Convertible delta-wing aircraft for teaching and research

Tudor-Bogdan Airimitoaie, Christophe Farges, Loïc Lavigne, and Franck Cazaurang

Univ. Bordeaux, Bordeaux INP, CNRS, IMS, 33405 Talence, France

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What is a convertible aircraft ?

A combination between:

- a multicopter

➜ hover at fixed point

➜ take-off and landing vertically

  ➥ reduced environmental footprint (no need for a runway)

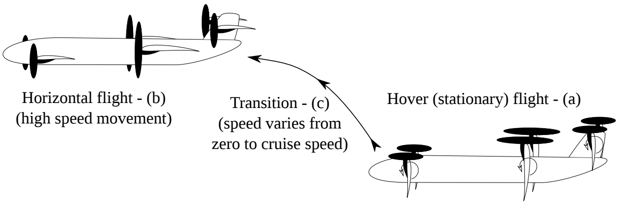
- a fixed-wing aircraft

➜ improve aerodynamic efficiency using wings

  ➥ reduced energy consumption

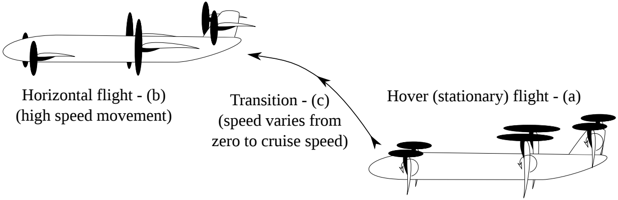
  ➥ increased flight length

Proposed convertible aircraft concept



- 6 propeller-engines: 4 for VTOL and 2 for forward flight
- 3 pairs of wings: canard, main and elevator
- tilt-wing design: wings and propellers are fixed together

Proposed convertible aircraft concept



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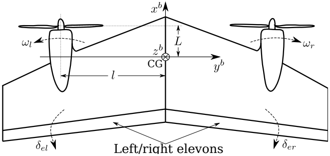
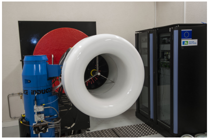
Initial (simpler) configurations:



Univ. Bordeaux - IMA

Master programs : automatic control and aeronautics maintenance
Aeronautics maintenance (IMA) : avionics, mechanical structure, composite materials, embedded systems



Part I – Multidisciplinary student project

Project main activities

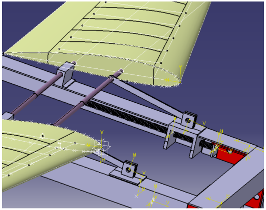
Multidisciplinary project:

- mechanical system design and build (composite materials)
- numerical wind-tunnel analysis by CFD
- embedded system design and programming
- control law design including FTC and FDI

CAD of the mechanical system

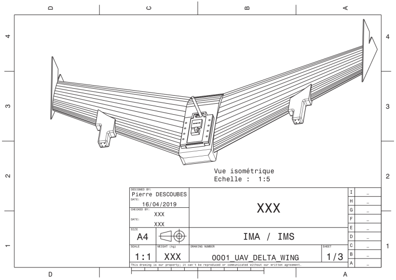
- reduce cost and time before production
- necessary before construction of any modern aircraft

First example: tilt-wing mechanism



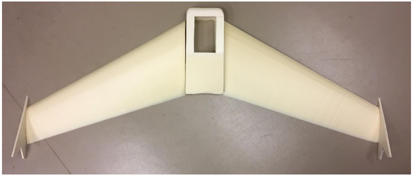
Second example: delta-wing

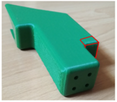
- motors holds
- central bloc (electronics components)
- structural analysis

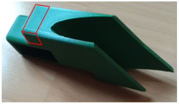


Composite materials

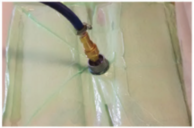
Design lighter, more resistant frames:



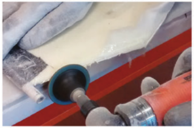




POSE DE FIBRE CARBONE SUR LES BORDS D'ATTAQUE

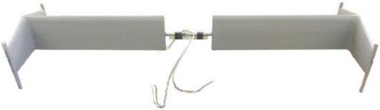


MOULAGE À L'AIDE D'UNE BÂCHE À VIDE



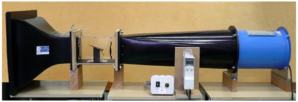
PONÇAGE DES WINGLETS

AILE GAUCHE APRÈS ASSEMBLAGE ET AVANT PEINTURE



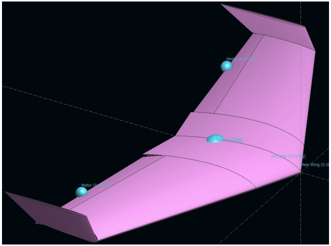
Numerical wind-tunnel analysis (CFD)

Non-linear modelling : need to know the aerodynamic coefficients
Specificities: complex procedure requiring good knowledge of numerical solvers.



