Robust aerial docking of a ducted fan

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Joint work with Roberto Naldi

AETOS Conference, Université Bordeaux 1

Summary

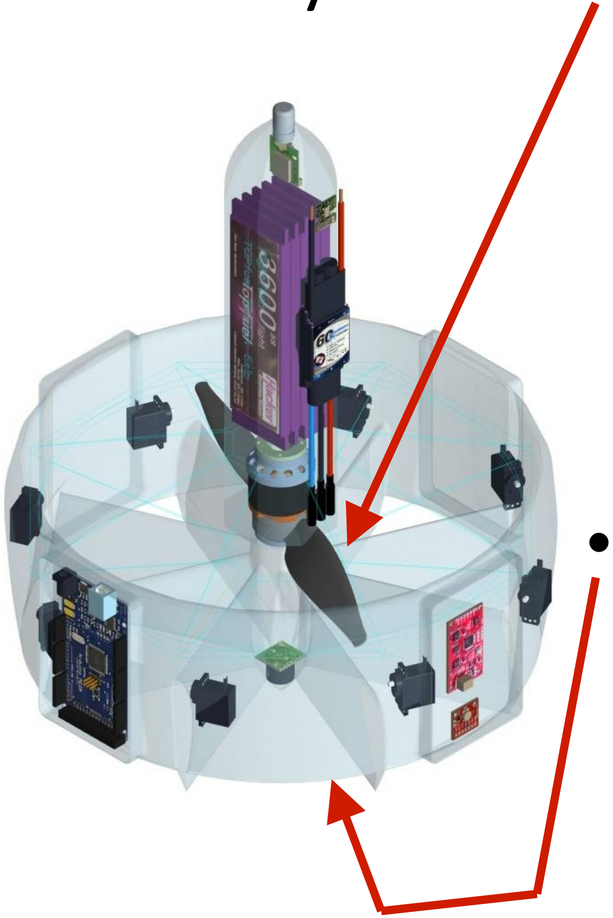
- The CASY Ducted-fan
    - Safe interaction with the environment
    - Efficient fast forward-flight

- Flying robots
    - The European project AIRobots
    - Modeling the UAV interacting with the environment
    - Controlling the flying robots in a docking maneuver

- Ongoing research activities at CASY in the field

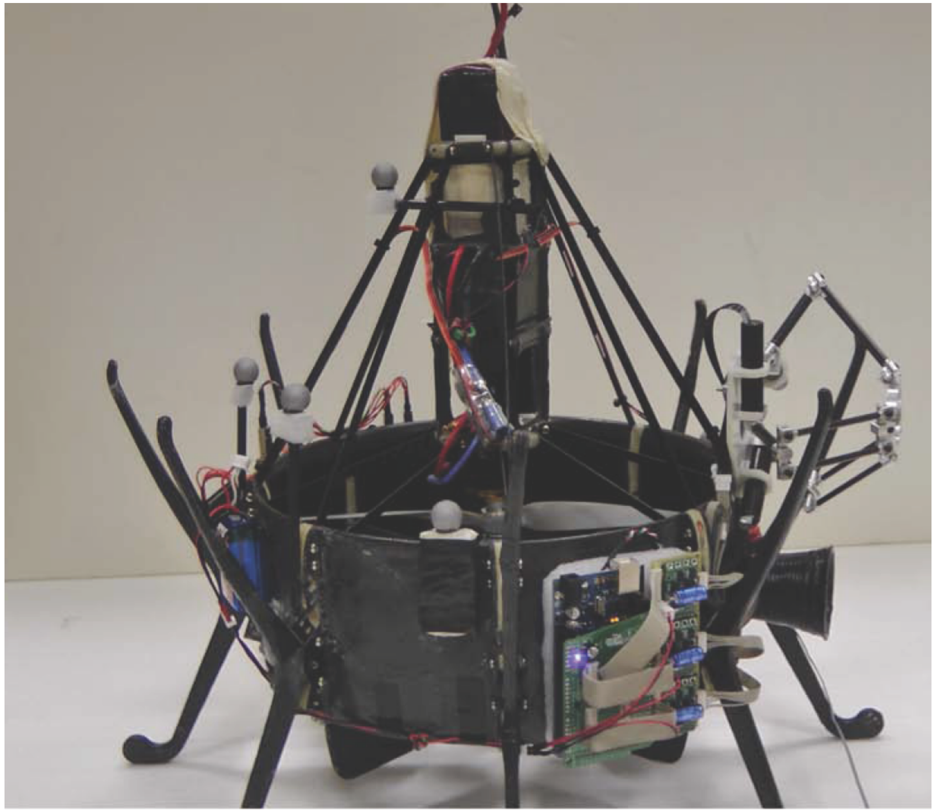
The CASY Ducted Fan

Two subsystems:



- A fixed pitch propeller powered by electric motor
  - Ducted fan structure to
    - Protect the environment from moving parts
    - Improve the efficiency of the propeller
- A set of actuated control surfaces
  - Profiled surfaces driven by a servo controller
    - Counteract engine torque (balancing the yaw momentum)
    - “Vectorize” the thrust generated by the propeller

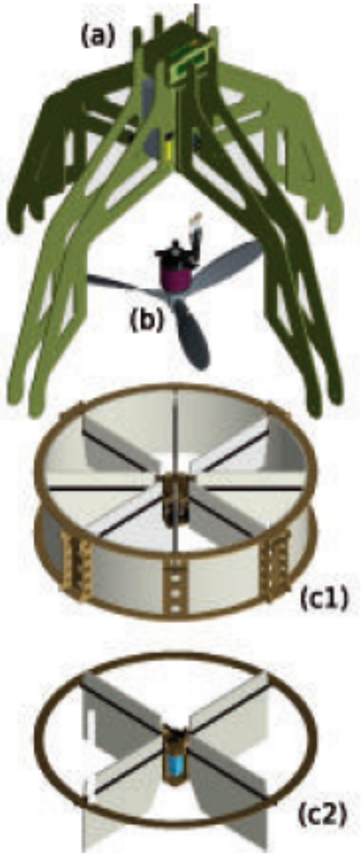
The CASY prototype

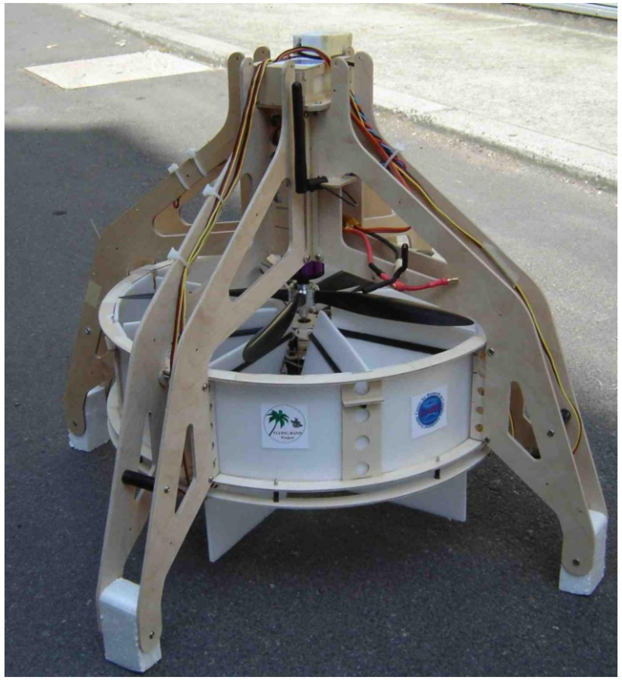


- Diameter: 40cm
- Weight: 1.2 Kg
- Payload: 1 Kg
- Batteries LiPo 5s 3500 mAh
- brushless motor Scorpion SII 3020 (840 Watts)
- Arduino Mega (ATMega 2560 a 18 Mhz) Low-level IO
- AStec Atom board (Intel Atom 1.6 Ghz) for control
- WI-FI 802.11 G, Xbee 900 Mhz for communication

The CASY Ducted Fan

Two-level option:





One-level option:

The CASY Ducted Fan

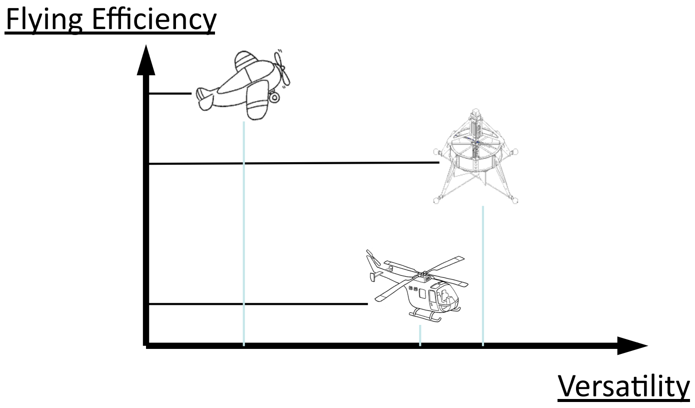
Not New:

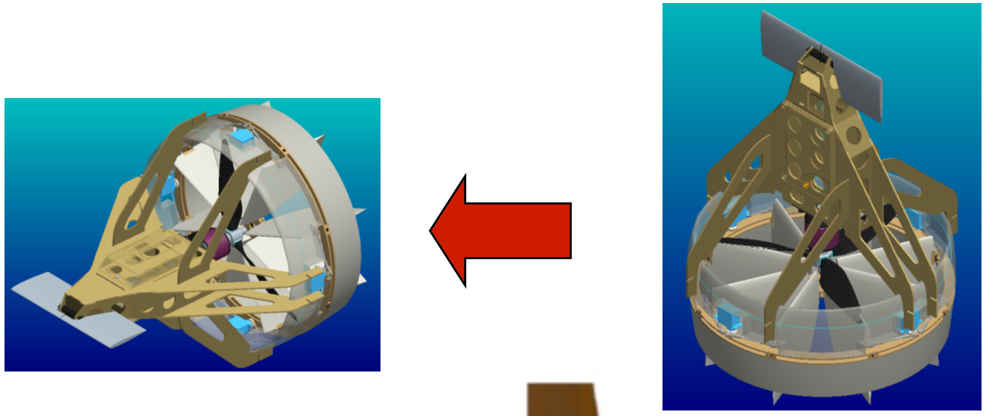
- Caltech Ducted-Fan [A. Jadbabaie et al., 1999] , [J. Yu et al, 1999]
- iSTAR Micro Air Vehicle [L. Lipera et al, 2001], [I. Guerrero et al, 2001] , Allied Aerospace
- GTSpy Ducted-Fan [E. N. Johnson and M. A. Turbe, 2004] Georgia tech
- "Hovereye" [Pflimlin et al., 2004] (supported by BERTIN tech)
- …….

