Homography based visual servoing for aircraft approach and landing

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Outline

- background
- Pegase project
  - objectives / simulators
- Reference control
- Cimar approach using runway lines
- Homography approach
  - visual servoing / issues
- conclusions

Background

- Flight Testing (1988→)

- ARMOR UAV aircraft project (1991→2004)
  - X7 UAV model
  - collaboration w/ Patrick Rives (1998→)

- AURORA Airship UAV project (1998→)
  - with Samuel Bueno CTI / Campinas / Brazil
  - DIVA Portuguese Airship project (2004→2007)

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Background

- collaboration w/ Patrick Rives (1998→)
  - filght control + image = visual servoing
  - UAV aircraft auto landing w/ image (CIMAR)
    - INRIA RR 2002
    - IJO 2008
  - Aurora Airship visual servoing
    - hover
    - road or river following
  - simulation results w/o experimental validation

PEGASE project

http://dassault.ddo.net/pegase/

- European FP6/STREP project 2006-2009
  - aeronautical actors (Dassault / Alenia / Eurocopter)
  - image experts (INRIA / EPFL / CNIT...) -IST
  - + databases / control -IST
- Purpose
  - evaluate in simulation
  - visual aid and servoing
  - ILS like positioning for aircraft landing

- IST / INRIA collaboration:
  P. Rives, Tiago Gonçalves (PhD student)

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PEGASE project

- use of image tracking for:
  - localization: estimate position from image
  - and servoing: feedback from image to control
- 2 approaches for tracking:
  - using lines of runway (following CIMAR)
  - using full image, tracking key elements
- 2 approaches for servoing:
  - PBVS: use estimated pose for usual control
  - IBVS: use error from image directly for control

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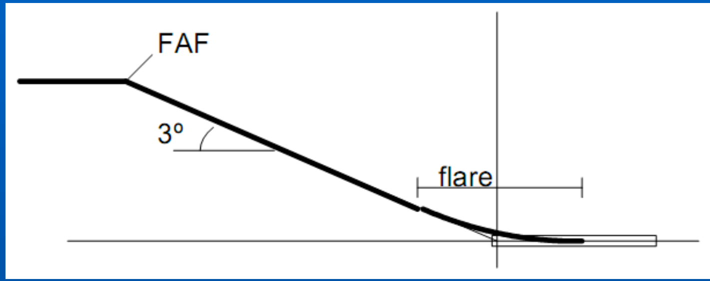
PEGASE project scenario

- **landing procedure:**
  - **alignment 10NM from runway**
  - **very slow descent**
    - **time to allow for corrections and landing decision**



ZEBRA	Alignment on FAF 15 Nm	3500ft, 134°	IAS-60 m/s Landing gear Approach speed
FAF 13L	FAF, descent 3° 10.7 Nm	3500ft, 134°	IAS 60 m/s Flaps 40 °
DA/DH	Decision Altitude / Height		
THR	Runway threshold		

PEGASE Marignane landing

PEGASE project requirements

- **Precision approach and landing figures**
  - **SBAS / ILS positioning accuracy figures**
  - **integrity and protection levels**
    guarantee that position measure is better than given value

	DH/DA [m]	RVR [m]	Required accuracy Horiz. [m]	Required accuracy Vert. [m]	
APV - I	50		16	20	
APV - II	20		16	8	
CAT I	**60**	**>550**	**16**	**4**	0,050º
CAT-II	**30**	**>350**	**6**	**1.4**	0,015º
CAT IIIb	**15**	**>50**	**4**	**0.6**	

PEGASE scenario images

– **Runway 13R**

Illustrative image from Google Earth Zenith view

PEGASE scenario images

Illustrative image from Google Earth from near FAF

PEGASE scenario images

Illustrative image
from Google Earth
200m altitude

PEGASE tracking approaches

- first feeling from images
  - full image is good choice when far from runway
  - runway tracking is better when near touchdown or for rollout

- both approaches were used and compared
  - EPFL / INRIA-Sophia / IST : full image
  - CNIT / CNRS / INRIA-Lagadic : runway

PEGASE simulator

- PEGASE shared simulator includes:
  - aircraft model (Alenia) in Matlab/Simulink
  - Flight gear as imaging tool in OpenGL
  - sensor models (EADS) in C/C++:
    camera parameters / errors / noise
  - integration and scenario setup:
    day or night / rain or fog (Dassault)

  - purpose was global assessment
  - was also used as development tool

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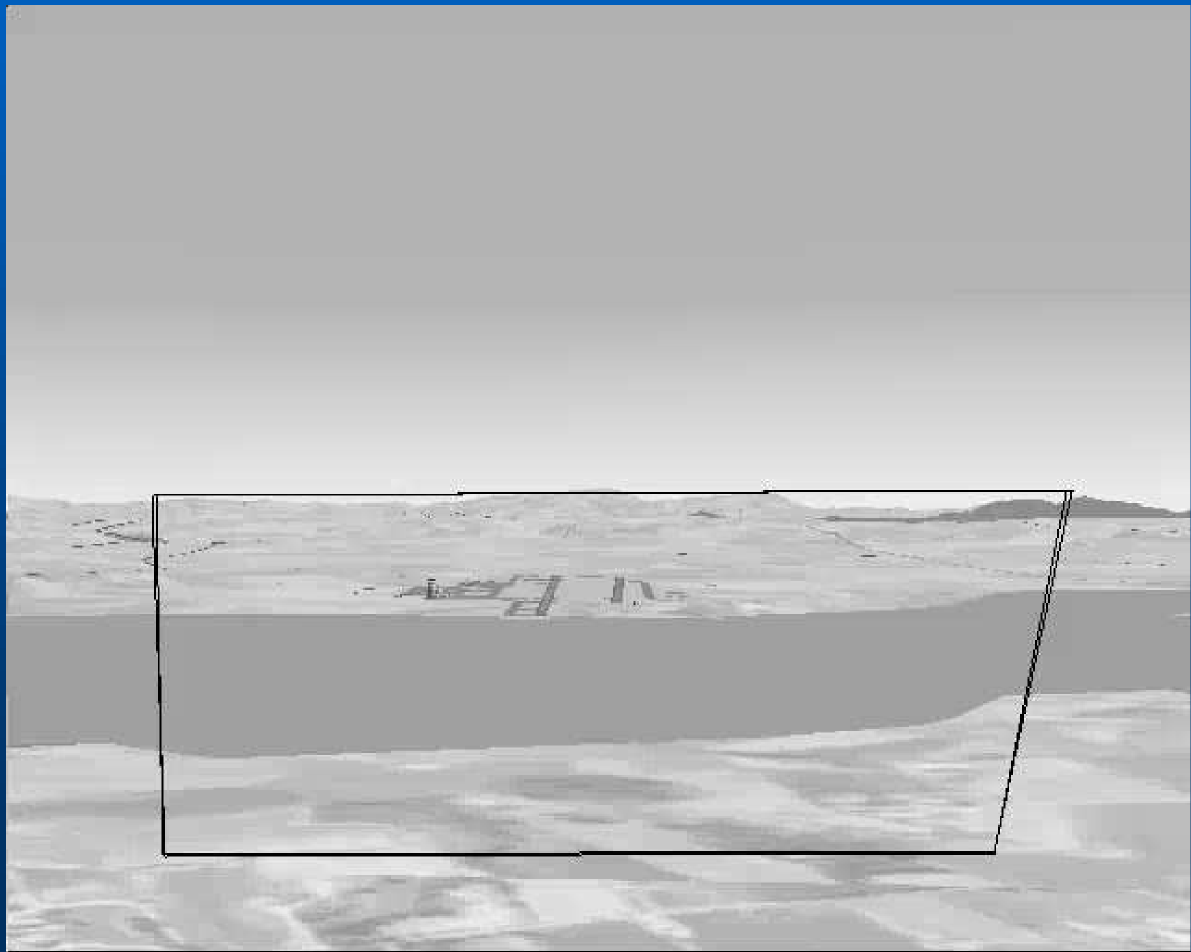
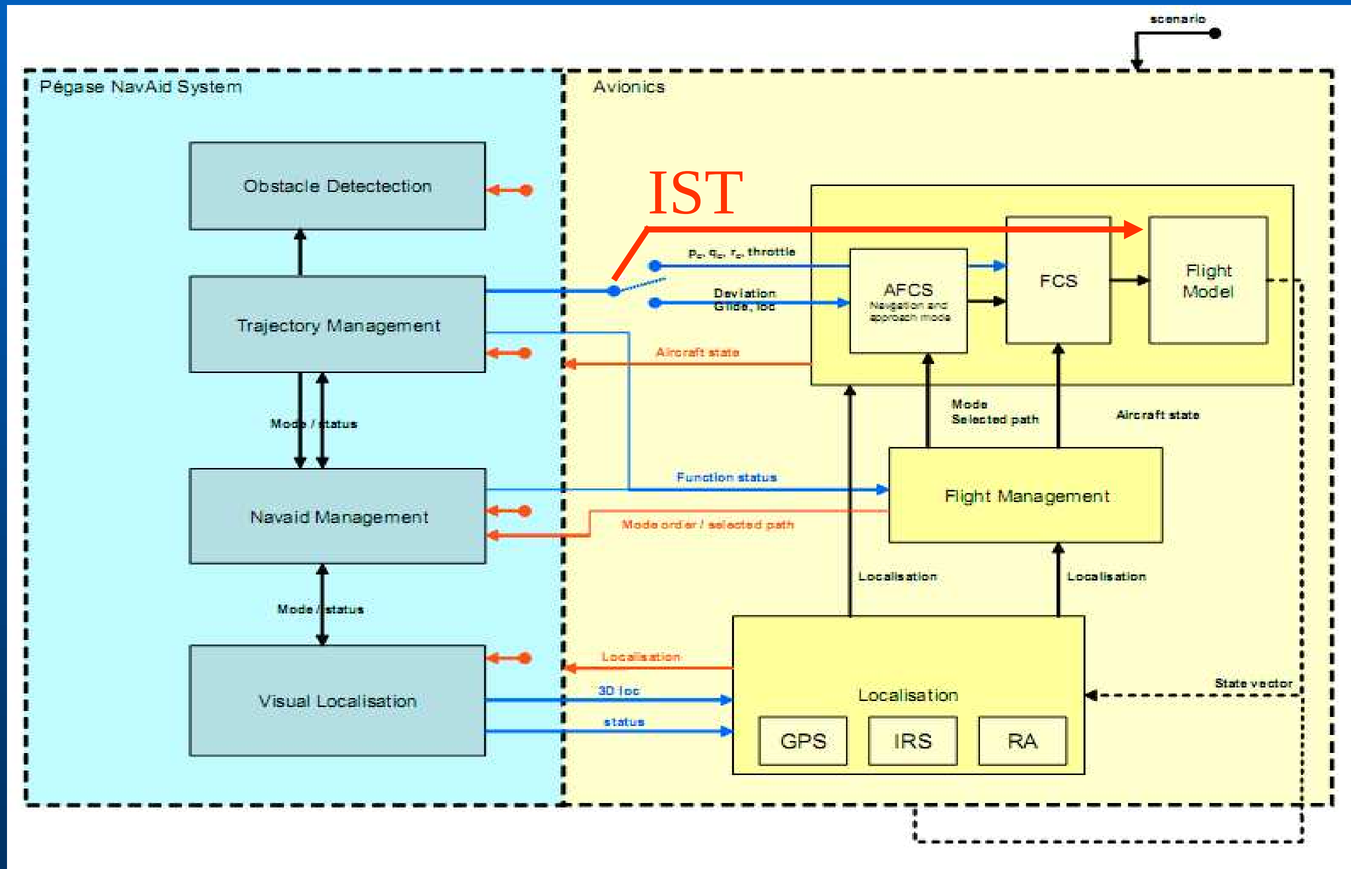
PEGASE simulator image example



