CONTROL OF AIRCRAFT
INTRODUCTION

Jean-Pierre NOUAILLE

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CONTROL AIRCRAFT

In this course we will try to answer to these questions:

- What is precisely control of aircraft?
- Why is a controller used for aircraft?
- How do we build this controller?

DEFINITION

CONTROL

Control is a functional chain that ensures:

- the stabilization of aircraft attitude around its center of gravity;
- the control of aircraft states (such as acceleration, flight path angle, velocity azimuth, attitude . . .) to values assigned by guidance algorithms;
- performances and stability robustness in presence of all kind of errors or disturbances, under the condition that they are bounded.

DEFINITION

GUIDANCE

Guidance is the set of actions that must fulfill an aircraft in order to reach a target while respecting constraints (such as intermediate position, velocity, attitude, acceleration, actuator consumption, fuel consumption . . .).
For most aircrafts, guidance is the set of actions to accomplish to control the movements of its center of gravity, by using commands transmitted to control loop.

DEFINITION

NAVIGATION

The navigation chain is the function of an aircraft allowing to know some of its state, in a defined frame and referential, such as:

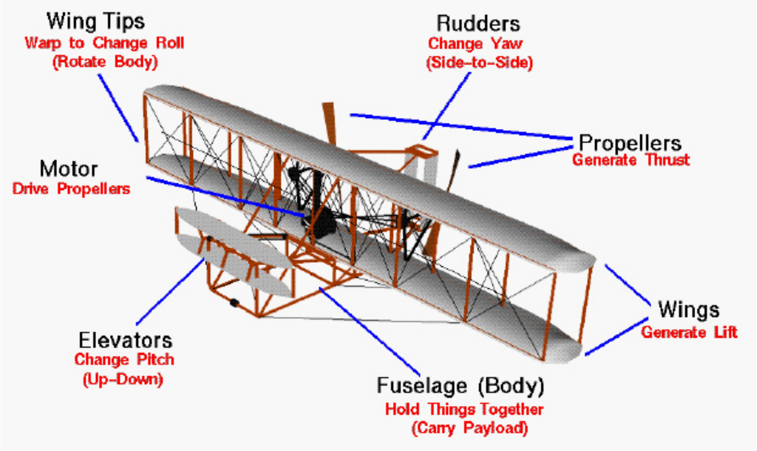
- its position
- its velocity
- its acceleration
- its attitude
- its rotation speed
- ...

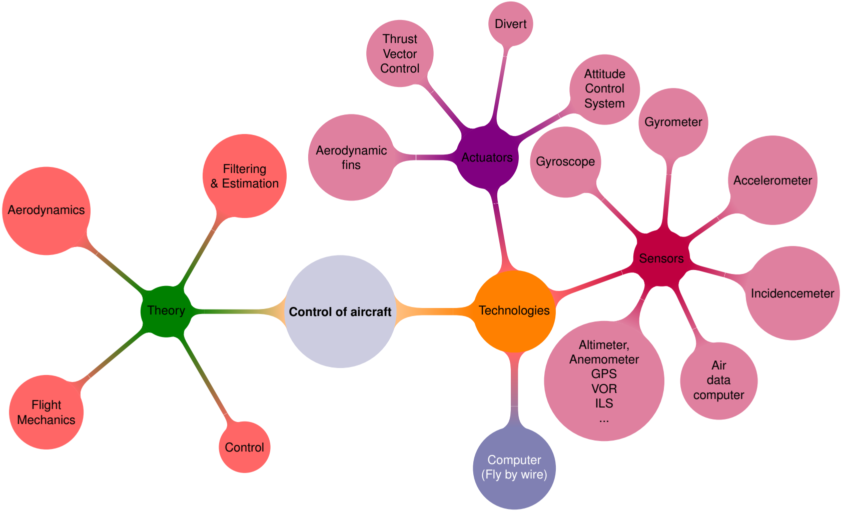
QUIZZ

When happened the following events?

- First powered flight of an aircraft
- First automatic control of an aircraft (altitude control)
- First ”blind” flight of an aircraft (take off, cruise flight and landing only using instruments, but with a human pilot)
- First automatic landing of an aircraft
- First controlled flight of the V2 ballistic missile
- First whole automatic flight of aircraft (including take-off and landing)

And today ?