Ducted Fan features

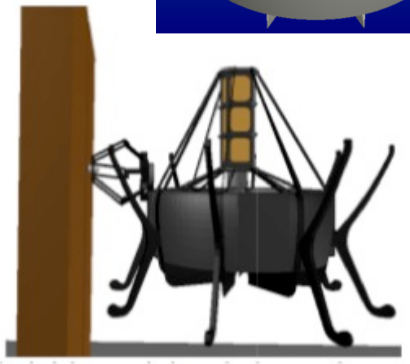
- **Mechanical simplicity**: Obtain the same maneuverability of a helicopter reducing as far as possible the mechanical complexity (No cyclic and collective pitches, stabilizer bar)

- UAV **combining** the positive features of helicopters and fixed-wing





- Ability to **physically interact** with the environment



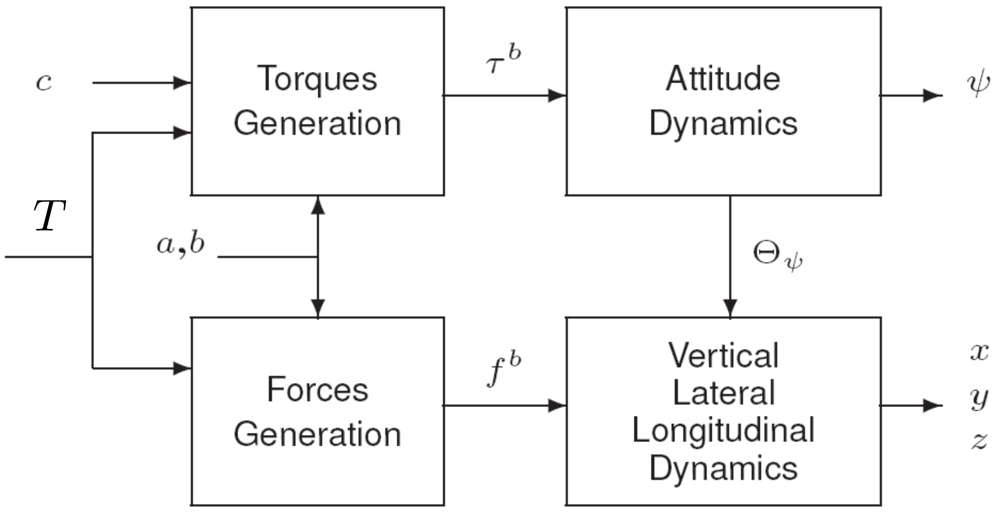
The CASY Ducted Fan: Model

- Rigid body dynamics (Newton-Euler equations)
- Four control inputs $u = \text{col}\begin{pmatrix} T & a & b & c \end{pmatrix}$

Gyroscopic propeller torque $G = \begin{pmatrix} 0 & -I_{rot} & 0 \\ I_{rot} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

$$\begin{aligned} m\ddot{p} &= Rf^b \\ J\dot{\omega} &= -Skew(\omega)J\omega + \underset{\uparrow}{w_{\text{P}}G\omega} + \tau^b \end{aligned}$$

$$R = \begin{pmatrix} C_\psi C_\theta & -S_\psi C_\theta + C_\psi S_\theta S_\phi & S_\phi S_\psi + C_\phi S_\theta C_\psi \\ S_\psi C_\theta & C_\phi C_\psi + S_\phi S_\theta S_\psi & -C_\psi S_\phi + S_\psi S_\theta C_\phi \\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi \end{pmatrix}$$



c

T

a,b

Torques Generation

τ^b

Attitude Dynamics

ψ

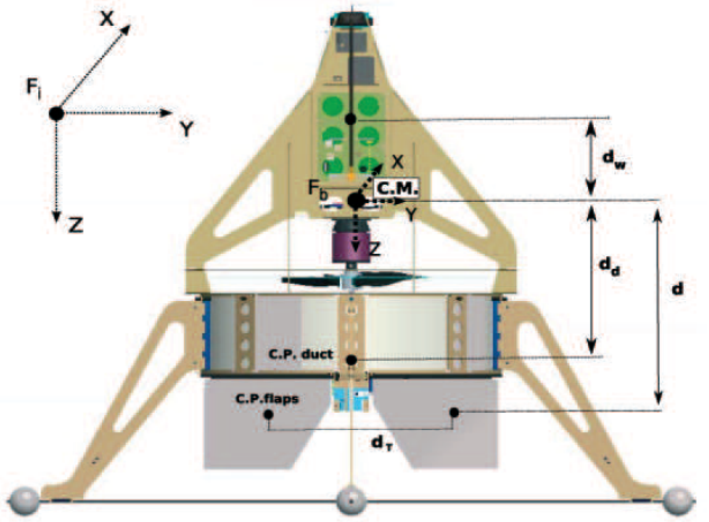
Θ_ψ

Forces Generation

f^b

Vertical Lateral Longitudinal Dynamics

x y z



The CASY Ducted Fan: Control

- Given the four time reference signals (position and orientation around the gravity-axis)
  - $x_r(t)$, $y_r(t)$, $z_r(t)$, $\psi_r(t)$
- design the four control inputs such that, assuming **parametric uncertainties** (arbitrarily large),
  - Track the four reference signals for a possibly large set of initial conditions
  - the ducted-fan does not “overturn”

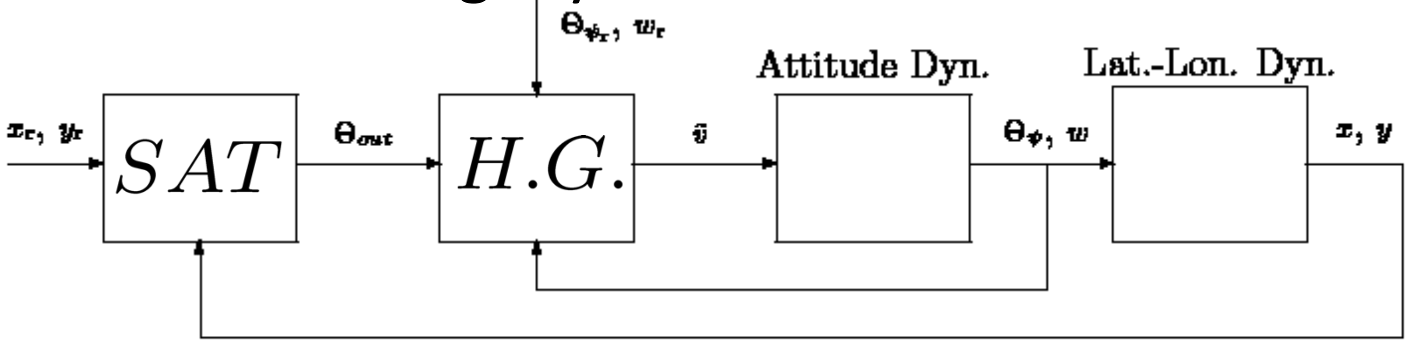
→ Semiglobal and robust

The CASY Ducted Fan: Control

Not surprisingly the control design (and stability proof) is not terribly different from the one of helicopters

- Vertical controller
- Attitude and lateral/longitudinal controller

→ Inner-Outer loop strategy: fast attitude dynamics, slow lat-long. dynamics



Marconi, Naldi, AUTOMATICA , 2008

The CASY Ducted Fan: Control

Vertical controller

$$m\ddot{z} = -T\Psi(\Theta) + mg$$

$$T = \frac{-T' + m_0(g - \ddot{z}_{\rm r})}{C_{\phi_{\rm s}} C_{\theta_{\rm s}}}$$

$$\begin{aligned} T' &= \xi - k_2(\dot{e}_z + k_1 e_z) \\ \dot{\xi} &= -k_2(\dot{e}_z + k_1 e_z) + m_0 \dot{e}_z \end{aligned}$$

