A terrain-following strategy for a VTOL UAV using translational optical flow.

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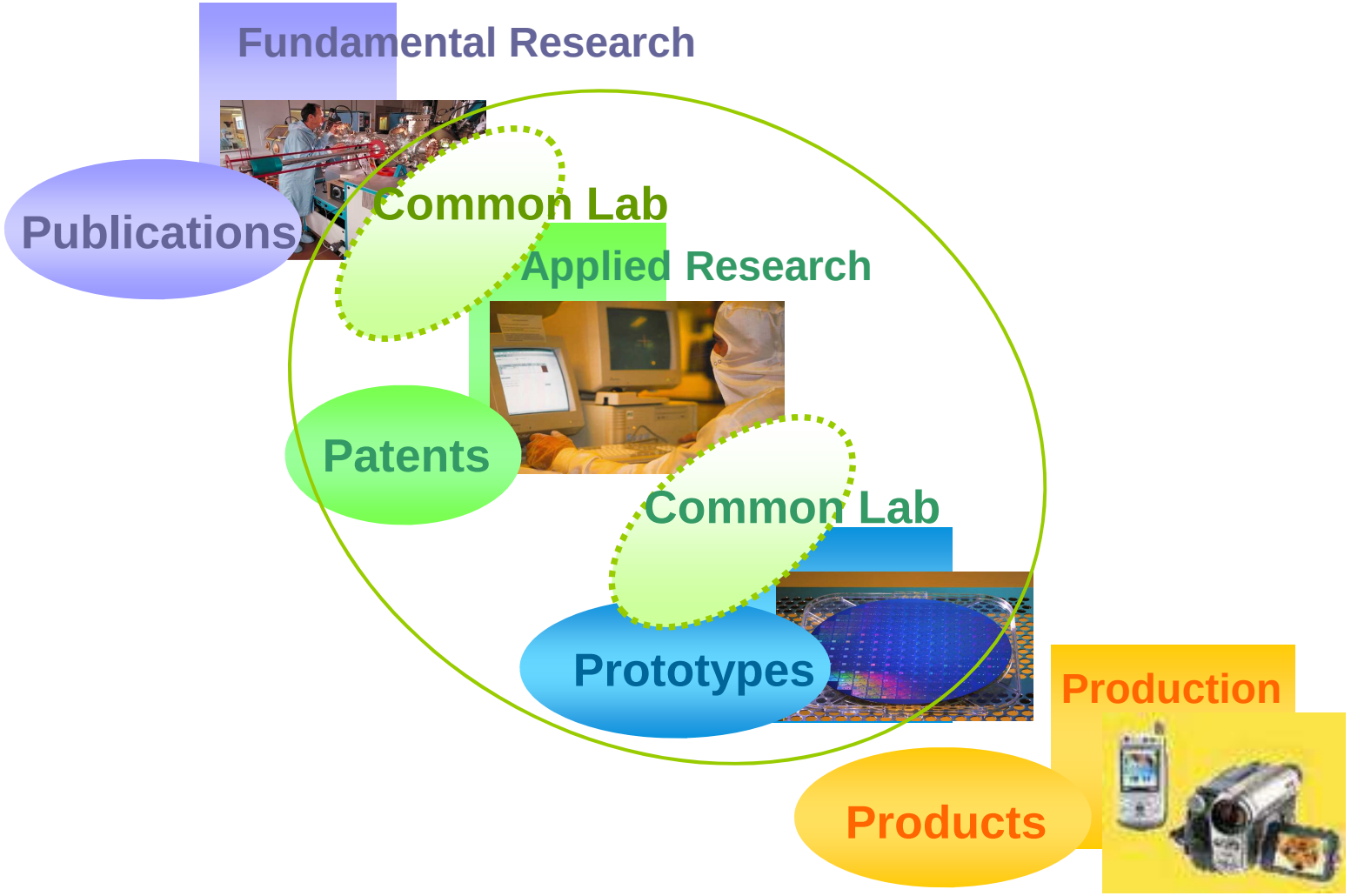
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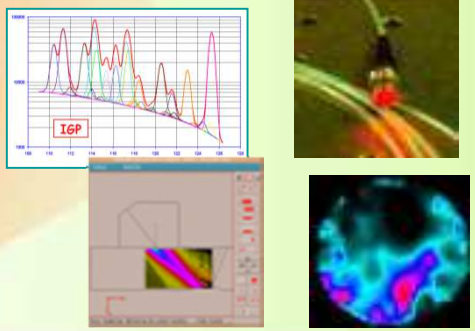
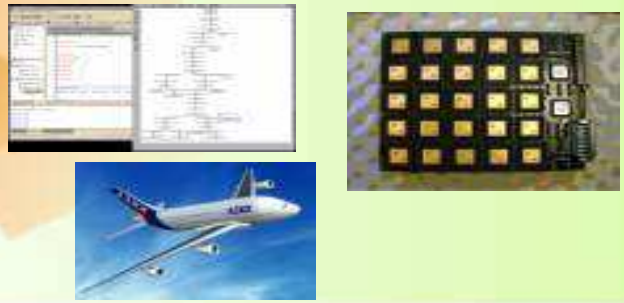


