On the Control of an Aerial Manipulator Interacting with the Environment

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Joint work with F. Forte, R. Naldi, A. Macchelli

Automatica, submitted

Motivation: AIRobots

Innovative aerial service robots for remote inspections by contact

(02/2010 – 01/2013)

www.airobots.eu

Motivation: SHERPA

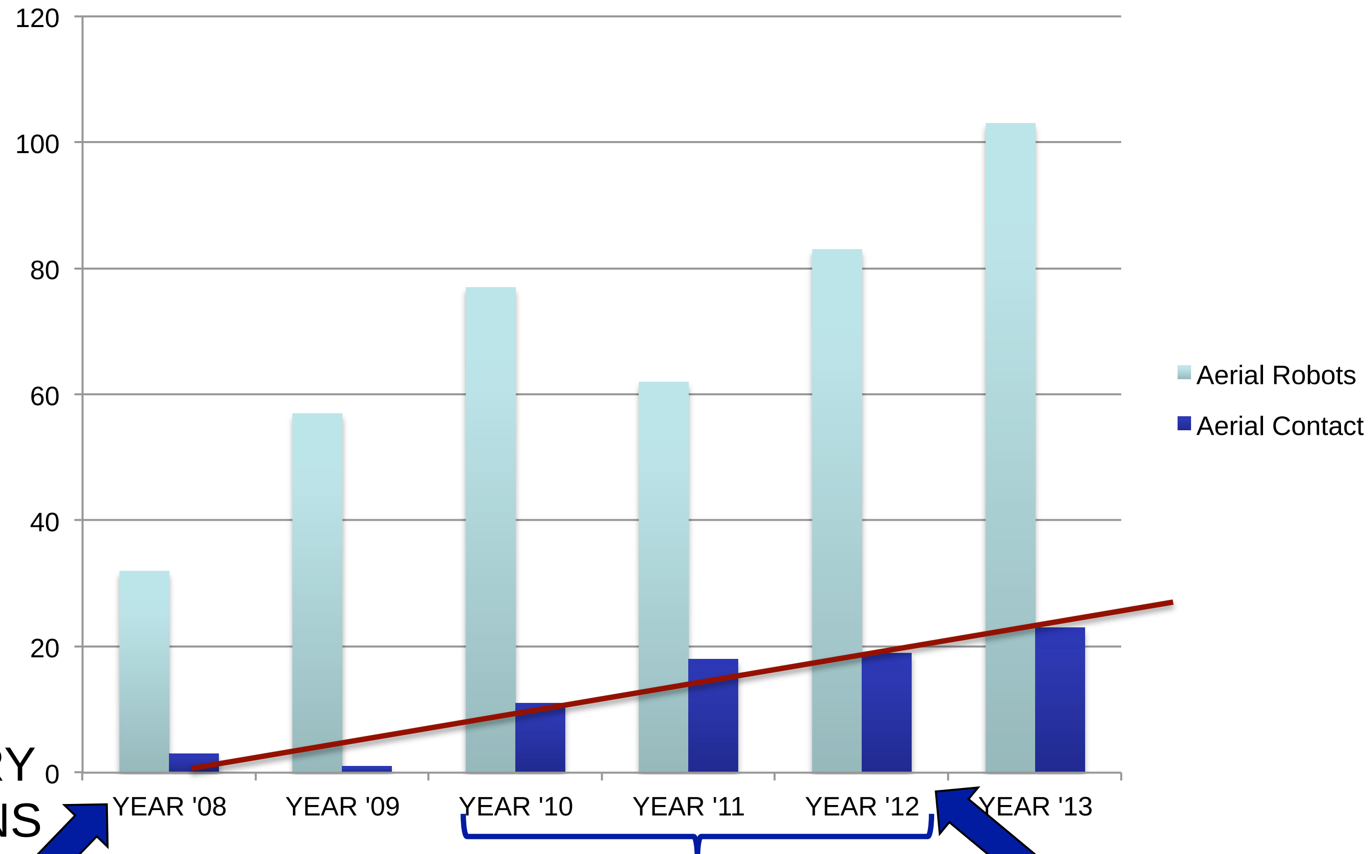
SHERPA Smart collaboration between Humans and ground-aErial Robots for imProving rescuing activities in Alpine environments

(02/2013 – 01/2017)
www.sherpa-project.eu

Trend of the idea

NUMBER OF PAPERS (ICRA + IROS) ABOUT ”AERIAL ROBOTICS” AND “AERIAL CONTACT”

SOURCE: IEEE EXPLORER

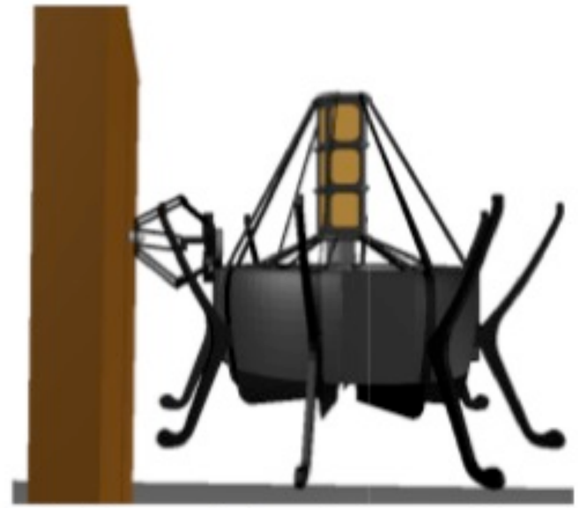


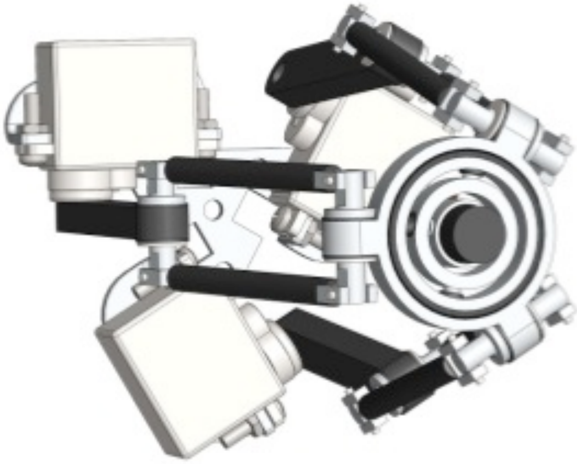
PRELIMINARY DISCUSSIONS WITHIN THE AIRobots CONSORTIUM