XFLR5:

- free software, much simpler, accurate for small angles of attack, fast results
- can be used for a first analysis

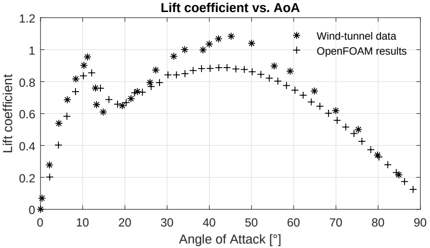


Numerical wind-tunnel analysis (CFD)

OpenFOAM:

- analysis of complex shapes under more general fluid flow conditions
- can be used for any angle of attack
- complex configuration of numerical solvers

Evaluation of a 2D NACA 0012 profile for high angles of attack and Re=5e5:

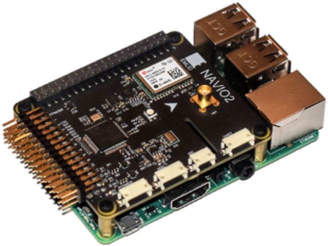


Wind-tunnel data from: Sheldahl & Klimas, Aerodynamic characteristics of seven symmetrical airfoil section through 180-degree anle of attack for use in aerodynamic analysis of vertical axis wind turbines, 1981.

Embedded systems design

Currently focusing on 2 autopilot off-the-shelf systems:

- RaspberryPI + Navio2 hat (from Emlid) using the ArduPilot flight stack
- Pixhawk using the PX4 flight stack



Remarks:

- ArduPilot: easier to program, less performance
- PX4: parallel programming using uORB messages
- offer SITL simulation capabilities
- include code for estimation (EKF) and control (PID) that can be modified in accordance with the controlled UAV

Part II – Controller design (flatness)

Flatness analysis

Recall on flat systems (J. Lévine, 2009):

$$\dot{x} = f(x, u), \ x \in \mathbb{R}^n, \ u \in \mathbb{R}^m, \ m \leq n$$

is differentially flat iff $\exists \ y \in \mathbb{R}^m$, $y = f_y(x, u, \dot{u}, \ldots, u^{(p)})$, s.t.

$$x = f_x(y, \dot{y}, \ddot{y}, \ldots, y^{(q)}),$$
$$u = f_u(y, \dot{y}, \ddot{y}, \ldots, y^{(q+1)}).$$

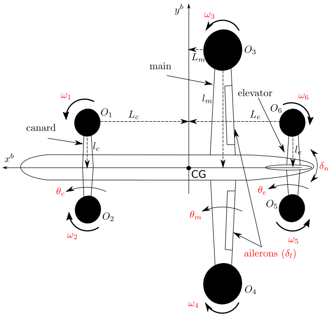
➜ y are called the flat outputs.

Applications of flatness: feedforward control, fault detection and isolation (FDI), ...

Flatness for quad-copter configuration: see Martinez Torres, PhD, Univ. Bordeaux 2014.

Control inputs

- 3 wing rotation angles (θ_c, θ_m, and θ_e),
- rotation speeds of 6 propeller-engines (ω_1, ω_2, ω_3, ω_4, ω_5, and ω_6),
- main wing aileron deflection (δ_l),
- rudder tilt angle (δ_n)

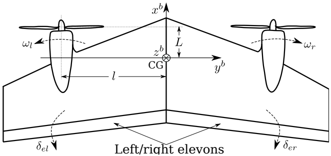


There are only 5 independent control inputs:

- Take-off, landing, and hover
  - ➥ ω_1, ω_2, ω_5, ω_6, and $\theta_c = \theta_e$
- Fast forward flight
  - ➥ ω_3, ω_4, δ_l, δ_n, and θ_c

The delta-wing convertible aircraft has:

- 2 propeller-engines
- 2 elevons



How to handle the gimbal lock?

