Hovering flight stabilization in wind gusts for a ducted fan UAV

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Presentation outline

- Introduction
- System Modelling
- Control design
- Conclusion

Introduction

Bertin Technologies VTOL UAV history

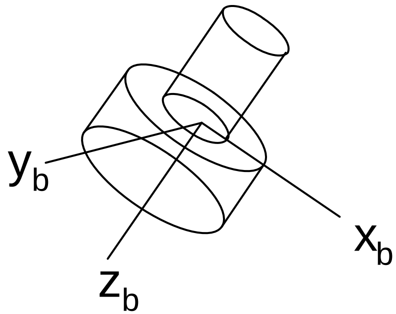
Internal studies
SFER

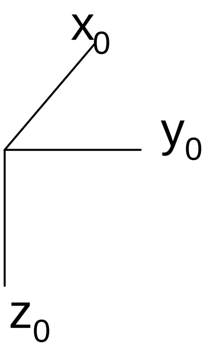
American VTOL UAVs

• Kestrel (Honeywell)
• iSTAR (Allied Aerospace)
• …

Bertin VTOL UAV

System Modelling
Dynamic representation





Notations :

$$e_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad e_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \quad e_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

- Reference frames
  - Inertial frame I (NED - North East Down) : (x_0, y_0, z_0)
  - Body fixed A : (x_b, y_b, z_b)
- Dynamic representation

ξ : Center of Gravity G position / I

v : CoG velocity vector/ I

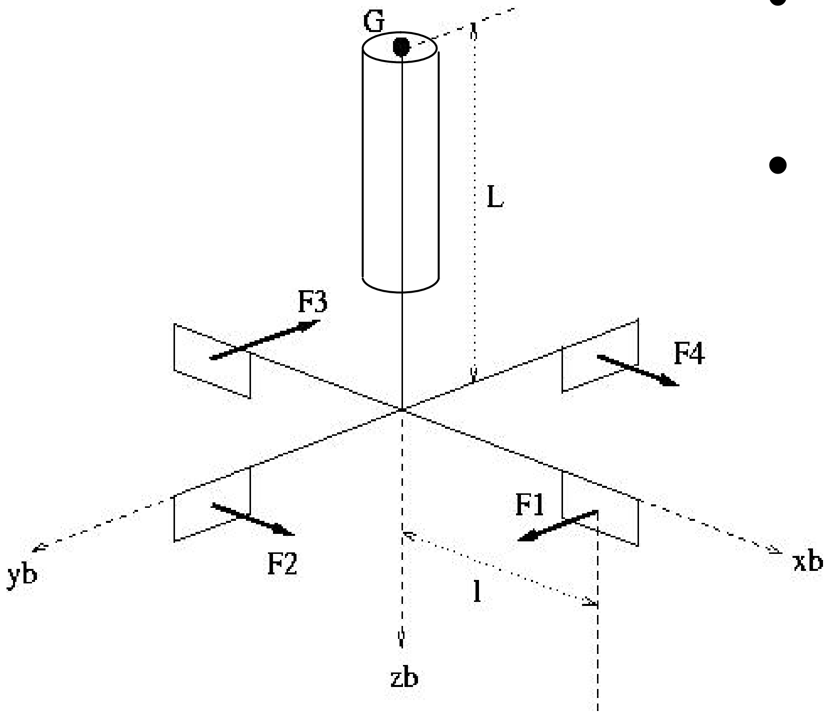
R : transformation matrix from I to A :