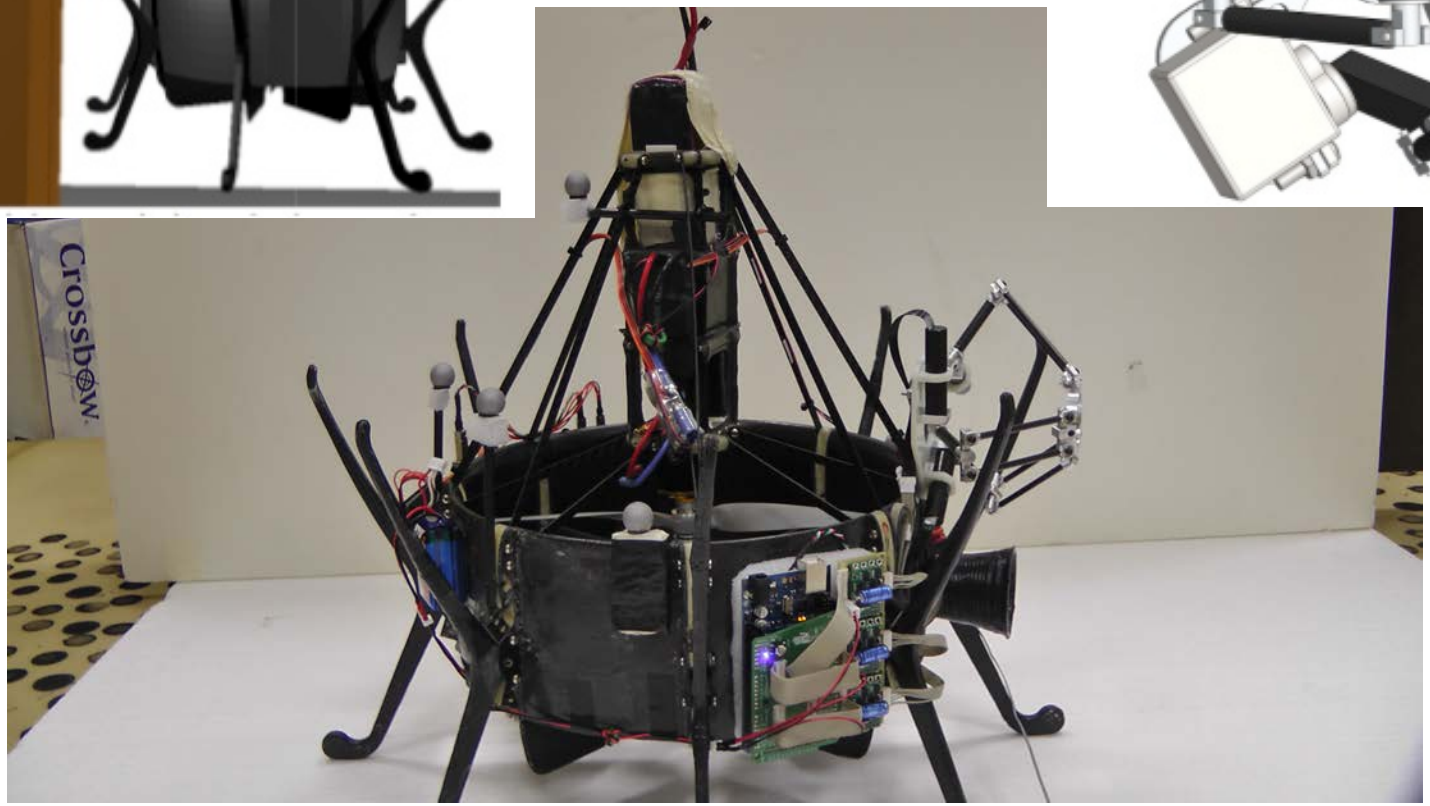
AIROBOTS

START OF INDUSTRIAL EXPLOITATION

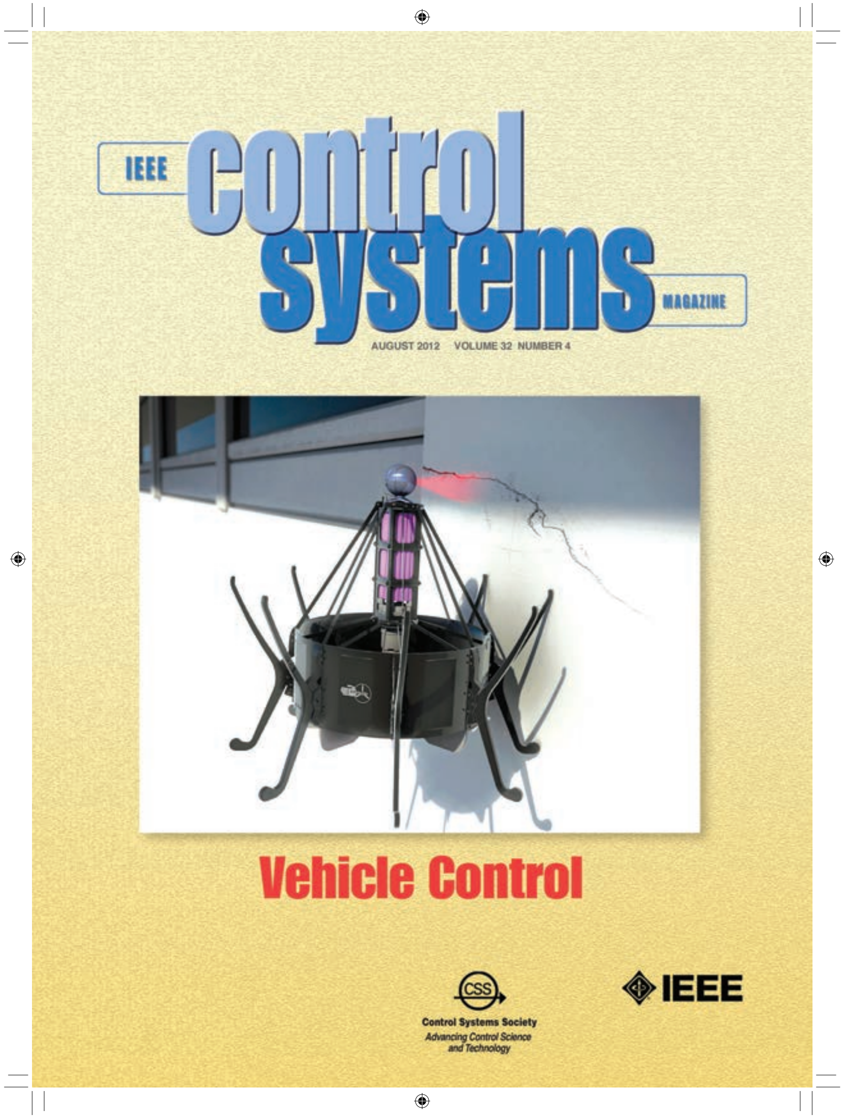
Improving Design and Systems





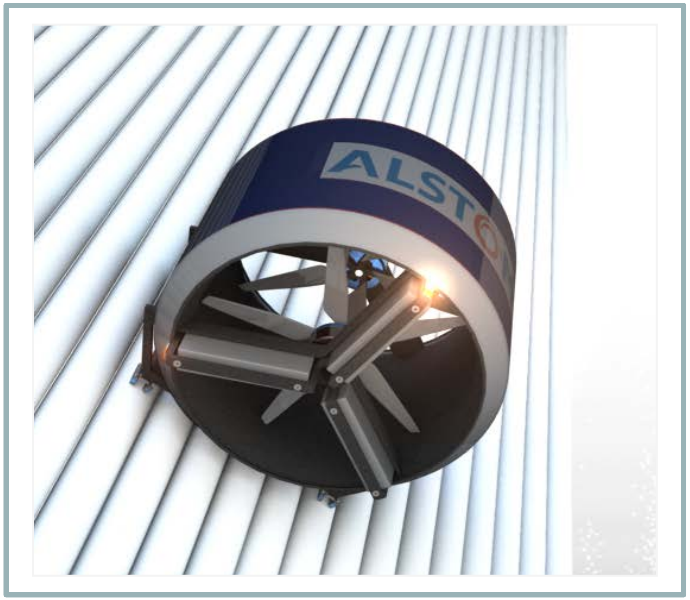


Better machines: Control



The industrial vision

Human Inspector today



Aerial Robot Inspector 2015 ….

Physical Interaction

- The challenge: control the vehicle in order to preserve stability in presence of physical interaction

- The goal
  - perform physical interaction tasks such as
    - **navigation** in cluttered environments, maneuvering between obstacles
    - **aerial manipulation**
    - **...**

Naldi et al. CST 2014.

Fumagalli et al., RAM, to appear

Marconi et al., Automatica, 2013

Background

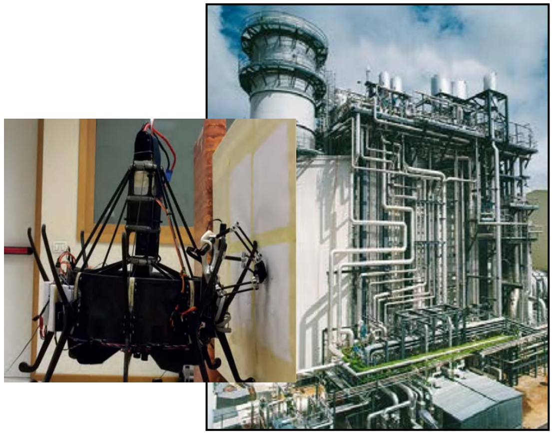
- Grasping and transportation
  - [Mellinger et al, DARS 2013], [Willmann et al, IJAC 2012]
- Physical interaction
  - docking to a vertical surface
    - [Marconi and Naldi, CSM 2013], ...
- Aerial manipulation
  - stability of a helicopter equipped with a robotic arm
    - [Pounds et al, ICRA 2011], ...
  - control of aerial manipulators (geometric methods)
    - [Kobilarov, JINT 2014], ...
  - stability of a quadcopter endowed with a robotic arm
    - [Fumagalli et al, IROS 2012], ...
    - [PhD thesis Abeje Mersha]
- Projects
  - EU projects AIRobots, ARCAS, ...

ICRA 2014
- *Mersha et al*
- *Alexis et al*
- *Kondak et all*
- *Ruggero et al*
- *Thomas et al*
- *...*

Workshop SAWT13

Contribution

- Scenario:
  - – inspection by contact of an infrastructure
- Design a stabilizing control law for the aerial manipulator (aerial basis + robotic arm)
  - free-flight
  - physical interaction