Att- Lat- Long controller

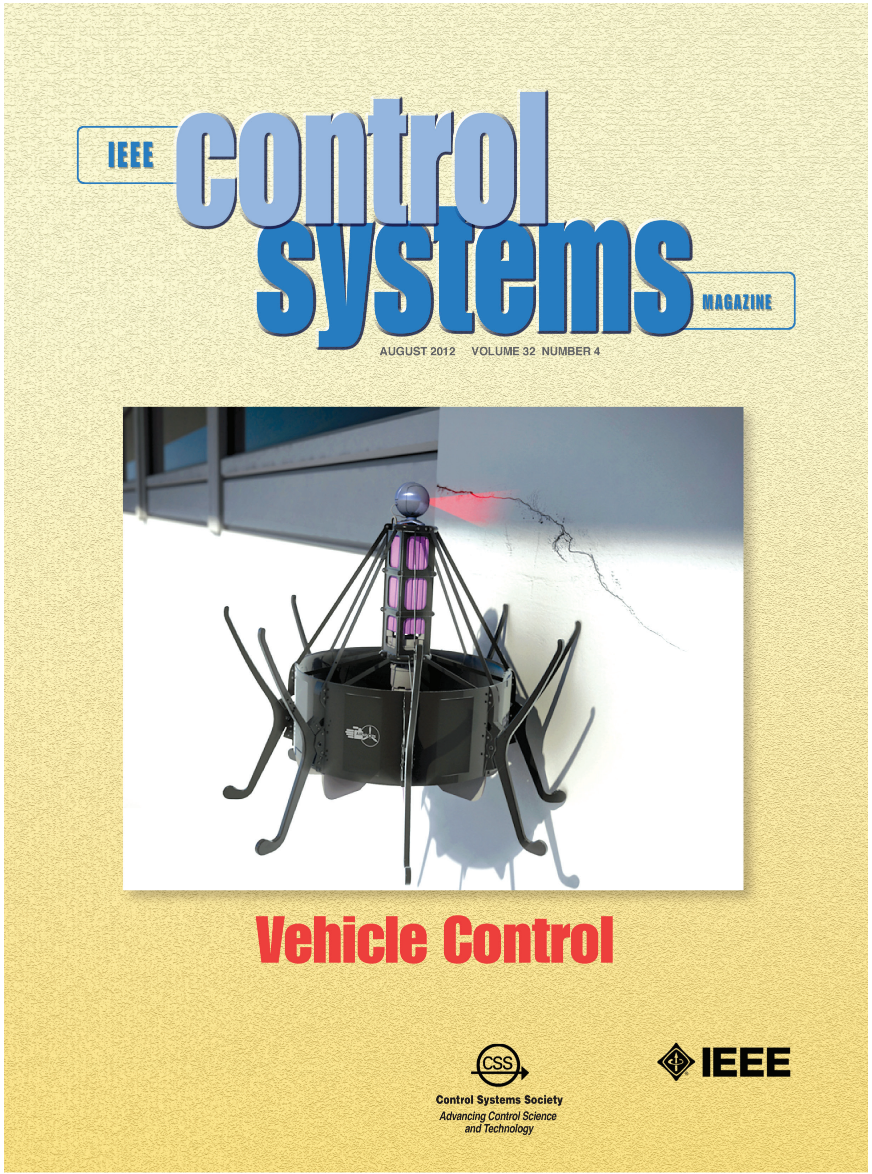
$$\begin{aligned} \Theta_{\rm out} &= \lambda_3 \sigma\left(\frac{K_3}{\lambda_3}\xi_3\right) \\ \xi_3 &:= \begin{pmatrix} \dot{e}_y & \dot{e}_x \end{pmatrix}^{\rm T} + \lambda_2 \sigma\left(\frac{K_2}{\lambda_2}\xi_2\right) \\ \xi_2 &:= \begin{pmatrix} e_y & e_x \end{pmatrix}^{\rm T} + \lambda_1 \sigma\left(\frac{K_1}{\lambda_1}\xi_1\right) \\ \xi_1 &:= \begin{pmatrix} \eta_y & \eta_x \end{pmatrix}^{\rm T} \end{aligned}$$

$$\dot{\eta}_y = e_y \,, \qquad \dot{\eta}_x = e_x \,. \; \dot{\eta}_\psi = \psi - \psi_{\rm r}$$

$$v = A_0^{-1}(T)\left(\tilde{v} - B_0(T)\right) \tag{3.22}$$

$$\begin{aligned} \tilde{v} = {} & -K_P\left(K_D\omega + \begin{pmatrix} \tan\Theta - A(\Theta_\psi)\Theta_{\rm out} \\ \psi + K_\psi \eta_\psi \end{pmatrix}\right) + K_P K_D \omega_{\rm r} + K_P \begin{pmatrix} \tan\Theta_{\rm r} \\ \psi_{\rm r} \end{pmatrix} + \\ & + J_0\dot{\omega}_{\rm r} + \mathrm{Skew}(\omega_{\rm r}) J_0 \omega_{\rm r} - w_{P_{\rm r}} G_0 \omega_{\rm r} \end{aligned}$$

CSM: August issue



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Advancing Control Science and Technology

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Flying Robots

Idea: to employ the “safe interaction” capabilities of the ducted-fan in unconventional scenarios

European Project **AIRobots** (Innovative aerial service robots for remote inspections by contact)

→ FP7, THEME ICT-4-2.1, Cognitive Systems and Robotics

- University of Bologna
- ETH Zurich
- University of Naples
- University of Twente
- Alstom Inspection Robotics

www.airobots.eu

AIRobots: the vision

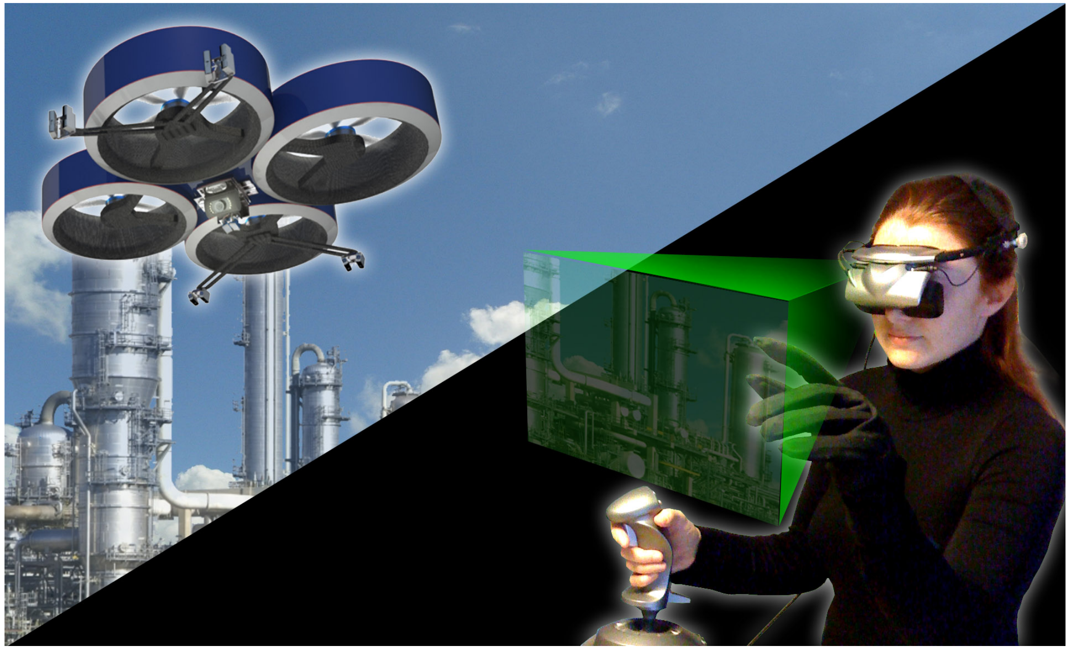
- To develop aerial vehicles able to interact with the human world in order to accomplish typical robotic tasks in air rather than constrained on ground

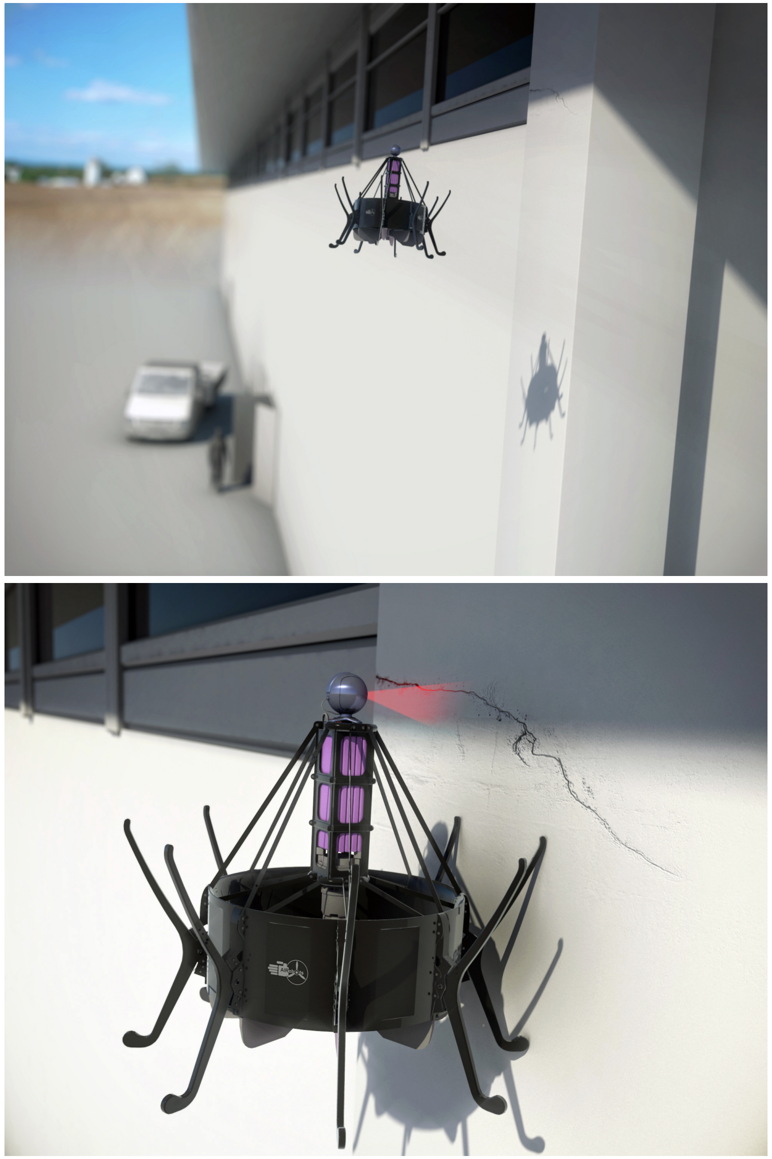
➡ Aerial Service Robotics

- To develop advanced automatic control strategies and “human-in-the-loop” strategies which allow an intuitive tele-operation of the vehicle by means of haptic devices