Embedded systems



Interactive Systems

Interactive Systems

Virtual reality

haption

Robotics

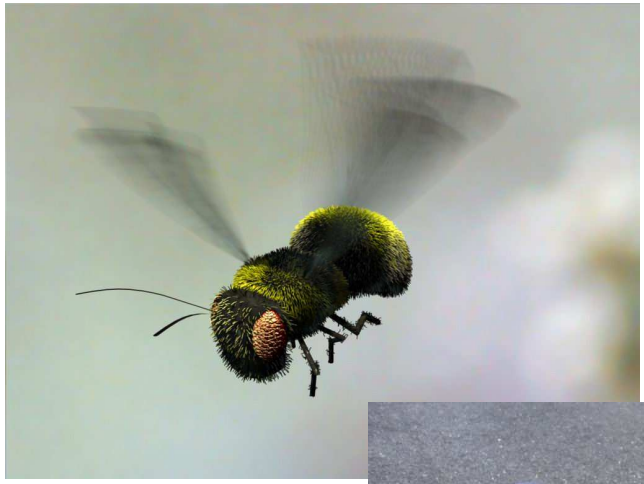
NEWPHENIX

Knowledge engineering

The size of the picture is 384x307 pixels. The ground of the picture is black. It is made of 3 objects. The main topic of the picture is toys. The main object is a beige teddy bear on the left of the picture. In the middle we can see a green and white ball. On the right, we notice a multicolored cube.

Outline

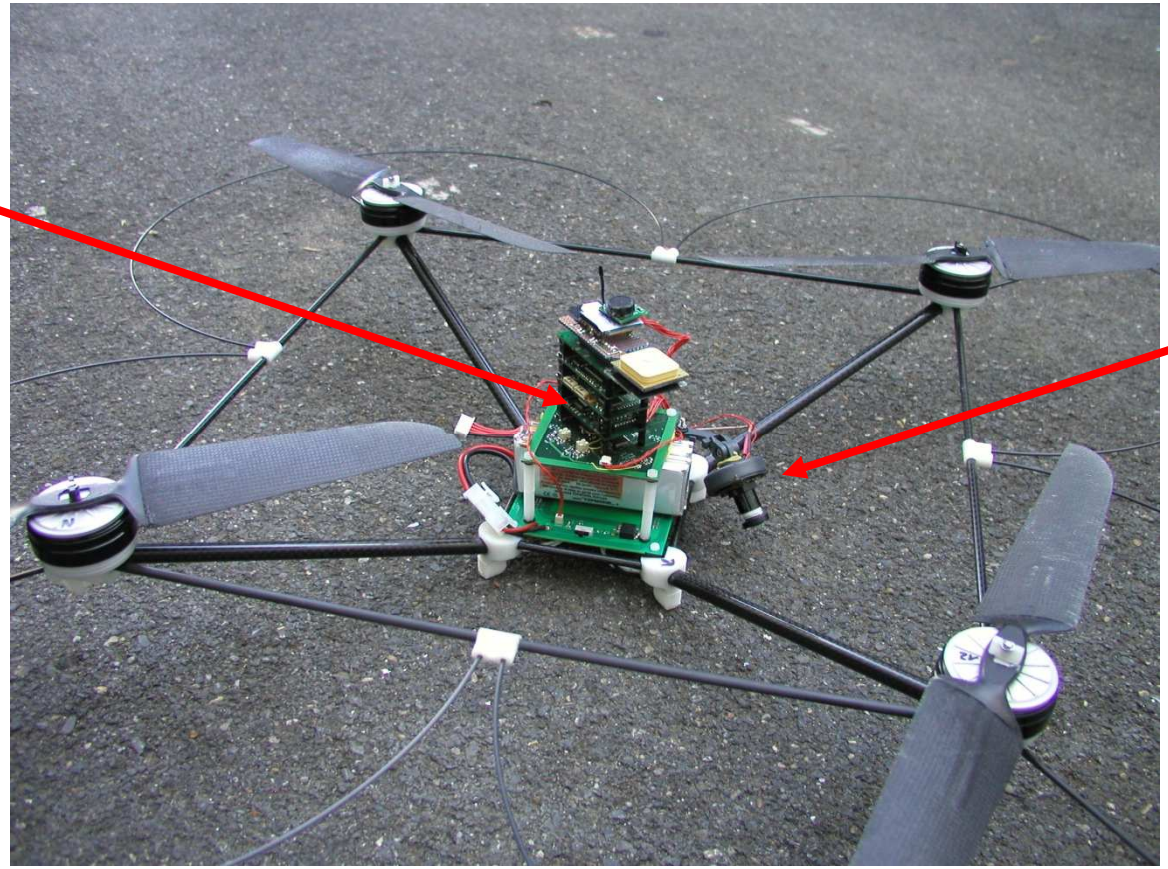
- CEA's UAV
- Optical Flow
- Terrain Following strategy
- Experiments on the quad-rotor UAV.



Introduction

➢ **Purpose:** Design of controllers for a VTOL UAV using **inertial data** and **visual optical flow** measurements.