PEGASE simulator -BD

- **Simplified BD:**
  - **IST servoing acts directly into flight model**



PEGASE simulator

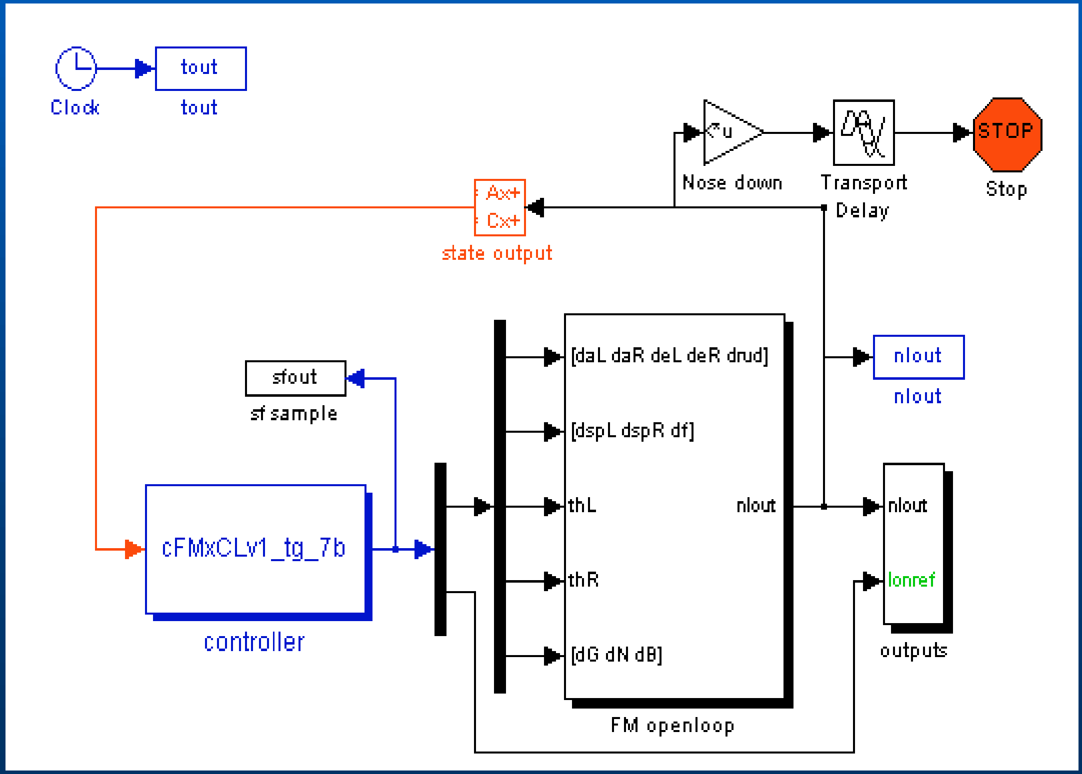
- Facts:
  - PEGASE simulator was under constant development during project
  - it was heavy and complex: too slow to be used in first development phase

- The idea was to build a pure Matlab / Simulink simulator
  - quickly evaluate / compare options
  - prepare work and then implement into PEGASE simulator

Matlab / Simulink simulator

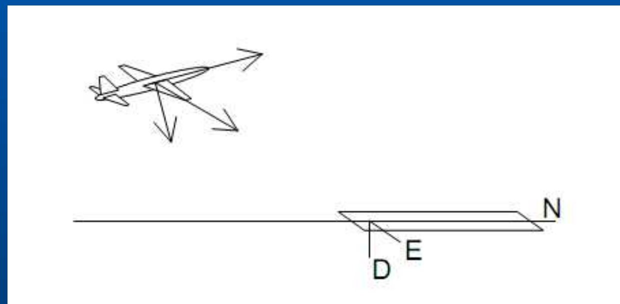
- full non-linear aircraft model from Alenia
- with wind and turbulence included
- image simplified model in Matlab

- easy to isolate parameters
- sensitivity analysis



Reference control approach

- **state:** $$X = [V_a, \alpha, \beta, p, q, r, N, E, D, \phi, \theta, \psi]$$
  - **airspeed, angle of attack, sideslip angle**
  - **angular rates**
  - **NED aircraft cg position**
  - **Euler angles (attitude)**



- **usual flight inputs:** $$U = [\delta_E, \delta_T, \delta_A, \delta_R]$$
  - **elevator and throttle**
  - **ailerons and rudder**

Reference control approach

- **To focus onto image tracking and servoing issues and options, it was here chosen:**
  - **standard reference control strategy:**
    linear / decoupled / full state feedback
  - **from ideal sensors to flight model inputs**
  - **regulate airspeed**
  - **LTI model based**

  - **airspeed and altitude tracking (optimal control)**
  - **optimal horizontal guidance with lateral modal control in coordinated flight**

Reference control approach

- **Longitudinal control**

$$U_v = U_v^0 - K_v\left(X_v - X_v^{ref}\right)$$

$$U_v = [\delta_E, \delta_T]^T$$
$$X_v = [V_a, \alpha, q, \theta, D]^T$$
$$X_v^{ref} = \left[V_a^0, \alpha^0, 0, \theta^0 + \gamma^*, D^*\right]$$

Trim values with superscript 0
Profile values with superscript * (function of distance to THR)

