



 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](mailto: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 seminarsfor a total of 6 CFU.



## Exam

Two options available for the exam:

- oral exam
- a project (more on this later), to be developed either individually or in teams of up to three students.

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)



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](http://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/](http://www.nt.ntnu.no/users/skoge/book/)



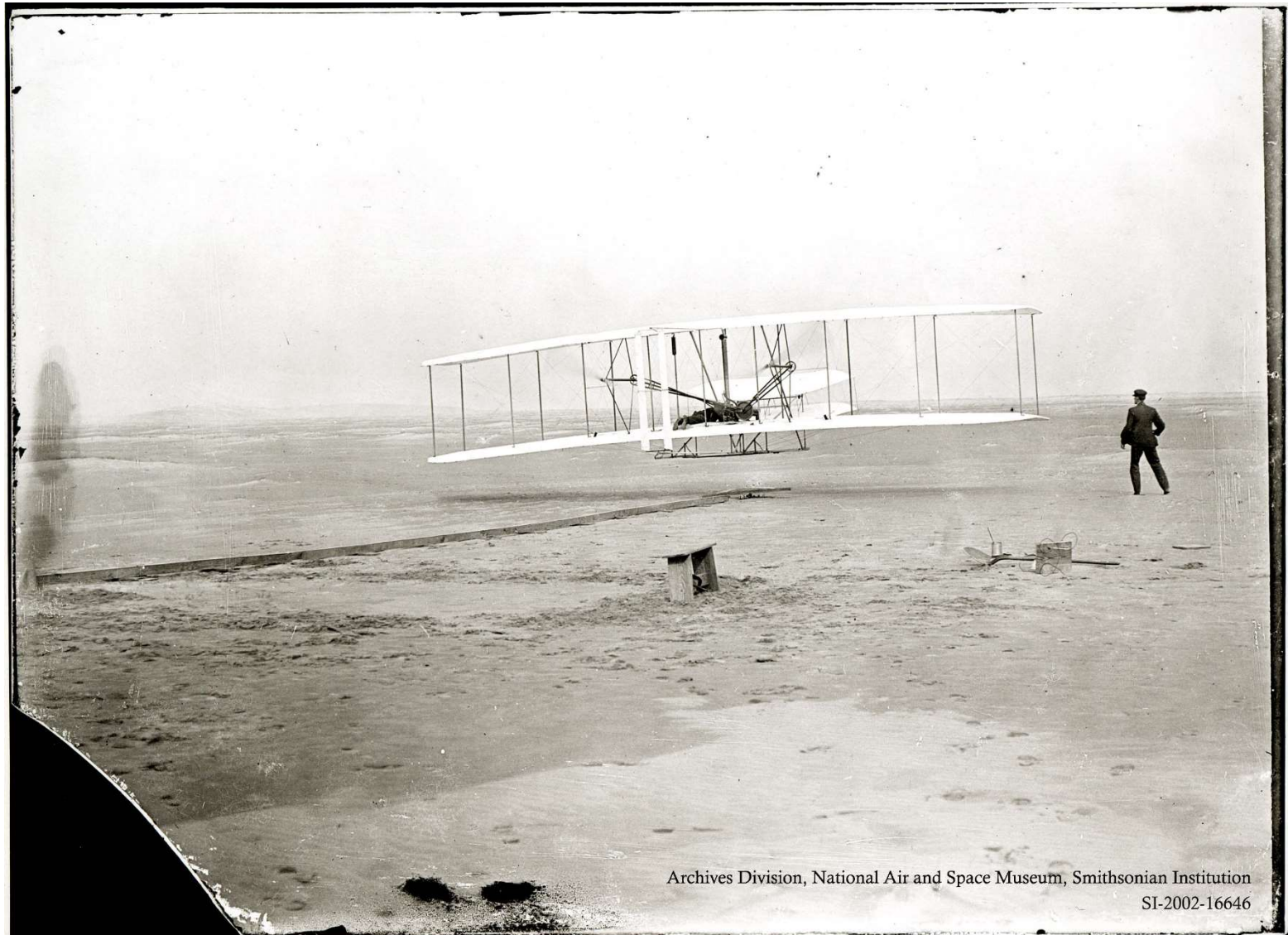
## Aerospace and Control?





## Kitty Hawk, December 1903

9





## The main difficulty...

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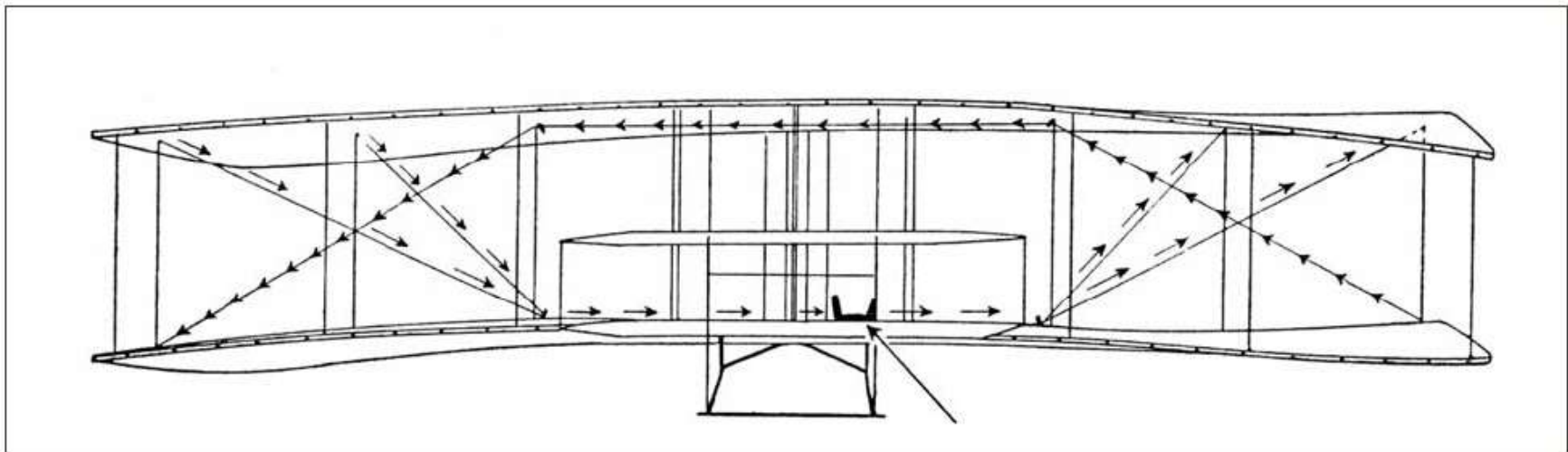
“Men already know how to construct wings or airplanes...