➡ “Flying hand” of the operator

AIRobots: the vision



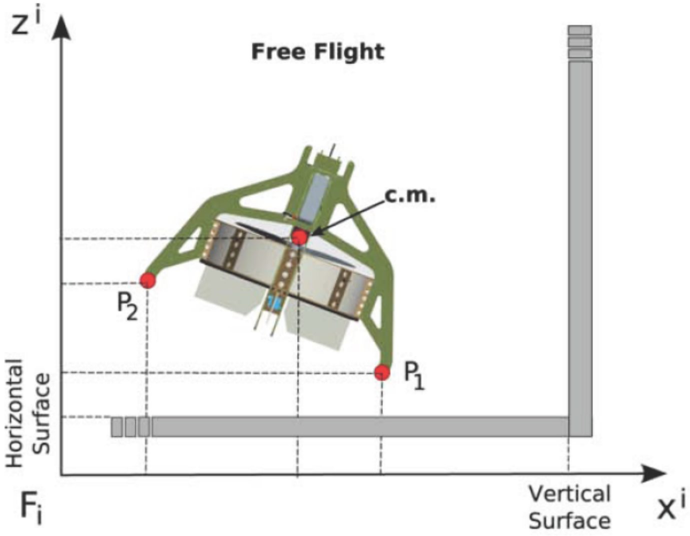


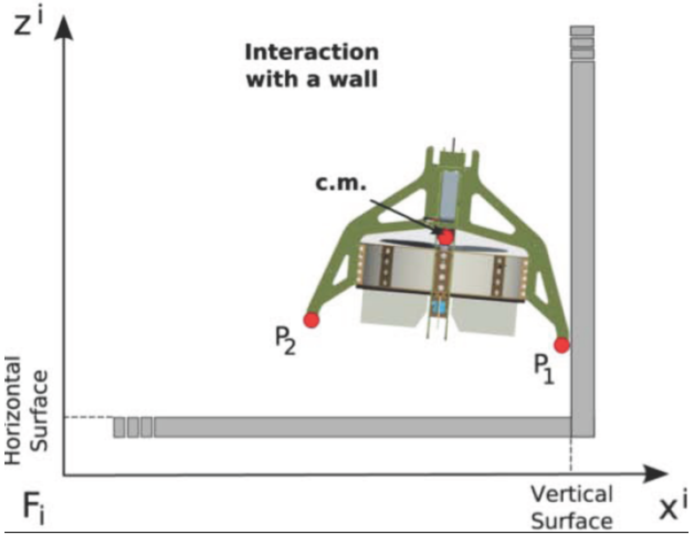
AIRobots: Driving industrial scenarios

Mainly within maintenance industry:

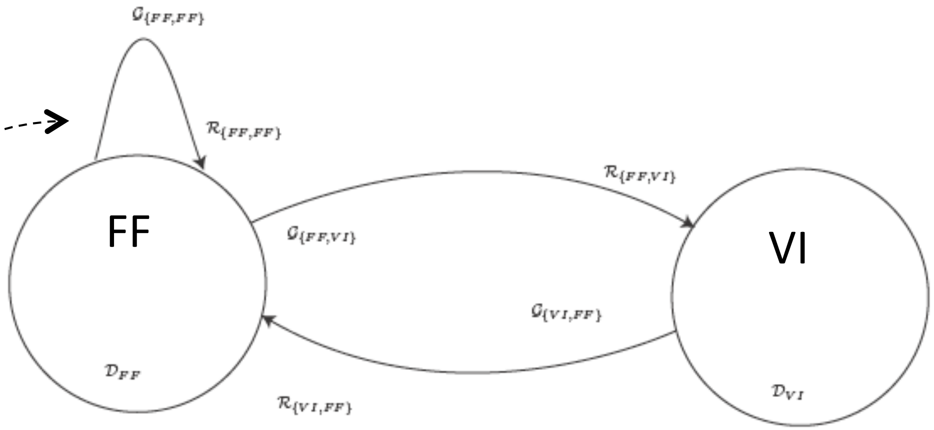
- Inspection of power plant structures (boilers, environmental filters, etc.)
- Inspection of structures within oil and gas industry (large scaled chimneys, flare systems, refining columns, pipelines and pipewebs)
- Cleaning of infrastructures

The docking scenario





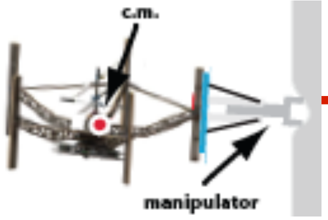
Rebounds



The docking scenario

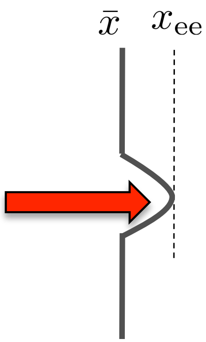
Two different approaches:

UAV without unilateral constraint



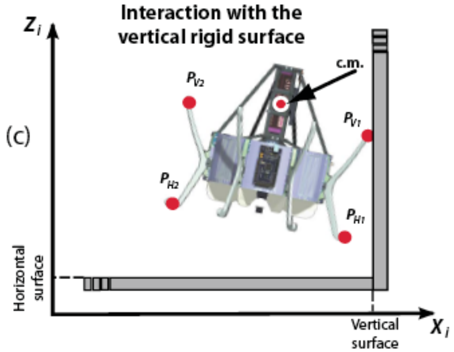
F_c External forces acting on the UAV. Compliant contact model:

$$F_c(x_{\mathrm{ee}}) = \begin{cases} -k_x(x_{\mathrm{ee}} - \bar{x}) & \text{if } x_{\mathrm{ee}} - \bar{x} > 0 \\ 0 & \text{otherwise} \end{cases}$$

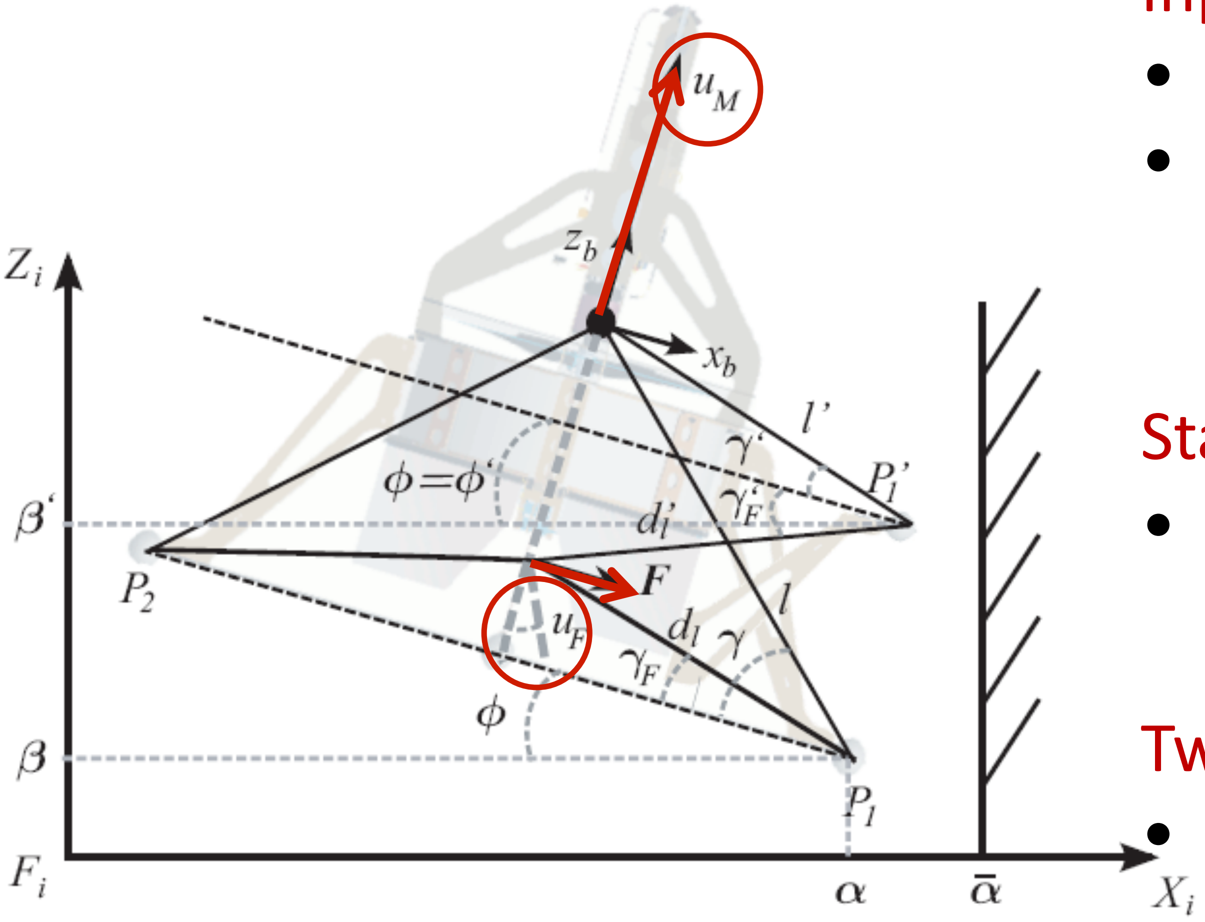


UAV with unilateral constraint

Reduced energy function as a consequence of the constrained dof.