IMU
(Inertial Measurments Unit)

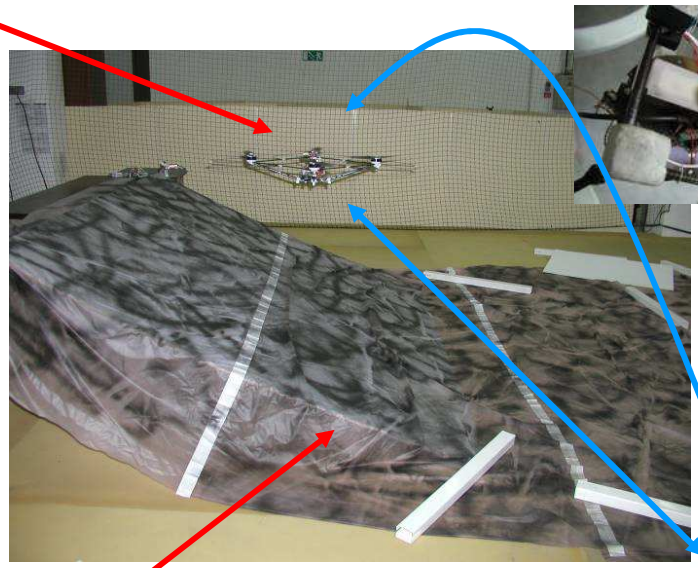


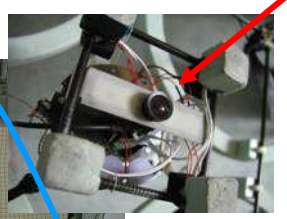
Camera
(OF Measurments)

Experimental setup

Drone:
- Embeded attitude control
-running at 166Hz

Camera:
- Focus: 2.1mm





Numerical transmission:
- Attitude
- IMU data
- 70 ms required

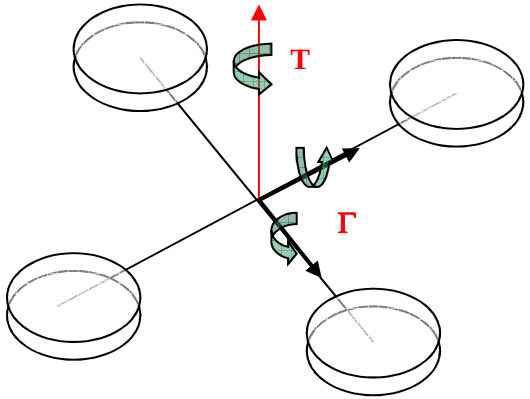
Analogical transmission:
- 2.4GHz
- 20Hz

Textured terrain

Ground station:
- OF Processing
- 15Hz

State Model of the UAV

- **The system is nonlinear and under actuated.**
- **Definition of the used reference frames.**
  - ✓ I : Inertial frame attached to the earth
  - ✓ B : body-fixed frame attached to the vehicle at the center of mass.
- **Vehicle state:**
  - ✓ ξ : position of the center of mass in I
  - ✓ v : speed of the center of mass in I
  - ✓ 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:**

Translational dynamics

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

$$m\dot{v} = F + mge_3$$

Rotational Dynamics

$$\dot{\Omega} = \Omega \times I\Omega + \Gamma$$

F=f(T,R)

Already controlled

High gain controller

Related work on optical flow

- **Obstacle avoidance**

  [Barrows 2002, Zufferey 2006, Muratet 2005, Green 2008]

- **Docking strategy**

  [McCarthy 2008, Hérissé 2008]

- **Terrain following / Landing**

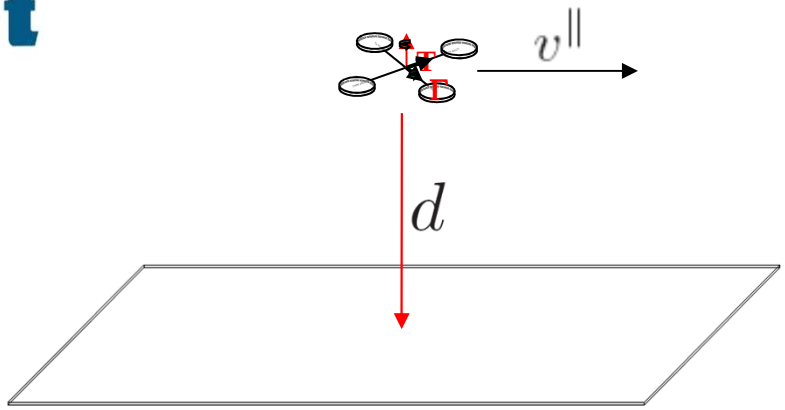
  [Srinivasan 2000, Ruffier&Franceschini 2005, Ruffier&Franceschini 2008, Garratt 2008, Humbert 2005]

Terrain following: the contribution

- **The full dynamics is considered.**
- **A Lyapunov analysis shows the convergence of the controller.**
- **The non-collision is ensured.**