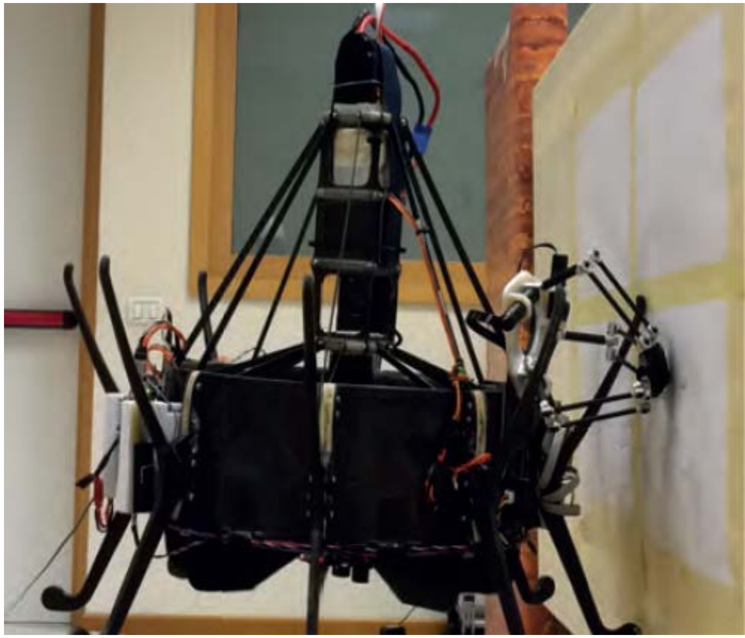


- Robustness wrt unknown contact forces
  - – no force / contact sensor needed

The Aerial Manipulator

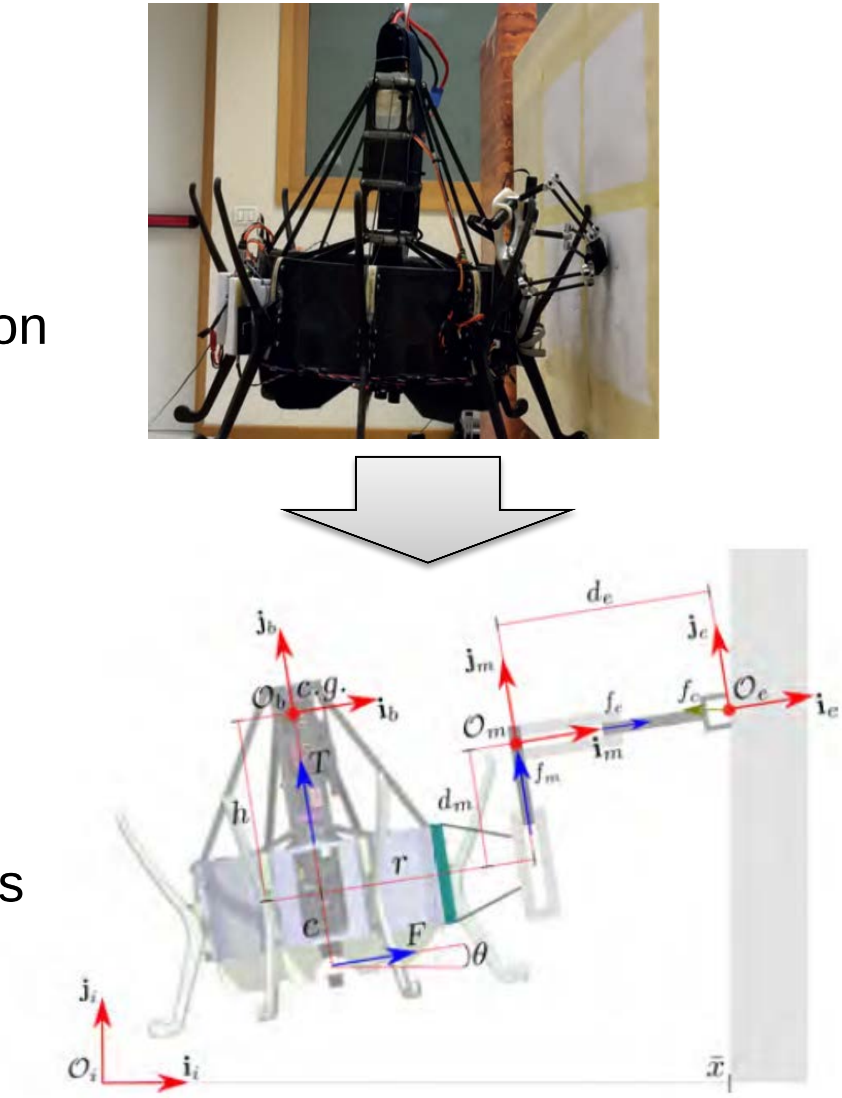
- Two main subsystems
  - ducted-fan aircraft
    - under-actuated dynamics
  - parallel manipulator (Delta)
    - fully-actuated

Results apply to any under-actuated VTOL system
-**quadrotors,**
-**helicopters,**
- **...**



Dynamical Model

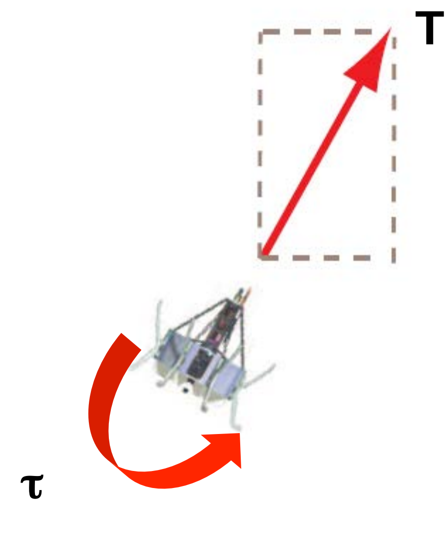
- Planar dynamical model
  - DFMAV (longitudinal dyn.)
    - state: $[x,\, \dot{x},\, y,\, \dot{y},\, \theta,\, \dot{\theta}]$
      - lateral /vertical / attitude position and velocity
    - inputs: $[T,\, F]$
      - propeller thrust and flap aerodynamic force
  - Manipulator (2 prismatic joints):
    - state: $[d_e,\, \dot{d}_e,\, d_m,\, \dot{d}_m]$
      - position an velocity of the joints
    - inputs: $[f_e,\, f_m]$
      - joints forces



Full model

- Lagrangian arguments
- Simplifying assumptions for control purposes:
  - Mass of the manipulator negligible with respect to the mass of the vehicle (1.8 Kg vs 0.1 Kg)
  - Small velocities leading to negligible Corolis contributions
  - Negligible side forces (state feedback)
- Aerial vehicle plus manipulator

Aerial Vehicle



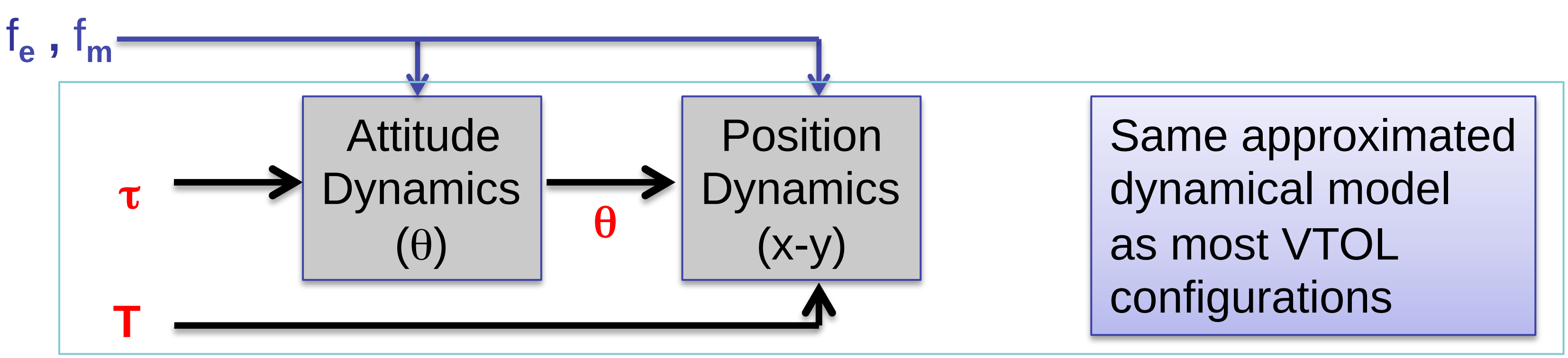
- Position dynamics
  - vectored-thrust approximation

$$M\begin{bmatrix}\ddot{x}\\ \ddot{y}\end{bmatrix} = -R(\theta)\begin{bmatrix}f_e\\ f_m\end{bmatrix} + R(\theta)\begin{bmatrix}0\\ T\end{bmatrix} - \begin{bmatrix}0\\ Mg\end{bmatrix}$$