Wing Tips
Warp to Change Roll
(Rotate Body)
Rudders
Change Yaw
(Side-to-Side)
Propellers
Generate Thrust
Motor
Drive Propellers
Wings
Generate Lift
Elevators
Change Pitch
(Up-Down)
Fuselage (Body)
Hold Things Together
(Carry Payload)


Control of aircraft
Theory
Aerodynamics
Filtering & Estimation
Flight Mechanics
Control
Technologies
Actuators
Aerodynamic fins
Thrust Vector Control
Divert
Attitude Control System
Sensors
Gyroscope
Gyrometer
Accelerometer
Incidencemeter
Air data computer
Altimeter, Anemometer GPS VOR ILS ...
Computer (Fly by wire)

Control of aircraft related fields

For the study of control of aircraft, we need the following technical fields:

- Automatic control (linear time invariant systems and linear controllers in this course)
- Flight Mechanics
- Aerodynamics
- Signal processing

Control of aircraft applies to

- Airplane
- Missiles
- UAV ...

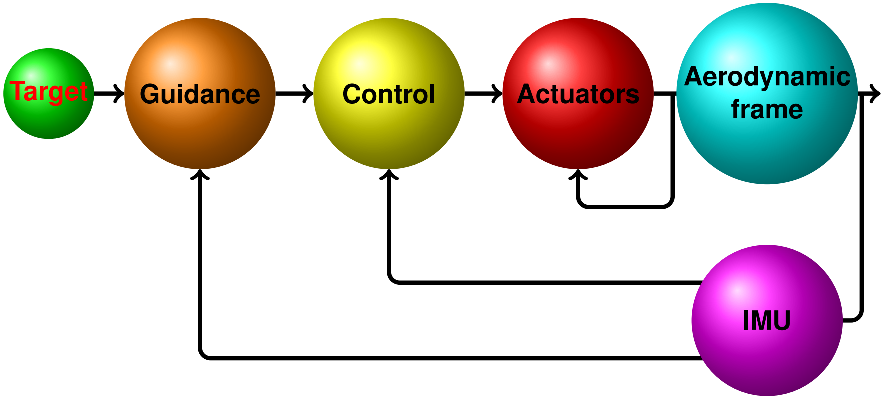
CONTROLLER SYNTHESIS

- design requirements: stabilization of the aerodynamic frame in its whole flight domain, response time, damping ratio, maximum overshoot, bandwidth, robustness (depending on guidance requirements)
- study of the process to control, build of a synthesis model
- controller synthesis, including filters on measurements, saturations ...
- performances and robustness assessment (non linear numerical simulations, hardware in the loop simulation, flight tests) taking into account measurement noise, disturbances, model variations and uncertainties, sensors and actuators characteristics
- iterations on control design or if needed on airframe design. . .

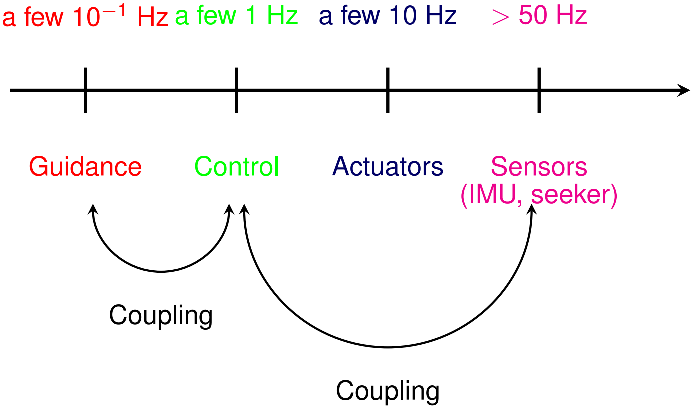
What we will see during this course

- Control of aircraft Principle
- Aircraft modelization
- Transient response description
- Introduction to guidance and control in the pitch plane: with controllers using acceleration, angle of attack, attitude, flight path angle rotation speed, altitude
- Introduction to lateral autopilot design

GUIDANCE AND CONTROL LOOPS

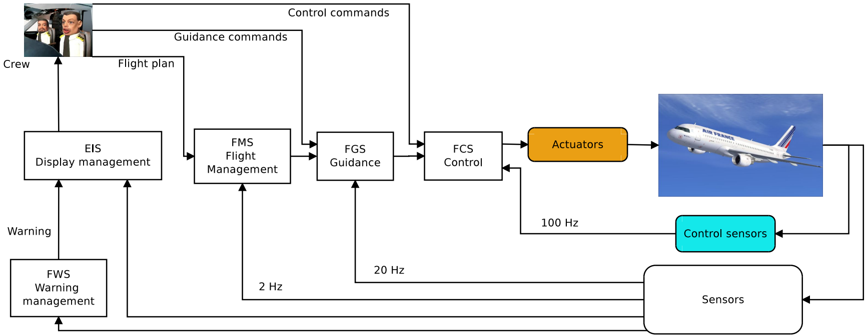


Bandwidth of the different control and guidance loops



This justify that generally guidance and control can be treated separately (frequency decoupling).

FUNCTIONS OF AN AIRCRAFT AUTOPILOT



The frequency indicated here are the sampling rates.

