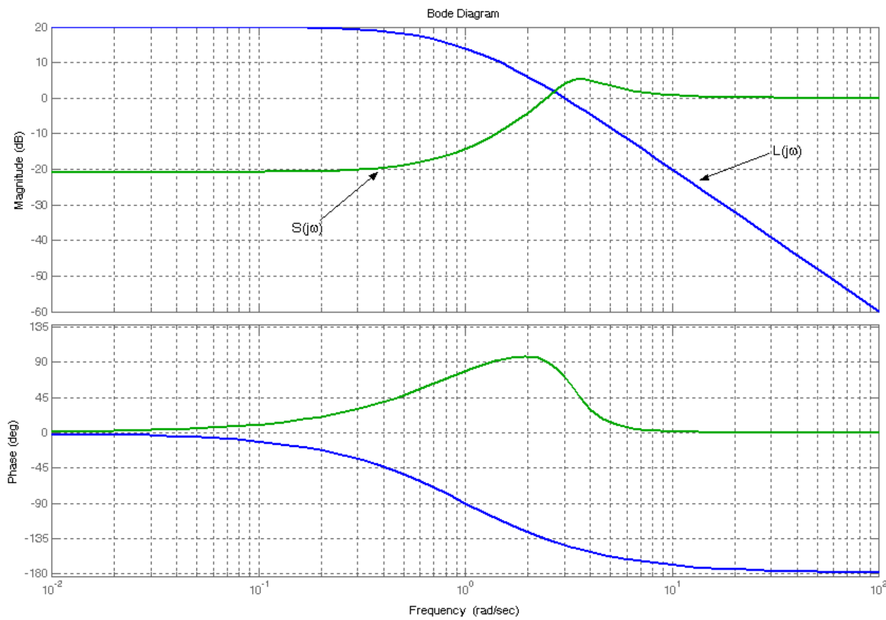
- to provide a sound background on modern methods and tools for the stability and performance analysis of linear and nonlinear systems;
- to cover robust analysis and design of SISO and MIMO linear time-invariant (LTI) feedback control systems;
- to discuss basic ideas on the linear parameter-varying (LPV) framework for gain-scheduled control systems design;
- to present classical results on nonlinear analysis;
- to illustrate the above methods using detailed case studies.

- Basic control courses deal with:
  - SISO plants and controllers
  - Analysis and design for:
    - nominal stability
    - nominal performance.



- Restrictive setting for us, as in aerospace problems
  - uncertainty matters, so robustness of stability and performance is an issue
  - the plant is MIMO, so methods for SISO analysis and design break down.



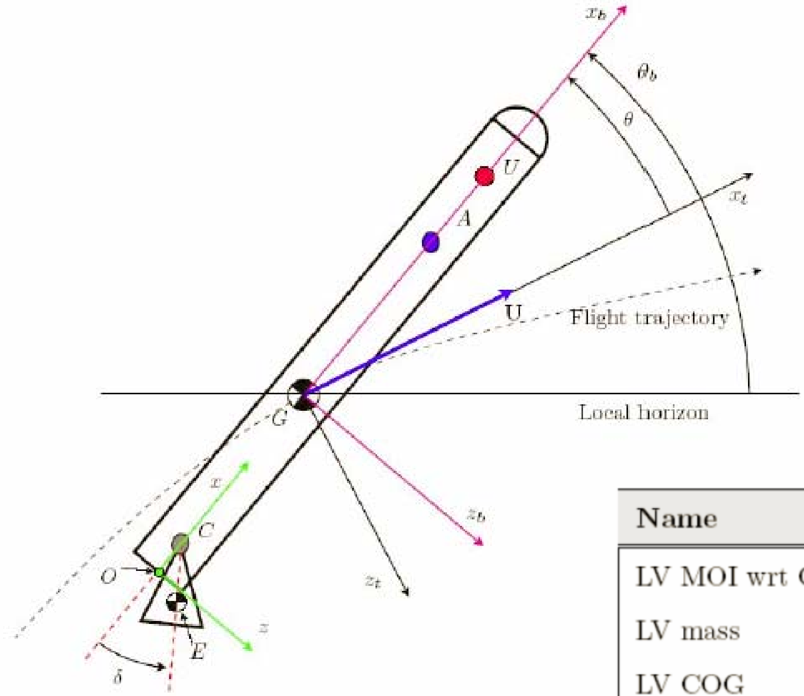


Why is robust control harder?