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.







96

SCIENTIFIC AMERICAN

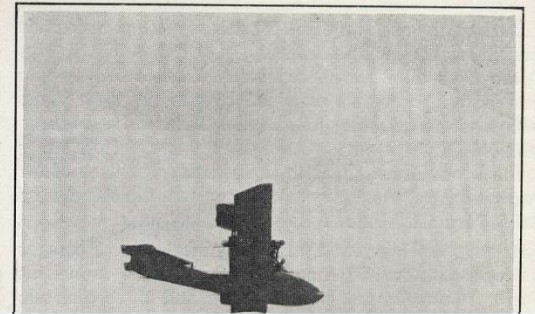
August 8, 1914



Commandant Barres and Lawrence  
conclusion of a flight

## The Sperry Gyroscopic Stabilizer

How It is Constructed, How It Operates, and How It Demonstrated Its Capabilities During

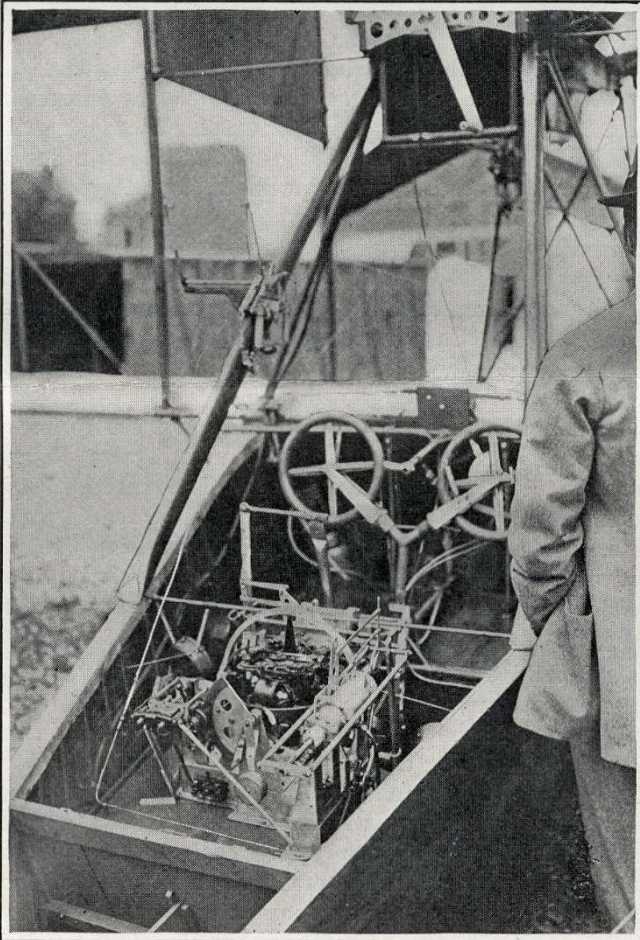






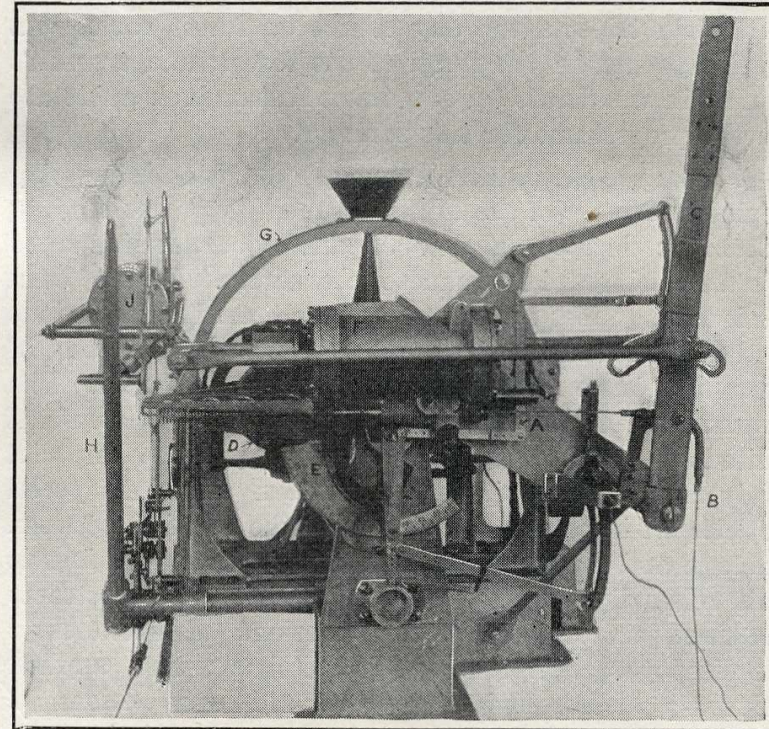
# The first autopilot: entirely electro-mechanical and designed empirically

