Other examples of innovative UAV technologies: flapping wings, guided parafoil systems, distributed actuation

Thierry Le Moing (DCSD), Carsten Döll (DCSD), Clément Toussaint (DCSD), Jean-Bernard Paquet (DAAP)
Flapping wing Unmanned Aerial Vehicles
Flapping wing Unmanned Aerial Vehicles

Wide range of bio-inspired configurations
Various concepts and performances
  Importance of vortex wake structure – Wing wake interaction
  Reynolds Number – Added mass – Inertial forces

RoboBee
Harvard 2011
3cm - 80mg

DelFly Micro
TU Delft 2008
10cm – 3g

Nano-Hummingbird
Aerovironment 2011
16cm – 19g

SmartBird
Festo 2011
2m – 450g

Several aeromechanic architectures

Flapping actuator
  • dc motor + crank-rocker mechanism
  • vibrating piezoelectric lamella

Control
  • wing-stroke frequency (crank-rocker)
  • wing-stroke amplitude (vibrating lamella)
  • control surfaces
  • wing shape deformation
  • wing-stroke shape

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3 4 5
Flapping wings at ONERA

2002-2006 : ONERA federative research project REMANTA
(REsearch project on Micro Air vehicles and New Technologies Applications)
Multidisciplinary project (aérodynamics, materials, flight dynamics and control)
Objective : scientific understanding of flapping flight at low Reynolds
Identifying of technological difficulties (no MAV demonstrator)

Potentiel interest of flapping MAV
- Hovering flight capacity and manoeuvrability at low speed
- Low-intensity acoustic signature / multirotor MAV

REMANTA project outcomes
- Resonant thorax concept (importance of inertial effects)
- Flight dynamics model : OSCAB simulation software
  Exact modeling of wing kinematics
  Blade-element aerodynamics modeling
REMANTA benefits for flight dynamics studies

Preliminary evaluation of various control strategies (rigid wing and ideal flapping actuator)

- Backstepping method
- Sliding mode control
- Averaging methods for control of periodic systems
- PVTOL (Planar Vertical Take-Off and Landing) control approaches

Online optimization of wing kinematics (DCSD-DAAP 2007–2008)

- Scale wing model
- 2 dof mechanism
  - flapping
  - pitching

Water tank at ONERA/DAAP (Lille)

Partial validation Aerodynamic modelling

- Lift is increasing at high angles of attack (>30°)
In-Art ANR Project (2009-2013)

**Objective**
Design of a bio-inspired Nano-Air-Vehicle
*IEMN*, LPPI, ONERA/DAAP
"Aeroelastic framework of insect-like flapping-wing applied to the design of a resonant nano air vehicle"

**Concept**
- Actuation on an active bending and passive torsion
- No articulations – rigid thorax
- Wing mode-shape designed to reproduce insect wing kinematics
- SU-8 Manufacturing
  - wingspan: 3cm
  - weight: 30mg
ONERA/DCSD Flapping wing studies

Proposed concept in REMANTA project (2002)
- flapping in horizontal stroke plane
- lift, propulsion and stabilization driven by wing stroke control
- wingspan 15-20cm
- flexible wings
- wing stroke frequency ~30Hz
- weight ~ 20g

Nano Hummingbird characteristics

Technological locks
- design and realization of flapping mechanism capable of controlling several DoF
- design and realization of flexible wings with adequate wing profile

Wing motion & lift in hovering flight
Flapping wing system

- Resonant mechanism (minimum losses)
- Direct control of 3 DoF (lift, pitch, roll) by adjustment of wing stroke amplitude and middle position
- Passive wing rotation (only flapping actuator) → Optimization of wing flexibility

Expected performances

- Hovering flight capacity without additional actuators
Ongoing activities

Tools development for wing structure designing and dimensioning
Simulation of wing deformation using Absolute Nodal Coordinates Formulation (ANCF) method

Finite element modeling for large displacements (applied to flexible multibody dynamics)

Design of an onboard flapping mechanism

- Resonant mechanism
  
  ONERA patent pending

- Use of micro electrical motors (coreless et brushless motors)

- Design of specific motor controllers

Experimental performances
75mm wing
  frequency 28Hz
  amplitude +/- 70°

100mm wing
  frequency 23Hz
  amplitude +/- 60°
Guided parafoil air delivery systems
Guided parafoil air delivery systems

**General objective**
Enhancement of all weather operational performance (wrt. existing US systems)
DGA-TA research focus:

**FAWOPADS** (Future All Weather Operations Payload Aerial Delivery Systems)

- Improving knowledge of parafoil flight dynamics
- Analysis of factors influencing landing accuracy

Development of a network of expertise (DGA-TA, ISAE, ONERA, …)

**DGA-TA contracts** *(2010-2011 & 2013-2015)*
- Development of flight dynamics modeling and analysis tools
- Parameter estimation of parafoil modeling from flight test data
- Development of a new guidance strategies

**ONERA/DCSD experimental activity**
Improving our experimental knowledge with a mini powered paraglider
Mini powered paraglider: OPALE Paramodels
Canopy: SPIRAL 2.4m²
Payload: 2-3kg

No technological locks
- Off-the-shelf components: sensors, actuators, controller, …
Development of parafoil modeling