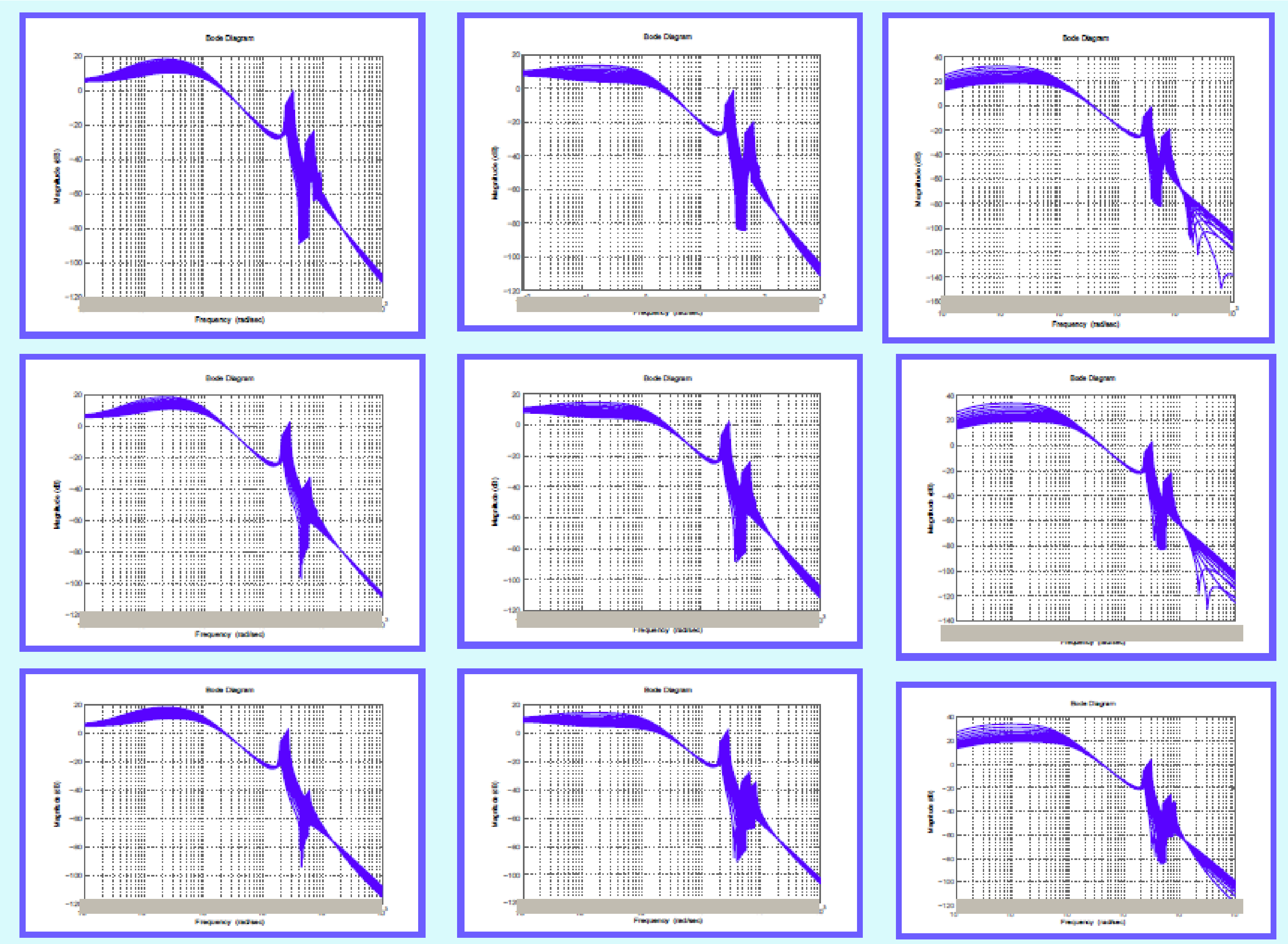
- the response of uncertain plants is harder to characterise
- predicting stability and performance is more complicated

And why is it relevant?