13



**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.



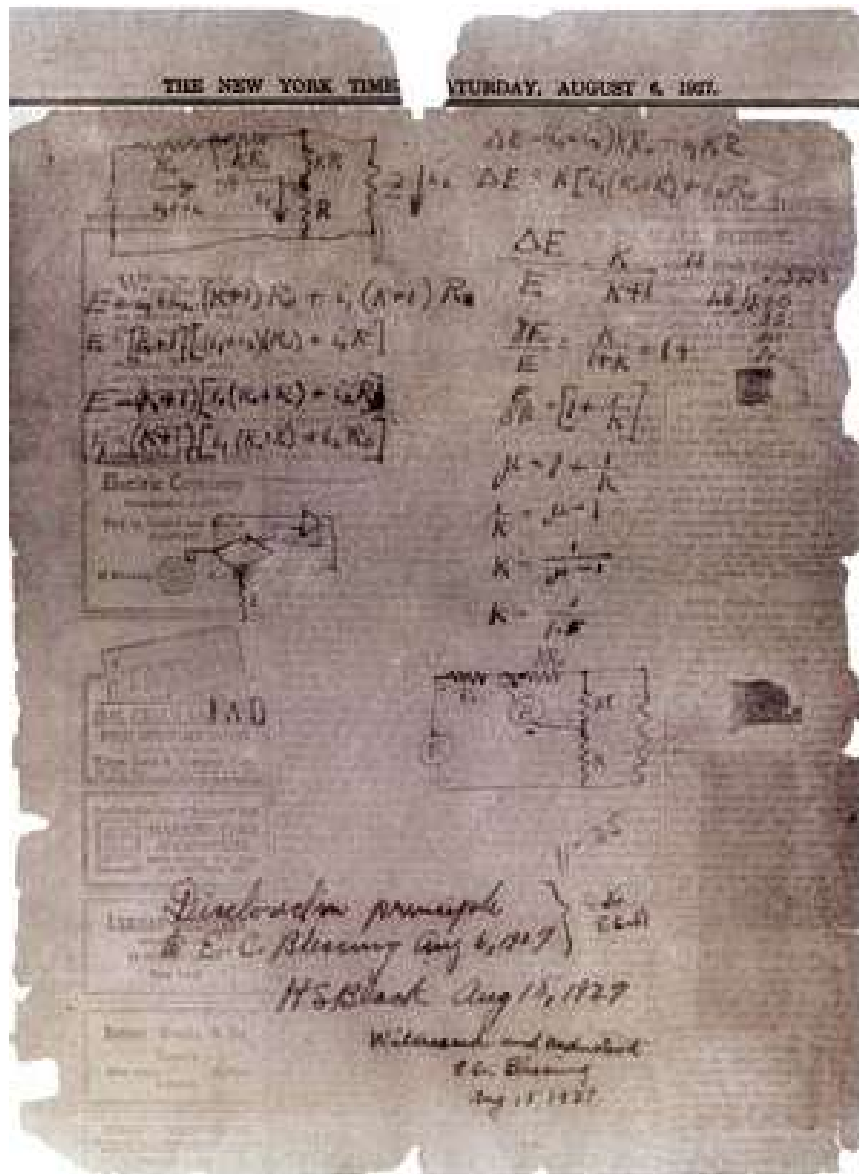
**Rear view of Sperry stabilizer.**

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...

14







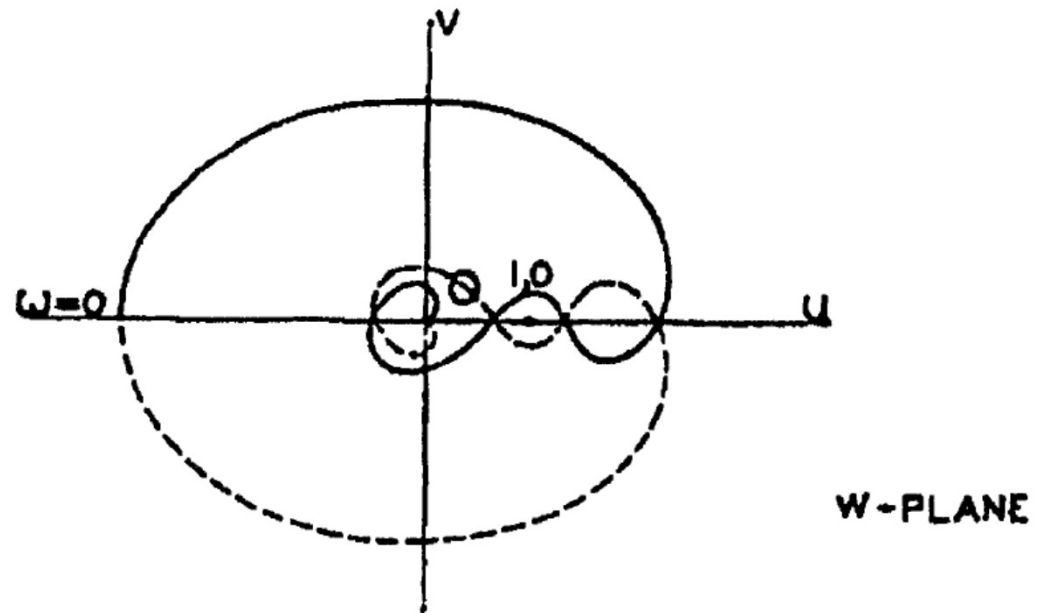
## ... and November 1932: the foundations of control theory

