

# CONTRIBUTIONS TO THE AUTOMATIC CONTROL OF AERIAL VEHICLES

**MINH DUC HUA<sup>1</sup>**

<sup>1</sup>INRIA Sophia Antipolis, AROBAS team

IS3-CNRS Sophia Antipolis, CONDOR team

Project ANR SCUAV

Supervisors: Pascal MORIN, Tarek HAMEL, Claude SAMSON

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# Outline

- 1 Motivations
- 2 Nonlinear Feedback Control Design
- 3 Attitude Estimation
- 4 Conclusion

# Underactuated Aerial Robots

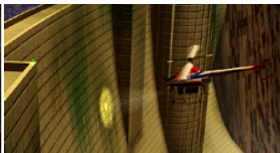
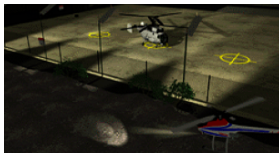


## ● APPLICATIONS:

Surveillance, Inspection, Searching and rescuing, Cartography (SLAM), ...

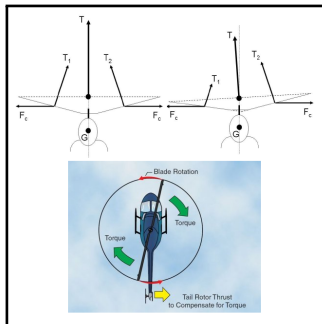
## ● Development challenges

- ▷ Mechanical and geometrical conception.
- ▷ Modeling of aerodynamic forces.
- ▷ State reconstruction.
- ▷ Control design.



# How do they fly?

- 1 **Thrust force** to monitor the translational motion and to counterbalance the weight.
- 2 **Actuation system to generate torque** for orientation control.

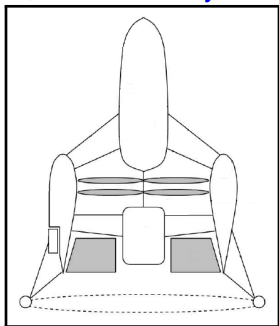


## EXAMPLES:

- Tail-rotor Helicopters
- Ducted fan Tailsitters
- Quadrotor Helicopters

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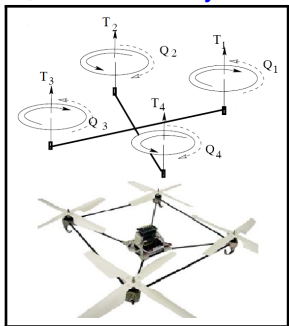


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# Motivation 1 – Control design

**OBJECTIVE:** Unifying control approach

- robust w.r.t. external perturbations, modeling errors, and measurement/estimation errors.
- with “large” domain of stability.



Ship



Hovercraft



Helicopter



Tailsitter



Blimp



Submarine



Airplane



Rocket

## Motivation 2 – Attitude estimation

- **Attitude information is required for feedback control.**
- In the 2D-case (ex. Ships), attitude can be directly measured (ex. using a magnetic compass).
- In the 3D-case (ex. VTOL drones), obtaining attitude is more complicated.

**OBJECTIVE:** Robust and effective attitude estimation algorithms using an Inertial Measurement Unit (IMU) and a GPS.



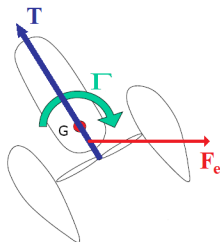
## System modeling (1/2)

### FORCES APPLIED

- $\vec{T}$  : Thrust force control
- $\vec{F}_e$  : sum of all external forces

### TORQUES APPLIED (EXPRESSED IN $\mathcal{B}$ )

- $\Gamma \in \mathbb{R}^3$  : Torque control input
- $\Gamma_e \in \mathbb{R}^3$  : sum of torques created by all external forces



## System modeling (2/2)

### EQUATIONS OF MOTION:

$$\begin{pmatrix} \dot{x} \\ m\dot{v} \\ \dot{R} \\ J\dot{\omega} \end{pmatrix} = \begin{pmatrix} v \\ -TRe_3 + F_e \\ R\omega_{\times} \\ -\omega \times J\omega + \Gamma + \Gamma_e \end{pmatrix}, \quad e_3 \triangleq \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

### CONTROL DIFFICULTIES:

- Unavailability of a precise model of  $F_e$  and  $\Gamma_e$  valid in a large domain.
- Fast and unpredictable variation of external forces.
- Limited actuation power to counter environmental perturbations.
- Parameter uncertainties (ex.  $m$ ,  $J$ ).
- Measurement/estimation errors of the vehicle's state.