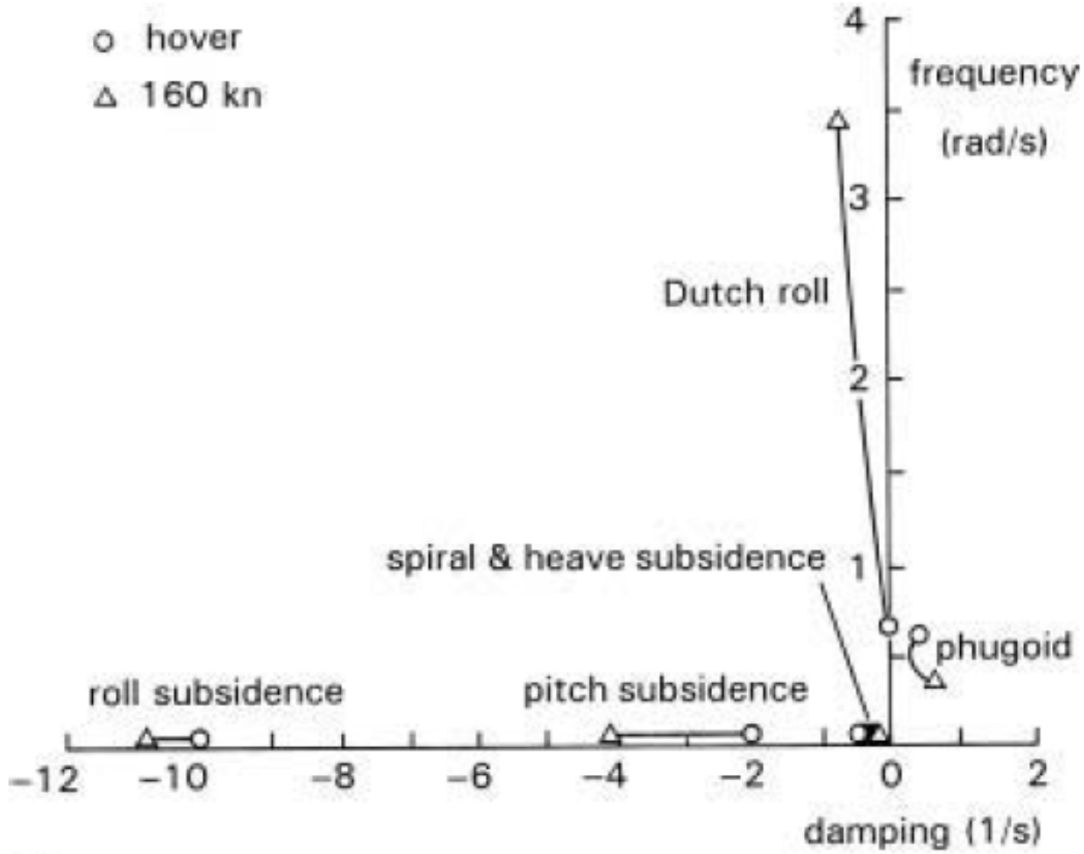
- variation of dynamics over envelope
- modelling of aerodynamics and structural dynamics
- actuator/sensor dynamics
- delays due to implementation