$$R = [x_b, y_b, z_b]_I$$

Ω : angular velocity vector of A relative to I, expressed in A

$$\Omega = [p, q, r]_A^T$$

System Modelling
Control inputs



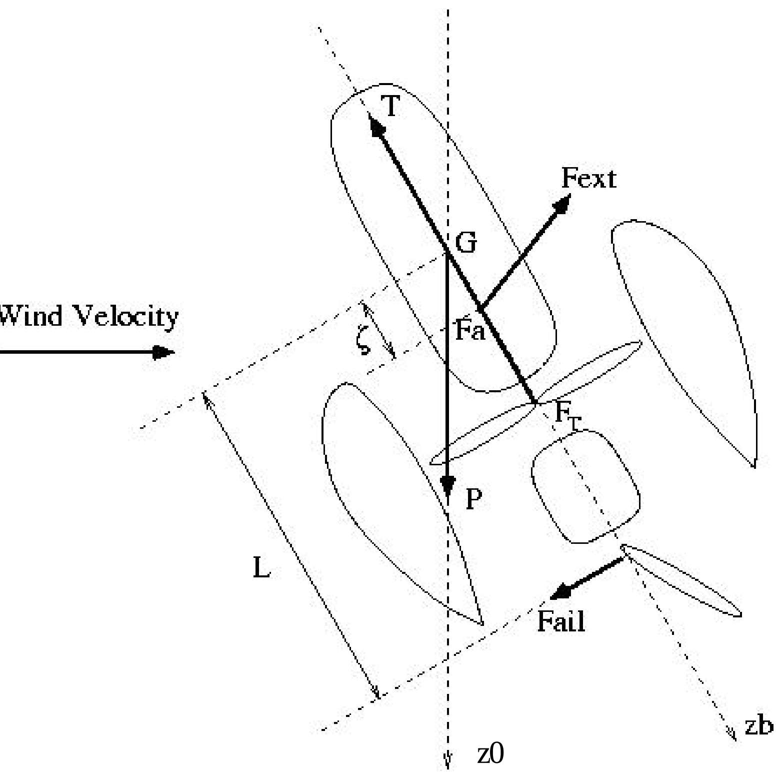
- Thrust intensity
  - u = ~ ω^2 (propeller's RPM)
- Control surfaces efforts
  - F_i effort of control grid i ($F_i \sim \delta\alpha_i$)
  - Resulting efforts F_{ail} et Γ_{ail} (expressed in A)

$$F_{ail} = \sum_{i=1}^{4} F_i \qquad \Gamma_{ail} = \sum_{i=1}^{4} \overrightarrow{GA_i} \wedge F_i$$

It can be shown that

$$[F_i]_{i=1..4} = P^T (PP^T)^{-1} \Gamma_{ail} \qquad F_{ail} = -\frac{1}{L} \breve{e}_3 . \Gamma_{ail}$$

System Modelling
Wrenches acting on the system



- Weight $\vec{P} = mgz_0 = \begin{Bmatrix} mg\,.e_3 \\ 0 \end{Bmatrix}_G$
- Thrust $\vec{T} = -u.z_b = \begin{Bmatrix} -u.R.e_3 \\ 0 \end{Bmatrix}_G$
- Control vanes $\overrightarrow{F_{ail}} = \begin{Bmatrix} R.\Sigma\Gamma_{ail} \\ \Gamma_{ail} \end{Bmatrix}_G$
- Wind perturbations

$$\overrightarrow{F_{ext}} = \begin{Bmatrix} F_{ext} \\ z\,.\breve{e}_3 R^T F_{ext} \end{Bmatrix}_G$$

System Modelling

Dynamic equations

- Kinematic equation of position
- Newton’s theorem expressed in I
- Kinematic equation of attitude
- Euler’s theorem expressed in A

$$
\begin{cases}
\dot{x} & = & v \\
m\dot{v} & = & -uR.e_3 + mge_3 + R\Sigma\Gamma_{ail} + F_{ext} \\
\dot{R} & = & R\breve{\Omega} \\
I\dot{\Omega} & = & -\Omega \wedge I\Omega + \Gamma_{ail} + \breve{e}_3 R^T (z\ .F_{ext})
\end{cases}
$$

Null as long as yaw rate is kept to zero

Control design

Objectives – Constraints – Design

- Objectives : stabilize the vehicle in hovering flight at a constant position x_s despite of wind gusts

- Constraints : unknown aerodynamical efforts, but slowly varying

- Design :
  - Full state feedback available [ξ,v,R,Ω]
  - Non linear control design based on Backstepping
  - Adaptive control to estimate in real time unknown aerodynamic efforts F_{ext} and $z.F_{ext}$