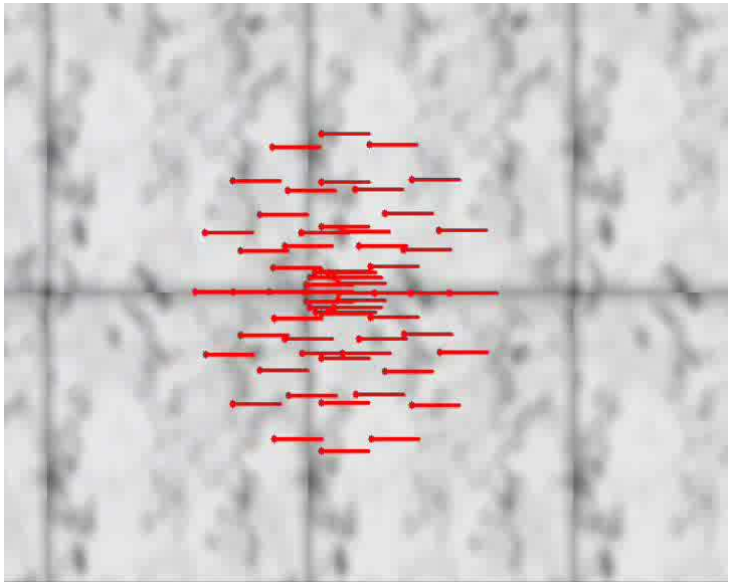
Forward optical Flow

- **Optical Flow is the relative velocity of objects in the image plane**

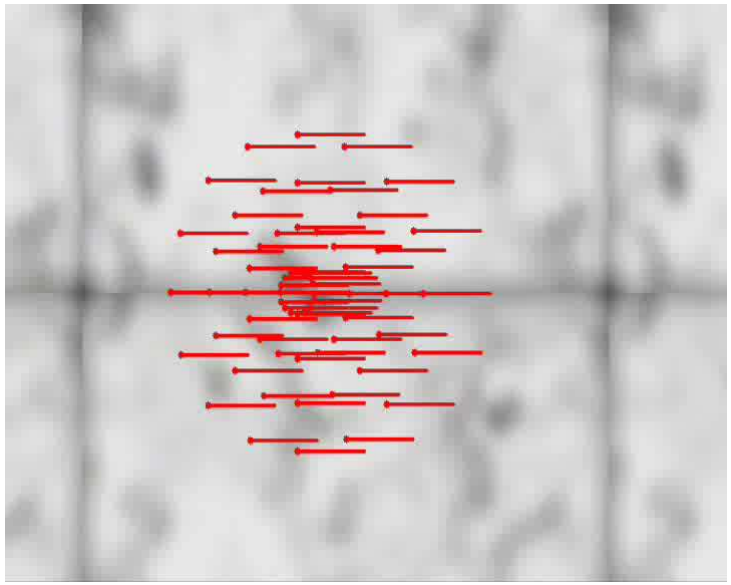


$$w^{\parallel} = \frac{v^{\parallel}}{d}$$

d_0



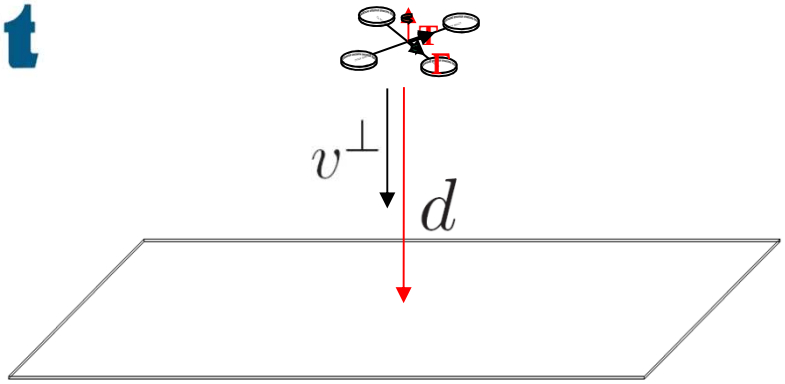
v_0



$\frac{d_0}{2}$

Divergent Flow

- **Optical Flow is the relative velocity of objects in the image plane**



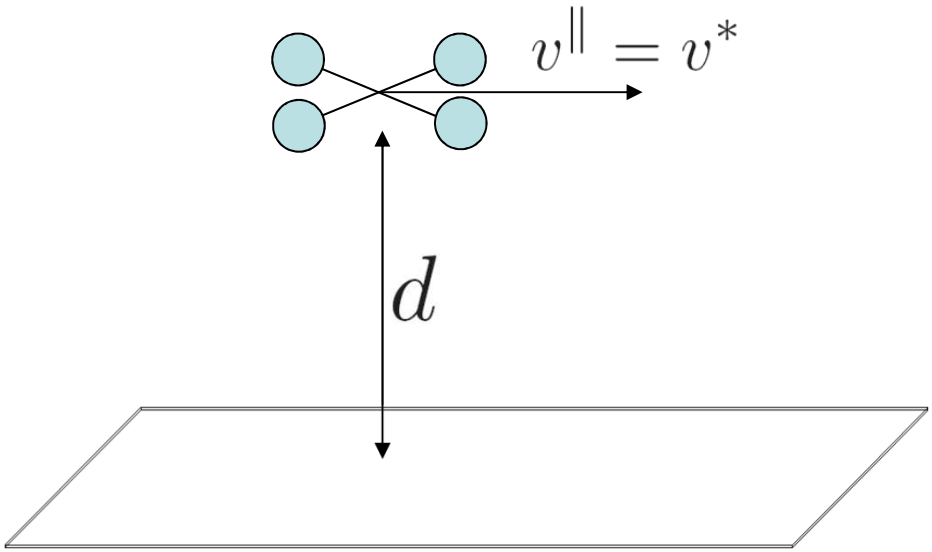
$$w^{\perp} = \frac{v^{\perp}}{d} = -\frac{\dot{d}}{d} = \frac{1}{\tau}$$