PROCESS TO CONTROL

Airframe with

- its aerodynamic characteristics
- its mass, its center of gravity position, its inertia
- its propulsion

Using

- *sensors* (inertial sensors, incidence meter ...) and generally an associated Kalman filter to filter noises and fuse the data from the sensors
- *actuators* (aerodynamic fins, rudders in exhaust jet (jet deviator), orientable nozzle, jets, propulsion when controllable. . .)

Additional Constraints

- security/robustness to breakdown (degraded modes, redundancy)
- flight comfort
- performances (reactivity, optimization of fuel consumption)

Existing autopilots can be

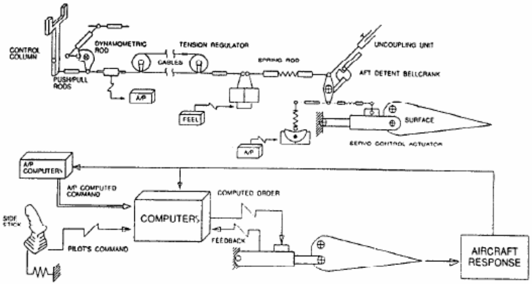
- one axis: the roll axis only is controlled (this autopilot is often called wing leveller)
- two axis: the pitch and the roll axis are controlled
- three axis: the yaw, the pitch and the roll axis are controlled

They can have an action during taxi, takeoff, climb, cruise (level flight), descent, approach, and landing phases and current autopilot can automate all this phases except taxi and take off.

CONVENTIONAL CONTROL AND FLY BY WIRE FLIGHT CONTROL

Conventional flight controls

Fly by wire flight controls



DIFFERENT AUTOPILOT FUNCTIONS

An autopilot is used to stabilize automatically the flight of an aircraft around its trajectory (control), to modify its trajectory (guidance), to execute precisely delicate maneuvers and to improve its flight qualities.

For current aircraft (airliners, fighter aircraft), the flights control are no longer mechanical, but pilot orders are transmitted using electrical wires (fly by wire technology). But on small planes (e.g. Cap 10), the controls are still using cables and rods.

This allows to introduce a low level control loop, which can :

- stabilize an unstable aircraft
- modify the behavior of the aircraft (add a pitch damping)
- limit the amplitude of the input command given by a human pilot, so that the aircraft stays in its safety flight envelope (maximum flight path angle, minimum and maximum speed, maximum roll angle ...)

Typical fly by wire control laws and protections for the different modes are the following (protections aim at preventing stalling or structure destruction):

- Ground mode
- Take-off mode
  - Angle of attack protection
- Flight mode
  - Pitch attitude protection
  - Load factor protection
  - Bank angle protection
  - Angle of attack protection
  - High speed protection
- Landing mode
  - Bank angle protection
  - Angle of attack protection

- Normal law is applied when all systems work or a single failure exists
- Alternate law applies when multiple redundant system failure are experienced
- Direct law is applied when certain multiple system failures are experienced
- Ground law
- Flare law (landing)

Note that automatic landing allows the aircraft to land at night, or when weather reduces the visibility (fog, rain...).

DIFFERENT AUTOPILOT FUNCTIONS

Longitudinal autopilot modes

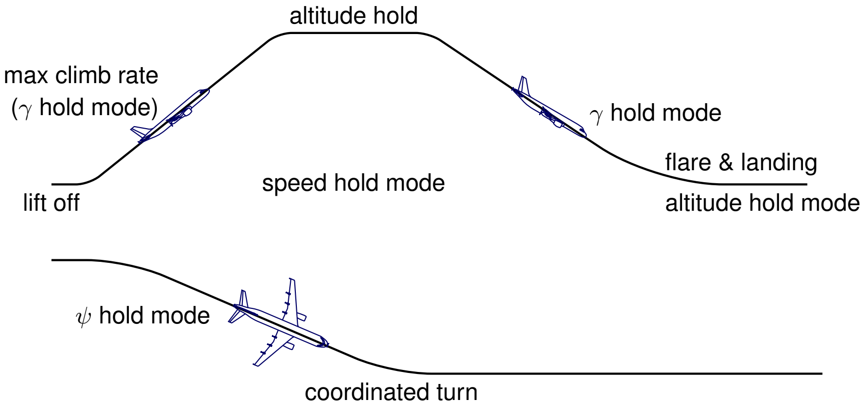
- pitch angle hold
- altitude hold
- climb rate (or descent rate) hold mode
- total speed hold
- flight path angle hold
- descent following a radio frequency axis (ILS: instrument landing system)

Lateral autopilot

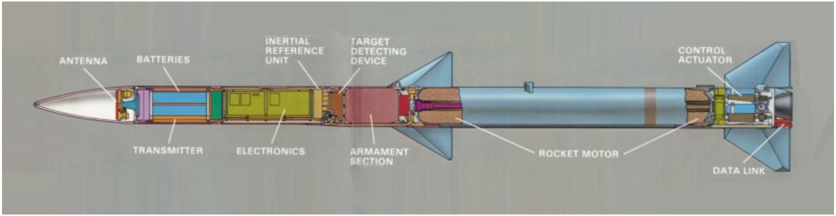
- yaw angle hold
- turn at constant roll angle
- follow a radio frequency axis (VOR, TACAN, ILS)

There exist different command modes (e.g. airbus: normal, alternate, direct) in case of computer failure, each of them with a different level of assistance to the human pilot.