Control Design
Control model

- Pb : the control input Γ_{ail} acts on translational dynamics and makes the system strictly non-minimum phase
- Choosing a control point away from G allows to cancel the term $R\Sigma\Gamma_{ail}$ thanks to centrifugal forces

- The control model is then given by :

$$\begin{cases} \dot{x}_D & = & v_D \\ m\dot{v}_D & = & -\bar{u}R.e_3 + mge_3 + F_{ext} \\ \dot{R} & = & R\breve{\Omega} \\ I\dot{\Omega} & = & \Gamma_{ail} + \breve{e}_3 R^T M_{ext} \end{cases}$$

$$\boxed{M_{ext} = z\,.F_{ext}}$$

Control Design

Backstepping process

i	d_i	S_i	$\dot{S}_i$
1	$d_1 = x_D - x_s$ $\tilde{F}_{ext} = F_{ext} - \hat{F}_{ext}$ $\tilde{M}_{ext} = M_{ext} - \hat{M}_{ext}$	$S_1 = \frac{1}{2}\lvert d_1\rvert^2 + \frac{1}{2g}\lvert\tilde{F}_{ext}\rvert^2 + \frac{1}{2m}\lvert\tilde{M}_{ext}\rvert^2$	$\dot{S}_1 = -k_1\lvert d_1\rvert^2 + d_1^T(v_D - a_0) - \frac{1}{g}\tilde{F}_{ext}^T\dot{\hat{F}}_{ext} - \frac{1}{g}\tilde{M}_{ext}^T\dot{\hat{M}}_{ext}$
2	$d_2 = m(v_D - a_0)$	$S_2 = S_1 + \frac{1}{2}\lvert d_2\rvert^2$	$\dot{S}_2 = -\sum_{i=1}^{2} k_i\lvert d_i\rvert^2 - d_2^T(\bar{u}R.e_3 - a_1) + \frac{1}{g}\tilde{F}_{ext}^T(t_1 - \dot{\hat{F}}_{ext}) - \frac{1}{m}\tilde{M}_{ext}^T\dot{\hat{M}}_{ext}$
3	$d_3 = \bar{u}R.e_3 - a_1$	$S_3 = S_2 + \frac{1}{2}\lvert d_3\rvert^2$	$\dot{S}_3 = -\sum_{i=1}^{3} k_i\lvert d_i\rvert^2 + d_3^T\left(R\begin{bmatrix}\bar{u}q \\ -\bar{u}p \\ \dot{\bar{u}}\end{bmatrix} - a_2\right) + \frac{1}{g}\tilde{F}_{ext}^T(t_2 - \dot{\hat{F}}_{ext}) - \frac{1}{m}\tilde{M}_{ext}^T\dot{\hat{M}}_{ext} + d_3^T(gt_2 - \dot{\hat{F}}_{ext})$
4	$d_4 = R\begin{bmatrix}\bar{u}q \\ -\bar{u}p \\ \dot{\bar{u}}\end{bmatrix} - a_2$	$S_4 = S_3 + \frac{1}{2}\lvert d_4\rvert^2$	$\dot{S}_4 = -\sum_{i=1}^{4} k_i\lvert d_i\rvert^2 + d_3^T\left(R\begin{bmatrix}(\bar{u}/I_1)\Gamma_m \\ -(\bar{u}/I_1)\Gamma_l \\ \ddot{\bar{u}}\end{bmatrix} - a_3\right) + \frac{1}{g}\tilde{F}_{ext}^T(t_3 - \dot{\hat{F}}_{ext}) + \frac{1}{m}\tilde{M}_{ext}^T(t_M - \dot{\hat{M}}_{ext}) + \underbrace{d_3^T K d_4}_{=-d_4^T n}$

Control Design
Definition of the control law

- Final step of Backstepping :
  - Control Law

$$\begin{bmatrix} \Gamma_n \\ \hline (\overline{u} / I_1)\Gamma_m \\ -(\overline{u} / I_1)\Gamma_l \\ \ddot{\overline{u}} \end{bmatrix} = \begin{bmatrix} -k_r r \\ \hline R^T (a_3 + n) \end{bmatrix}$$

