Hovering flight and vertical landing control of a VTOL Unmanned Aerial Vehicle using Optical Flow

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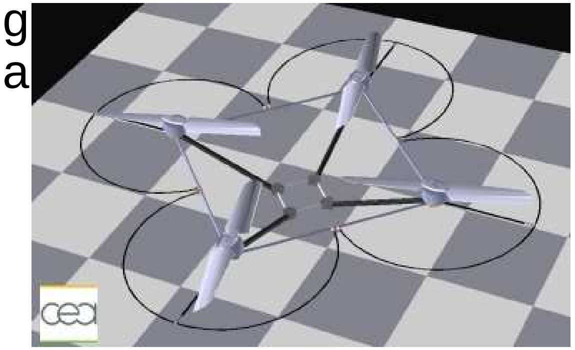
Introduction

- **Purpose :** elaboration of controllers for hovering flight and vertical landing of a VTOL UAV above a textured target.



- **We use optical flow**
  - ✓ **Computation of the translational optical flow**

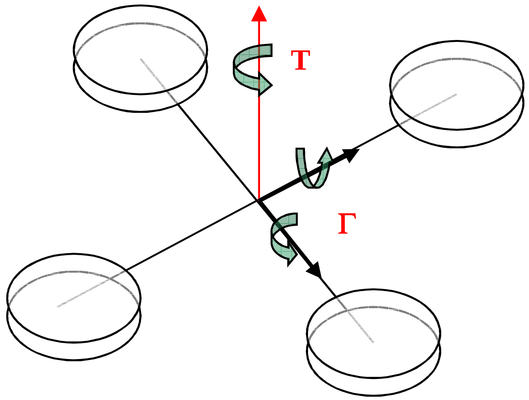
- **Stabilization of the hovering flight with a PI-type controller.**

- **A non-linear controller for a smooth vertical landing.**

- **Experimentations on a quad-rotor UAV.**

Modeling of the « X4-flyer »

- The system is nonlinear and under actuated.
- Definition of used frames.
  - ✓ I : Inertial frame attached to the earth,
  - ✓ B : body-fixed frame attached to the vehicle's center of mass.
- Vehicle state:
  - ✓ ξ: position of the center of mass in I
  - ✓ V: speed of the center of mass in B
  - ✓ R : orientation matrix from B to I
  - ✓ Ω: rotational velocity in B
- Inputs:
  - ✓ T: Global thrust in B
  - ✓ Γ: Control torque in B



- Dynamic Model used :

F=f(T,R)

Translational dynamics

$$\dot{\xi} = v$$

$$\dot{\xi} = v$$

$$m\dot{v} = F + \Delta$$

Constant forces

Rotational Dynamics

Already controlled

High gain controller

Kinematics of an image point under spherical projection

➢ **Optical flow from an image plane to a spherical retina.**

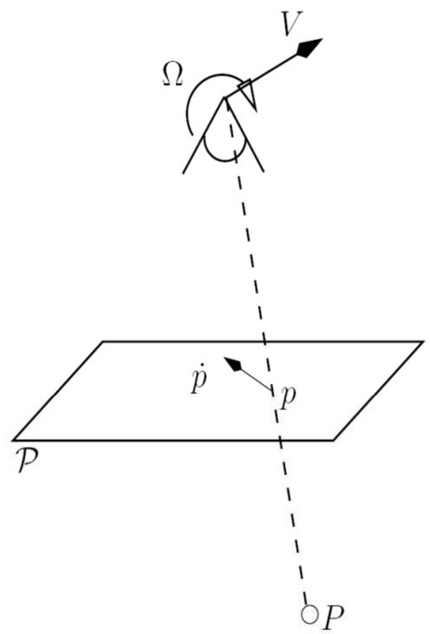


Fig. 1: Image dynamics for rectilinear camera image geom-
etry

$$P = \begin{pmatrix} X & Y & Z \end{pmatrix}$$

$$p = \frac{P}{|Z|}$$

$$\dot{p} = \frac{1}{|Z|}\begin{pmatrix} -1 & 0 & x \\ 0 & -1 & y \end{pmatrix} V + \begin{pmatrix} xy & -(1+x^2) & y \\ 1+y^2 & -xy & -x \end{pmatrix} \cdot \Omega$$