15

### Regeneration Theory

By H. NYQUIST

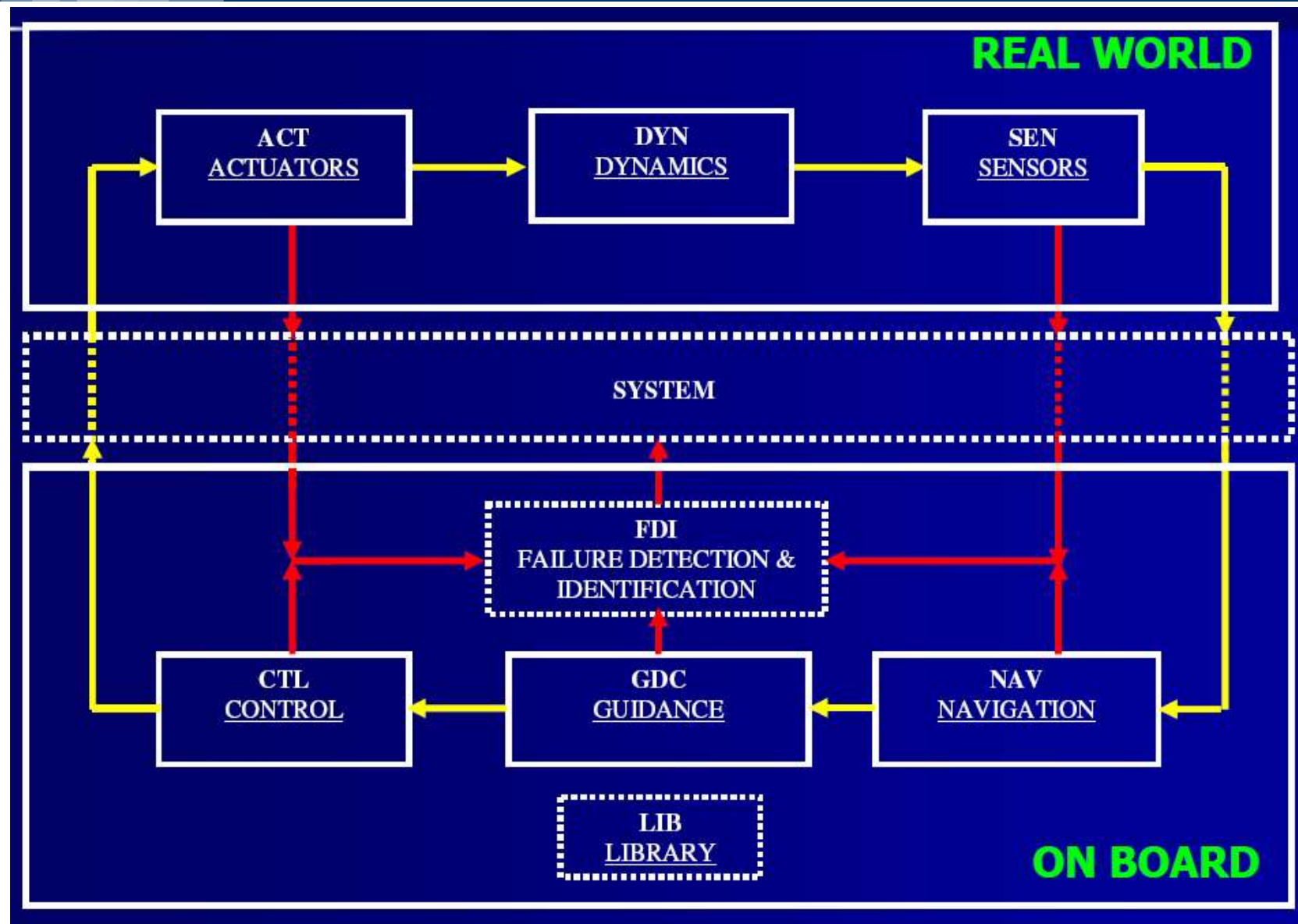
Regeneration or feed-back is of considerable importance in many applications of vacuum tubes. The most obvious example is that of vacuum tube oscillators, where the feed-back is carried beyond the singing point. Another application is the 21-circuit test of balance, in which the current due to the unbalance 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

16







## Introduction to Advanced Aerospace Control

- 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.



# Introduction to Advanced Aerospace Control

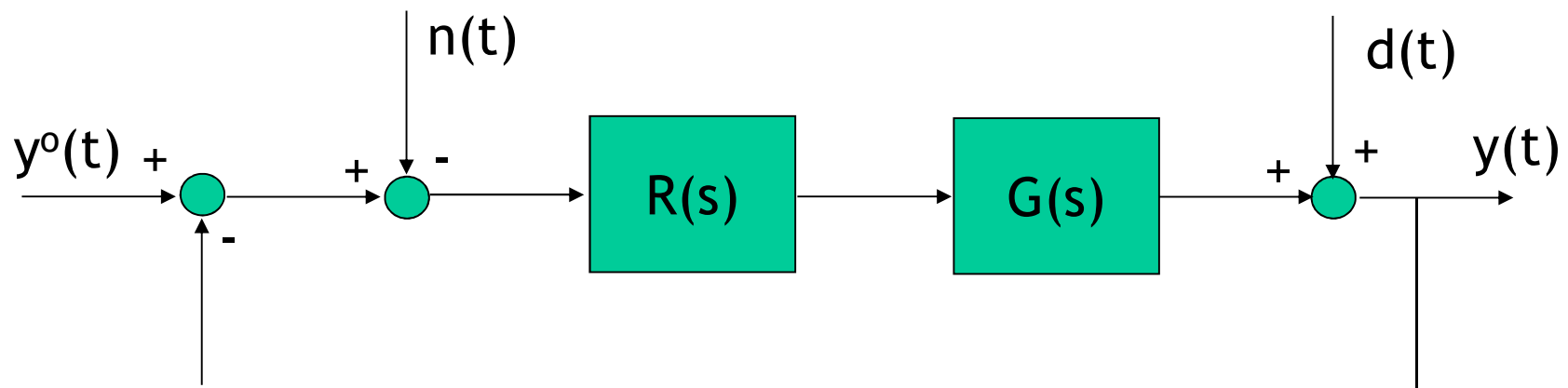
In view of the above, the course aims at the following goals:

- 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.