- Attitude dynamics
  - torque control input

$$J_{uav}\ddot{\theta} = \tau + (d_m - h)f_e - (r + d_e)f_m$$

$$\tau := F\,c$$

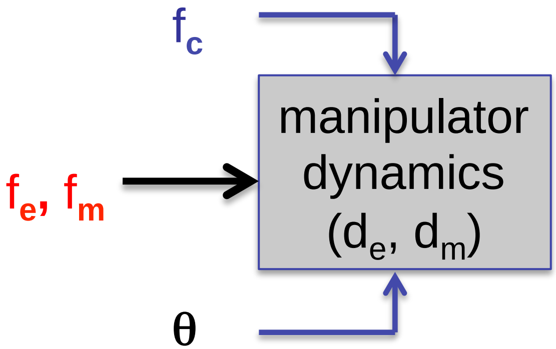


Robotic Arm

- Dynamical model

$$m \begin{bmatrix} \ddot{d}_e \\ \ddot{d}_m \end{bmatrix} = \begin{bmatrix} f_e \\ f_m \end{bmatrix} - R^{\mathrm{T}}(\theta) \begin{bmatrix} f_c \\ mg \end{bmatrix}$$

  - f_c: force applied by the environment (unknown, unmodeled)



Approximated Dynamics

f_e, f_m

$$m\begin{bmatrix}\ddot{d}_e\\ \ddot{d}_m\end{bmatrix} = \begin{bmatrix}f_e\\ f_m\end{bmatrix} - R^{\mathrm{T}}(\theta)\begin{bmatrix}f_c\\ mg\end{bmatrix}$$

f_c

θ

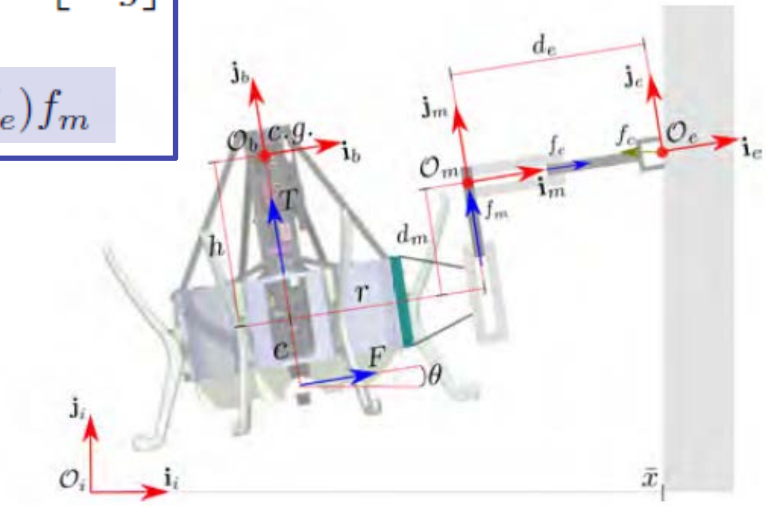
$f_e,\ f_m$

T

τ

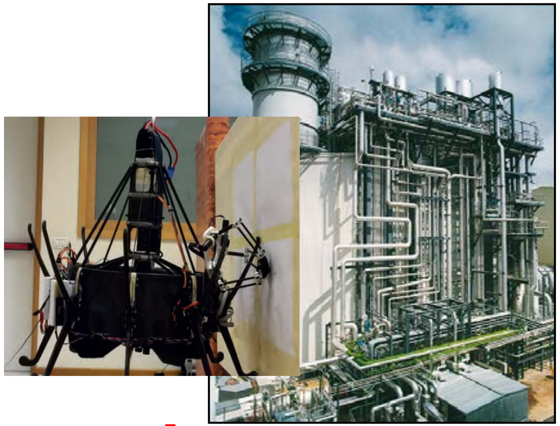
$$M\begin{bmatrix}\ddot{x}\\ \ddot{y}\end{bmatrix} = -R(\theta)\begin{bmatrix}f_e\\ f_m\end{bmatrix} + R(\theta)\begin{bmatrix}0\\ T\end{bmatrix} - \begin{bmatrix}0\\ Mg\end{bmatrix}$$

$$J_{uav}\ddot{\theta} = \tau + (d_m - h)f_e - (r + d_e)f_m$$



Control Goal

- Constant reference position for the DFMAV
  - x^*, y^*
- Reference trajectory for the manipulator
  - $d_e^*(t)$, $d_m^*(t)$
- Goal
  - free-flight: $f_c \equiv 0$
  - physical-interaction: $f_c \neq 0$
    - investigate conditions for **asymptotic or practical tracking** of the desired references



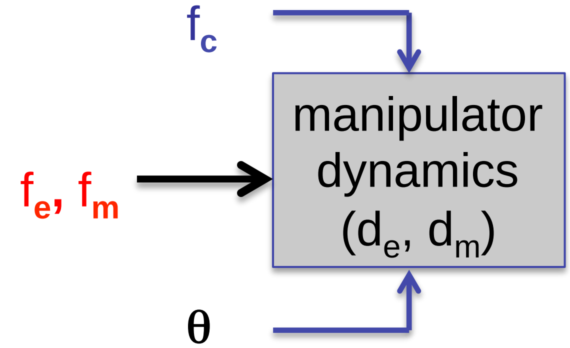
- Almost global results

Control of the robotic arm

- Control law:
  - error coordinates
  - state feedback law

$$\tilde{d}_e := d_e - d_e^\star$$
$$\tilde{d}_m := d_m - d_m^\star$$

$$m\begin{bmatrix}\ddot{d}_e\\ \ddot{d}_m\end{bmatrix} = \begin{bmatrix}f_e\\ f_m\end{bmatrix} - R^{\mathrm{T}}(\theta)\begin{bmatrix}f_c\\ mg\end{bmatrix}$$



$$\begin{bmatrix}f_e\\ f_m\end{bmatrix} = R^{\mathrm{T}}(\theta)\begin{bmatrix}0\\ mg\end{bmatrix} + m\begin{bmatrix}\ddot{d}_e^\star\\ \ddot{d}_m^\star\end{bmatrix} + $$
$$+ \kappa_m\left(\tilde{d}_e, \tilde{d}_m, \dot{\tilde{d}}_e, \dot{\tilde{d}}_m\right)$$