Reference control approach

- **Lateral control and guidance**

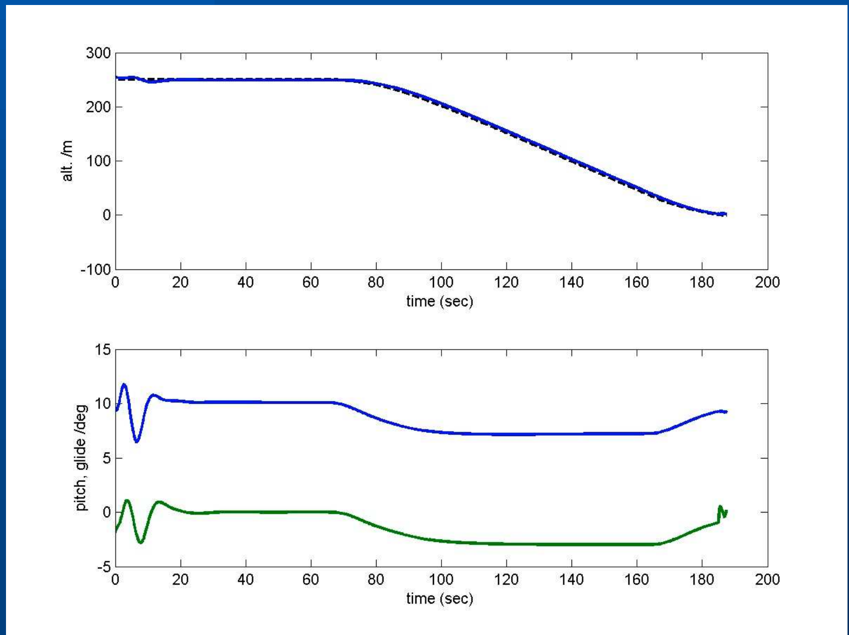
$$U_h = F\phi^{ref} - K_h X_h$$

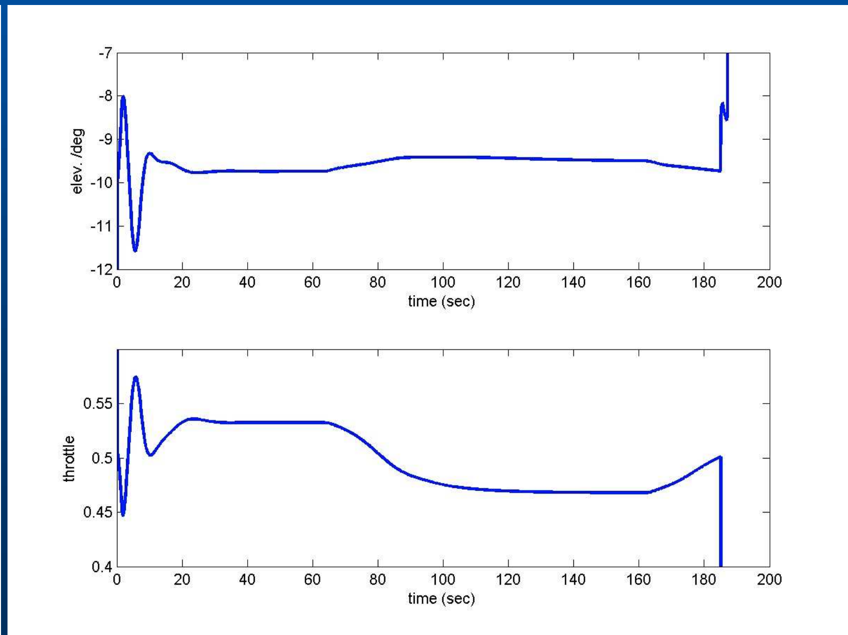
$$U_h = [\delta_A, \delta_R]^T$$
$$X_h = [\beta, p, r, \phi]^T$$
$$\phi^{ref} = K_g \left[\psi, E, \int Edt\right]^T$$

Assuming runway is aligned with North:
•East is crosstrack error
•and yaw is angular error
•integral E component to compensate wind lateral input

Reference control

- **Illustrative example: longitudinal**
  - **from 250m + initial 5m error**
  - **constant nose wind (10m/sN,3m/sE)**
  - **stabilize then descent**





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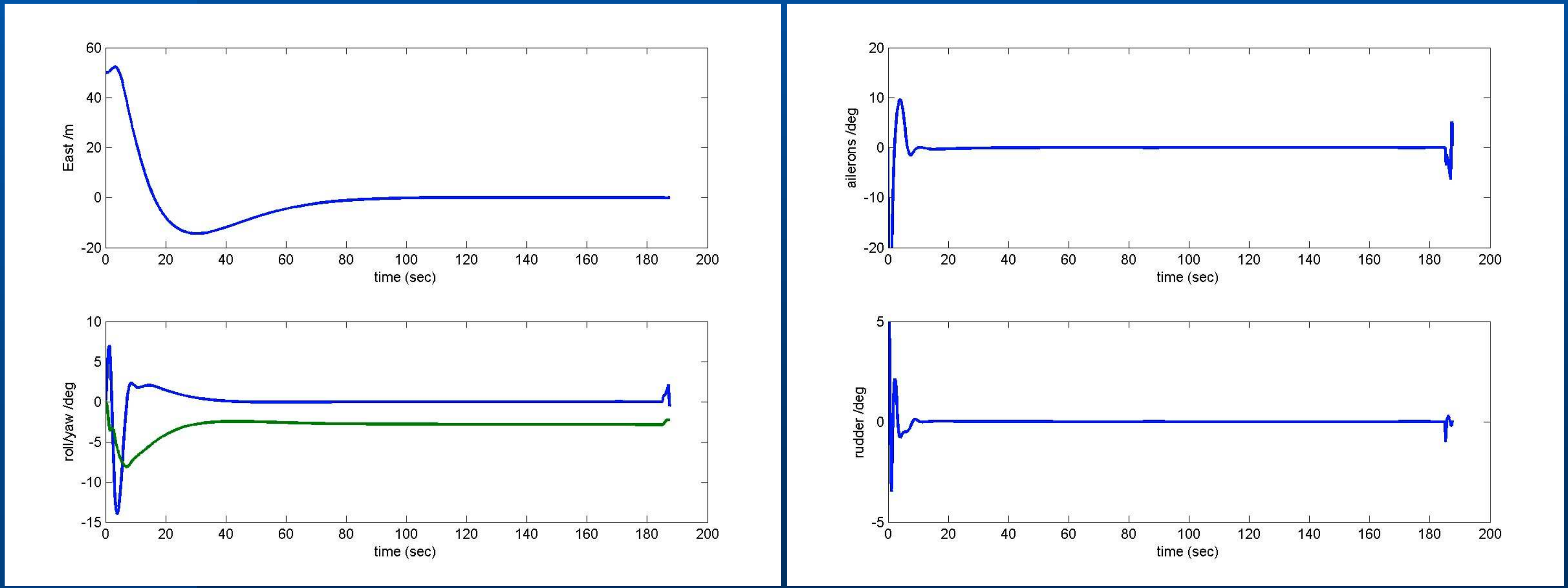
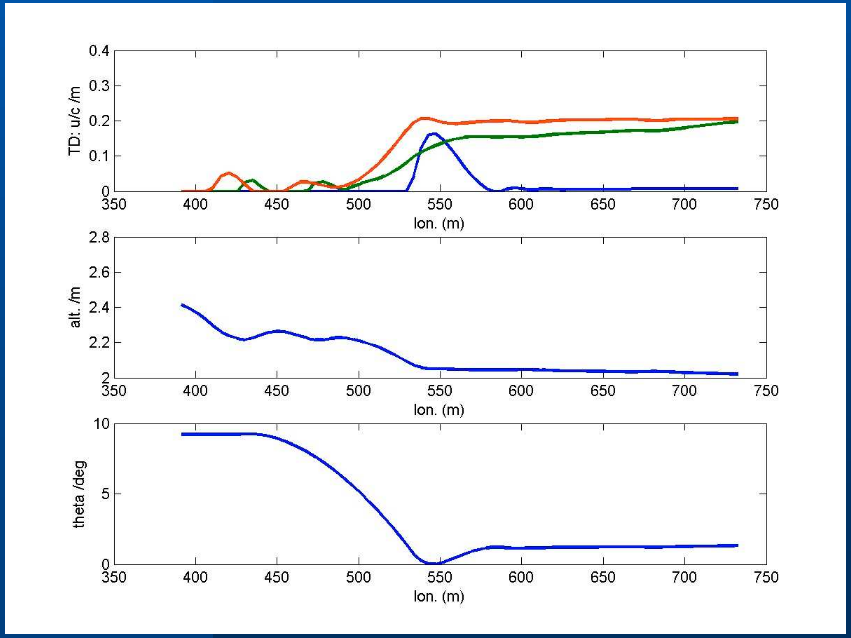
Reference control