# Introduction to Advanced Aerospace Control

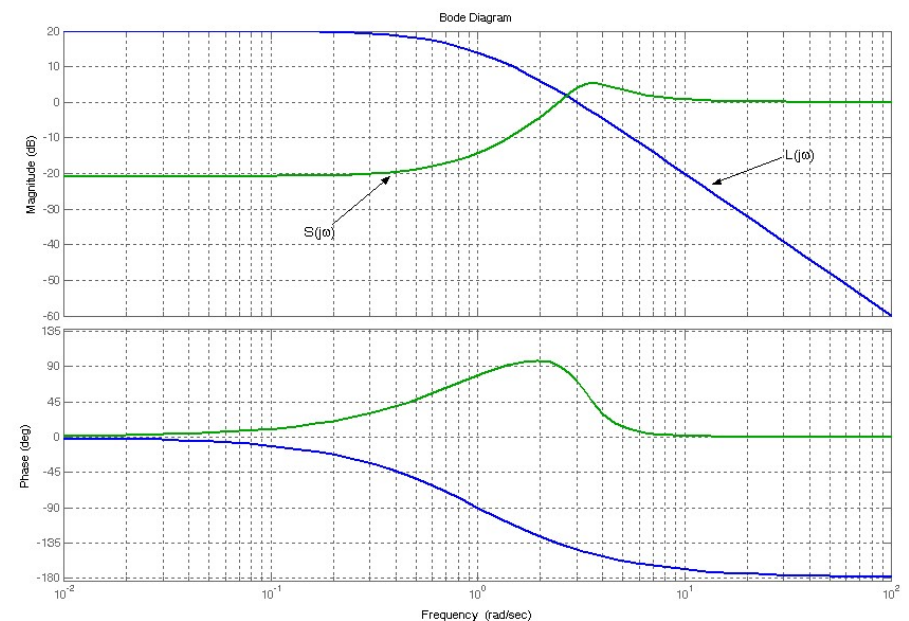
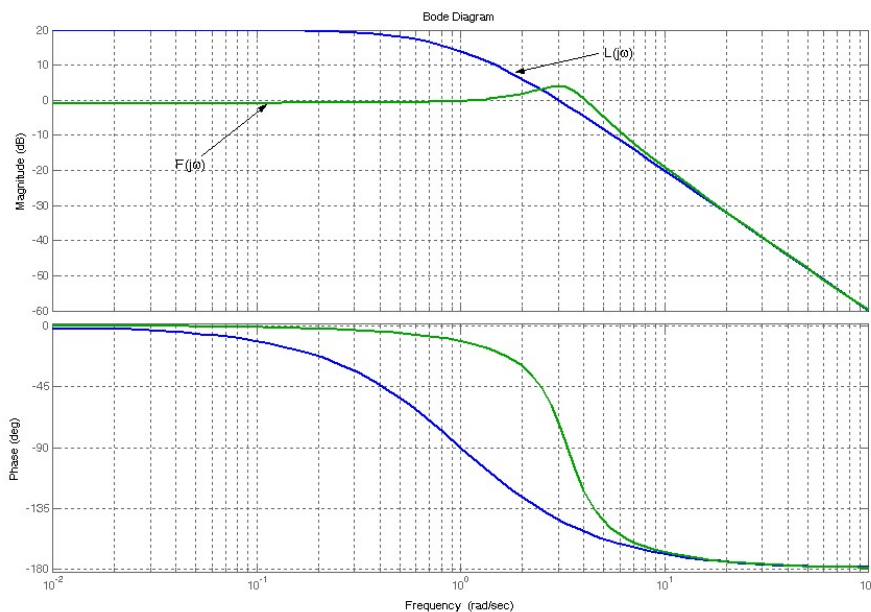
- Basic control courses deal with:
  - SISO plants and controllers
  - Analysis and design for:
    - nominal stability
    - nominal performance.





# Introduction to Advanced Aerospace Control

- 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.





# Introduction to Advanced Aerospace Control

Why is robust control harder?

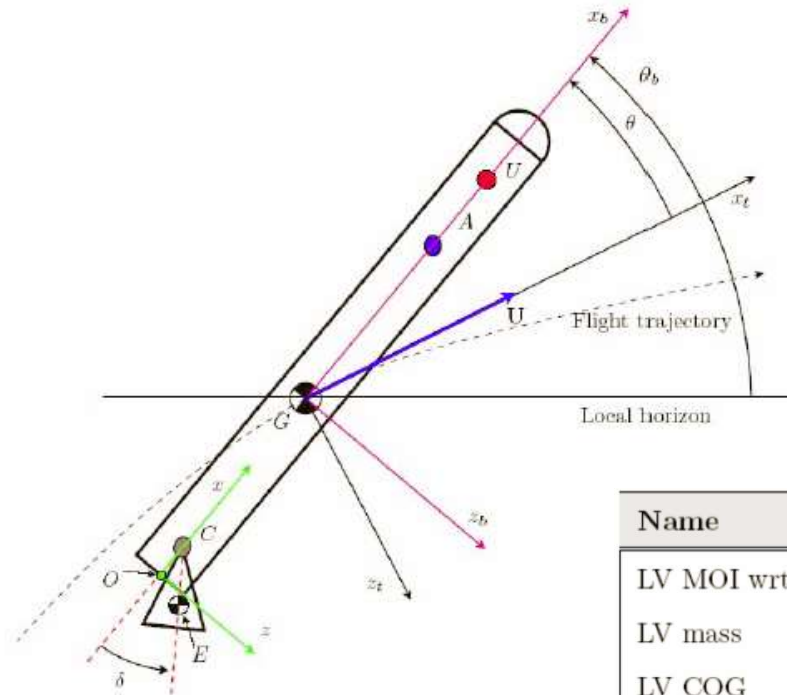
- the response of uncertain plants is harder to characterise
- predicting stability and performance is more complicated

And why is it relevant?