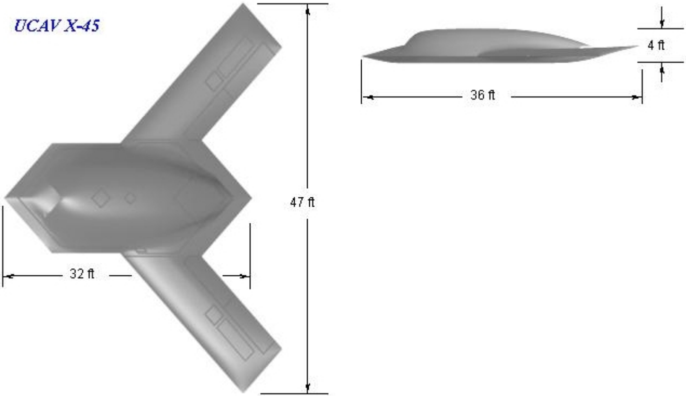
GUIDANCE MODES SCHEDULING



AIR-AIR MISSILE ARCHITECTURE



UAV ARCHITECTURE



Flight control System of an airplane

AIRLINER ARCHITECTURE

Note redundancy for safety reason.

On this airliner :

- the elevators control the pitch
- the rudder controls the yaw
- the ailerons control the roll
- the flaps are used to modify the wing profile and increase lift at low speed
- the thrust reverser are used to reduce aircraft speed when it has landed
- the spoilers are aerodynamic brakes, that are also use together with the ailerons for roll control

Fighter aircraft

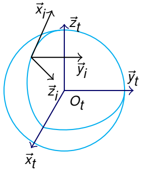
Note that for the Rafale there are four actuators for the pitch plane.

FORWARD-SWEPT WING

QUADROTOR

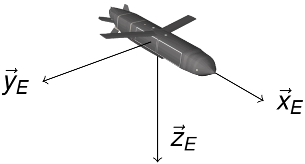
Reference Frames

Local geographic frame

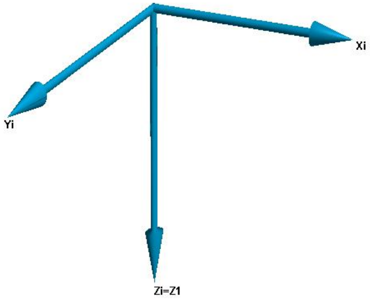


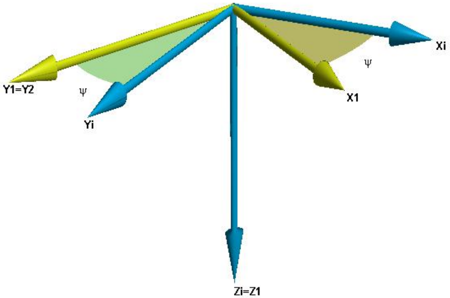
$\vec{x}_i$: tangent to the current meridian, towards North
$\vec{y}_i$: tangent to the current parallel, towards East
$\vec{z}_i$: downward

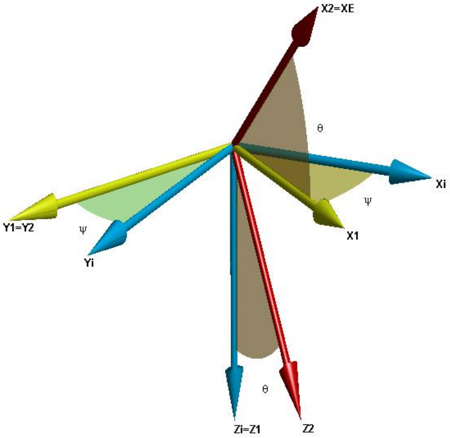
Aircraft frame

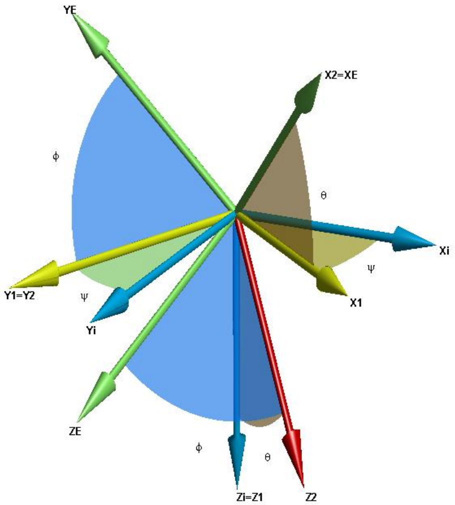


$\vec{x}_E$: longitudinal aircraft axis
$\vec{y}_E$: perpendicular to x aircraft axis, towards right
$\vec{z}_E$: perpendicular to x aircraft axis, downward