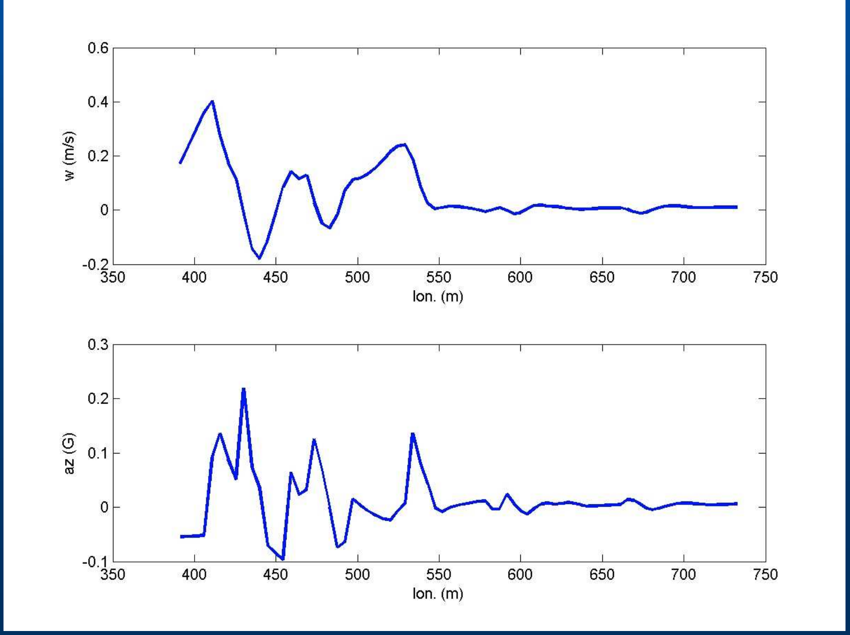
- **Illustrative example: lateral**
  - **from initial 50m East error**
  - **constant cross wind : yaw ~ - 3deg**



Reference control

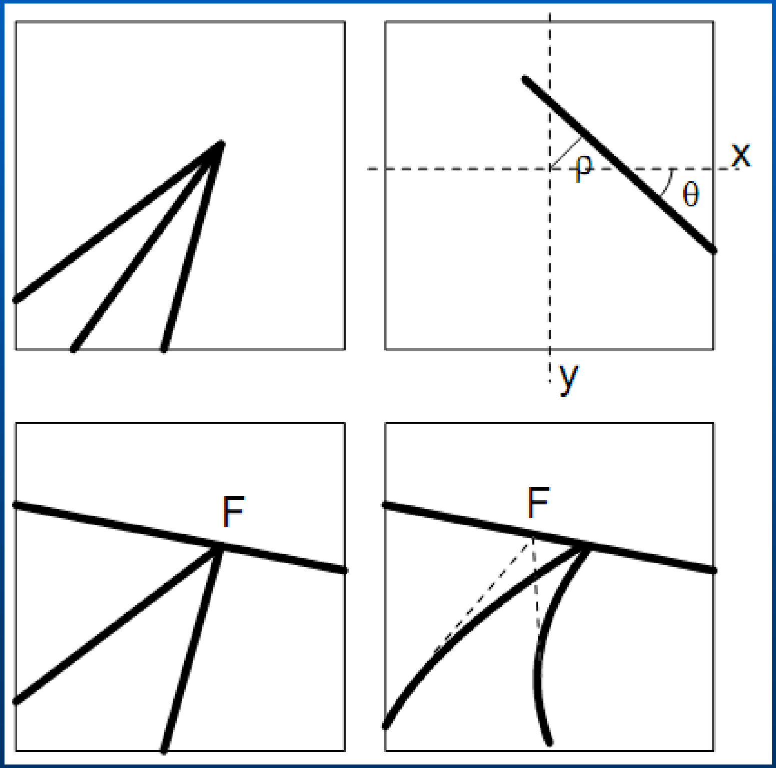
- **Illustrative example: touchdown zoom**
  - **undercarriage and pitch, altitude (left)**
  - **vertical acceleration and speed (right)**





CIMAR approach

- **CIMAR approach:**
  - **runway lines in 2D image as features**
    Right, Center and Left lines
  - **R and L lines and vanishing line angle**
  - **R and L angles + vanishing line and vanishing point F**



CIMAR approach

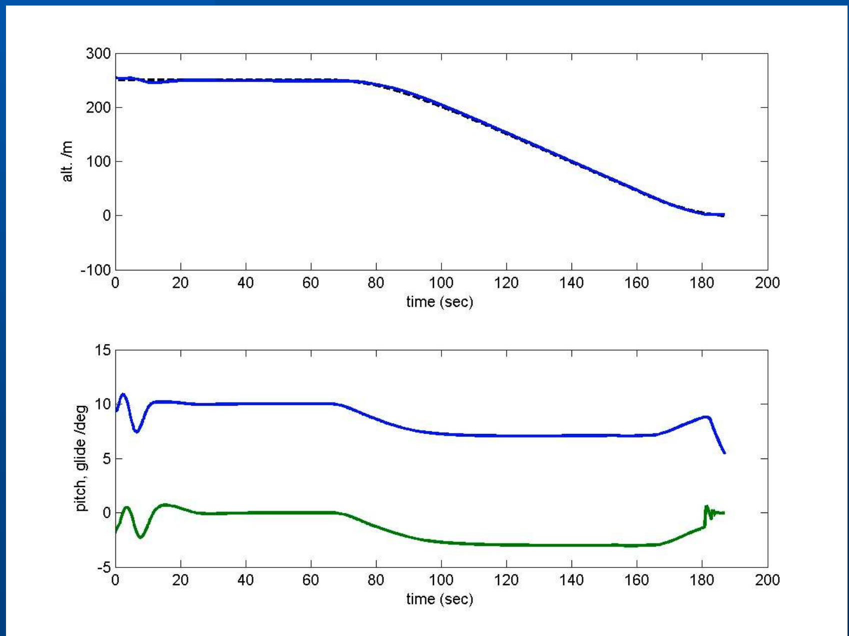
- Image is function of position and attitude (=pose P): $s = f(P)$
- From RCL lines (parallels on ground):

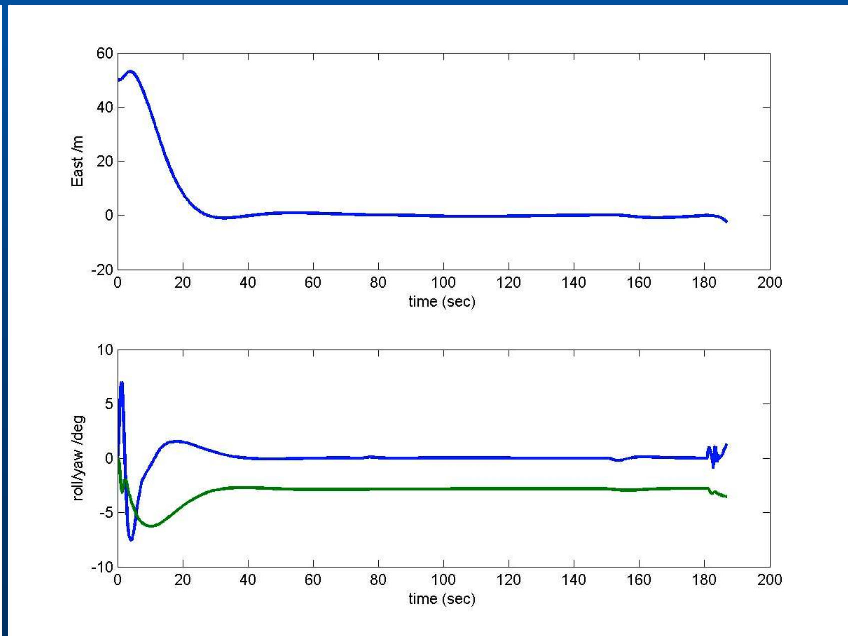
$$s = [\rho_R, \theta_R, \rho_C, \theta_C, \rho_L, \theta_L]^T$$

  - distance between lines must be known
  - only 5 dof are observable: longitudinal position (along lines) is not
  - instead of longitudinal position, regulate airspeed
  - PBVS: estimate pose from image: $\hat{P} = f^{-1}(s)$
  - IBVS: desired image from desired pose: $s^* = f(P^*)$

CIMAR approach

- **PBVS results from lines:**
  - **result is quite similar to ref. control**
  - **issue is on real image tracking (not here)**



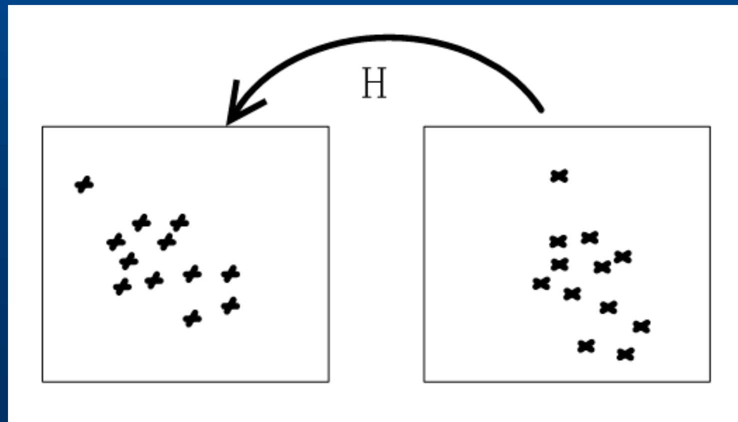


Homography approach

- use full image or window within image
- needs enough relevant points in image to allow tracking (étang de Berre!)
- assumes points are coplanar: ground plane

homography between 2 images
is function of camera pose change

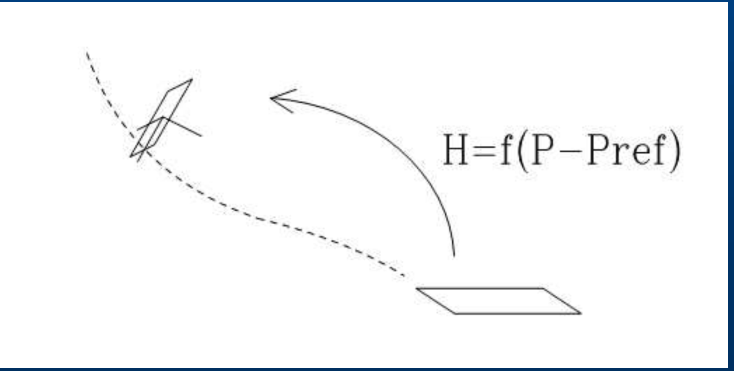
$$H = f(P) = \alpha R\left(I + \frac{1}{d} t n^T\right)$$