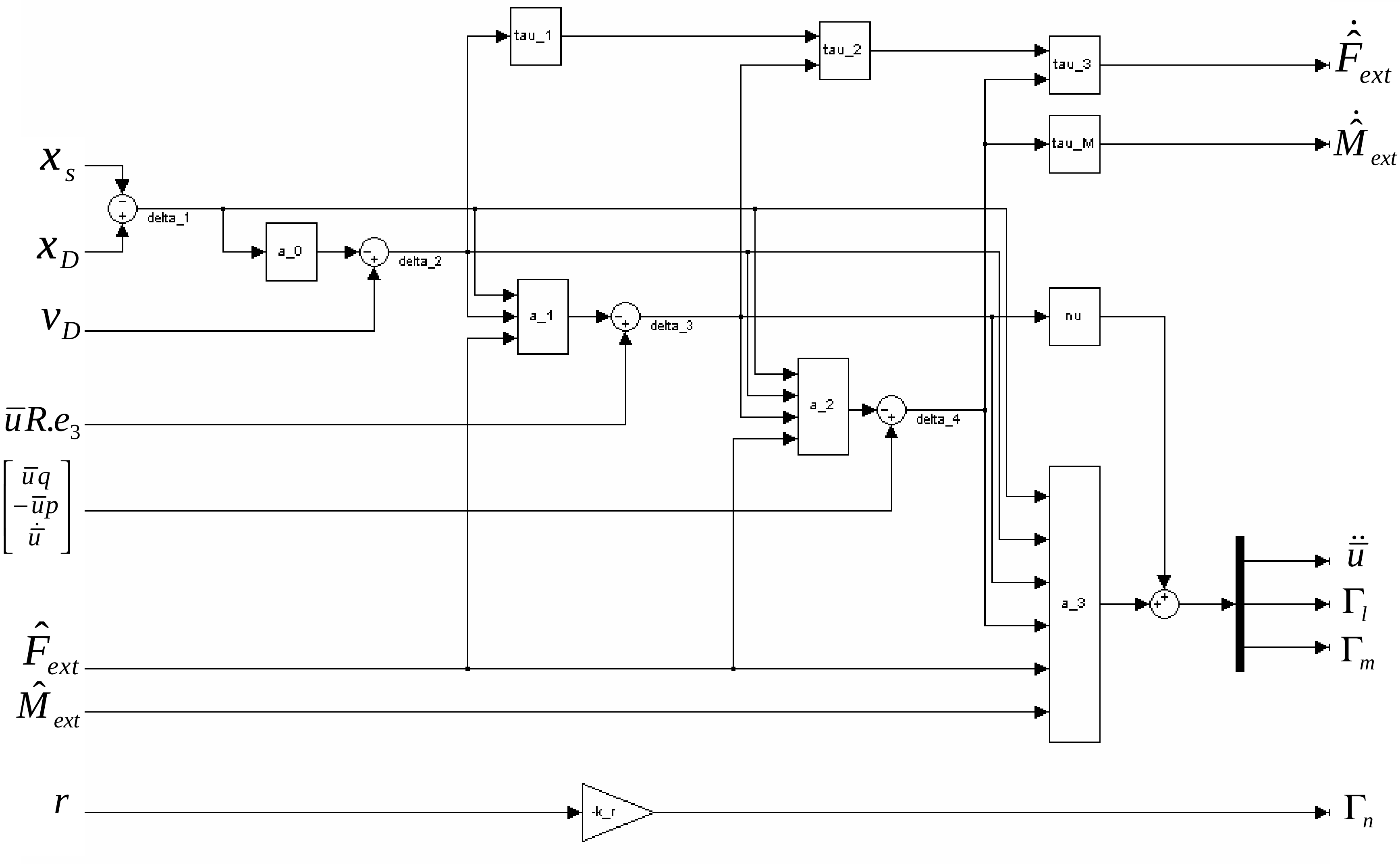
  - Adaptive filters

$$\begin{bmatrix} \dot{\hat{F}}_{ext} \\ \dot{\hat{M}}_{ext} \end{bmatrix} = \begin{bmatrix} g t_3 \\ m t_M \end{bmatrix}$$