# Existing control approaches

## LINEAR CONTROLLERS

- Local stability.
- Difficulty of stabilization of unknown dynamical equilibria.
- Singularities of attitude minimal parametrization.

## NONLINEAR CONTROLLERS

- Feedback exact linearization (Koo et al., CDC 1998).
- Backstepping-based (Mahony and Hamel, CDC 1999).
- Hierarchical (Pflimlin et al., ICRA 2006).
- Nested-saturation (Marconi et al., Automatica 2002).

# Contributions

- **Unifying control framework** in the sense of taking into account a large class of environmental forces.  
Assumption:  $F_e$  depends only on  $\dot{x}$  and  $t$ 
  - example: a spherical vehicle
  - counter-example: airplanes with lift forces depending on the angle of attack
- Global stability for simple geometries (spherical body), by exploiting “dissipativity” of drag forces.
- Compensation of measurement/estimation error of  $F_e$  and modeling errors by using a novel integral correction technique.
- **Robustification** w.r.t. situations when  $|F_e|$  crosses zero, or becomes small.

## ZOOM ON NOVEL INTEGRAL CORRECTION TECHNIQUE

**OBJECTIVE:** stabilization of the equilibrium  $\tilde{x} = 0$  despite the poor knowledge of the external forces.

**SOLUTIONS:** compensation by means of integral correction.

- **Classical integrator**  $z = \int \tilde{x}$  can yield large overshoot.
- **Saturated integrator**  $z = \text{sat}_\Delta(\int \tilde{x})$ : no large overshoot but slow desaturation.
- **Proposed integrator:**  $z$  solution to

$$\ddot{z} + 2k_z \dot{z} + k_z^2(z - \text{sat}_\Delta(z)) = f(\tilde{x})$$

with  $k_z > 0$ ,  $f(\cdot)$  a bounded monotonic function

$\Rightarrow z, \dot{z}, \ddot{z}$  are bounded and can be desaturated rapidly

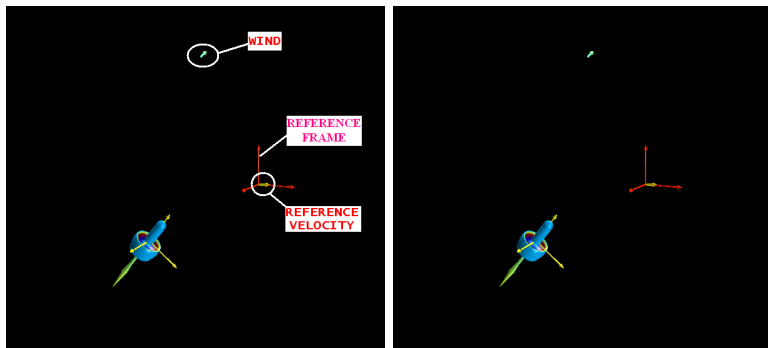
- If  $|z| \leq \Delta \Rightarrow \ddot{z} + 2k_z \dot{z} = f(\tilde{x})$
- If  $|z| > \Delta \Rightarrow \ddot{z} + 2k_z \dot{z} + k_z^2 z = f(\tilde{x}) + k_z^2 \Delta$ : left part is a critically damped system

## Aspects of the proposed control design

- Thrust direction control (joystick mode).
- Velocity control (joystick mode).
- Horizontal velocity and altitude control (joystick mode).
- Position control, i.e. tracking trajectory (automatic flight).
- Non-invertibility of the thrust direction is taken into account.
- High-gain estimator of  $F_e$ .

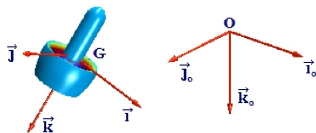
## Simulation results

Trajectory tracking for a ducted fan tailsitter model in wind gusts



# Estimation objective

Estimation of the **rotation matrix**  $R \in \text{SO}(3)$  between the body frame and the inertial frame



$$\dot{R} = R\omega_{\times}$$



# Classical solutions

- **Integrating the kinematics of rotation** using the angular velocity measurement:
  - Estimation error diverges.
  - Precise gyroscopes reduce the divergence rate, but are expensive and heavy.
- **Algebraic solutions** requiring at least two vectors (**Black, 1964**), (**Wahba, 1965**)
- **Fusion solutions** using the angular velocity measurements and two vectors observations, and exploiting complementary characteristics of sensors (ex.: frequency, precision).