Homography approach

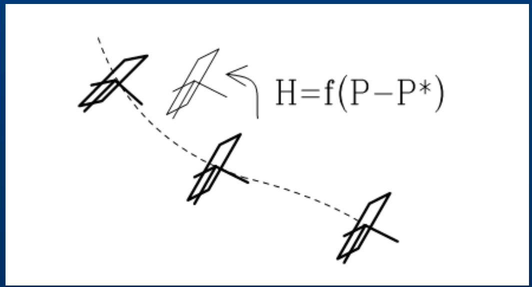
- **first idea: use a unique static reference image**
  - **zenith view of runway**
  - **unique pose as reference (Pref)**

  - **but change between reference image and current image during approach is too high and homography estimation not robust nor accurate**



Homography approach

- **second idea: use a sequence of images**
  - **build a database of images from ideal landing**
  - **homography represents error between current pose (P) and desired ideal pose (P*)**
  - **near regulation, the change between current image and reference image should be small:**
    - **tracking is more robust and accurate**
    - **it is easier to estimate homography**
  - **allows curved approach procedures!**



Homography visual servoing

- **PBVS**
  - **approach is already known for a static reference (and successfully tested in real time experiments)**
  - **to be adapted for sequence of reference images**

$$H = h\left(P - P^*\right) \quad \Rightarrow \quad \hat{P} = P^* + h^{-1}(H)$$

  - **may use reference control with estimated pose**

Homography visual servoing

- **IBVS**
  - **visual output is homography as a column vector s=H(:)**
  - **desired output is s***

$$H^* = I_3 \quad \Rightarrow \quad s^* = H^*(:)$$

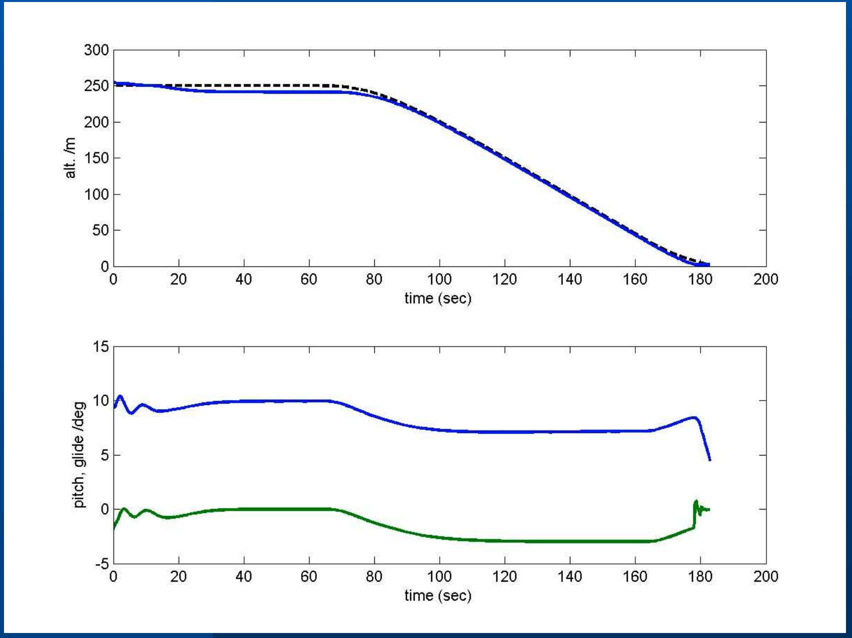
  - **then**

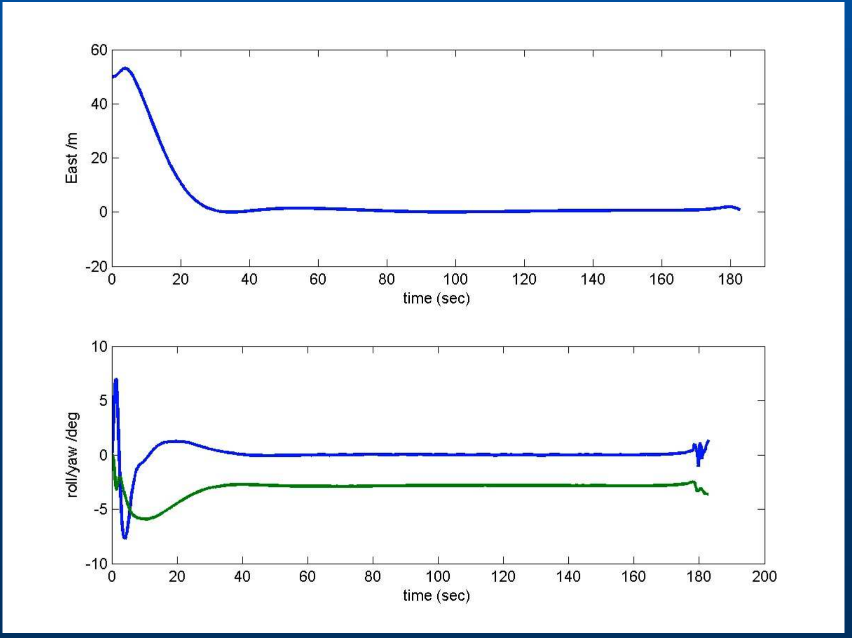
$$\dot{s} = L_T V \approx \begin{bmatrix} \frac{n_1}{d} I_3 & [H(:,1)]_\times \\ \frac{n_2}{d} I_3 & [H(:,2)]_\times \\ \frac{n_3}{d} I_3 & [H(:,3)]_\times \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \quad \Rightarrow \quad P - P^* \approx L_T^{-1}\left(s - s^*\right)$$

$$\Rightarrow \quad U = U^0 - K_V\left(V - V^*\right) - K_P L_T^{-1}\left(s - s^*\right)$$

Homography IBVS 1st example

- same conditions as previously
- 50m between reference images





Homography servoing issues

- **longitudinal regulation variable**
- **tolerance to pose error and accuracy**
- **number of images in database**
- **flare and touchdown**

Homography issues -1

- **longitudinal regulation variable:**
  - **in ideal conditions the desired pose could simply be a function of time**
  - **because of disturbances, (wind) for longitudinal position, it is better to regulate airspeed, as it is usual for aircraft and similar to CIMAR approach**
  - **then use current longitudinal position to regulate remaining pose**

Homography issues -2

- **tolerance to pose error and accuracy**
  - **clearly, we must have enough intersection between current image and reference image in order to estimate homography**
  - **higher pose error, namely higher angular error, will not allow to evaluate the homography**
  - **pan-tilt control:**

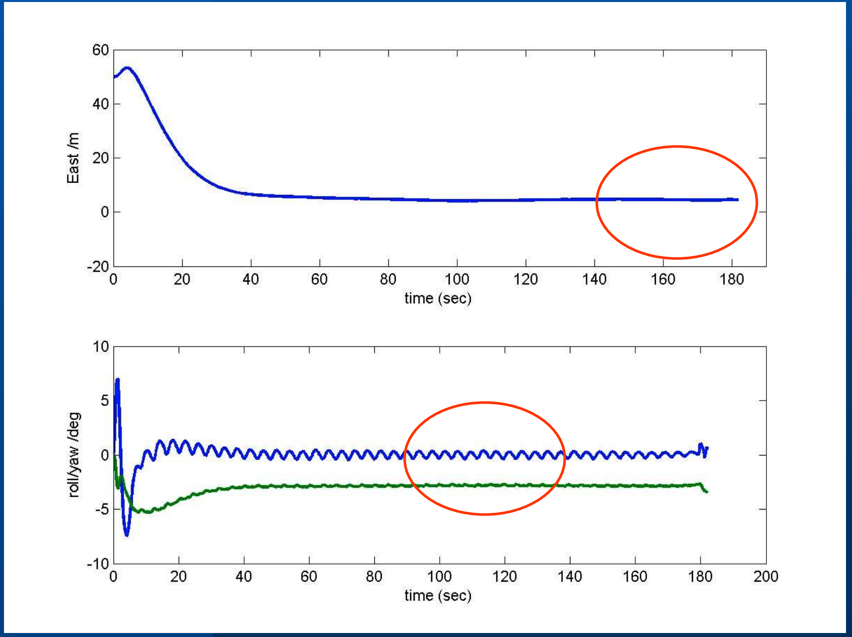
$$\psi_{k+1}^{cam} = \psi_k^{cam} - k_\psi\left(\psi_{img} - \psi_{img}^*\right) \qquad \theta_{k+1}^{cam} = \theta_k^{cam} - k_\theta\left(\theta_{img} - \theta_{img}^*\right)$$