Euler angles: gimbal lock at $\gamma(t) = 90°$

- ➥ problem during vertical take-off and landing

Solution 1: use a second set of Euler angles $\mu_v(t)$, $\gamma_v(t)$, and $\chi_v(t)$ known as vertical Euler angles (Castillo et al. (2005))

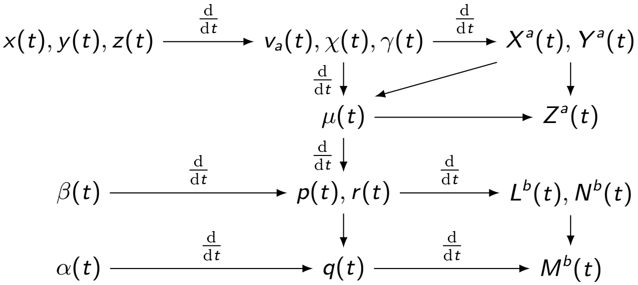
$$R^o_{a_v} = R_y(\pi/2)R_z(\chi_v(t))R_y(\gamma_v(t))R_x(\mu_v(t)) \quad (1)$$

Solution 2: use other parametrisations for attitude representation (quaternion, MRP, etc.)

- ➥ difficult to find the flat output and to prove flatness
- ➥ symbolic computation tools needed (thesis of Rym Rammal)

Flatness analysis – flat outputs

Proposed set of flat outputs: $x(t)$, $y(t)$, $z(t)$, $\alpha(t)$, and $\beta(t)$.



What happens if $v_a(t)$ is small?

Problem: model written using vertical Euler angles becomes singular.

Proposed solution: write Newton's second law in frame $\mathcal{B}$

$$\dot{\xi} = V_o^o, \tag{2}$$

$$m\frac{\mathrm{d}V_o^o}{\mathrm{d}t} = R_b^o F_p^b + G^o, \tag{3}$$

$$\dot{R}_b^o = R_b^o \left[\Omega_{bo}^b\right]_\times, \tag{4}$$

$$\frac{\mathrm{d}\left(I\Omega_{bo}^b(t)\right)}{\mathrm{d}t} = -\,\Omega_{bo}^b(t) \wedge I\Omega_{bo}^b(t) + \tau_b(t). \tag{5}$$

where $F_p^b(t) = R_y(\theta_e(t))\left[F_p^e(t)\ 0\ 0\right]^T$.

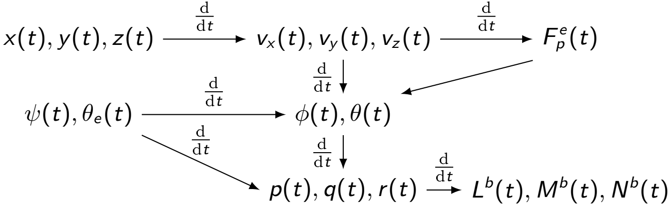
$$\begin{bmatrix}\dot{x}(t)\\ \dot{y}(t)\\ \dot{z}(t)\end{bmatrix} = \begin{bmatrix}v_x\\ v_y\\ v_z\end{bmatrix} \tag{6a}$$

$$\begin{bmatrix}\dot{v}_x(t)\\ \dot{v}_y(t)\\ \dot{v}_z(t)\end{bmatrix} = R_z(\psi)R_y(\theta)R_x(\phi)R_y(\theta_e)\begin{bmatrix}F_p^e\\ 0\\ 0\end{bmatrix} + G^o \tag{6b}$$

$$\begin{bmatrix}\dot{\phi}(t)\\ \dot{\theta}(t)\\ \dot{\psi}(t)\end{bmatrix} = \begin{bmatrix}1 & \mathrm{s}\phi\mathrm{t}\theta & \mathrm{c}\phi\mathrm{t}\theta\\ 0 & \mathrm{c}\phi & -\mathrm{s}\phi\\ 0 & \frac{\mathrm{s}\phi}{\mathrm{c}\theta} & \frac{\mathrm{c}\phi}{\mathrm{c}\theta}\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix} \tag{6c}$$

$$I\begin{bmatrix}\dot{p}(t)\\ \dot{q}(t)\\ \dot{r}(t)\end{bmatrix} = -\begin{bmatrix}p\\ q\\ r\end{bmatrix} \wedge I\begin{bmatrix}p\\ q\\ r\end{bmatrix} + \begin{bmatrix}L^b\\ M^b\\ N^b\end{bmatrix} \tag{6d}$$

Flat outputs: $x(t, y(t), z(t), \psi(t)$, and $\theta_e(t) = \theta_c(t)$.



Conclusions and perspectives

- Multidisciplinary: students with different scientific background need to work together
- Great hands-on experience and opportunity to apply theory learnt in classes
- Automatic control law design needs good knowledge of the system that it is designing for

Thank you for your attention!

Project web page: http://tudor-bogdan.airimitoaie.name/mica/