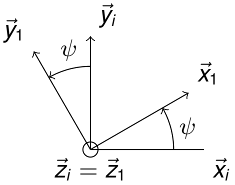

Xi
Yi
Zi=Z1


Xi
ψ
X1
Y1=Y2
ψ
Yi
Zi=Z1


X2=XE
θ
Xi
ψ
X1
Y1=Y2
ψ
Yi
θ
Zi=Z1
Z2

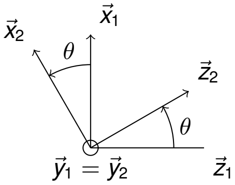

YE
X2=XE
ϕ
θ
Xi
ψ
X1
Y1=Y2
ψ
Yi
ZE
ϕ
θ
Zi=Z1
Z2

Frames: Euler angles



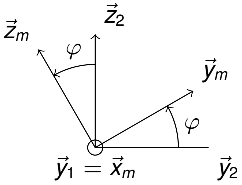
$$\vec{e}_i = M_{R_1 \to R_i} \vec{e}_1 = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \vec{e}_1$$

Figure: Frame change $R_1 \to R_i$



$$\vec{e}_1 = M_{R_2 \to R_1} \vec{e}_2 = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} \vec{e}_2$$

Figure: Frame change $R_2 \to R_1$



$$\vec{e}_2 = M_{R_m \to R_2} \vec{e}_m = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{pmatrix} \vec{e}_m$$

Figure: Frame change $R_m \to R_2$

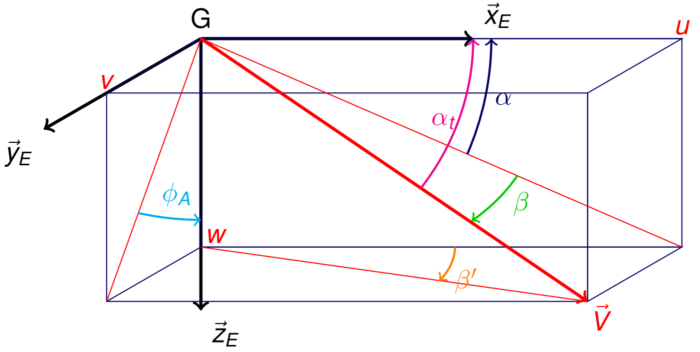
Transition matrix from aircraft frame $R_m(\vec{x}_m, \vec{y}_m, \vec{z}_m)$ to geographic local frame (or inertial frame) $R_i(\vec{x}_i, \vec{y}_i, \vec{z}_i)$ $R_m \rightarrow R_i$

$$\vec{e}_i = M_{R_m \rightarrow R_i} \vec{e}_m = M_{R_1 \rightarrow R_i} M_{R_2 \rightarrow R_1} M_{R_m \rightarrow R_2} \vec{e}_m =$$

$$\begin{pmatrix} \cos\theta\cos\psi & \cos\psi\sin\theta\sin\varphi - \sin\psi\cos\varphi & \cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi \\ \cos\theta\sin\psi & \sin\psi\sin\theta\sin\varphi + \cos\psi\cos\varphi & \cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi \\ -\sin\theta & \cos\theta\sin\varphi & \cos\varphi\cos\theta \end{pmatrix} \vec{e}_m$$

φ : roll angle (or bank angle), $\varphi \in [-180°, +180°]$
θ : pitch angle (or pitch attitude or inclination), $\theta \in [-90°, +90°]$
ψ : yaw angle (or heading), $\psi \in [-180°, +180°]$

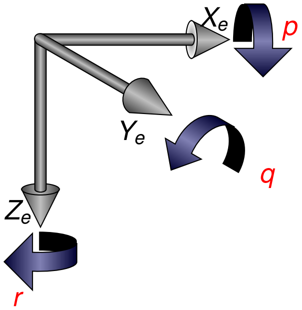
Incidence (angle of attack) and sideslip (Norm NF X02-115)