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



# Introduction to Advanced Aerospace Control

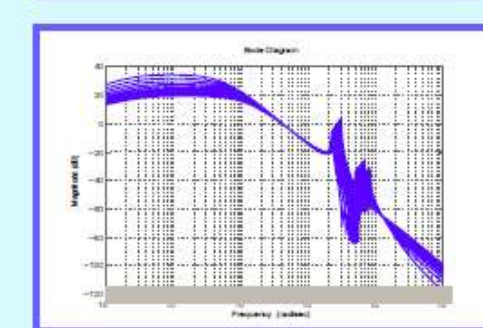
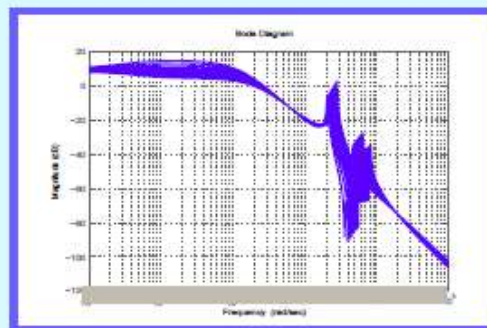
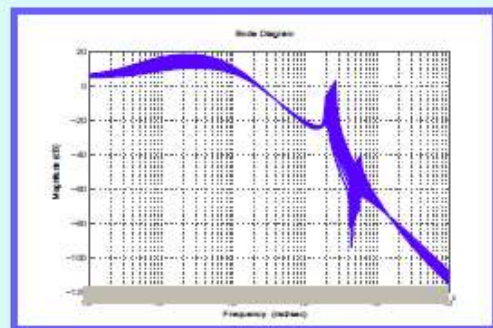
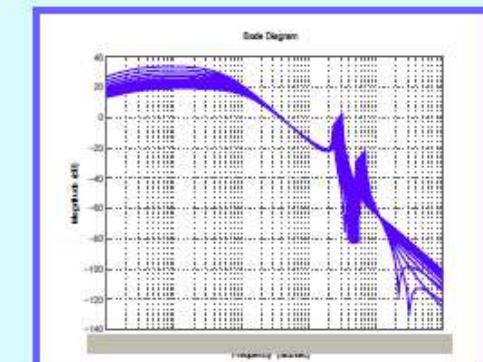
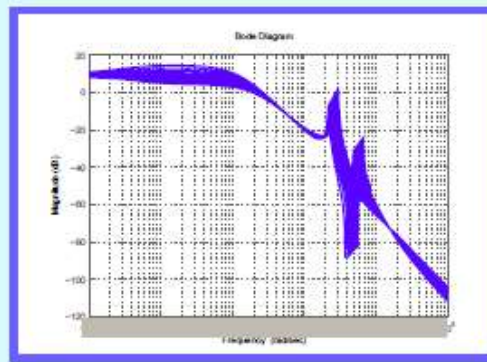
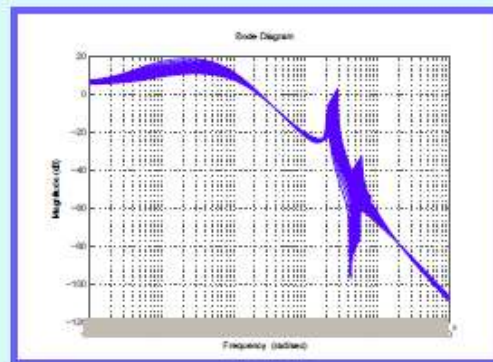
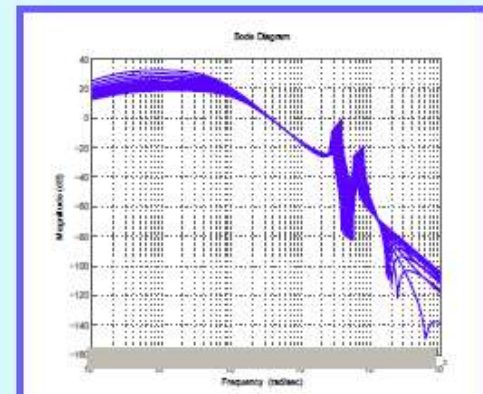
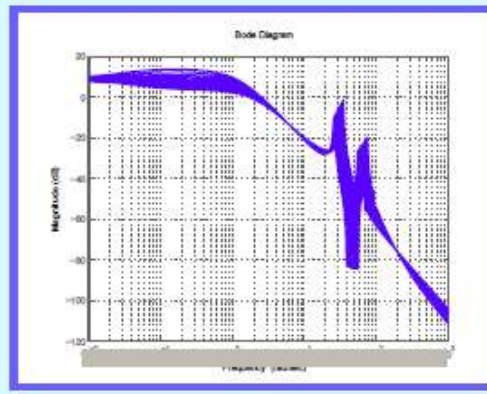
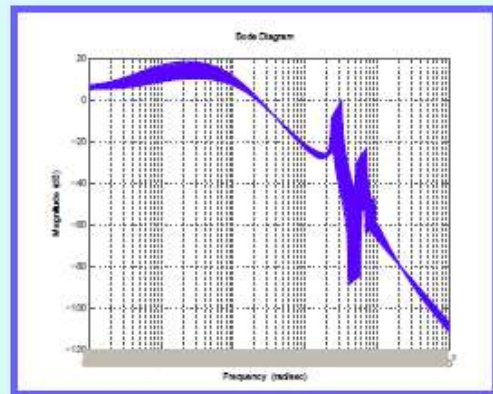


Name	Symbol	Uncertainty	Type
LV MOI wrt COG	$J_{lv}$	$\delta_{J_{lv}} = 15\%$	multiplicative
LV mass	$m_{lv}$	$\delta_{m_{lv}} = 5\%$	multiplicative
LV COG	$\ell_{lv}$	$\delta_{\ell_{lv}}$	additive
Thrust	$T$	$\delta_T = 10\%$	multiplicative
Thrust Pivot Offset	$\ell_{OC}$	$\delta_{\ell_{OC}} =$	additive
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	$\ell_{OA}$	$\delta_{\ell_{OA}} =$	additive
Mode frequency	$\omega$	$\delta_{\omega} = 15\%$	multiplicative
Mode shape	$\sigma/\phi$	$\delta_{\sigma/\phi} = 30\%$	multiplicative