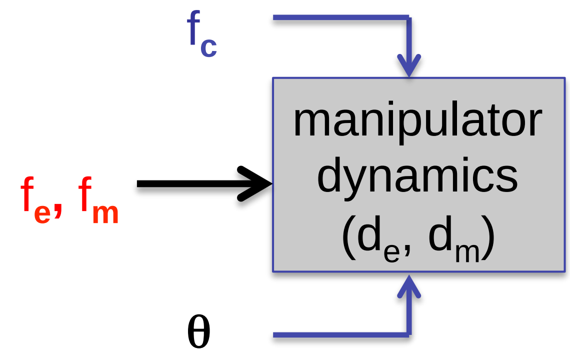
Nested saturation

$$\kappa_m(\cdot) :=$$
$$:= \lambda_2^m \sigma\left(\frac{k_2^m}{\lambda_2^m}\left(\begin{bmatrix}\dot{\tilde{d}}_e\\ \dot{\tilde{d}}_m\end{bmatrix} + \lambda_1^m \sigma\left(\frac{k_1^m}{\lambda_1^m}\begin{bmatrix}\tilde{d}_e\\ \tilde{d}_m\end{bmatrix}\right)\right)\right)$$

$$\lambda_i^m = \epsilon_m^{(i-1)}\lambda_i^\star \qquad k_i^m = \epsilon_m k_i^\star$$

[Isidori, Marconi, Serrani, 2003]

Control of the robotic arm



- Result (global)
  - bounded control inputs:

$$\left\|\begin{bmatrix} f_e \\ f_m \end{bmatrix}\right\|_\infty \le mg + m\left\|\begin{bmatrix} \ddot{d}_e^\star \\ \ddot{d}_m^\star \end{bmatrix}\right\|_\infty + \sqrt{2}\lambda_2^\star \epsilon_m$$

  - nested saturation properties

$$\left|\frac{\mathrm{d}}{\mathrm{d}t}\kappa_m(\cdot)\right|_\infty \le \Gamma_1^m \epsilon_m^2 + \Gamma_2^m \epsilon_m |f_c|_\infty$$

"**Disturbance response**" of the manipulator controller

  - tracking performances

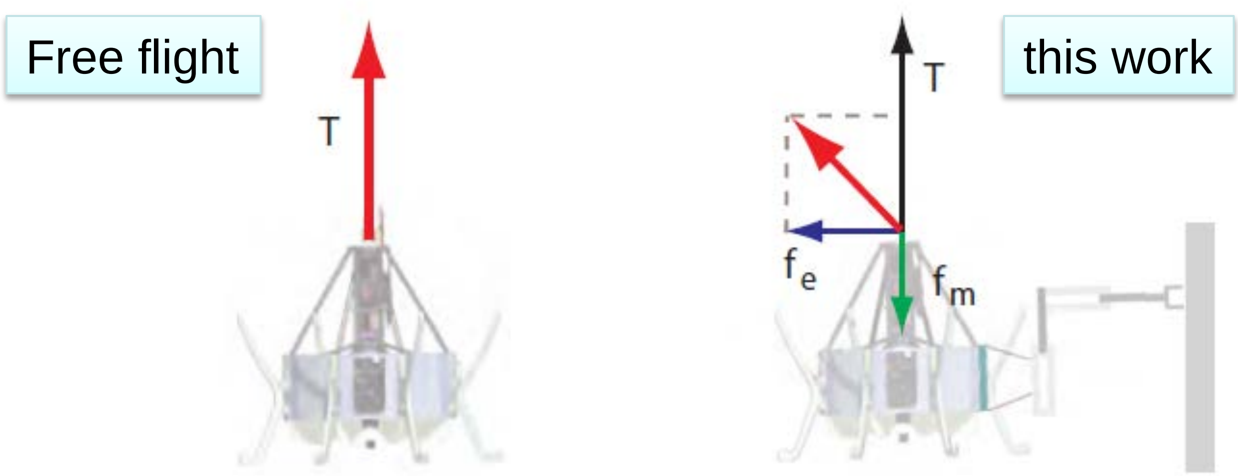
if $|f_c|_\infty \le \Delta(\varepsilon_m)$

$$\left\|\begin{bmatrix} \tilde{d}_e \\ \tilde{d}_m \end{bmatrix}\right\|_a \le \gamma_{\epsilon_m}(|f_c|_a)$$

- free-flight ($f_c \equiv 0$): asymptotic tracking
- physical interaction: practical tracking

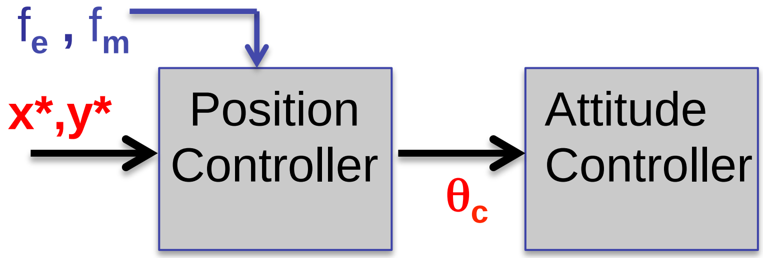
Control of the aerial platform

- Idea:
  - take into account for the knowledge of the manipulator forces f_e, f_m
    - modified vectored-thrust control paradigm!



IDEA:
"vectorize" the resultant vector

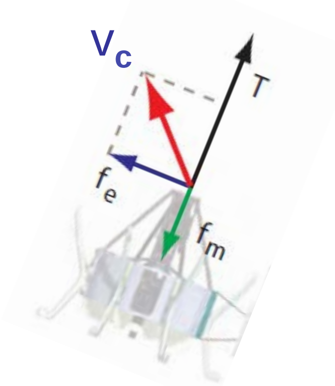
Control of the aerial platform



– Position error coordinates

$$\tilde{x} := x - x^\star \quad \tilde{y} := y - y^\star$$

– Desired control vector: $v_c := \begin{bmatrix} 0 \\ Mg \end{bmatrix} - \kappa\left(\tilde{x}, \dot{\tilde{x}}, \tilde{y}, \dot{\tilde{y}}\right)$



- to obtain v_c we must have

$$R(\theta_c)\begin{bmatrix} -f_e \\ T_c - f_m \end{bmatrix} = v_c$$

- hence

$$\left| R(\theta_c)\begin{bmatrix} -f_e \\ T_c - f_m \end{bmatrix} \right| = |v_c| \qquad \arg\left(R(\theta_c)\begin{bmatrix} -f_e \\ T_c - f_m \end{bmatrix} \right) = \arg(v_c)$$

$$\boxed{\begin{aligned} T_c &= \sqrt{v_c^{\mathrm{T}} v_c - f_e^2} + f_m, \\ \theta_c &= \arg(v_c) + \arg\left(\left[f_e, \sqrt{v_c^{\mathrm{T}} v_c - f_e^2} \right]^{\mathrm{T}} \right) \end{aligned}}$$