Constitutive elements

• Mechanical modeling
  relative motions of payload wrt canopy
  → from 6 DOF (no relative motion) to 9 DOF (3 rotations)

• Aerodynamic modeling
  aerodynamic coefficients relative to canopy
  Well documented for longitudinal coefficients
  Poorly documented for lateral coefficients
  Canopy unsteady aerodynamics: added mass and inertia

Model implementation in Matlab

• Matlab / Simulink simulation
  Trimming and linearizing models

• Flight Gear tool
  Open source flight simulator
  Flight visualization
Introduction to flight dynamic analysis

Objective
Better understanding of flight dynamics
- turn equilibrium analysis
- parafoil – aircraft differences

Approach
Trim points computing / brake position
- longitudinal equilibrium
- lateral/turn equilibrium

Main characteristics
Low velocity / Wind sensitivity
Commands : 2 brake control lines
Longitudinal
- low controllability of glide slope
Lateral
- classical turn (≠aircraft)
  spiral motion
Additional modes : pendulum motion
DGA-TA flight tests

Objective
Parafoil modeling updating from DGA-TA flight test data
   2 Flight test campaigns (nov. 2013, dec. 2014)

Flight data reconstruction

Ground data reconstruction (attitude, ground speed, position)
   Difficulties (Parafoil flight dynamics specificities)
      • persistent load factors ≠ g (erroneous attitude angles with IRS/AHRS)
      • pendulum motion
      • biased magnetometer measurements

   Method
      • a posteriori calibration of magnetometer measurements
      • precise GPS IMU integration (Invariant Extended Kalman Filter)

Air data reconstruction
   Difficulties : no onboard anemometric sensors

   Method
      wind estimation on stabilized phases of flight
      assumptions :
         • constant air velocity
         • null sideslip angle
         • introduction of lift equation in a filter error approach
Block diagram of flight parameter reconstruction

**GPS**
- \( v_N, v_E, v_Z \)
- \( x_0, y_0, h_0 \)
- \( h_x, h_y, h_z \)

**IMU**
- \( p, q, r \)
- \( \alpha_x, \alpha_y, \alpha_z \)

**Load sensors**
- \( e_{fd}, e_{fg} \)

**Ground state Estimation**
- Invariant extended Kalman filter

**Stabilized phases detection**

**Air data Estimation**
- Filter error

**Wind**
- \( \alpha_{w_0}, \beta_{w_0} \)

**Radar Wind profiler**

**Weather data**

**Aircraft data**

**assumptions:**
- air velocity \( \sim \) constant sideslip \( \sim 0 \)
- Long time-varying wind

**magnetometer measurement recalibration**
Selection et evaluation of an advanced off-the-shelf controller

**PIXHAWK** (ETH Zurich)
Open-source, open-hardware project
2 processors
- PX4 FMU Cortex M4 – 168MHz – FPU
- PX4 IO Cortex M3
RTOS : NuttX
μObject Request Broker
Drivers – μSD Data logging

**Ground state estimation**
First component for the design of an automatic landing system
**Invariant extended Kalman Filter** (15 states)
3 correction modes
- alignment (inertial)
- navigation without GPS (inertial + magnetometer)
- data fusion with GPS (inertial + magnetometer + GPS)
C++ programming
Matrix library (symmetric matrices)
Estimation and logging at 100Hz
On-going DGA-TA activities

- Parameter estimation of parafoil modeling

- Development of a new adaptive guidance strategy to ensure accurate delivery providing good wind resistance

  Efficient use of parafoil flight dynamics capabilities

- First experiments of flight control laws on the ONERA mini-powered paraglider
Wing demonstrator with innovative control surfaces

DEVIS
Objective: Wing weight reduction while ensuring the required reliability and performance levels for a fixed wing A/C (study case light aircraft)

Realised by:

1. Suppression of metallic ironware within the transmission chain from the stick to the control surface using 5 redundant brushless electrical motors and a simplified gear mechanism without backlash suggested by ONERA.

2. Better repartition of the stress introduction into one classical or several distributed control surfaces using the concept of a flexible hinge proposed by our partner PROTOPLANE (Soleau No.481616).
**Wing demonstrator with innovative control surfaces**

**DEVIS**

**Objective:** Wing weight reduction while ensuring the required reliability and performance levels for a fixed wing A/C (study case light aircraft)

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Ball-joint concept "without backlash"
Direct transmission concept

Flexible hinge

Deflection : 0°
Wing demonstrator with innovative control surfaces

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Objective: Wing weight reduction while ensuring the required reliability and performance levels for a fixed wing A/C (study case light aircraft)

Realised by:

3. Test and validation of a new avionics architecture based on ethernet wiring suggested by ONERA

4. Test and validation of new reconfiguration laws in the failure case foreseen by ONERA (planned, see also European Project RECONFIGURE and internal project FAUST)
Objective: Wing weight reduction while ensuring the required reliability and performance levels for a fixed wing A/C (study case light aircraft)

Hardware

- Modules:
  - Open Controller OC8S
  - Arm9 @400Mhz 64M ram, 1G rom
  - POE, uart, dac, adc, thermal/accelero sensors ...
  - 360mW

- Switch
  - Trendnet TPE-80WS
  - 8 x 15.4W
  - IEEE802.1 p/Q (Qos/VLAN)
  - 10/100/1000Mbps

Realised by:

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