$$p = \frac{P}{|P|}$$

$$\dot{p} = -\Omega \times p - \frac{\pi_p V}{|P|}$$

$$\pi_p = I - pp^T$$

Optical Flow

=>Passivity-Like property

Translational optical flow computation

Rotational term

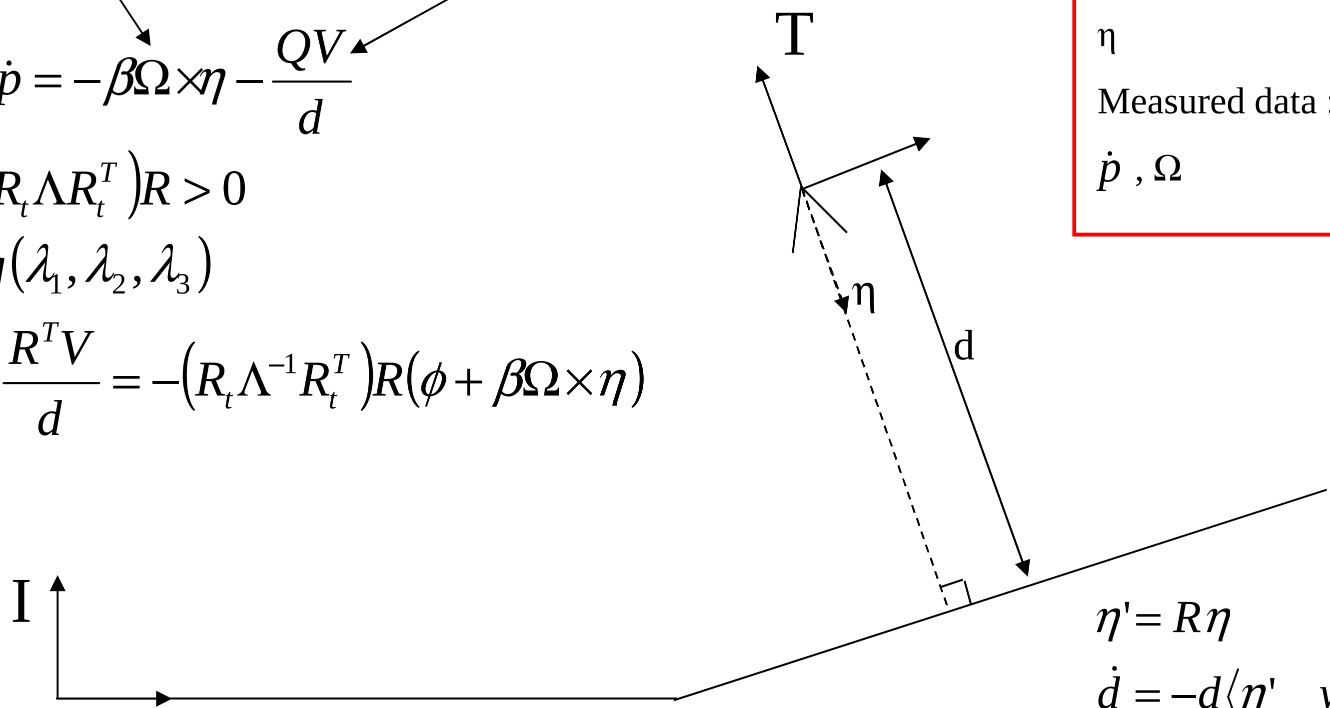
Translational term

$$\phi = \iint_{W^2} \dot{p} = \underbrace{-\beta\Omega\times\eta}_{\text{Rotational term}} - \underbrace{\frac{QV}{d}}_{\text{Translational term}}$$

$$Q = R^T\left(R_t \Lambda R_t^T\right)R > 0$$

$$\Lambda = diag\left(\lambda_1, \lambda_2, \lambda_3\right)$$

$$\boxed{w = \frac{v}{d}} = \frac{R^T V}{d} = -\left(R_t \Lambda^{-1} R_t^T\right)R\left(\phi + \beta\Omega\times\eta\right)$$



Known data :

η

Measured data :

$\dot{p}$, Ω

$$\eta' = R\eta$$

$$\dot{d} = -d\langle \eta' \quad w\rangle$$

$$\boxed{\frac{d(t)}{d_0}} = \exp\left(-\int_0^t \langle \eta' \quad w\rangle d\tau\right)$$