- Incidence (or angle of attack) $\alpha = \arctan\left(\frac{w}{u}\right)$ if $u \neq 0$ and $\alpha = sign(w)\frac{\pi}{2}$ otherwise
- Sideslip (first definition) $\beta = \arcsin\left(\frac{v}{V_a}\right)$ with $V_a = \sqrt{u^2 + v^2 + w^2}$
- Sideslip (second definition) $\beta' = \arctan\left(\frac{v}{u}\right)$ if $u \neq 0$ and $\beta' = sign(v)\frac{\pi}{2}$ otherwise
- Aerodynamic roll $\phi_A = \arctan\left(\frac{v}{w}\right)$ if $w \neq 0$ and $\phi_A = sign(v)\frac{\pi}{2}$ otherwise
- Total incidence $\alpha_T = \arcsin\left(\frac{u}{V_a}\right)$

ROTATION SPEED OF BODY FRAME

Rotation speed Ω_{R_e/R_i} of body frame wrt Earth frame projected in body frame is $\Omega_{R_e/R_i} = \begin{pmatrix} p & q & r \end{pmatrix}^T$

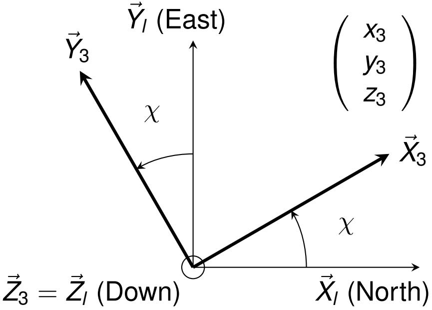


AERODYNAMIC FRAME

Change frame $R_I(North,\ East,\ Down) \rightarrow R_3$

χ: relative velocity azimuth $\vec{V}_r$ (defined counterclockwise)

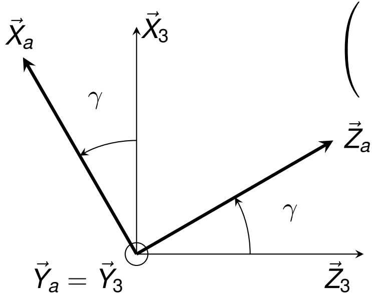
The relative velocity azimuth is defined with respect to North (vector $\vec{X}_I$).



$$\begin{pmatrix} x_3 \\ y_3 \\ z_3 \end{pmatrix} = \begin{pmatrix} \cos\chi & \sin\chi & 0 \\ -\sin\chi & \cos\chi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_I \\ y_I \\ z_I \end{pmatrix}$$

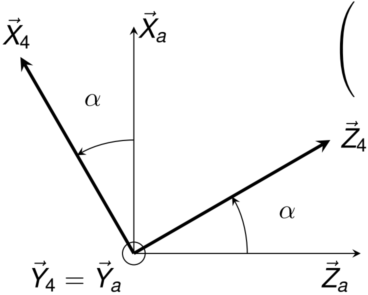
Frame transition $R_3 \rightarrow R_a$ (aerodynamic frame)

γ: relative velocity flight path angle $\vec{V}_r$ (defined counterclockwise)



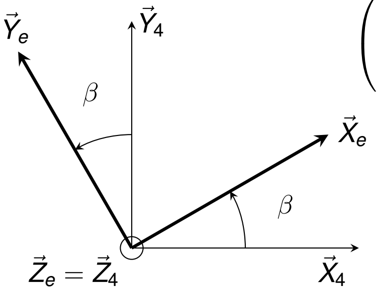
$$\begin{pmatrix} x_a \\ y_a \\ z_a \end{pmatrix} = \begin{pmatrix} \cos\gamma & 0 & -\sin\gamma \\ 0 & 1 & 0 \\ \sin\gamma & 0 & \cos\gamma \end{pmatrix} \begin{pmatrix} x_3 \\ y_3 \\ z_3 \end{pmatrix}$$

Frame transition $R_a \to R_4$
α: incidence



$$\begin{pmatrix} x_4 \\ y_4 \\ z_4 \end{pmatrix} = \begin{pmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{pmatrix} \begin{pmatrix} x_a \\ y_a \\ z_a \end{pmatrix}$$

Frame transition $R_4 \rightarrow R_e$ (aircraft frame)
β: sideslip



$$\begin{pmatrix} x_e \\ y_e \\ z_e \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_4 \\ y_4 \\ z_4 \end{pmatrix}$$

For instantaneous rotation speed vector components projected in aircraft frame $(p, q, r)^T$, the positive direction is counterclockwise.

- pitch $q > 0$: nose up
- pitch $q < 0$: dive
- yaw $r > 0$: flat turn toward right
- roll $p > 0$: inclination toward right

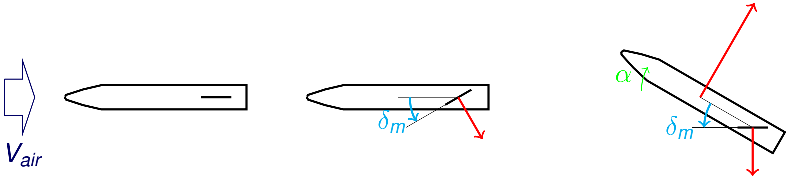
For equivalent steering angles (meaning intermediate angles which are different from real fin steering angles), the positive direction is counterclockwise.