Crucial constraints:

$$\|v_c\| > 0$$

$$\|f_e\| \leq \|v_c\|$$

Control of the aerial platform

– Position feedback stabilizer (nested saturations)

$$\kappa(\cdot) := \lambda_2 \sigma \left(\frac{k_2}{\lambda_2} \left(\begin{bmatrix} \dot{\tilde{x}} \\ \dot{\tilde{y}} \end{bmatrix} + \lambda_1 \sigma \left(\frac{k_1}{\lambda_1} \begin{bmatrix} \tilde{x} \\ \tilde{y} \end{bmatrix} \right) \right) \right)$$

$$\lambda_i = \epsilon^{(i-1)} \lambda_i^\star \qquad k_i = \epsilon k_i^\star$$

– **“Disturbance response”** of the position controller

- bounded control input regardless position error $|\kappa|_\infty \leq \sqrt{2}\lambda_2^\star \epsilon$
- bounded high-order derivatives

$$\left| \frac{\mathrm{d}}{\mathrm{d}t} \kappa(\cdot) \right|_\infty \leq \Gamma_{\bar{D}^\star} \epsilon$$

Control of the aerial platform

- Attitude controller $\tau_c := \tau_{FF}(d_e, d_m, f_e, f_m) + \tau_{FB}(\theta, \dot{\theta}, \theta_c)$
  - feedforward: $\tau_{FF}(d_e, d_m, f_e, f_m) = -(d_m - h) f_e + (r + d_e) f_m$
  - feedback: $\tau_{FB}(\theta, \dot{\theta}, \theta_c) = -k_P \left((\theta - \theta_c) + k_D \dot{\theta} \right)$

$$\boxed{\begin{aligned} mg < \underline{v} < Mg \\ \sqrt{2}\lambda_2^\star \epsilon \leq Mg - \underline{v} \\ mg + m\bar{D}^\star + \sqrt{2}\lambda_2^\star \epsilon_m \leq \underline{v} \end{aligned}}$$

- Control result
  - choice of ε, ε_m
  - assume $|f_c|_\infty \leq F^U$ for some $F^U > 0$
  - then there exist $k_D^* > 0$, k_p^* such that for all $k_p > k_p^*$ and $k_D < k_D^*$

$$\left\| \begin{bmatrix} \tilde{x} \\ \tilde{y} \end{bmatrix} \right\|_a \leq \gamma_p \left(\frac{k_D}{k_P} \left(|d_e^{\star,(3)}|_a + |f_c|_a \right) \right)$$

- free-flight ($f_c \equiv 0$) and constant d_e acceleration:
  - asymptotic tracking
  - otherwise: practical tracking

Control of the aerial platform

- Sketch of the proof

$$\eta_1 := \theta - \theta_c, \qquad \eta_2 := \dot{\theta} + \frac{1}{k_D}\eta_1$$

  – attitude dynamics

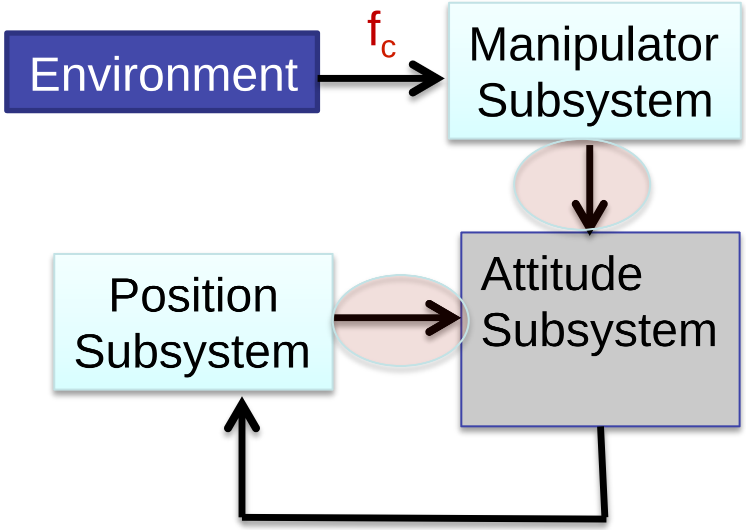
$$\dot{\eta}_1 = -\frac{1}{k_D}\eta_1 + \eta_2 - \dot{\theta}_c$$

$$J_{uav}\dot{\eta}_2 = -k_P K_D \eta_2 + \frac{J}{k_D}\left(-\frac{1}{k_D}\eta_1 + \eta_2 - \dot{\theta}_c\right)$$

  – where

$$\dot{\theta}_c = \frac{\mathrm{d}}{\mathrm{d}t}\arg(v_c) + \frac{\mathrm{d}}{\mathrm{d}t}\arg\left(\begin{bmatrix} \frac{f_e}{\sqrt{v_c^T v_c - f_e^2}} \end{bmatrix}\right)$$

$$= \frac{1}{v_c^T v_c}\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\left(\dot{v}_c + \begin{bmatrix} \frac{\dot{f}_e}{\frac{d}{dt}\sqrt{v_c^T v_c - f_e^2}} \end{bmatrix}\right)$$

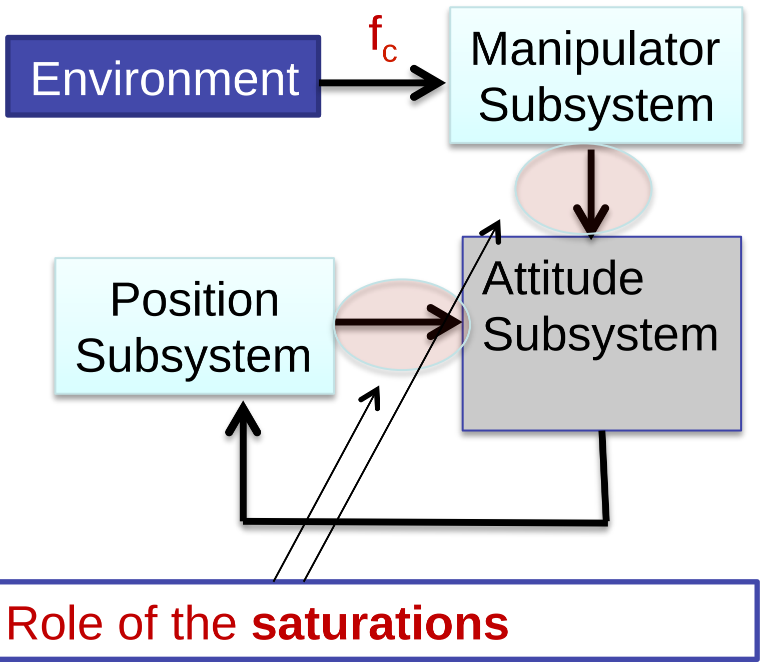


All terms are bounded thanks to the "**disturbance response**" properties of the position and manipulator controller!