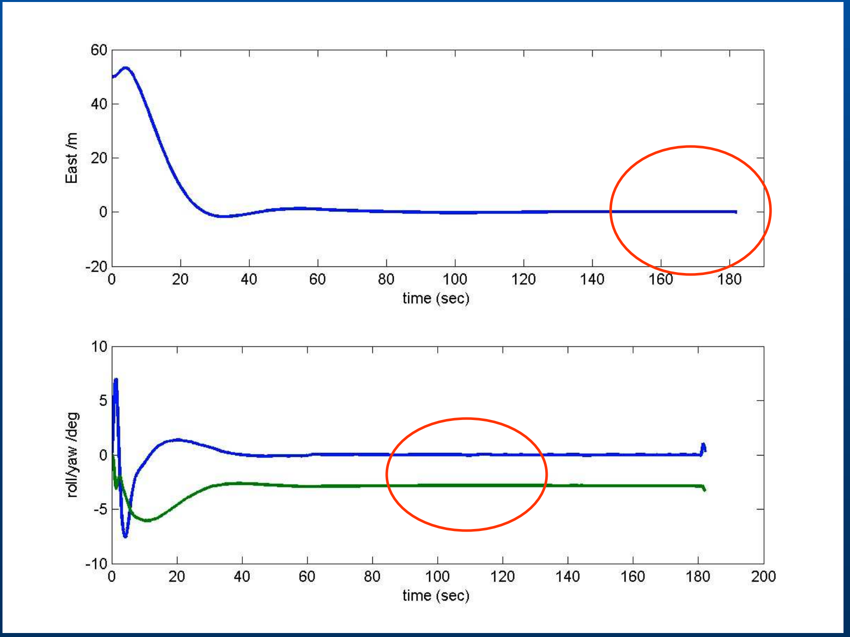
    - **center image and take it closer to reference image**
    - **tracking is more robust**
    - **useful for both PBVS and IBVS**
  - **zoom control may also help, namely before touchdown, but was not fully tested**

Homography IBVS -PanTilt -1

- **IBVS 200m +pan tilt**
  - **lateral regulation**

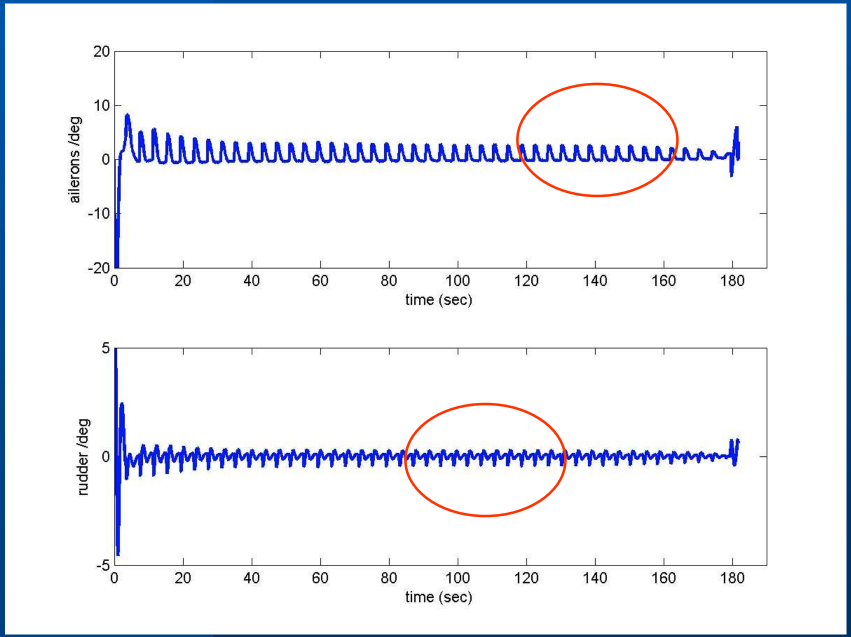
-crosswind compensated
-deals w/ step in ref. images