Planar dynamics



$$F = \frac{1}{2}\rho S_{flap} C_L V_i^2 = k_f u_F u_M$$

Inputs:

- **u_M**: propeller thrust (T)
- **u_F**: flap deflection (angle of attack with respect to propeller downwash)

States:

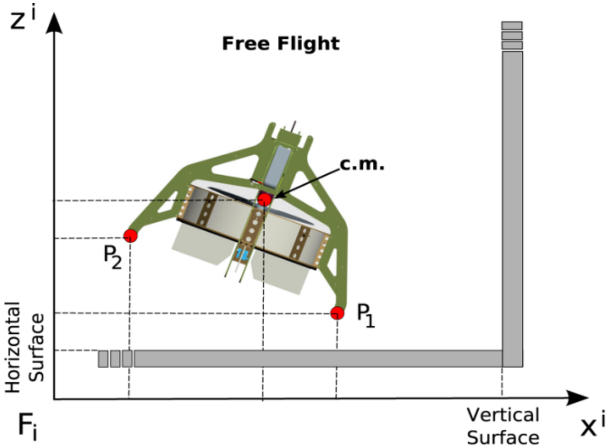
- Position of c.m. (or P1) and the attitude angle ϕ ($R^2 \times S_1$)

Two contact surfaces:

- vertical and horizontal

Contact points: P1, P2, P1'

Modeling: free flight



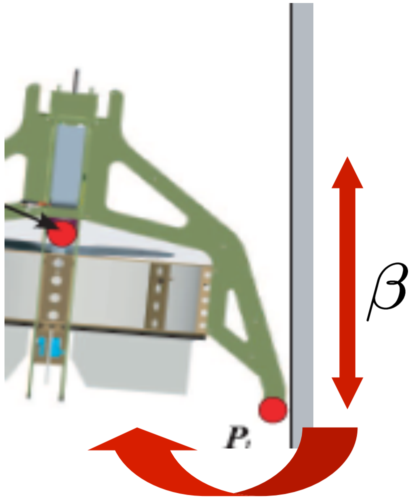
Free Flight (Newton-Euler)

$$\begin{aligned} M\ddot{x}^i &= u_M \sin\phi + k_F u_M u_F \cos\phi \\ M\ddot{z}^i &= u_M \cos\phi - k_F u_M u_F \sin\phi - Mg \\ J\ddot{\phi} &= -k_\tau u_M u_F \end{aligned}$$

→ 6th order model with two control inputs

Modeling: vertical contact

The system can rotate around P$_1$ (pivot) and translate vertically



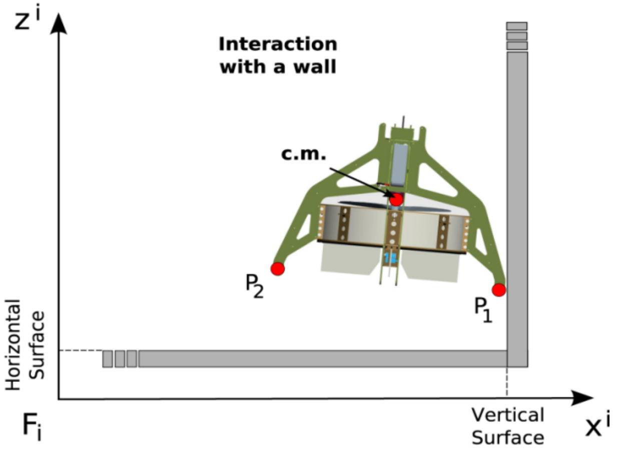
Constraint: $x = z - l\sin(\phi + \gamma)$

- Generalized coordinates: $\begin{cases} \beta = z - l\sin\theta \\ \theta = \phi + \gamma \end{cases}$
- Generalized forces:

$$\begin{aligned} \mathcal{F}_\beta &= -k_F u_M u_F \sin\phi + u_M \cos\phi - \lambda\dot{\beta} \\ \mathcal{F}_\theta &= k_F d_l \sin\gamma_F u_M u_F + l\cos\gamma u_M \end{aligned}$$

- Equation of motion (Lagrangian equations):

$$\begin{aligned} M\ddot{\beta} + Ml\cos\theta\ddot{\theta} - Ml\sin\theta\dot{\theta}^2 + Mg &= \mathcal{F}_\beta \\ Ml\ddot{\beta}\cos\theta + Ml^2\ddot{\theta} + Mgl\cos\theta &= \mathcal{F}_\theta \end{aligned}$$



Modeling: hybrid automaton

It seems natural to describe the overall dynamics in terms of hybrid automaton, namely as a collection of continuous time dynamics and conditions to switch from one state to the other

- Hybrid state: $q \in Q = \{FF, VI, O\}$

Free-Flight, Vertical-Interaction, Overturned

Modeling: hybrid automata

It seems natural to describe the overall dynamics in terms of hybrid automata, namely as a collection of continuous time dynamics and conditions to switch from one state to the other

- Hybrid state: $q \in Q = \{FF, VI, O\}$

Free-Flight, Vertical-Interaction, Overturned

- Domain mapping: $\mathcal{D} : Q \to \mathcal{R}^6 \times \mathcal{R}^2$

For any q in Q, the set of whole state and input space where the state variable and control input u may range in the specific operative mode.

Modeling: hybrid automata

It seems natural to describe the overall dynamics in terms of hybrid automata, namely as a collection of continuous time dynamics and conditions to switch from one state to the other

- Hybrid state: $q \in Q = \{FF, VI, O\}$

Free-Flight, Vertical-Interaction, Overturned

- Domain mapping: $\mathcal{D} : Q \rightarrow \mathcal{R}^6 \times \mathcal{R}^2$

- Edges: $\mathcal{E} \subset Q \times Q$

identifying pairs (q1,q2) such that the transition from the operative mode q1 to q2 is possible under certain condition

Modeling: hybrid automata

It seems natural to describe the overall dynamics in terms of hybrid automata, namely as a collection of continuous time dynamics and conditions to switch from one state to the other

- **Hybrid state**: $q \in Q = \{FF, VI, O\}$

Free-Flight, Vertical-Interaction, Overturned

- **Domain mapping**: $\mathcal{D} : Q \to \mathcal{R}^6 \times \mathcal{R}^2$
- **Edges**: $\mathcal{E} \subset Q \times Q$
- **Guard map**: $\mathcal{G} : \mathcal{E} \to S \subset \mathcal{R}^6 \times \mathcal{R}^2$

For each (q1,q2) in E, identifies the set to which the state and the control inputs u have to belong for the transition from q1 to q2 to be enabled.

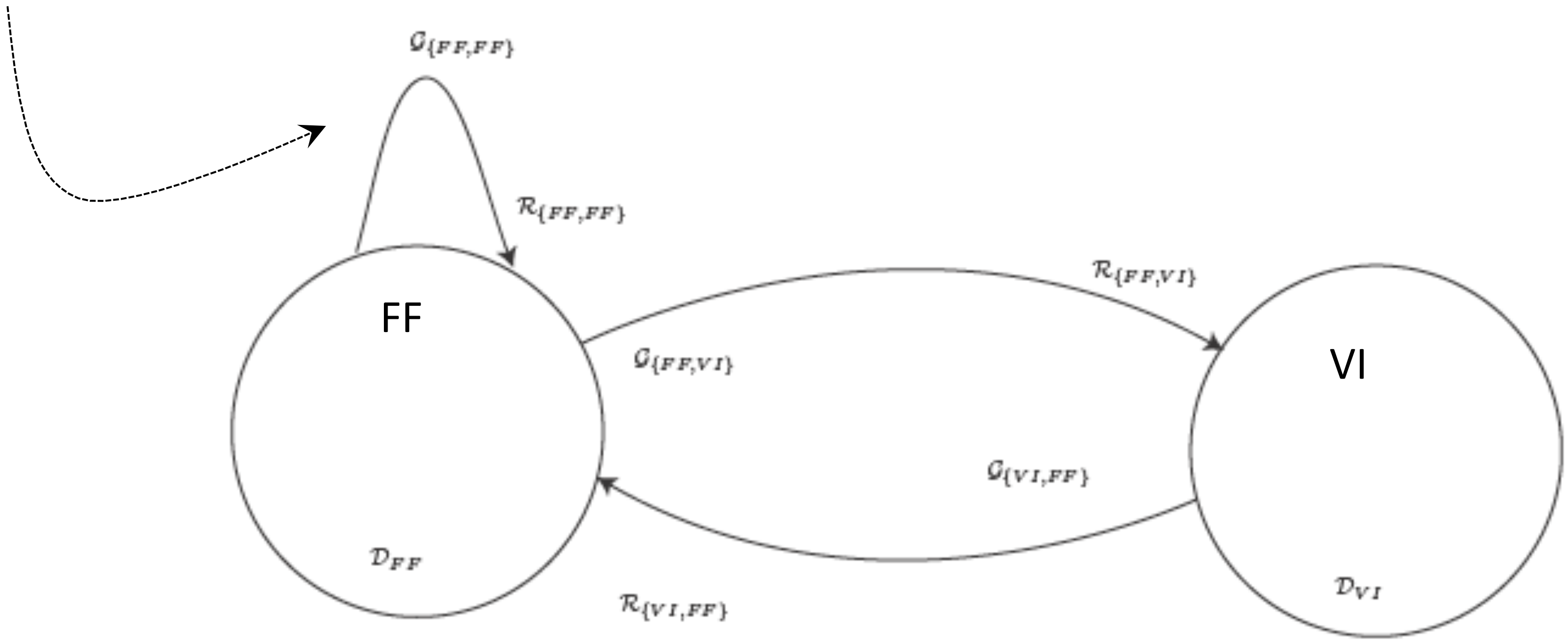
Modeling: hybrid automata

It seems natural to describe the overall dynamics in terms of hybrid automata, namely as a collection of continuous time dynamics and conditions to switch from one state to the other

- Hybrid state: $q \in Q = \{FF, VI, O\}$
  Free-Flight, Vertical-Interaction, Overturned
- Domain mapping: $\mathcal{D} : Q \to \mathcal{R}^6 \times \mathcal{R}^2$
- Edges: $\mathcal{E} \subset Q \times Q$
- Guard map: $\mathcal{G} : \mathcal{E} \to S \subset \mathcal{R}^6 \times \mathcal{R}^2$
- Reset map: $\mathcal{R} : \mathcal{E} \times \mathcal{R}^6 \times \mathcal{R}^2 \to \mathcal{R}^6$

for each (q1,q2) in E and (xi,u) in G (q_1,q_2), identifying the jump of the state variable during the transition from q1 to q2.