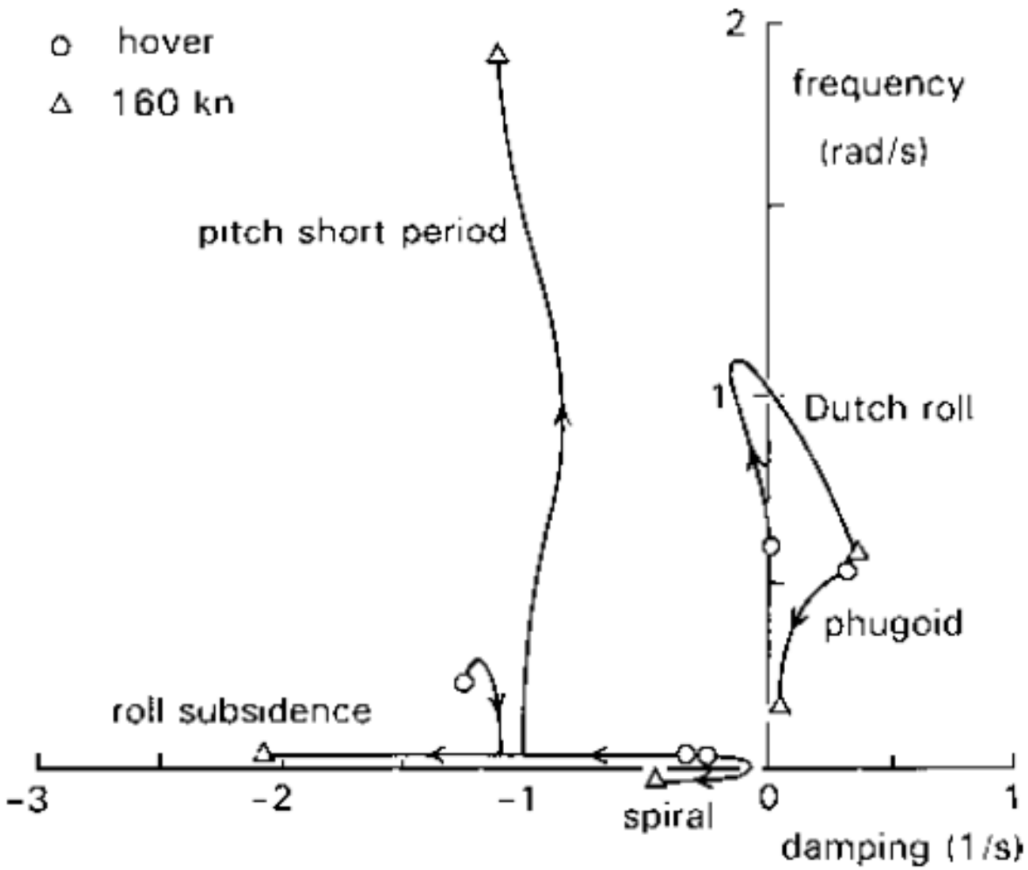
Name	Symbol	Uncertainty	Type
LV MOI wrt COG	J_{lv}	$\delta_{J_{lv}} = 15\%$	multiplicative
LV mass	m_{lv}	$\delta_{m_{lv}} = 5\%$	multiplicative
LV COG	ℓ_{lv}	$\delta_{\ell_{lv}}$	additive
Thrust	T	$\delta_T = 10\%$	multiplicative
Thrust Pivot Offset	ℓ_{OC}	$\delta_{\ell_{OC}} =$	additive
Dynamic pressure	Q	$\delta_Q =$	multiplicative
Lift coefficient	C_L	$\delta_{C_L} = 20\%$	multiplicative
Drag coefficient	C_D	$\delta_{C_D} = 20\%$	multiplicative
COP	ℓ_{OA}	$\delta_{\ell_{OA}} =$	additive
Mode frequency	ω	$\delta_\omega = 15\%$	multiplicative
Mode shape	σ/ϕ	$\delta_{\sigma/\phi} = 30\%$	multiplicative


Bode Diagram
Magnitude (dB)
Frequency (rad/sec)

- The linearised dynamics depend strongly on the operating condition.
- Examples (Padfield 2007): flight dynamics of the Westland Lynx:



Examples (Padfield 2007): flight dynamics of the Puma



Why is MIMO control harder?