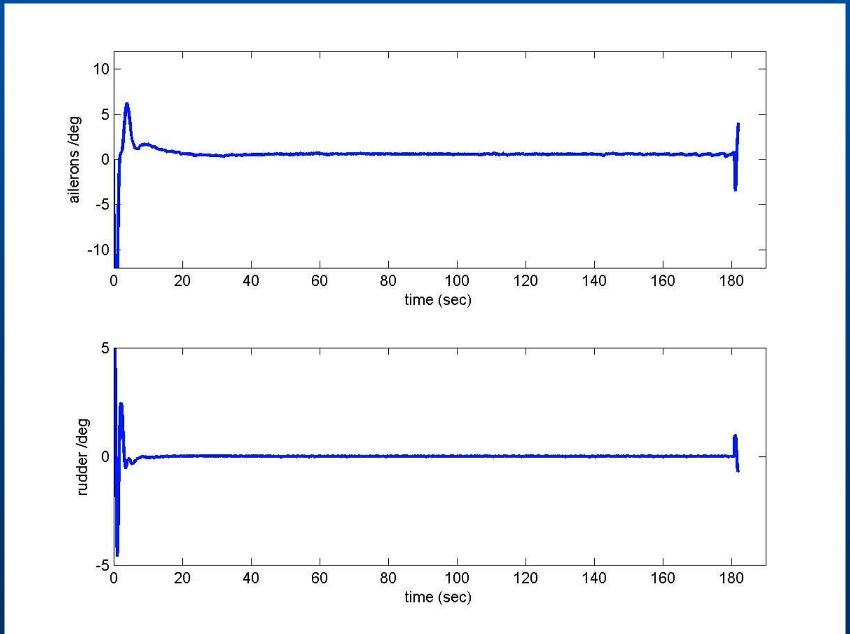




Homography IBVS -PanTilt -2

- **IBVS 200m + pan tilt**
  - **lateral inputs**

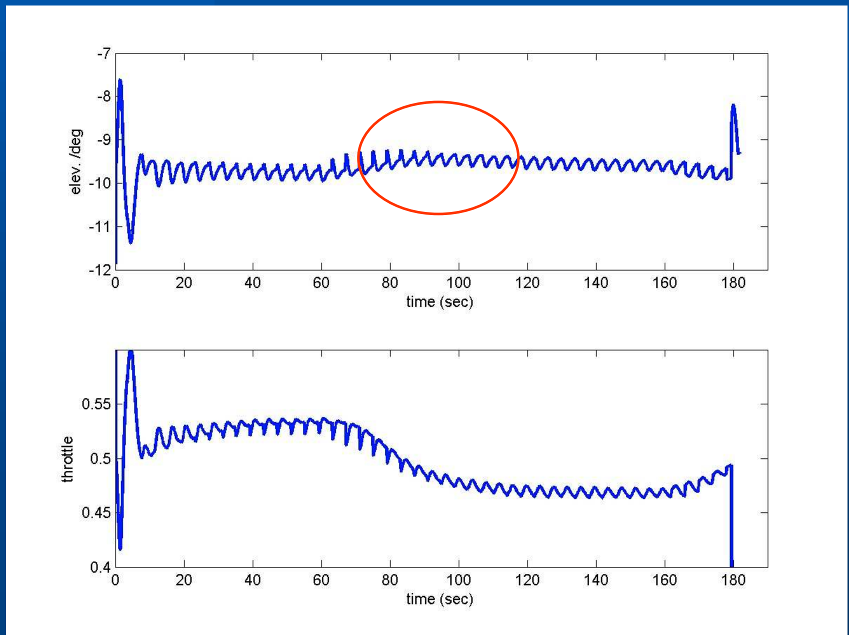


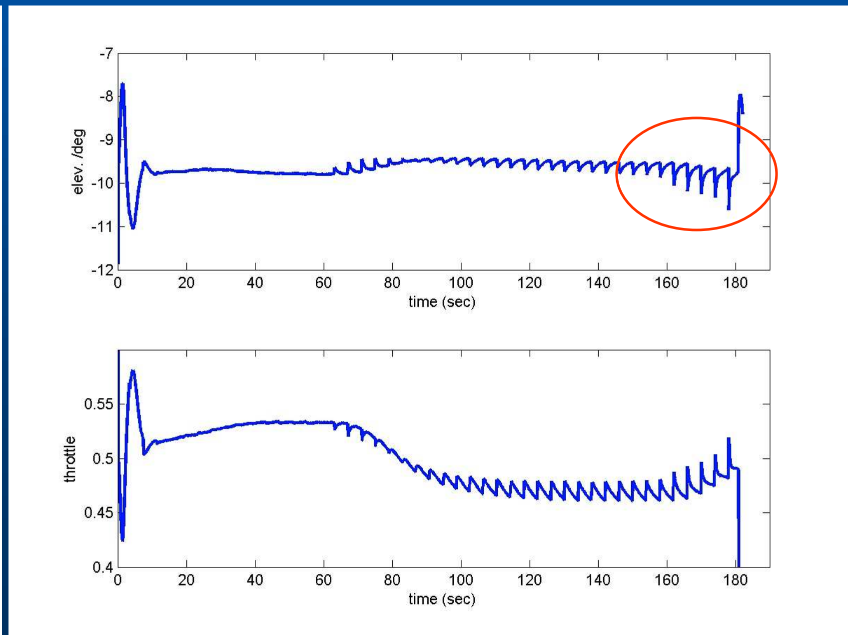


Homography IBVS -PanTilt -3

- **IBVS 200m + pan tilt**
  - **longitudinal inputs**

-still some sensitivity before TD





Homography issues -3

- **Number of images in database**
  - **need to reduce size of database**
  - **between images the tracked window is to be resized**
  - **each time the aircraft crosses a reference position there is a step to the next reference image:**
    - **tracking problems ?**
    - **feed of discontinuities to control and system ?**
  - **solution is to interpolate reference homography H*...**

Interpolate reference homography

Motion mostly along optical axis

- Estimate distance to next reference
- Estimate distance to previous reference
- compute rotation and translation of step homography

$$\mu_k = [1,0,0][H - H^T]_\times$$

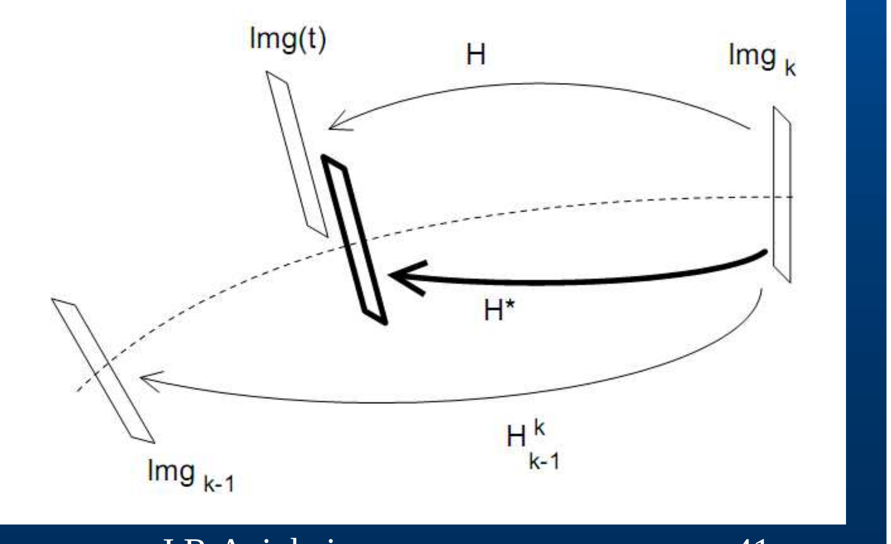
$$\mu_{k-1} = -[1,0,0][H_1 - H_1^T]_\times$$

$$H_{k-1}^k = \frac{1}{1 + t_d^T n} R_{\phi,\theta,\psi}\left(I + t_d n^T\right)$$

- result is desired homography

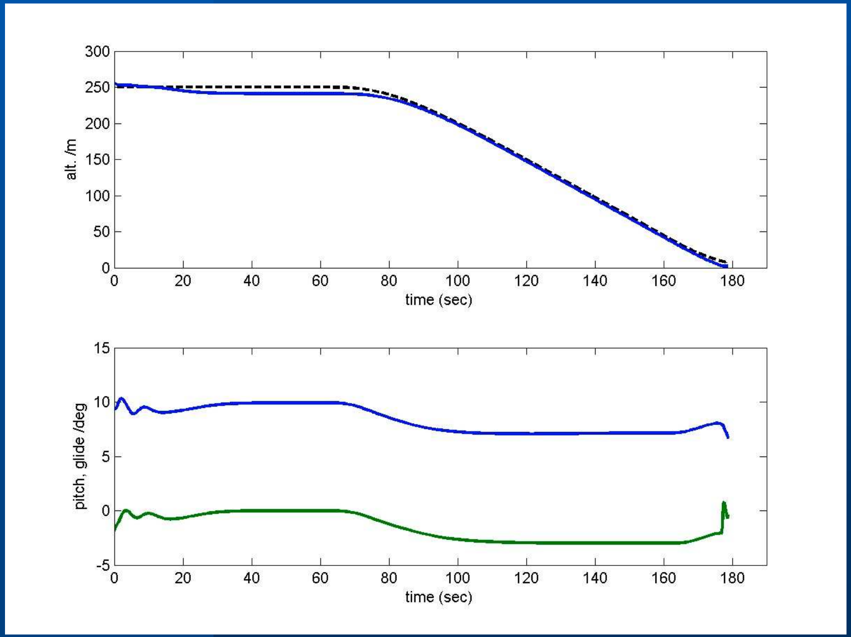
$$\lambda = \frac{\mu_k}{\mu_k + \mu_{k-1}}$$

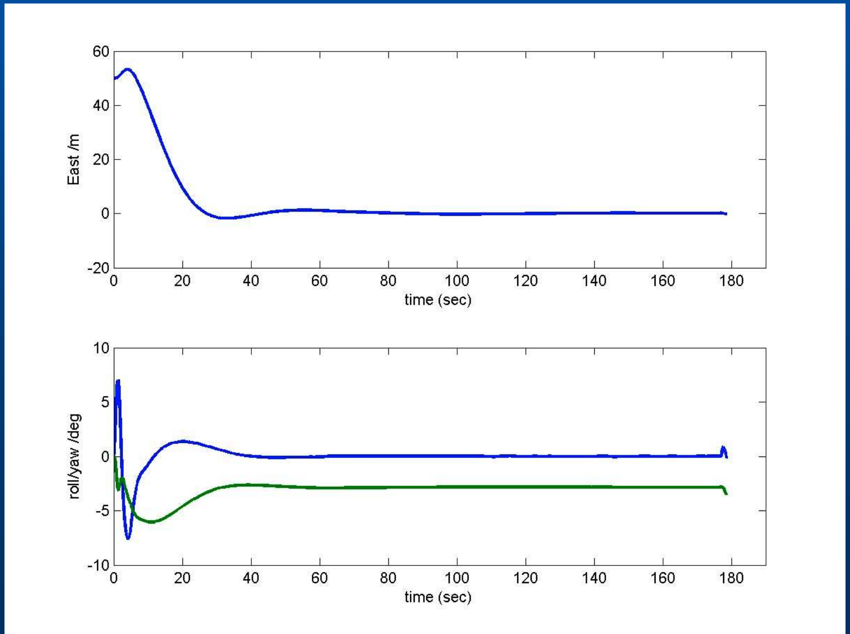
$$H^* = \frac{1}{1 + \lambda t_d^T n} R_{\lambda\phi,\lambda\theta,\lambda\psi}\left(I + \lambda t_d n^T\right)$$



Homography IBVS interpolate ref. homography -1

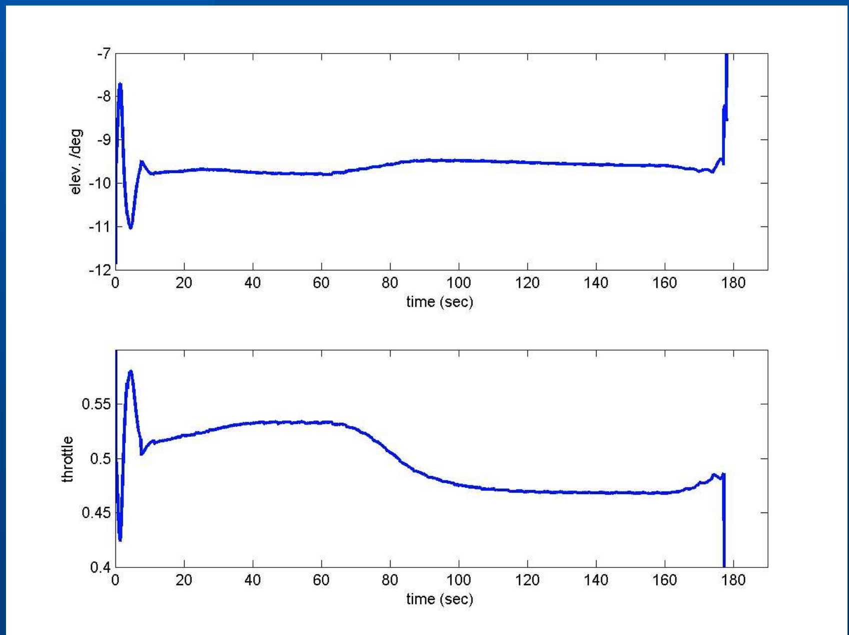
- **regulation of outputs**
  - **longitudinal left, lateral right**