- pitch $\delta_m > 0$: yoke frontwards, dive
- pitch $\delta_m < 0$: yoke rearwards, nose up
- yaw $\delta_n > 0$: rudder toward left, flat turn toward left
- roll $\delta_l > 0$: yoke toward left, inclination toward left

CONTROL AIRCRAFT

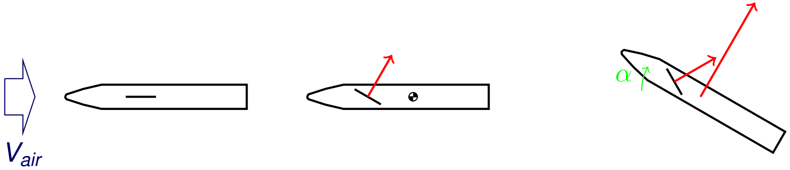
AERODYNAMIC CONTROL

A tail control surface deflection rotates the airframe and creates an incidence, which generates lift.



Aerodynamic control by canards

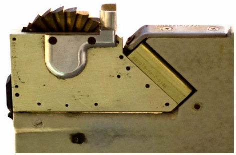
Canards deflexion rotates the airframe and creates incidence, which creates lift.



AERODYNAMIC CONTROL BY CANARDS

With canards,

- no non minimum phase behaviour,
- interactions between canards and tail aerodynamic wings makes roll difficult to control without special device (with a decoupled tail wings which are free to turn with respect to body of aircraft or with rollerons which are air driven gyroscope . . . , for example on Sidewinder missile)



JET CONTROL

- Thrust Vector Control
  - with deflectors located in the nozzle
  - with rotating nozzle
  - with shock wave in the nozzle
- Lateral jet control
  - applied to aircraft center of gravity to create a force with a short response time
  - applied to rear or front of the aircraft to create a moment

For lateral jet control, the combustion time is generally relatively short

EQUIVALENT FIN DEFLECTION ANGLE

For a missile with 4 fins for example, we define 3 equivalent fin deflection angles

δ_m pitch equivalent fin deflection angle

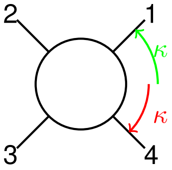
δ_n yaw pitch equivalent fin deflection angle

δ_l roll equivalent fin deflection angle

These equivalent deflection angles are used for aerodynamic models.

To obtain the real fin deflection angles from equivalent angle we use the following equations (for the case of cross fly configuration):

$$\sigma_1 = \frac{\delta_l}{4} + \frac{\delta_m}{4}\cos\kappa - \frac{\delta_n}{4}\sin\kappa$$
$$\sigma_2 = \frac{\delta_l}{4} - \frac{\delta_m}{4}\cos\kappa - \frac{\delta_n}{4}\sin\kappa$$
$$\sigma_3 = \frac{\delta_l}{4} - \frac{\delta_m}{4}\cos\kappa + \frac{\delta_n}{4}\sin\kappa$$
$$\sigma_4 = \frac{\delta_l}{4} + \frac{\delta_m}{4}\cos\kappa + \frac{\delta_n}{4}\sin\kappa$$
$$\kappa = 45°$$

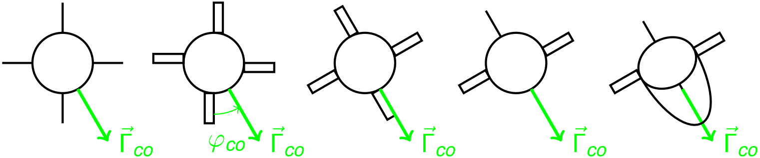


Here the σ_i are the real fin deflection angles, around the axes 1, 2, 3 and 4, counted counter clockwise.
The angle κ is the angle between the body reference plane and the real fin rotation axes.

BANK TO TURN

In order to generate an acceleration in a given direction:

- the aircraft rolls to align aircraft z axis with desired acceleration (modulo 180° or 360°, depending on the ability of the aircraft to take negative incidence)
- it rises its incidence to generate lift
- the sideslip is controlled to 0



Used in the case of an aerodynamic configuration with lifting surface greater on pitch axis than on yaw axis.