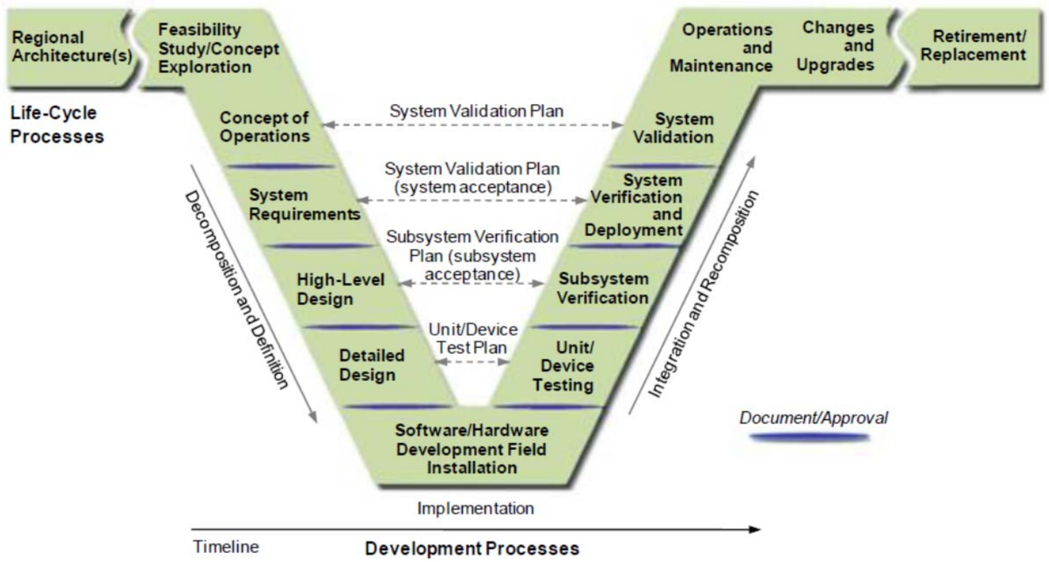
- MIMO plants exhibit more complex behaviour
- Performance requirements harder to formulate
- Design less intuitive than SISO case

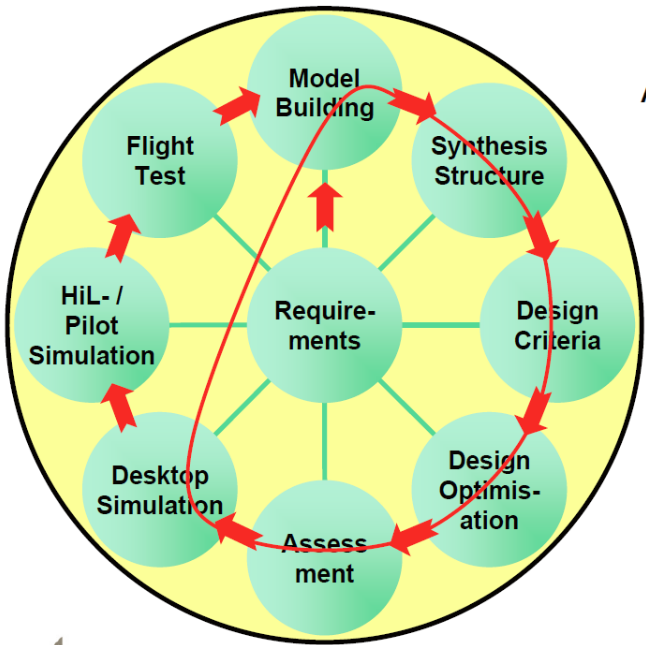
Why is MIMO control relevant?

- Besides single-axis autopilots (such as the 1912 Sperry), all FCS design problems are multivariable!

Course programme

1. **Introduction**:
   - Recap on linear systems and SISO analysis/design problems
   - Motivation for advanced analysis and design methods;
   - Introductory examples.





Course programme

2. Systems theory - stability:

- Equilibria of nonlinear systems;
- Lyapunov stability for equilibria of nonlinear systems: definition and examples;
- Stability for LTI systems: Lyapunov inequalities and equations.

Course programme

3. **Systems theory - performance:**
   - H_2 performance for linear systems;
   - Small gain and passivity theory;
   - H_∞ performance for linear systems.

Question addressed: for a generic feedback system, how do you formalize performance requirements in a way that is

- compatible with handling qualities requirements
- scalable from SISO to MIMO problems
- suitable for *automated* solution of design problems?

Course programme

4. Linear SISO feedback systems - robust analysis and design:

- Uncertainty modelling in SISO systems;
- Robust stability analysis of SISO feedback systems;
- Nominal and robust performance analysis;
- Requirement specification;
- Robust design: unstructured and structured mixed sensitivity synthesis.

Question addressed: for a generic feedback system, how do you formulate a control law design problem so that

- Nominal and robust stability
- Nominal and robust performance
- Control law structure

are all taken into account and the design problem is solved *automatically*?

Course programme

5. **Linear MIMO robust analysis and design:**
    - Introduction to MIMO linear systems;
    - Nominal stability and performance in the MIMO case;
    - Robust stability and performance in the MIMO case;
    - MIMO robust design.