Ensures $S_5 = S_4 + \frac{1}{2} r^2$ time derivative is $\dot{S}_5 = -\sum_{i=1}^{4} k_i \left| d_i \right|^2 - k_r r^2$

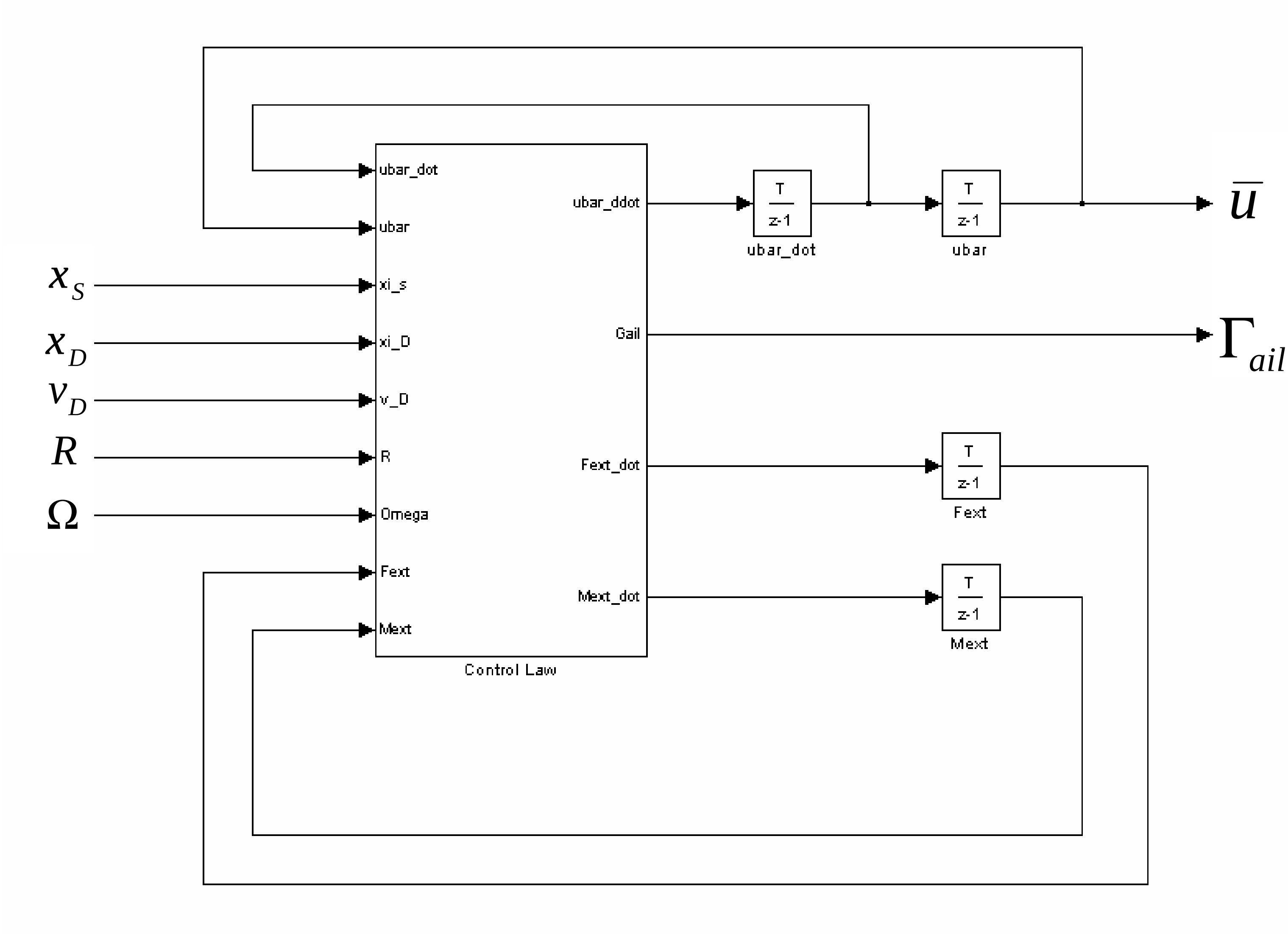
Control Design

Control law architecture



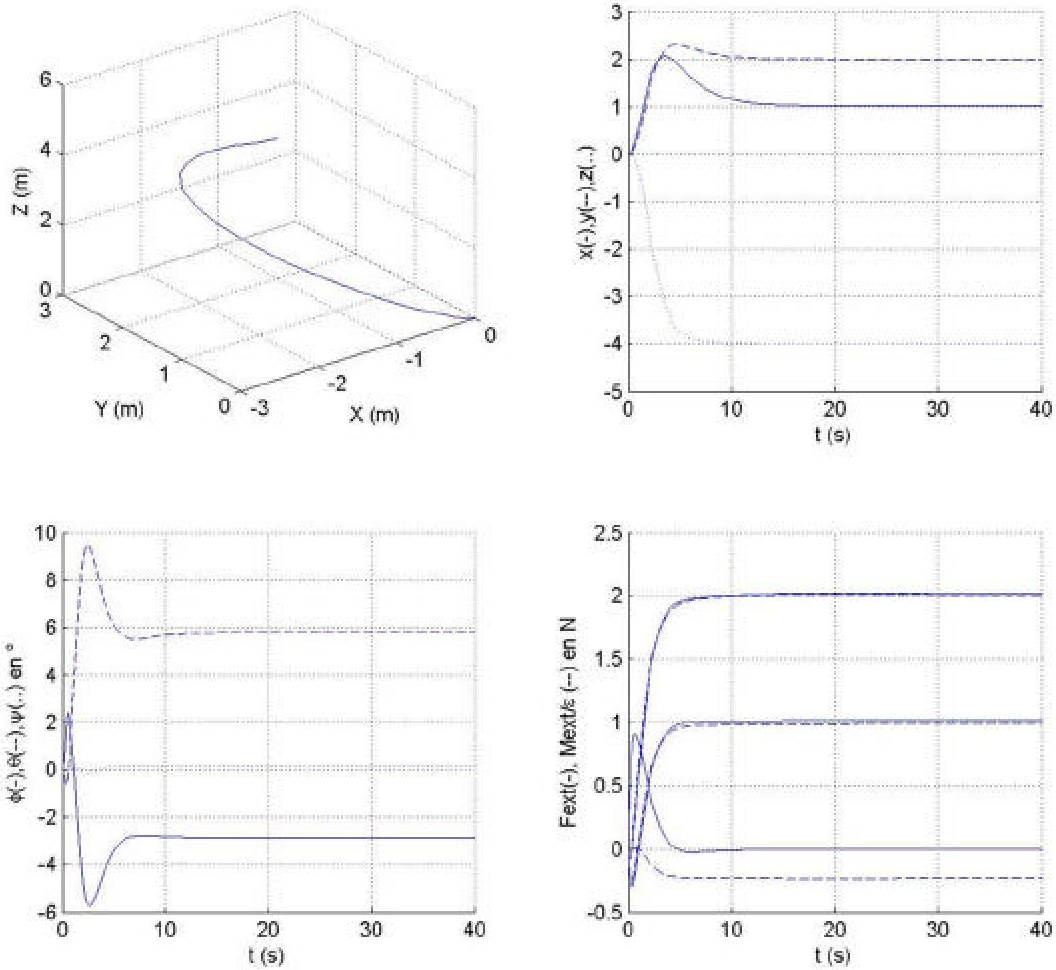
Control Design

Compensator implementation



Control design

Simulation results



Conclusion

To be continued…

- Decoupling of translational and rotational dynamics in the control law design

- Sensor fusion in order to give full state estimation
  - Attitude & Heading restitution system
  - INS/GPS Hybridization

- Saturation constraints: stability domain analysis and control design involving saturations