Time to contact
Time to collision

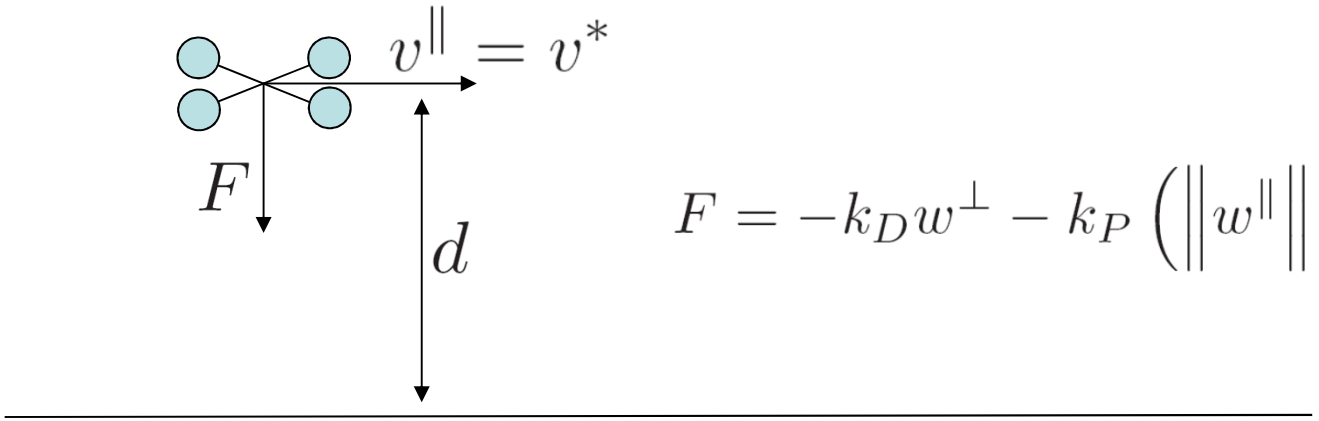
Terrain following

- **Terrain/Wall following [Hérissé-ICRA'09]**

$$w^{\|} = \frac{v^*}{d} = \omega^* = \frac{v^*}{d^*} \Rightarrow d = d^*$$



Terrain following



$$F = -k_D w^{\perp} - k_P \left(\left\| w^{\parallel} \right\| - \omega^* \right)$$

- The control law F ensures the asymptotic convergence of d to d^*

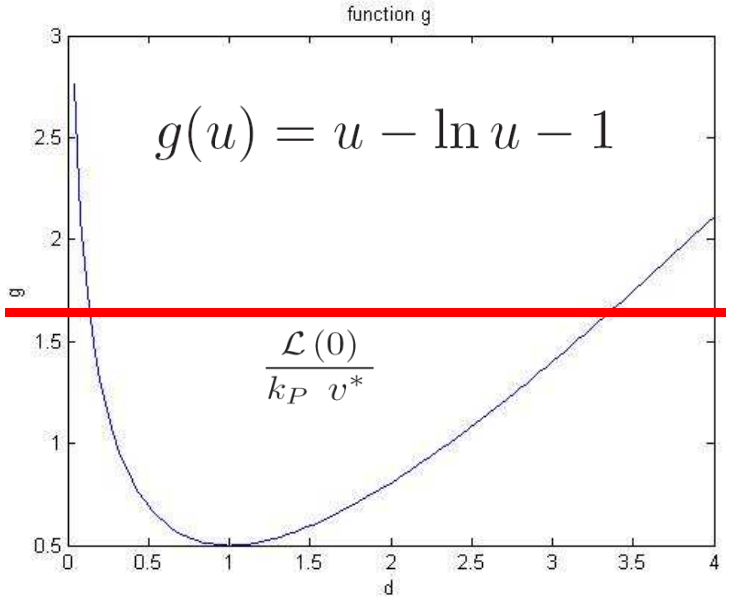
$$m\ddot{d} = -k_P \omega^* \frac{d - d^*}{d} - k_D \frac{\dot{d}}{d}$$

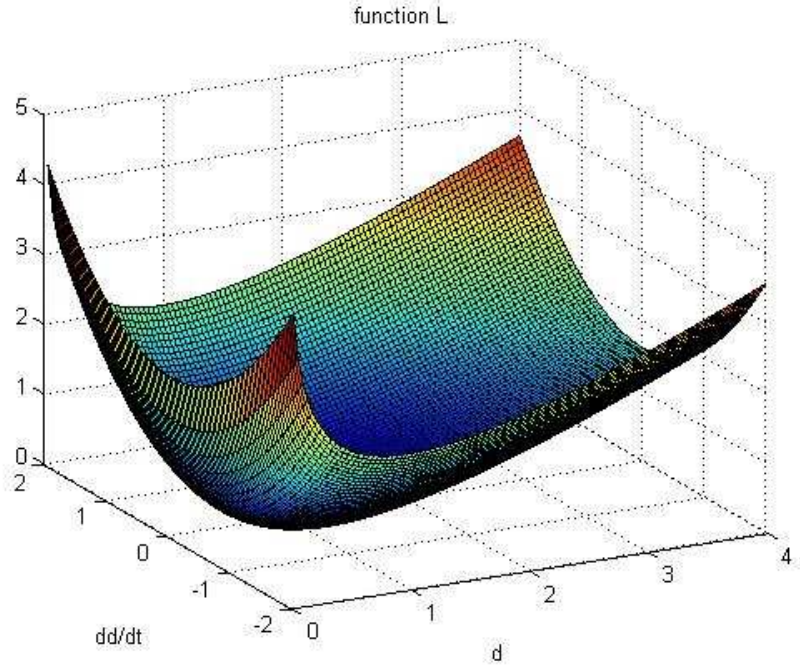
$$d^* = \frac{v^*}{\omega^*}$$

- The UAV does not collide the obstacle

Terrain following: proof of stability

- **Proof:**





$$\mathcal{L} = \frac{m}{2}\dot{d}^2 + k_P \ v^* \ g\left(\frac{d}{d^*}\right) \geq 0$$