BANK TO TURN (COORDINATED TURN)

Let R_g be the guidance frame obtained from geographic local frame by rotations of angle ψ and θ (but without roll).
In this frame R_g the guidance algorithm provides the commanded acceleration Γ_{yg} following the y guidance axis and acceleration Γ_{zg} following the z guidance axis.
Commanded accelerations in aircraft axes are :

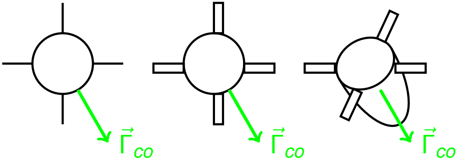
- following y aircraft axis $\Gamma_{ym_{co}} = 0$
- following z aircraft axis $\Gamma_{zm_{co}} = \left|\Gamma_{zg}\cos\varphi + \Gamma_{yg}\sin\varphi\right|$

The Commanded roll is $\varphi = Arctan2(\Gamma_{yg}, \Gamma_{zg})$

In this case, incidence α is always positive and φ may vary between $-180°$ and $180°$. But we could choose an incidence α possibly negative and $\varphi \in [-90°, +90°[$, if the aircraft is able to take negative incidence.

Skid to turn or flat turn

- The aircraft takes incidence and sideslip to generate acceleration in the desired direction
- Roll controlled to 0

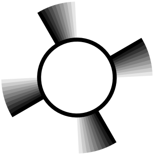


Used in the case of symmetric aerodynamic configuration in pitch and yaw axis.

BANKING WHILE TURNING

- Simultaneously, the aircraft takes incidence and sideslip to generate the commanded acceleration and takes roll to lead the pitch axis in the direction of the desired acceleration.
- Use in the same condition as BTT and could allow shortest response time, but might be more complex to tune (in case of pitch/yaw aerodynamic coupling).

AUTOROTATION



- Rotating missile around its longitudinal axis (roll stabilized)
- It is possible to use only one fin plane (for small diameter missiles) or two fin planes.
- The commands are modulated by roll.

Transverse acceleration capability

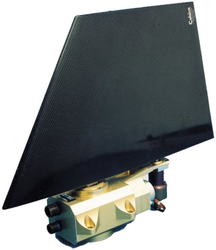
- For a flight in $+$ configuration, the acceleration capability for y and z axis is $\Gamma_{max\perp}$.
- For a flight $\times$ configuration, the acceleration capability for y and z axis is $\Gamma_{max\perp}\sqrt{2}$.
- In autoration, the acceleration capability is $\Gamma_{max\perp}$ with 2 fin planes and fin deflection angles modulated by roll.
- In autoration, the acceleration capability is $\Gamma_{max\perp}/2$ with 1 fin planes and fin deflection angles modulated by roll.

CONTROL AIRCRAFT

ACTUATORS : AERODYNAMIC FINS

Linear actuator + connecting rod Technology

- electric
- hydraulic
- pneumatic



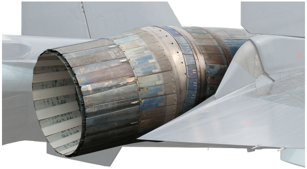
A control loop is in charge of ensuring that realized fin angular position is equal to commanded fin angular position, via a linear or angular position sensor (other sensors might be used e.g. rotation speed sensor).

In general, the fin control loop is modeled by a second order transfer function with angular position, speed and acceleration saturations.

$$\frac{\delta_m}{\delta_{m_c}} = \frac{1}{\frac{s^2}{\omega_a^2} + 2\frac{\xi_a}{\omega_a}s + 1}$$

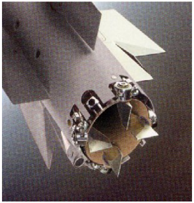
Actuator defaults: saturation, limited bandwidth, mechanical play, friction depending...
Saturations generally depend on hinge moment on actuators.

Thrust Vector Control



Sukhoi SU35 nozzle - photo Julian Herzog

Harrier nozzle - photo WyrdLight.com

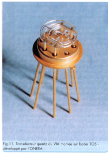


Here are 3 examples of thrust vector control (meaning control by deviating the thrust with a rotating nozzle or with vanes in the thrust jet). This can be very useful at low speed or high altitude, and can give a VTOL (Vertical Take Off and Landing) capability to a fighter.

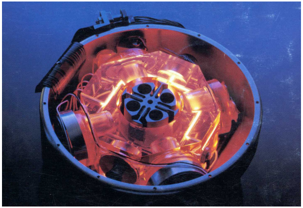
CONTROL AIRCRAFT

SENSORS

- Accelerometers (linear / angular)
- Gyrometers
- Gyroscopes
- Incidencemeters
- Air data computer
- GPS (radionavigation)
- Magnetometer
- Altimeter
- Radar (ILS, VOR ...)
- Telemeter
- Camera (vision)
- Ultrasound



A380 pitot tube - photo David Monniaux



Sensors Defaults: bias, scale factor, noise, limited bandwidth, saturations