⇒ **The choice of sensors and solutions may depend on applications.**

# Classical solution for aerial robots

## IMU = Gyrometers + Accelerometers + Magnetometers

- **Gyrometers:** measure angular velocity  $\omega$ .
- **Magnetometers:** measure the geomagnetic field  $m_{\mathcal{B}} = R^{\top} m_{\mathcal{I}}$
- **Accelerometers:** measure “specific acceleration”  $a_{\mathcal{B}} = R^{\top} (\dot{v} - g)$

## COMMON SOLUTIONS: Use Accelerometers as Inclinometers

$$\Rightarrow \boxed{\text{Assumption (weak acceleration): } \dot{v} \approx 0} \Rightarrow \boxed{a_{\mathcal{B}} \approx -R^{\top} g}$$

- Classical solutions can be applied.
- Precision problem in the case of strong accelerations.

$\Rightarrow$  (Martin, Salaun, IFAC 2007) use the measurement of  $v$  (given by GPS) and IMU measurements to estimate  $\dot{v}$  and improve the precision of the estimated attitude.

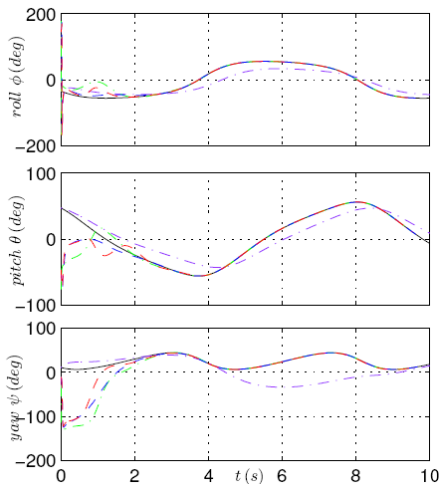
# Attitude estimation contributions

Inspired by the solutions of (Martin, Salaun, IFAC 2007) and (Mahony et al., CDC 2005), two novel attitude estimators are proposed

- 1st solution (high-gain type) ensures:
  - Semi-global convergence and stability.
- 2nd solution (non high-gain type) ensures:
  - Almost-global convergence,
  - Exponential stability when the acceleration is constant.

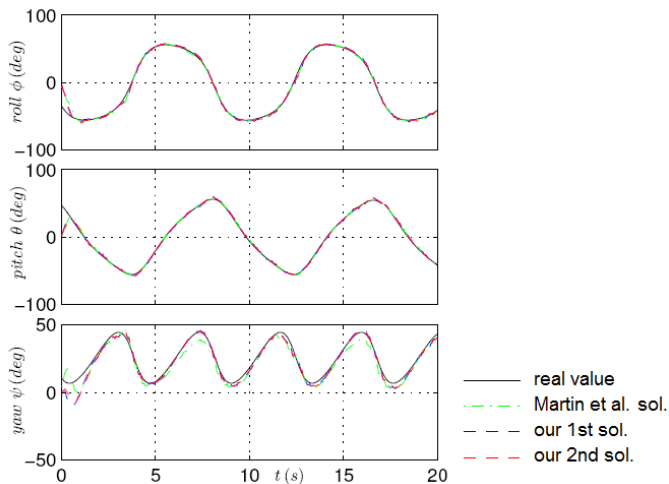
# Simulation results

Circle trajectory – perfect measures



# Simulation results

Circle trajectory – noisy and biased measures



# Perspectives

## CONTROL DESIGN:

- Extensions to vehicles subjected to important lift forces (ex. airplanes).
- Extensions for the situation when external forces vanish:
  - The system is Small-Time-Locally-Controllable, but its linearized system is not controllable.
  - Using non-classical techniques: Transverse Function (Morin, Samson, CDC 2005).
- Pursue works on the on-line estimation of  $F_e$ .

## ATTITUDE ESTIMATION:

- Compensation of measurement biases (gyro., accelero. biases).
- Robustness w.r.t. magnetic perturbation (Martin, Salaun, IFAC 2007).

## THANK YOU FOR YOUR ATTENTION



Ship



Hovercraft



Helicopter



Tailsitter



Blimp



Submarine



Airplane



Rocket