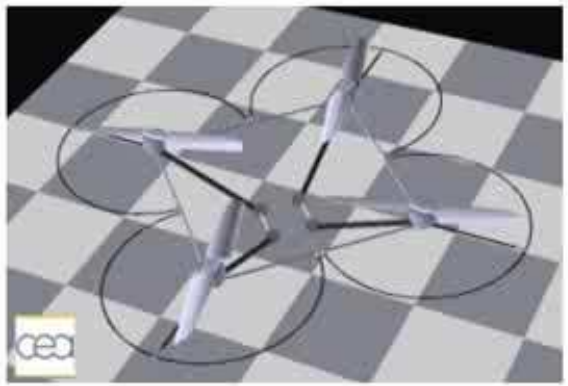
$$\dot{\mathcal{L}} = -k_D \frac{\dot{d}^2}{d}$$

Experiment: TF with 1camera

A nonlinear terrain-following controller

for a VTOL Unmanned Aerial Vehicle

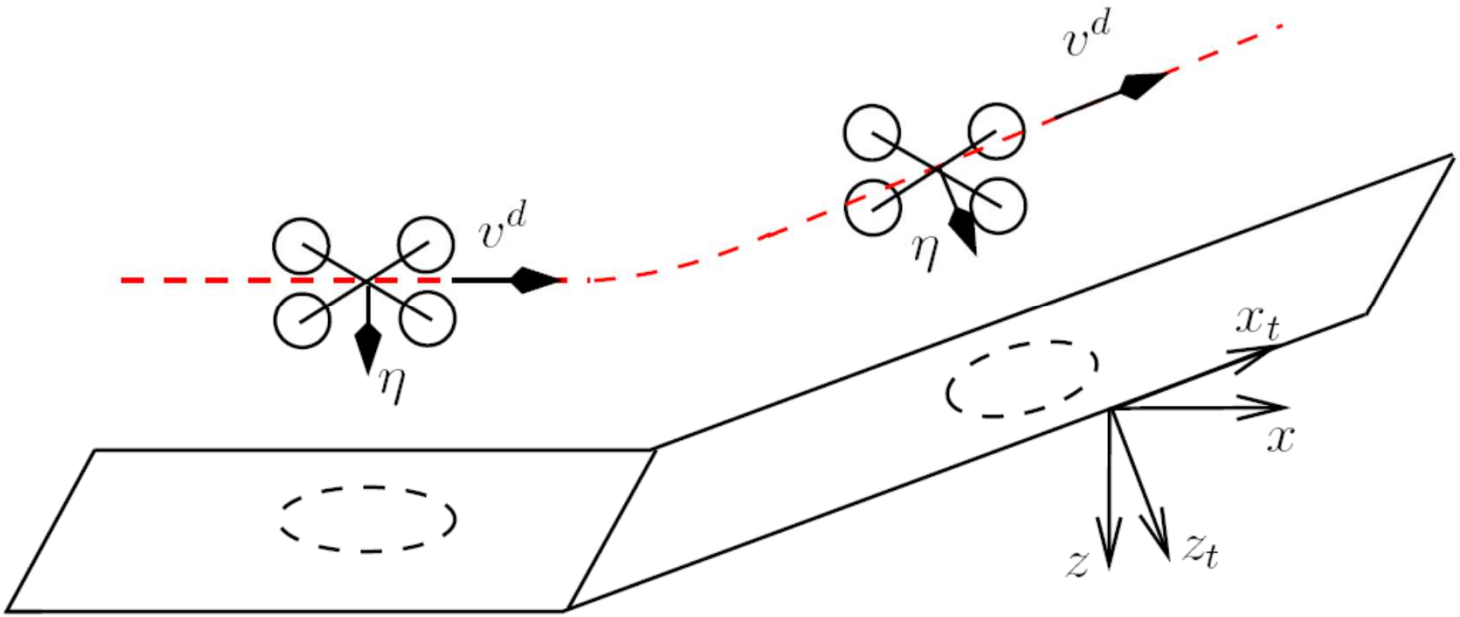
using translational optical flow



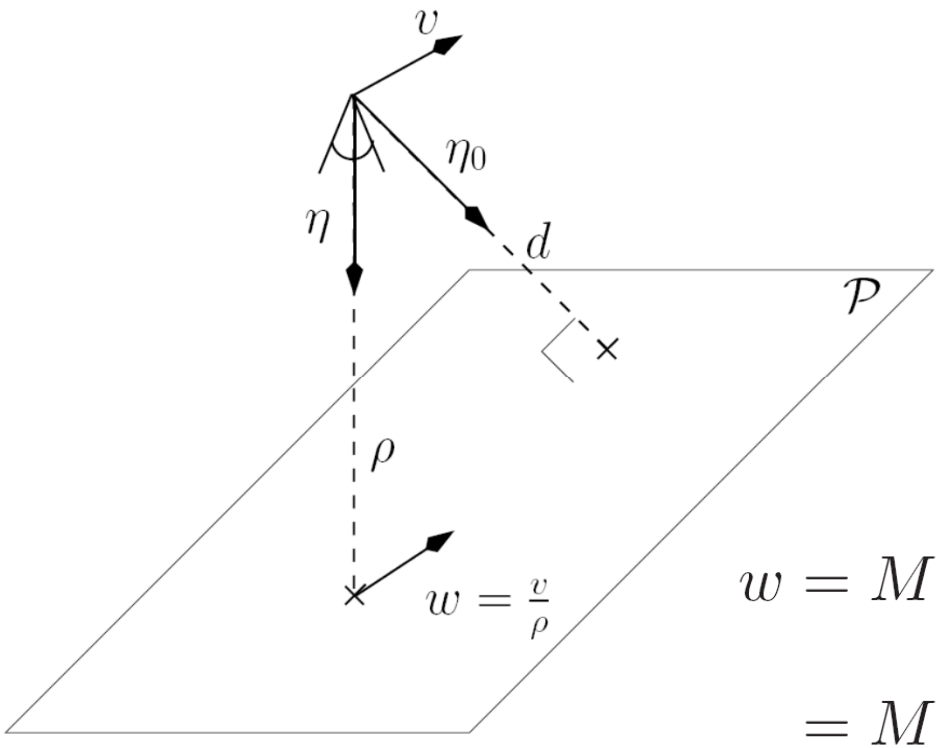
Terrain following: robustness?