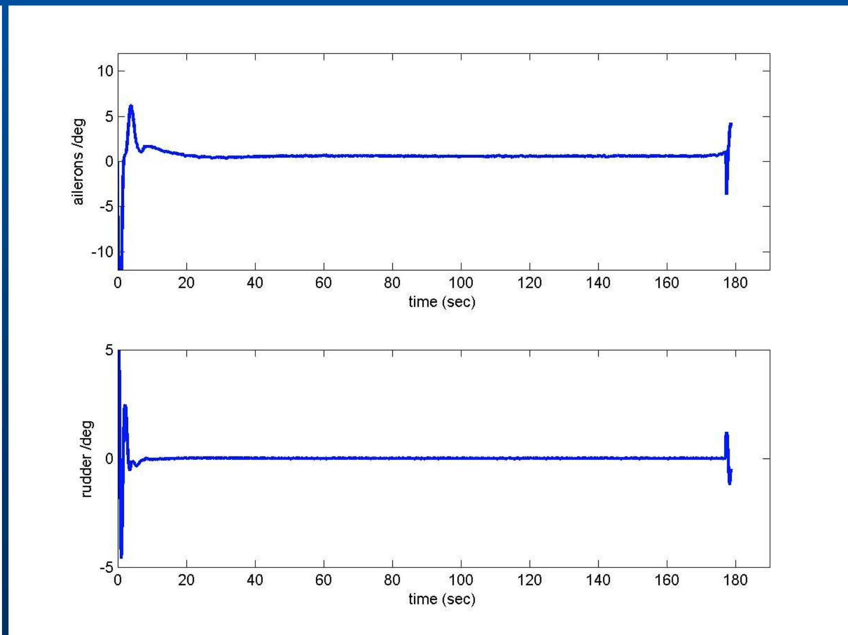




Homography IBVS interpolate ref. Homography -2

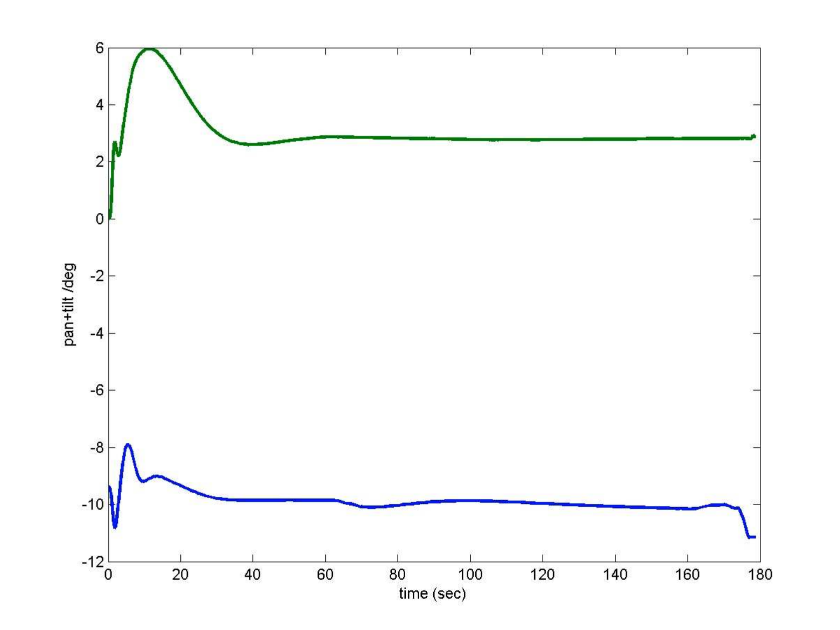
- **Inputs**
  - **longitudinal left, lateral right**

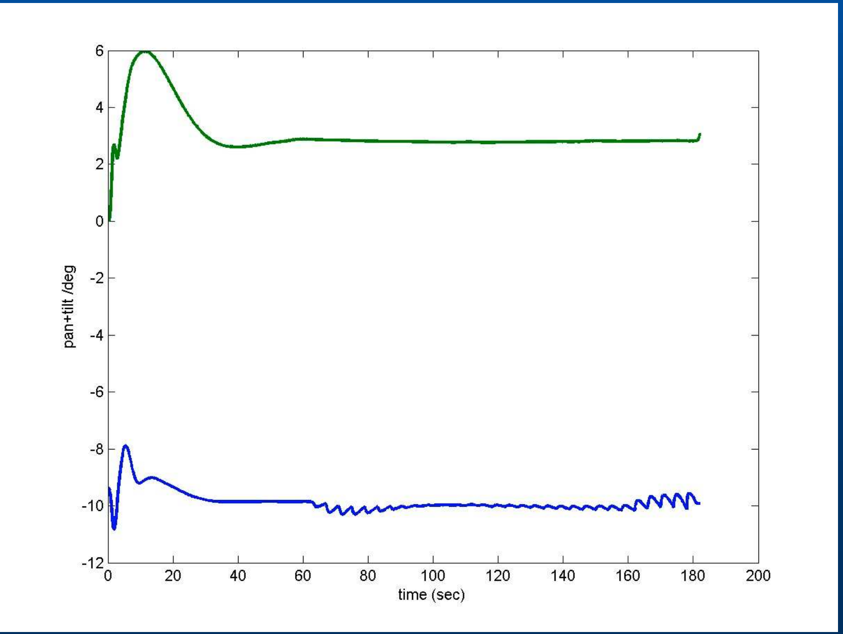




Homography IBVS interpolate ref. Homography -3

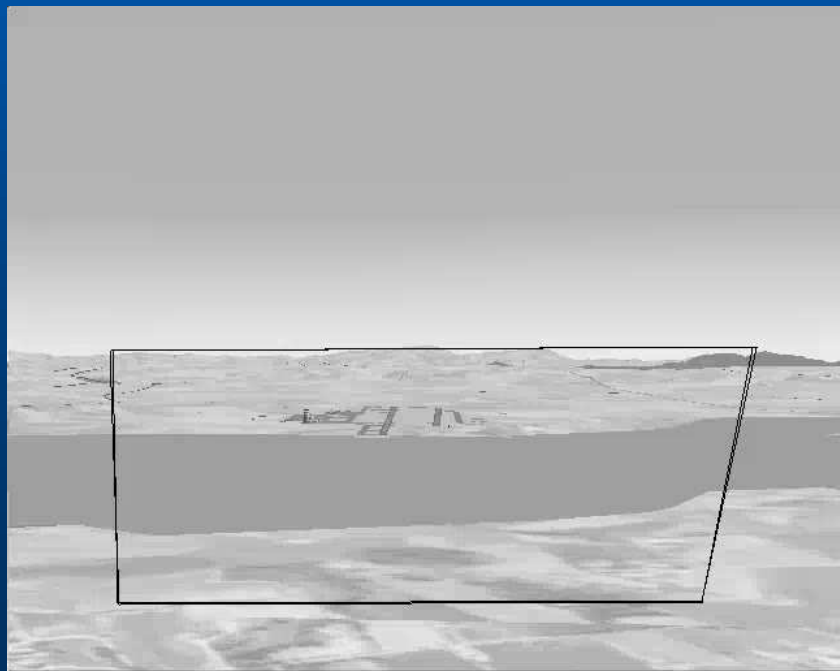
- **Pan-Tilt motion**
  - **tilt in blue, pan in green**
  - **right without interpolated reference**





Homography IBVS example with PEGASE simulator

- **Video from airborne camera**
  - **20Hz (in simulink 10Hz is enough)**
  - **visualize ROI for tracking**



Homography issues -4

- flare and touchdown
  - before touchdown change in image is getting faster
    - needs to increase sampling of images
  - homography estimation gets more difficult
    - assumption of planar ground is not so true
    - information in image gets poorer as runway fills image and looses points to track (see video end)
- solution?
  - It seems wiser to switch to lines approach
  - maybe controlling flare with usual radio-altimeter
  - and lateral rollout with lines approach

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Conclusion

- **PEGASE conclusion:**
  - **full image based navigation and servoing appears as a feasible solution**
  - **homography based approach and landing simulations are promising**
  - **a pan-tilt-zoom camera seems to be necessary**
  - **finalized with lines approach for flare/rollout**
- **still**
  - **misses a real demonstration experiment**

References

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Next...

- Dassault has launched a French sequence of Pegase
- in Portugal, IST and industrial partners have proposed a national project for UAV automatic landing on a Navy ship…

...?

Merci!!