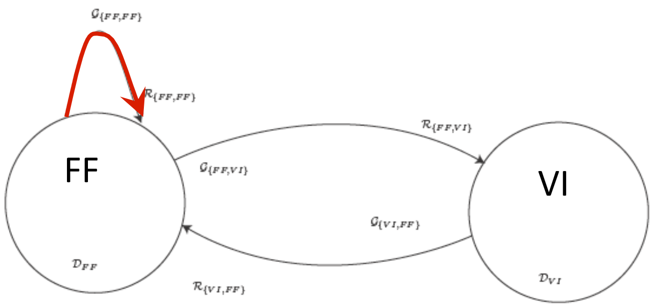
Modeling: hybrid automaton



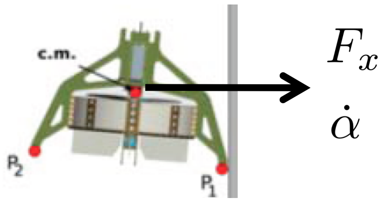
Rebounds

Marconi, Naldi, Gentili, Automatica, 2011

Impact modeling



- Impact theory of rigid bodies
- Coefficient of restitution c_R:
  - dimensionless coefficient in [0,1] relating the velocity of the contact point before and after the impact
  - totally inelastic/elastic impacts $c_R = 0\,,\ c_R = 1$
  - $C_R(F_x, \dot{\alpha})$:
    - F_x high, $\dot{\alpha}$ small $\Longrightarrow c_R \to 0$
    - F_x small, $\dot{\alpha}$ high $\Longrightarrow c_R \to 1$



- Guard map:

$$\mathcal{G}(\{FF,FF\}) = \{(\xi,u) \in \mathcal{D}(FF)\ :\ F_X \geq 0,\, \alpha \geq \bar{\alpha},\, c_R(F_X,\dot{\alpha}) > 0\}$$

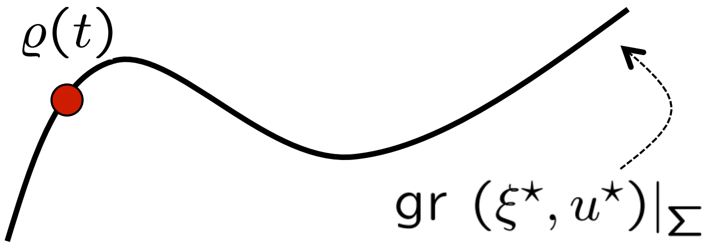
- Reset map: energy considerations

Controlling the flying robot

The control architecture rests upon a path-following strategy

The reference maneuver is defined as $(\xi^\star(\varrho(t)),\, u^\star(\varrho(t)))$

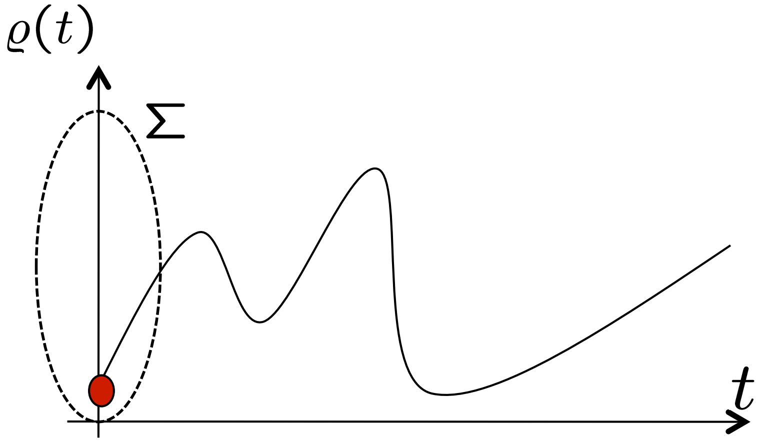
$$\frac{d\xi^\star(\varrho(t))}{d\varrho}\dot{\varrho}(t) = f(q, \xi^\star(\varrho(t)), u^\star(\varrho(t)))$$



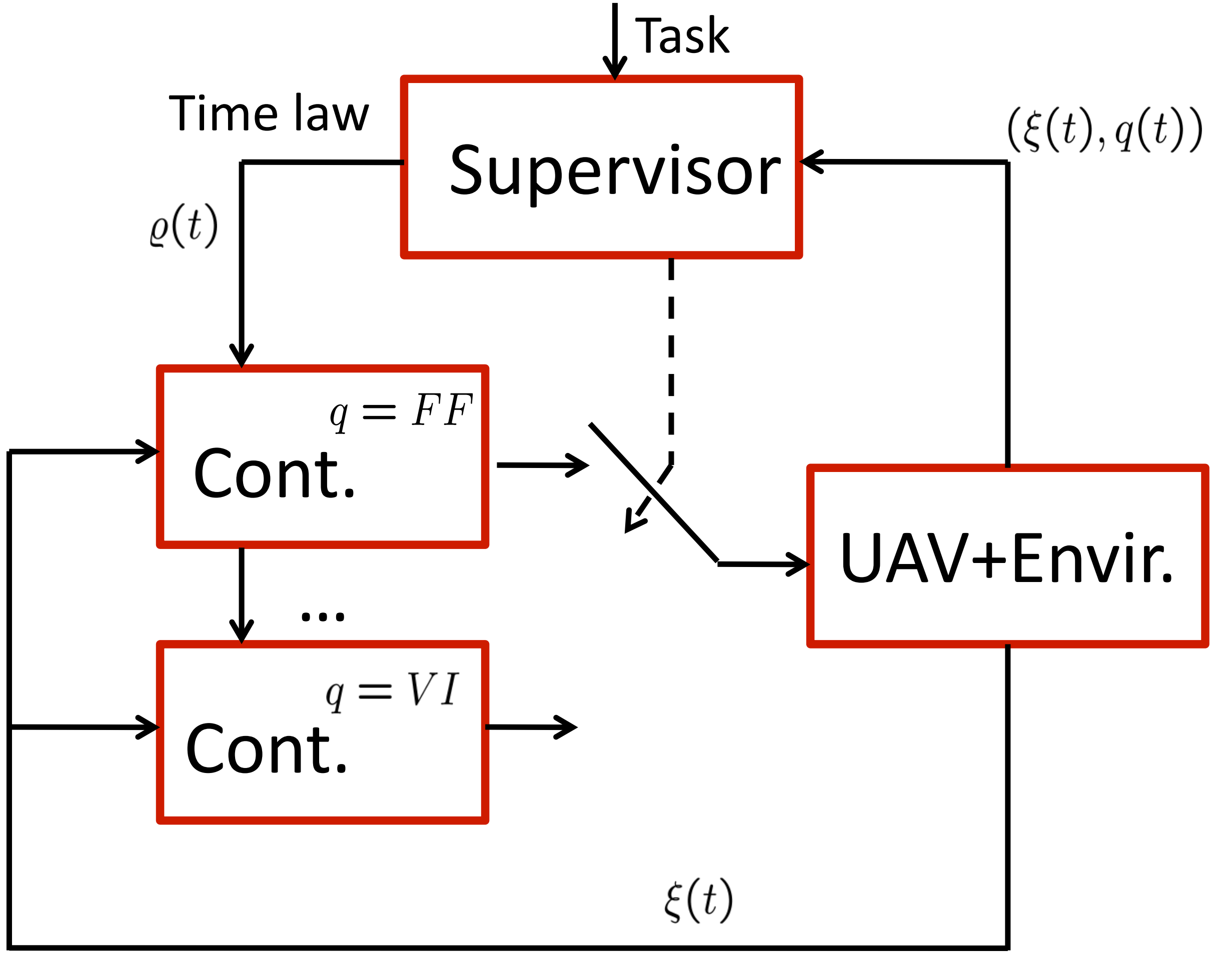
- Time law $\varrho(t) \in \Sigma$

- Geometric path

$$\text{gr } (\xi^\star, u^\star)|_\Sigma := \{(\xi', u') \in \mathcal{D}(q) \ : \ (\xi', u') = (\xi^\star(\varrho), u^\star(\varrho)) \, , \ \varrho \in \Sigma\}$$



Controlling the flying robot

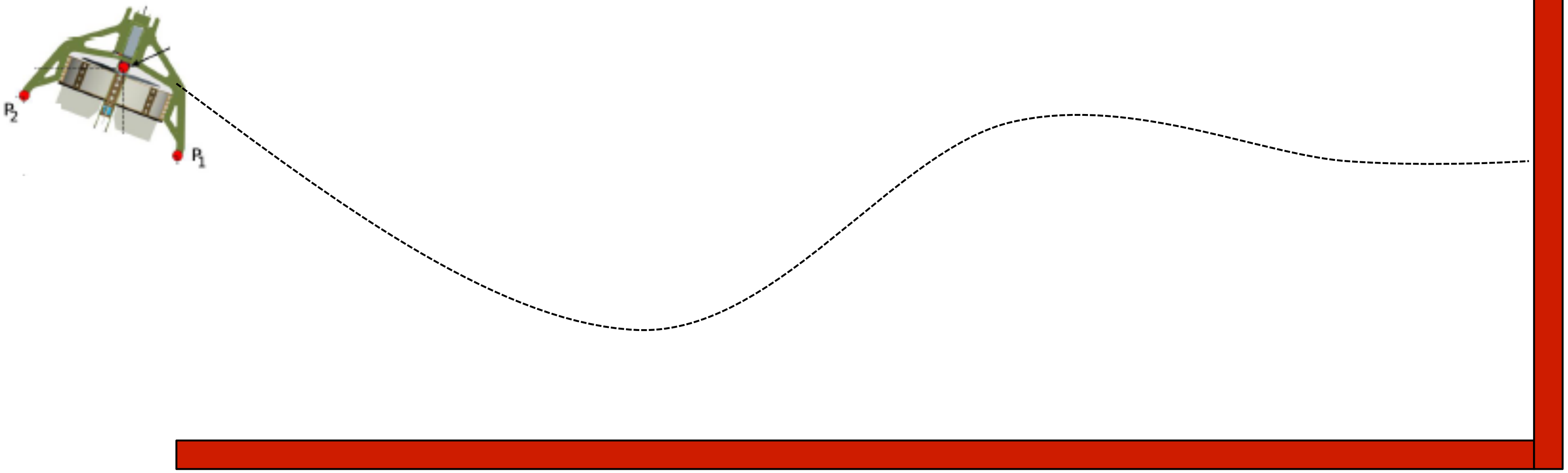


The resulting control architecture has a hierarchical structure with a bunch of low-level controllers and supervisor setting the appropriate time law according to the desired task

Robust reference maneuvers

The first issue is to design robust maneuvers whose practical (and not perfect) tracking does not generate unwanted switches between operative modes in the actual motion of the plant.