- The forward velocity $v^{\parallel}$ can vary over time.
- The target surface can be non-planar
- The optical flow is noisy
- The surface can be sloped…

Terrain following: sloped target



Terrain following: sloped target



$$w = M(\eta_0, \eta)\frac{v}{\rho}$$
$$= M(\eta_0, \eta)\frac{v}{d}\cos(\langle \eta_0, \eta \rangle)$$

$$M(\eta = \eta_0) = I_3$$

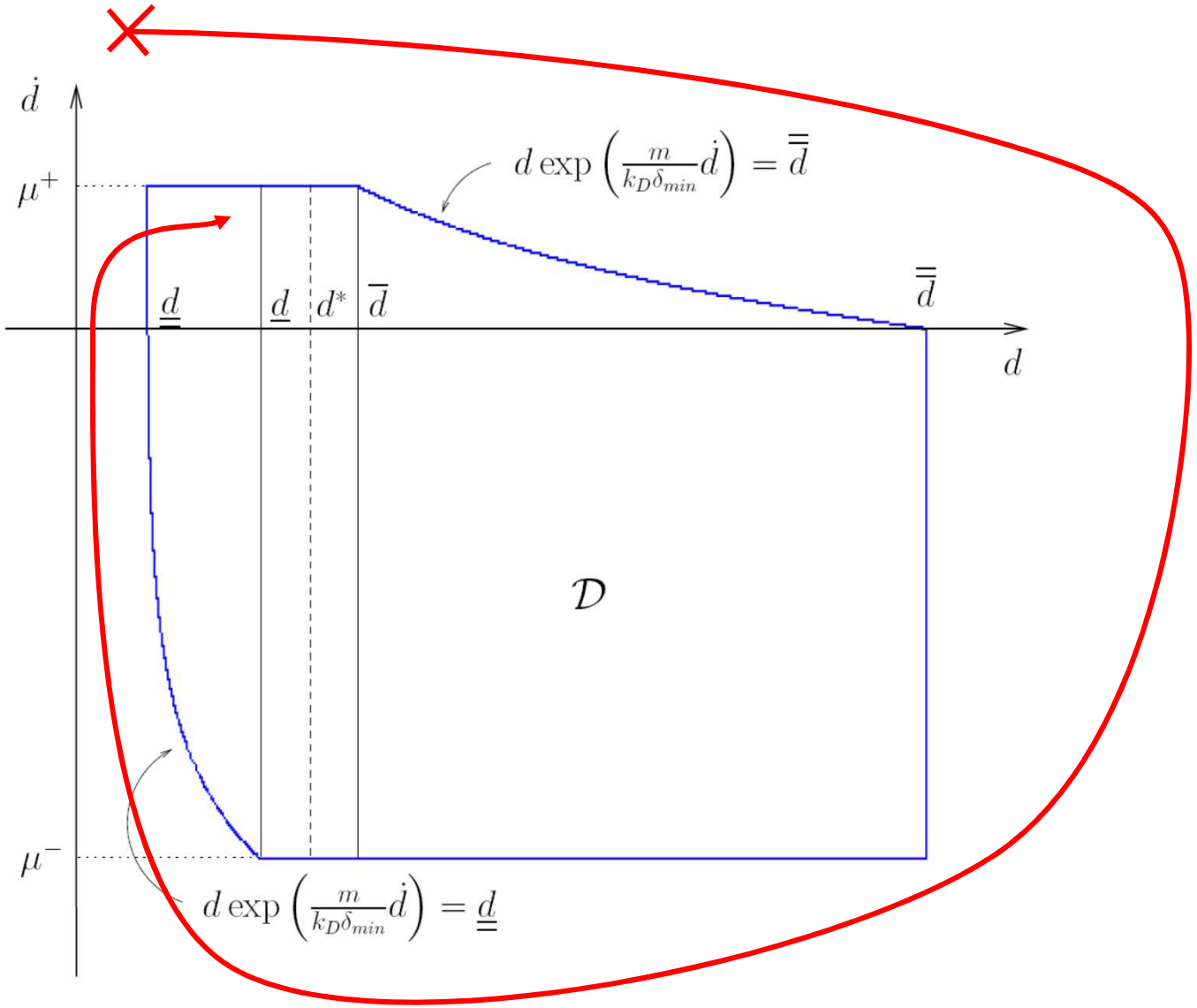
Terrain following: disturbed dynamics

$$m\ddot{d} = -k_P\omega^* \frac{d - d^*}{d} - k_D \frac{\dot{d}}{d}$$

$$m\ddot{d} = -k_P\omega^*\gamma(t)\left(1 - \frac{d^*}{d}\chi(t)\right) - k_D\delta(t)\frac{\dot{d}}{d}$$

$$\gamma, \chi, \delta > 0$$

Terrain following: the attractor



Relief following (n cameras) [Hérissé-ICRA'10]