Course programme

6. **Nonlinear analysis methods:**
    - Static nonlinearities: circle and Popov criteria;
    - Limit cycles and oscillations: the describing function method;
    - Introduction to nonlinear design: feedback linearisation, backstepping, adaptive control.

Questions addressed:

- for a typical FCS, actuator saturations are a key issue; is it possible to predict their role in the operation of the system?
- on UAVs it is possible to experiment with more advanced control laws, e.g., use adaptive/learning systems, can they be designed using the theory discussed so far?

7. Case studies

- Attitude control for a small-scale UAV: throughout the course we will develop as a case study the design of the control laws for a small scale UAV:
  - Modelling and simulation:
    - Equations of motion
    - Actuator and sensors modelling
    - Linearisation
    - Parameter estimation from data
    - Set up of a simulation environment
  - Definition of the control architecture
  - Design of the control laws
  - Verification in simulation environment.

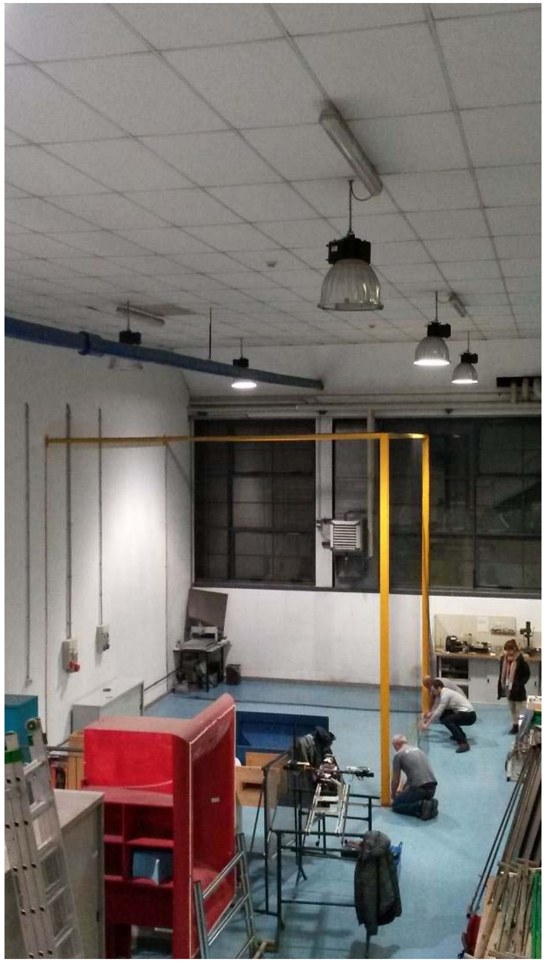
Course programme

7. Case studies

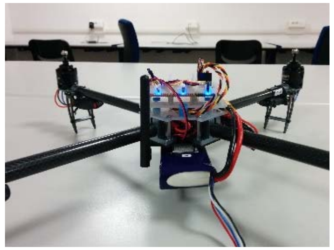
- Attitude control for a full-scale helicopter:
  - the main issues in the design of rotorcraft attitude control systems will be discussed
  - a design approach based on the previous topics will be presented
  - one (or more) lectures given by the flight control laws designers at Leonardo Helicopters will complement the discussion.

Exam project

The Aerospace Systems and Control Laboratory at DAER is currently setting up an indoor facility for multirotor UAVs.



A number of multirotor platforms have been designed and built in-house and are available for testing.



Exam project

The exam project, for the interested students, will consist in

- the design,
- implementation
- and in-flight performance verification

of flight control laws for a UAV.

Recap on LTI SISO systems: time domain

- LTI systems in state space form: definitions and notation
- SISO first order systems: solutions of state and output equations, free and forced response
- SISO higher order systems: solutions of state and output equations, free and forced response in formal analogy
- Matrix exponential and the response of higher order systems
- Coordinate changes in state space and equivalent representations
- Superposition principle
- Stability of LTI systems: definition via free motion and eigenvalues.

Recap on LTI SISO systems: frequency domain

- Transfer function definition and connection with impulse response
- Definition of poles, zeros, gain and response type
- Poles and eigenvalues: cancellations
- Definition of frequency response operator and sinusoidal response
- Minimum phase and nonminimum phase zeros.