The case of a docking maneuver

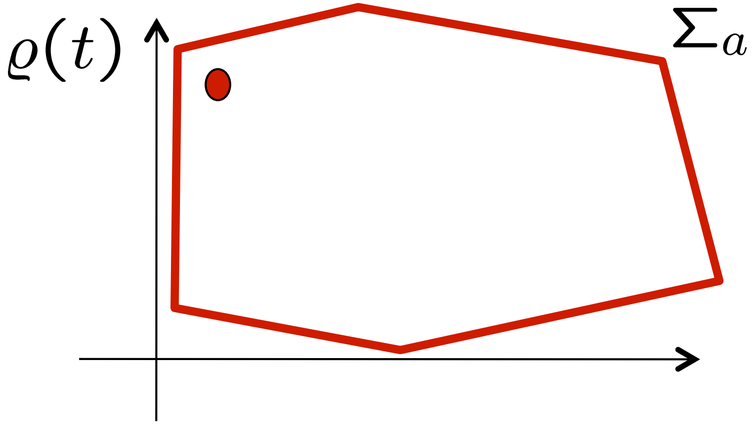


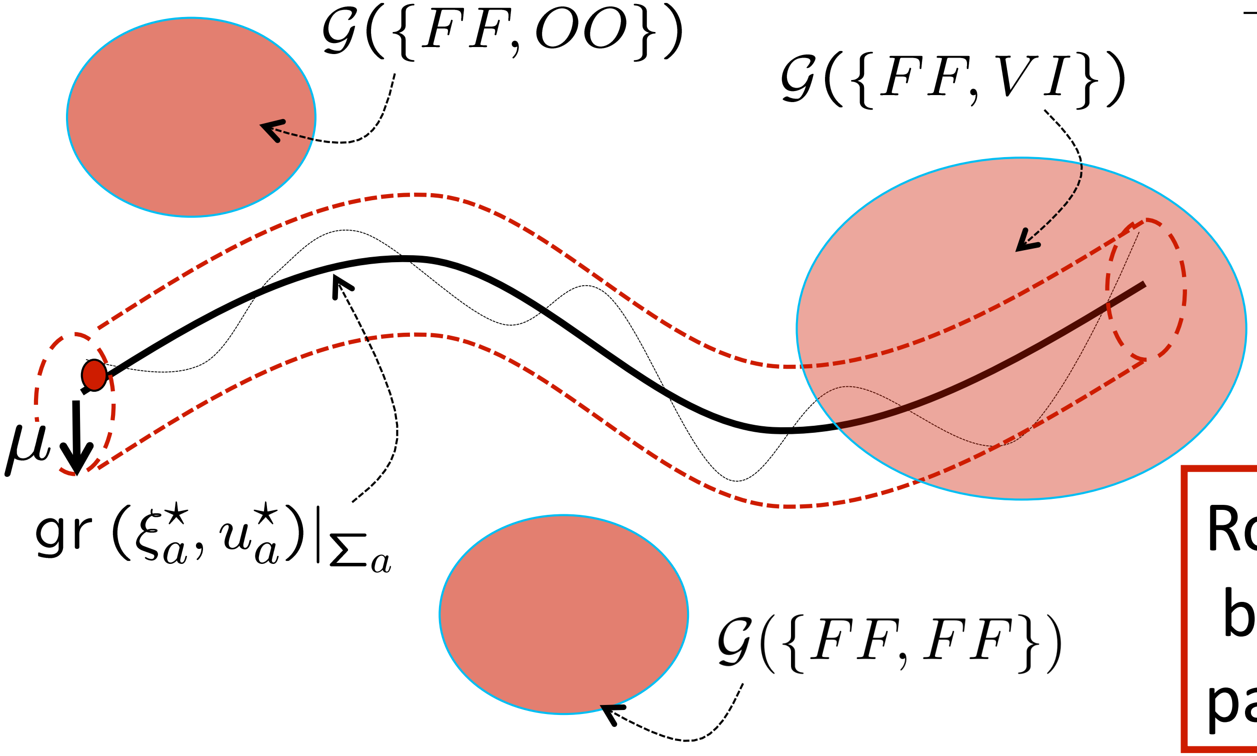
Robust reference maneuvers

Design $(\xi_a^\star(\varrho), u_a^\star(\varrho))$ s.t.

$$\frac{d\xi_a^\star(\varrho(t))}{d\varrho}\dot{\varrho} = f(FF, \xi_a^\star(\varrho), u_a^\star(\varrho))$$