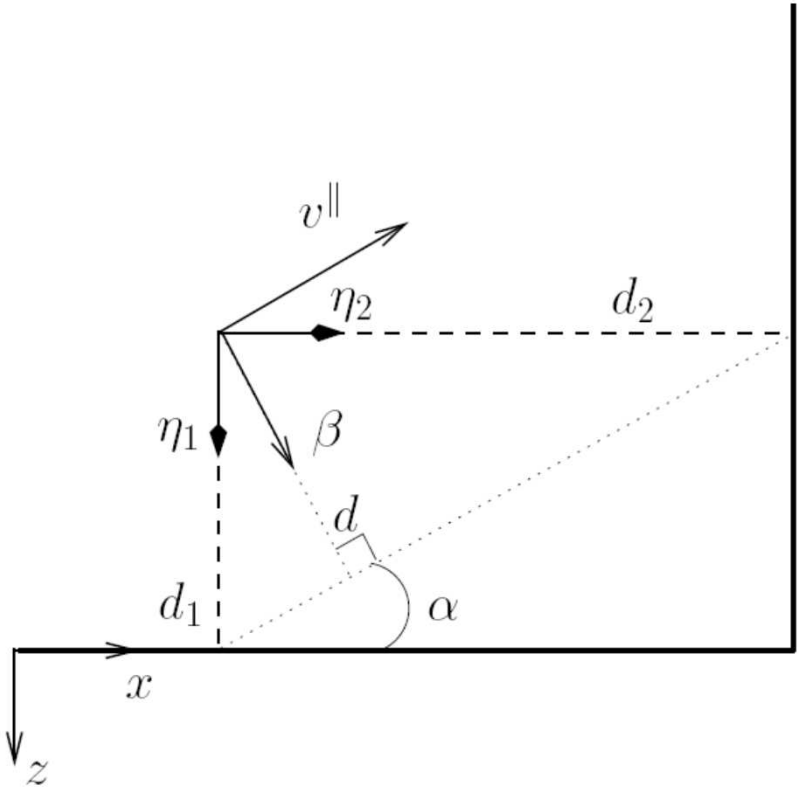
Let η_i be the ith direction of observation and let w_i be its associated translational optical flow.

$$\beta = \frac{\sum_{i=1}^{n} \|w_i\| \eta_i}{\|\sum_{i=1}^{n} \|w_i\| \eta_i\|} = \frac{\sum_{i=1}^{n} \eta_i/\rho_i}{\|\sum_{i=1}^{n} \eta_i/\rho_i\|}$$

$$w^{\perp} = \sum_{i=1}^{n} \langle \eta_i, w_i \rangle = \left\langle e_3, \sum_{i=1}^{n} R_i^T w_i \right\rangle$$

$$w^{\parallel} = \sum_{i=1}^{n} R_i^T \pi_{\eta_i} w_i = \pi_{e_3} \sum_{i=1}^{n} R_i^T w_i$$

Relief following (2 cameras) [Hérissé-ICRA'10]



$$\beta = \left(\frac{d_1}{\sqrt{d_1^2 + d_2^2}}, \frac{d_2}{\sqrt{d_1^2 + d_2^2}} \right) = (\sin\alpha, \cos\alpha)$$

$$w^{\perp} = \frac{v_z}{d_1} + \frac{v_x}{d_2} = \frac{v^{\perp}}{d}$$

$$w^{\parallel} = \left(\frac{v_x}{d_1} - \frac{v_z}{d_2}, 0 \right), \quad \left\| w^{\parallel} \right\| = \frac{\left\| v^{\parallel} \right\|}{d}$$

$$F = -k_D w^{\perp} - k_P \left(\left\| w^{\parallel} \right\| - \omega^* \right)$$

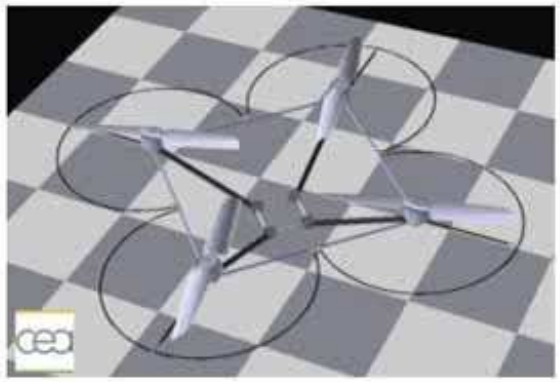
Wall following (2 cameras)

Experiment: TF with 2 cameras

A general optical flow based

terrain-following strategy

for a VTOL UAV using multiple views



Conclusion

- **Computation of the translational optical flow over a textured flat target plane.**
- **A robust strategy for navigation in cluttered environment**
- **Controllers prevent collisions with environment**
- **Control approach has been experimented on a quad-rotor UAV to demonstrate performance.**