Stabilization of the hovering flight

- For the hovering flight define the error term, $\hat{v} = w\dfrac{d}{d_0} = \dfrac{v}{d_0}$
- The goal is the regulation of $\hat{v}$ to zero : $\hat{v} \to 0$
- The control law $F = -k_P\hat{v} - k_I\int_0^t \hat{v}\,d\tau$ ensures the exponential

convergence of v to zero (PI controller)

$$m\dot{v} = k_P\frac{v}{d_0} + k_I\frac{\xi - \xi_0}{d_0} + \Delta$$

As a consequence $\xi \to \xi_0 + \dfrac{d_0}{k_I}\Delta$

Vertical landing control (1)

- Consider that $\eta' = e_3$, that is $d \equiv |z| \equiv h$ is the distance of the vehicle to the ground

- Define for the control of the third component of the dynamics the error term, $\tilde{w} = w_z - \omega^* = -\left(\frac{\dot{h}}{h} + \omega^*\right)$

Smooth vertical landing

- Goal: $\tilde{w} \to 0 \Rightarrow \frac{\dot{h}}{h} = -\omega^* \Rightarrow \boxed{h = h_0 e^{-\omega^* t}}$ and $h(t) > 0$ for all time

- <u>Proposition 1:</u> Consider the control law $F_z = -mk(w_z - \omega^*)$, then for all $k > k_{\lim}$ it ensures the exponential convergence of h to zero while keeping $h(t) > 0$ for all time.

Vertical landing control (2)

- **Proof:**
  - Define $\alpha = \omega^* + \frac{\Delta_z}{mk}$, and $\delta = \dot{h} + \alpha h$, and $L = \frac{1}{2}h^2 + \frac{1}{2\alpha}\delta^2$
  - The third component of the dynamics is: $m\ddot{h} = -k\left(\frac{\dot{h}}{h} + \alpha\right)$

Integrating this equation, it yields $h\exp\left(\frac{1}{k}\left(\dot{h} - \dot{h}_0\right)\right) = h_0 e^{-\alpha t} \geq 0$

- Differentiating L, it yields $\dot{L} = -\alpha h^2 - \frac{1}{\alpha^2}\left(\frac{k}{h} - \alpha\right)\delta^2$
- Chosing k_{lim} such that $\alpha > 0$ and $\left(\frac{k}{h_0} - \alpha\right) > 0$

It ensures that $\dot{h}$ is bounded. Consequently, h converges to zero with α as exponential decay constant.

Vertical landing control (3)

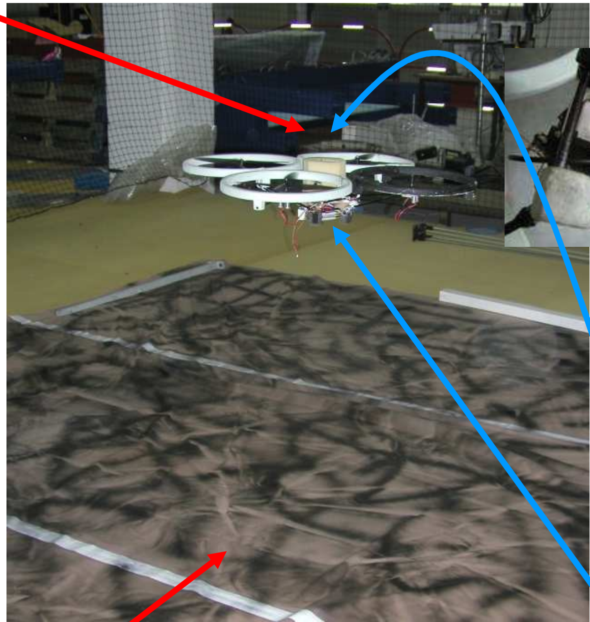
- **<u>Proposition 2:</u> Consider the following control law, then for all $k_P > k_{\lim}$ it ensures the exponential convergence of h to zero with ω^* as exponential decay constant while keeping $h(t) > 0$ for all time.**

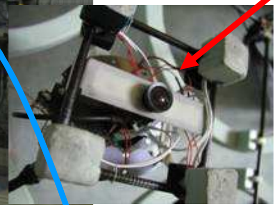
$$F_z = -k_P\left(w_z - \omega^*\right) - k_I \int_0^t \left(w_z - \omega^*\right) d\tau$$