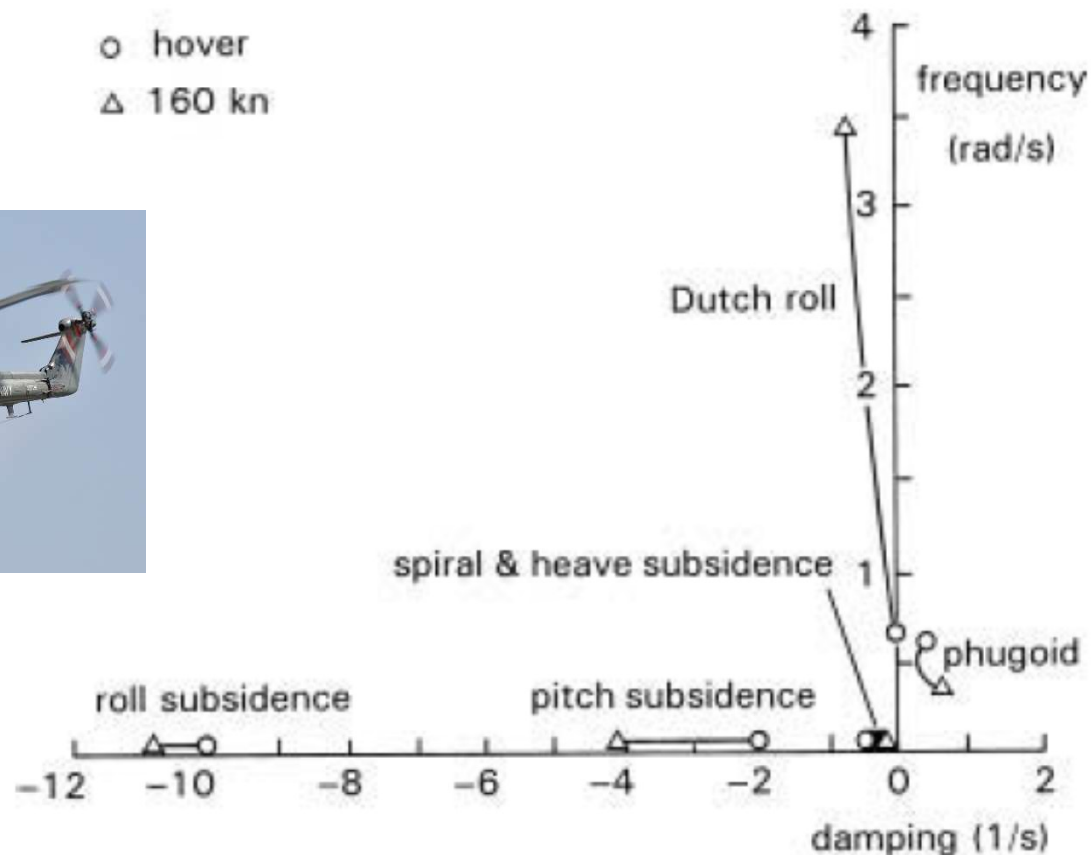
# Introduction to Advanced Aerospace Control





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

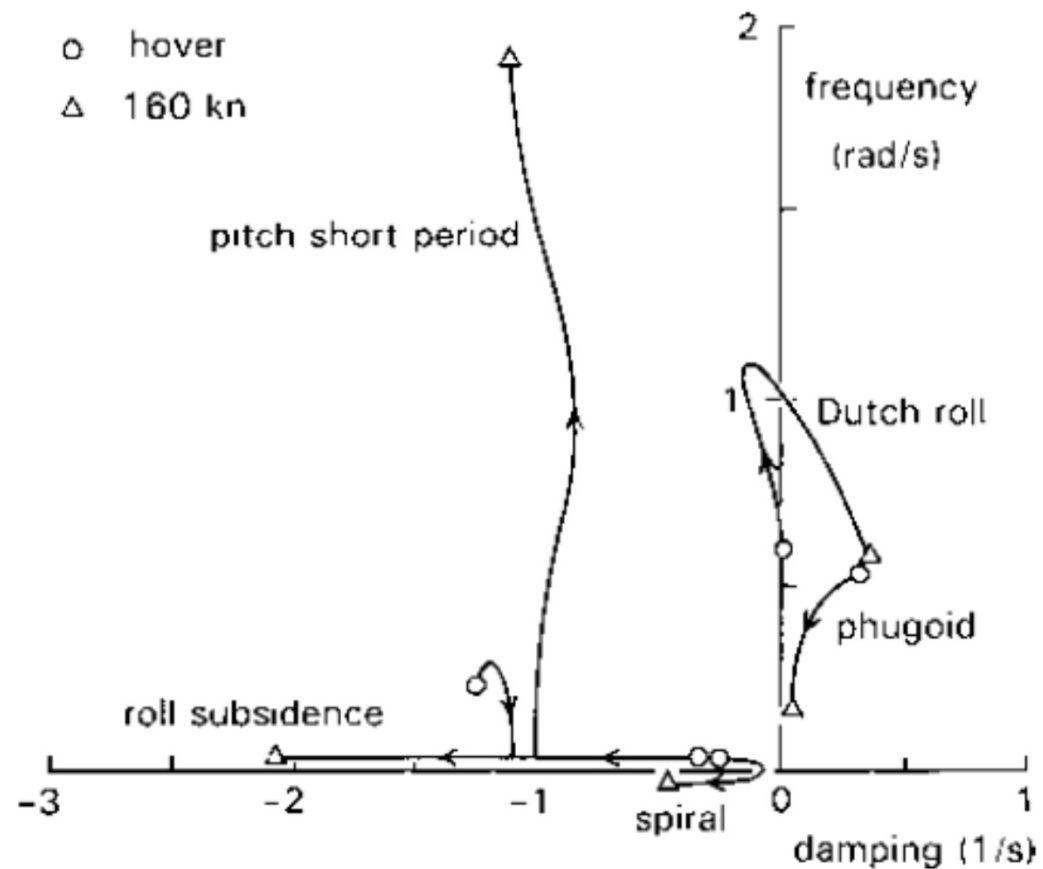
○ hover  
△ 160 kn







## Examples (Padfield 2007): flight dynamics of the Puma





# Introduction to Advanced Aerospace Control

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?