Role of the **saturations**

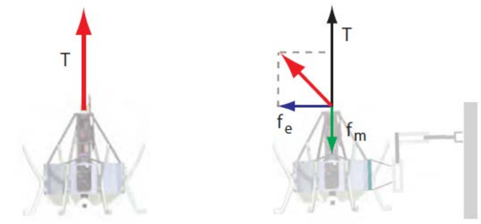
Control of the aerial platform

- Sketch of the proof
  - Position
    - ISS with restrictions
    - bounded influence on the attitude
  - Manipulator
    - bounded influence on the attitude
  - Attitude
    - ISS

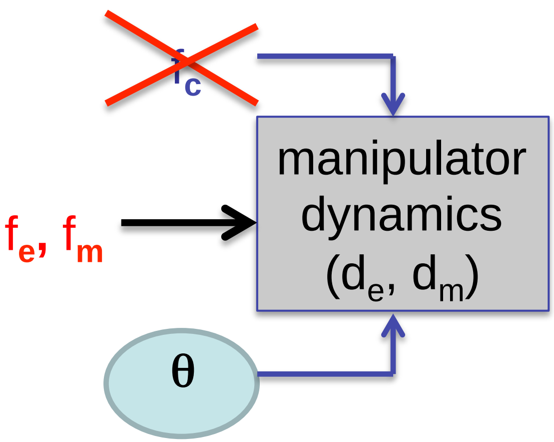


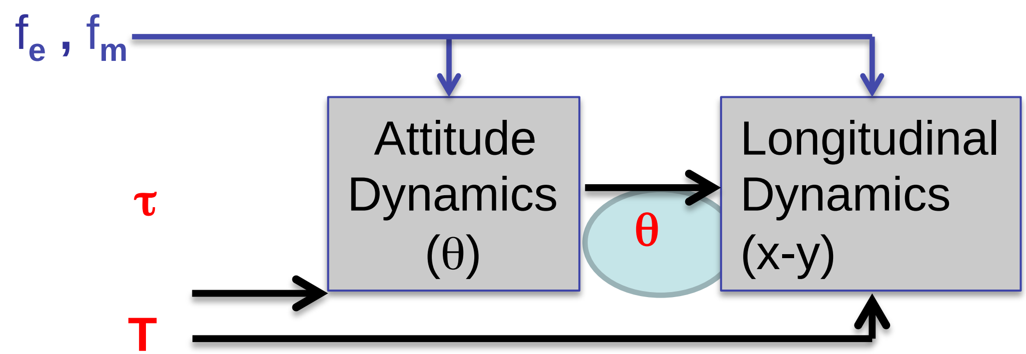
Since disturbances are bounded **small gain** conditions can be enforced to prove stability

Stability results

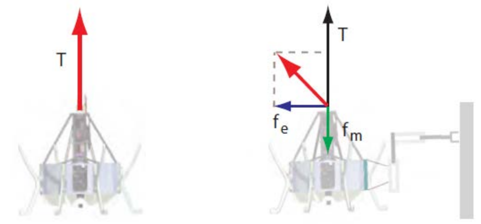


- Free-flight:
  - NOTE: "output tracking" of the UAV c.g. position
    - asymptotic tracking when $d^3/dt^3 \; d_e = 0$
    - practical tracking with arbitrarily small asymptotic gains when $d^3/dt^3 \; d_e \neq 0$
      - the control vector v_c does not compensate for h.o.d. of the manipulator reference

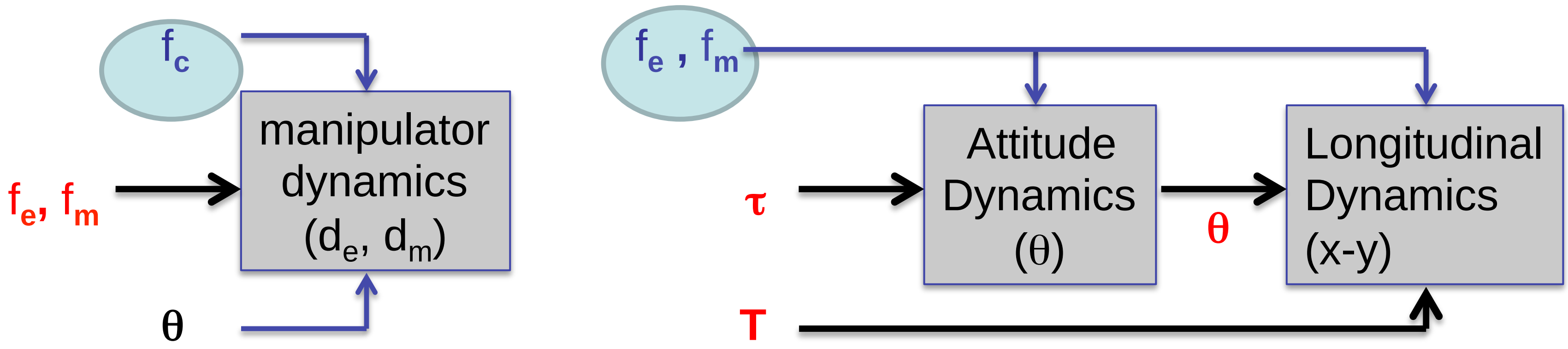




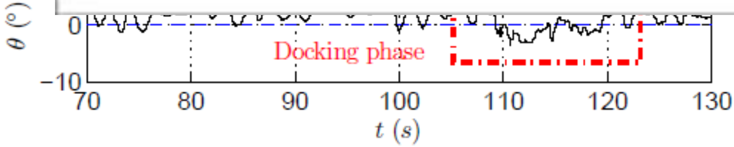
Stability results

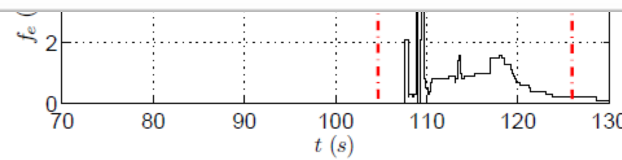


- Physical-interaction:
  - practical tracking
    - it is not possible to cancel the influence of the manipulator since the contact force is not known



Flight tests





Conclusions

- Results
  - new control approach for under-actuated aerial vehicles equipped with robotic manipulators
  - robustness in the presence of unknown contact forces
- Future works
  - force / position control of the end-effector during physical interaction