Experimental setup

Drone:
- Embeded attitude control from IMU data
-running at 166Hz

Camera:
-Focus: 2.1mm





Numerical transmission:
- Transmision of the desired attitude to the drone
- Transmision of IMU data to the ground station
- 70 ms are required for the data transmission

Analogical transmission:
-Transmission at 2.4GHz
- Associate with an acquisition card, a new image is available each 50 ms

Textured ground

Ground station:
Treatment of vision algorithms at 60 ms

Experiments (1)

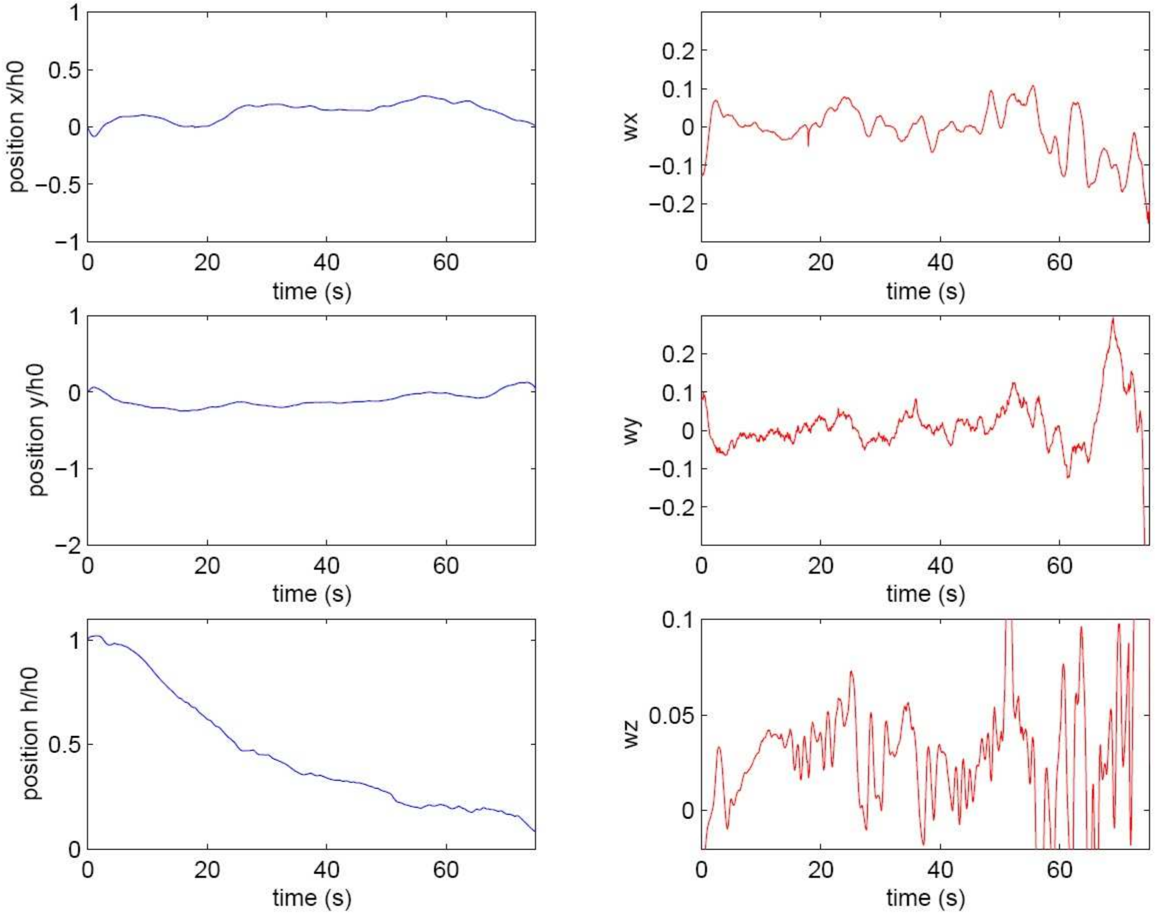


Fig. 5: Vertical landing using the controller (16)

Experiments (2)

Conclusion

- Computation of the translational optical flow over a textured flat target plane.
- PI-type controller for the stabilization of the hovering flight.
- A rigorous non-linear controller for vertical landing.
- The control approach has been experimented on a quad-rotor UAV to demonstrate the performance of controllers.

Acknowledgements

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