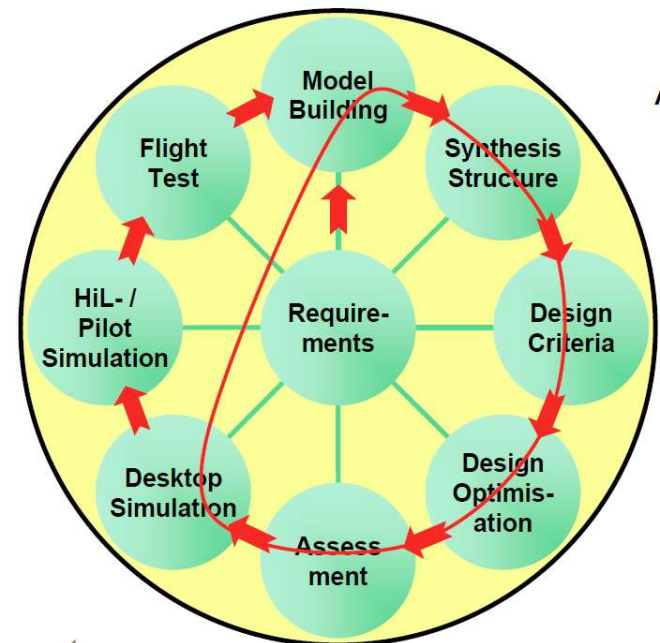
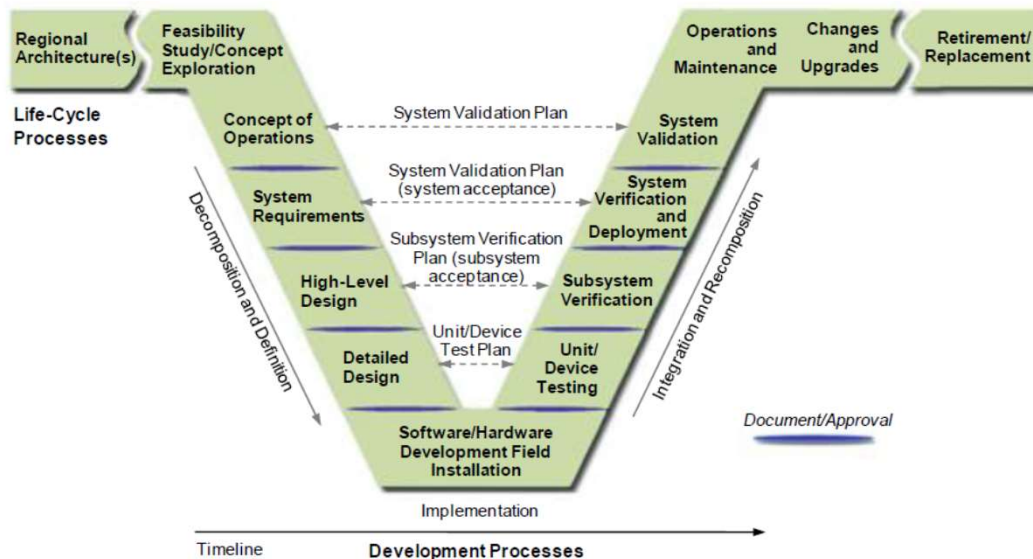
- Besides single-axis autopilots (such as the 1912 Sperry), all FCS design problems are multivariable!



# Course programme

## 1. Introduction:

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





### 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.

Question addressed: for a nonlinear system, how do you define stability of equilibria and how does this relate to stability of LTI systems? Are there simple computational tests for LTI stability analysis?



### 3. Systems theory - performance:

- $H_2$  performance for linear systems;
- Small gain and passivity theory;
- $H_\infty$  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?



### 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*?



### 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.

Question addressed: aerospace control problems are almost always multivariable in nature. How can we scale up results for SISO systems to the MIMO case?



### 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.



### 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

35

Inputs:

Simulation model (Simulink) for one of our multirotors

Uncertain design model, cascade of

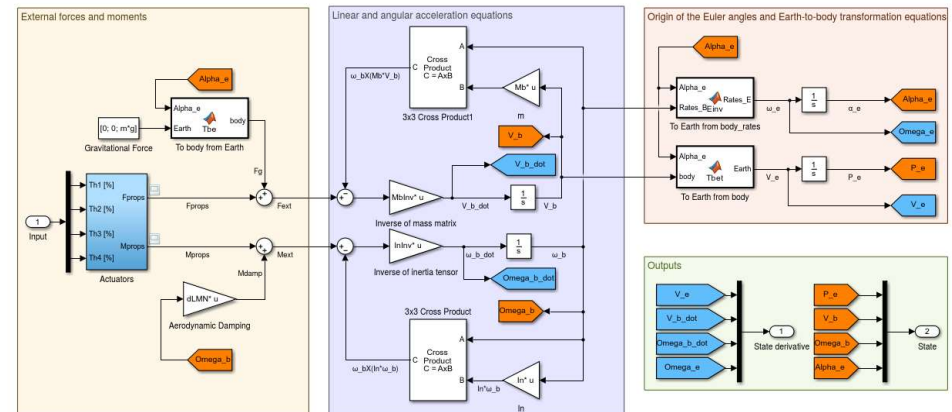
- identified attitude dynamics
- Actuator dynamics
- Dynamics of attitude estimation filter



Structure of current controller

Performance requirements:

- Tracking
- Disturbance attenuation



Benchmark mission profile: position and heading setpoint to be tracked



### Tasks:

- Construction of uncertain design model
- Definition of performance weights for (mixed sensitivity) control law synthesis
- Design of unstructured controller
- Design of structured controller matching current implementation
- Verification in simulation on benchmark mission profile
- In-flight validation on real quadrotor (with one possibility for re-tuning)



Expected outputs:

Presentation of adopted design approach and design results

In-flight validation.



- Presently located in building B14

- 5 x 5 x 5 m cage

- Optitrack 3D motion capture system

- Optitrack data (position and attitude) used on-board



- Available for project validation



- To do even minimal experimental work in the DAER labs an extra safety course must be taken.
- The course takes about half a day and takes place approximately once every two month.
- Next editions: March 8, March 22, May 10, May 25.
- So: if you are interested in the exam project AND plan to do the exam in June/July, let me know **asap** so I can register you for the course.



## 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.