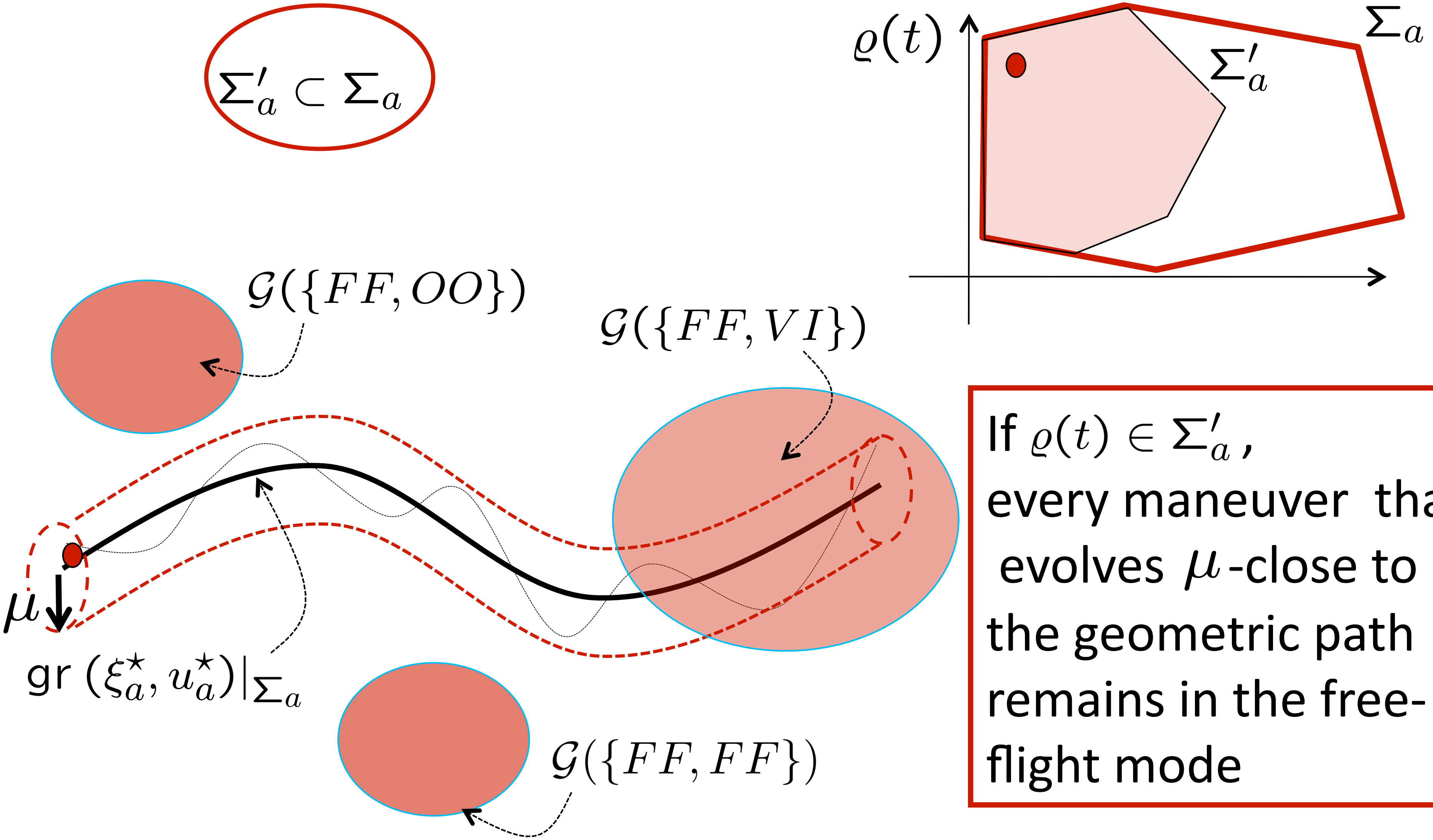
$$\varrho(t) \in \Sigma_a$$





Robustness quantified by means of a design parameter μ

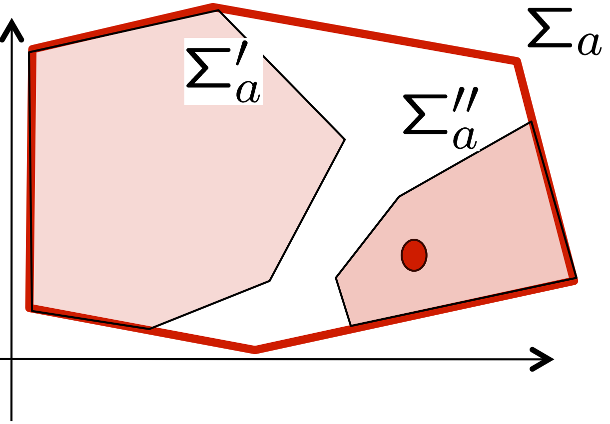
Robust reference maneuvers

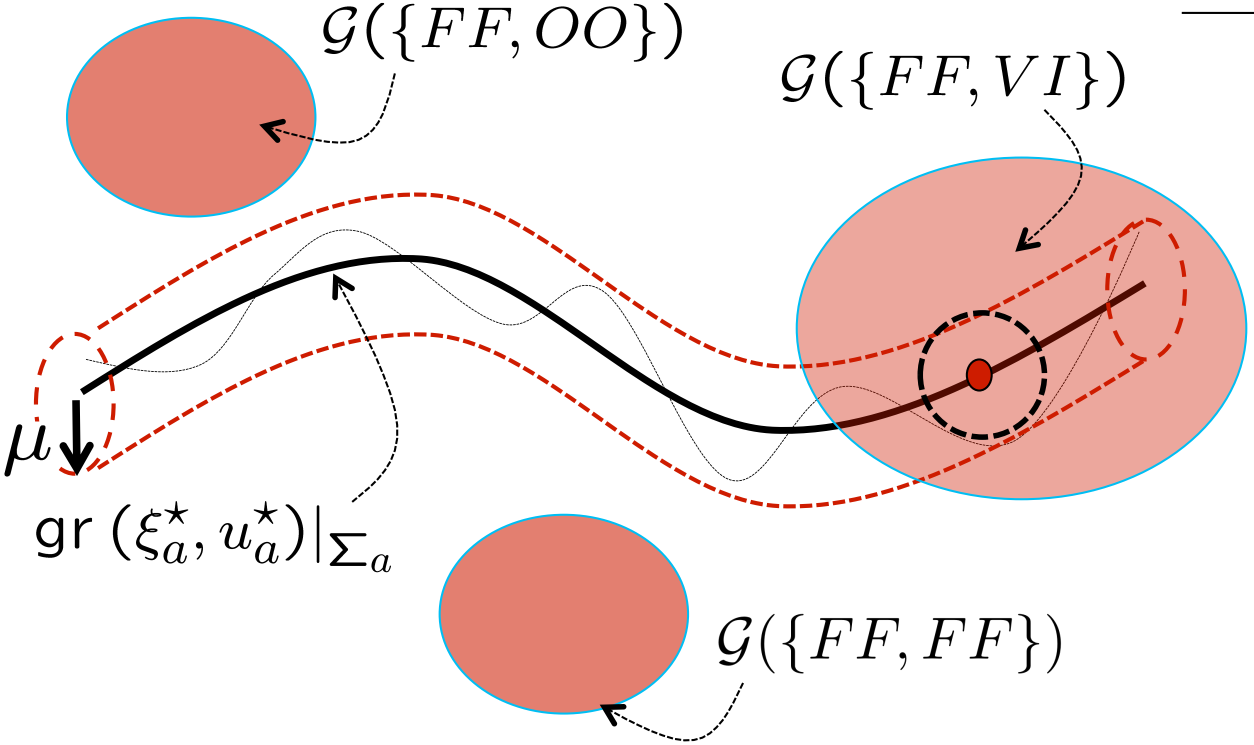


If $\varrho(t) \in \Sigma'_a$, every maneuver that evolves μ-close to the geometric path remains in the free-flight mode

Robust reference maneuvers

$\Sigma_a'' \subset \Sigma_a$





If $\varrho(t) \in \Sigma_a''$, every maneuver that evolves μ-close to the geometric path is within the guard set of interest

Robust reference maneuvers

$$\left(\mathrm{gr}\,(\xi_a^\star, u_a^\star)|_{\Sigma_a} + \mathcal{B}_\mu\right) \bigcap \left(\bigcup_{\{FF,q\}\in\mathcal{E}\setminus\{FF,VI\}} \mathcal{G}(\{FF,q\}) \right) = \emptyset\,;$$

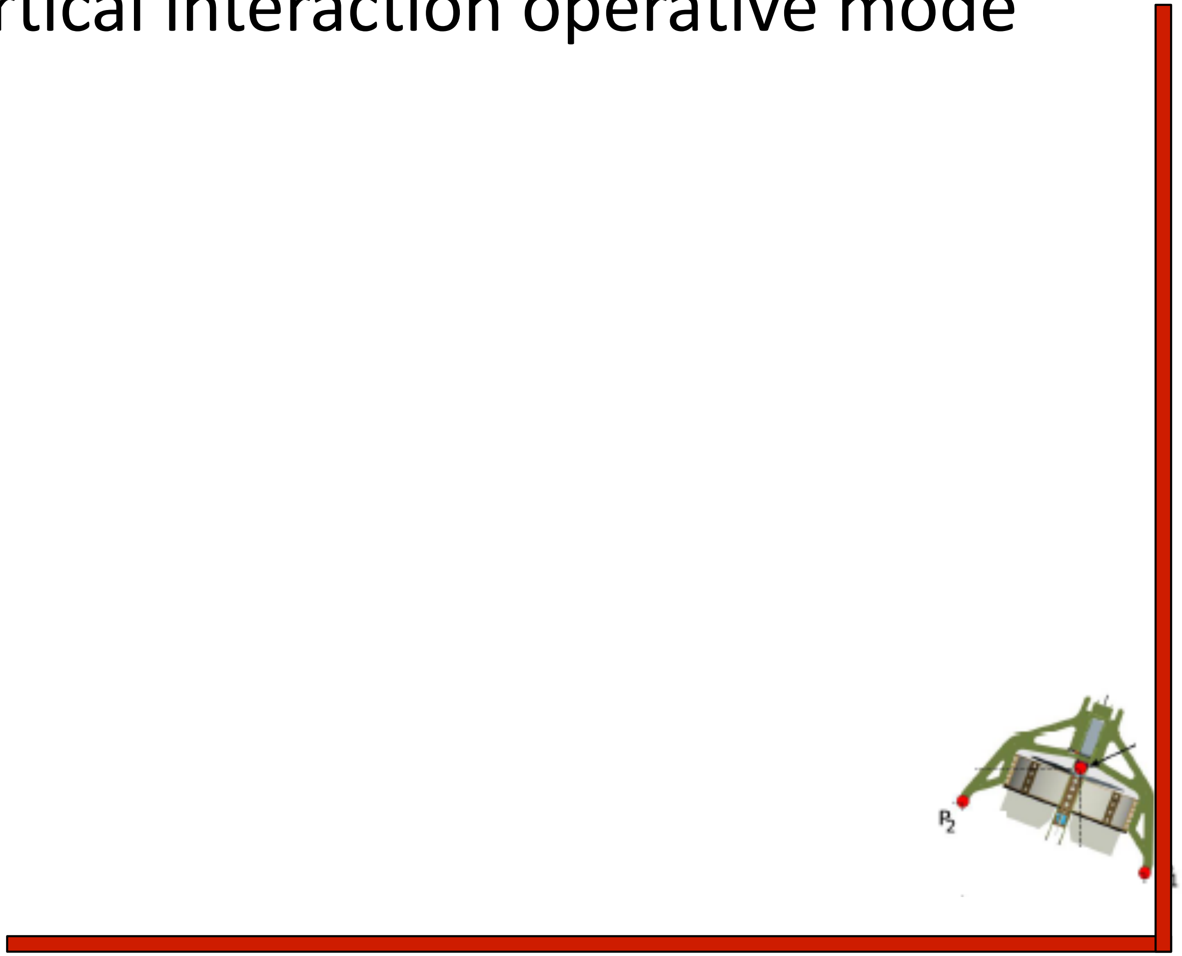
$$\left(\mathrm{gr}\,(\xi_a^\star, u_a^\star)|_{\Sigma'_a} + \mathcal{B}_\mu\right) \bigcap \left(\bigcup_{\{FF,q\}\in\mathcal{E}} \mathcal{G}(\{FF,q\}) \right) = \emptyset\,;$$

$$\left(\mathrm{gr}\,(\xi_a^\star, u_a^\star)|_{\Sigma''_a} + \mathcal{B}_\mu\right) \subset \mathcal{G}(\{FF,VI\})$$

Mathematically → dynamic inversion of the system

Robust reference maneuvers

Similar considerations can be done for maneuvers in the vertical interaction operative mode

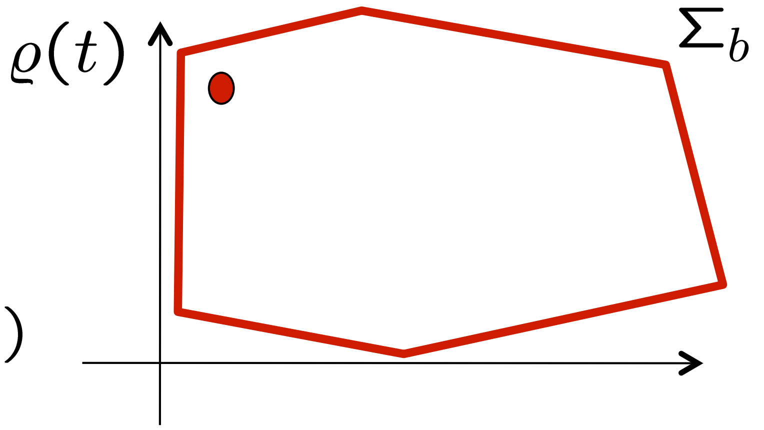


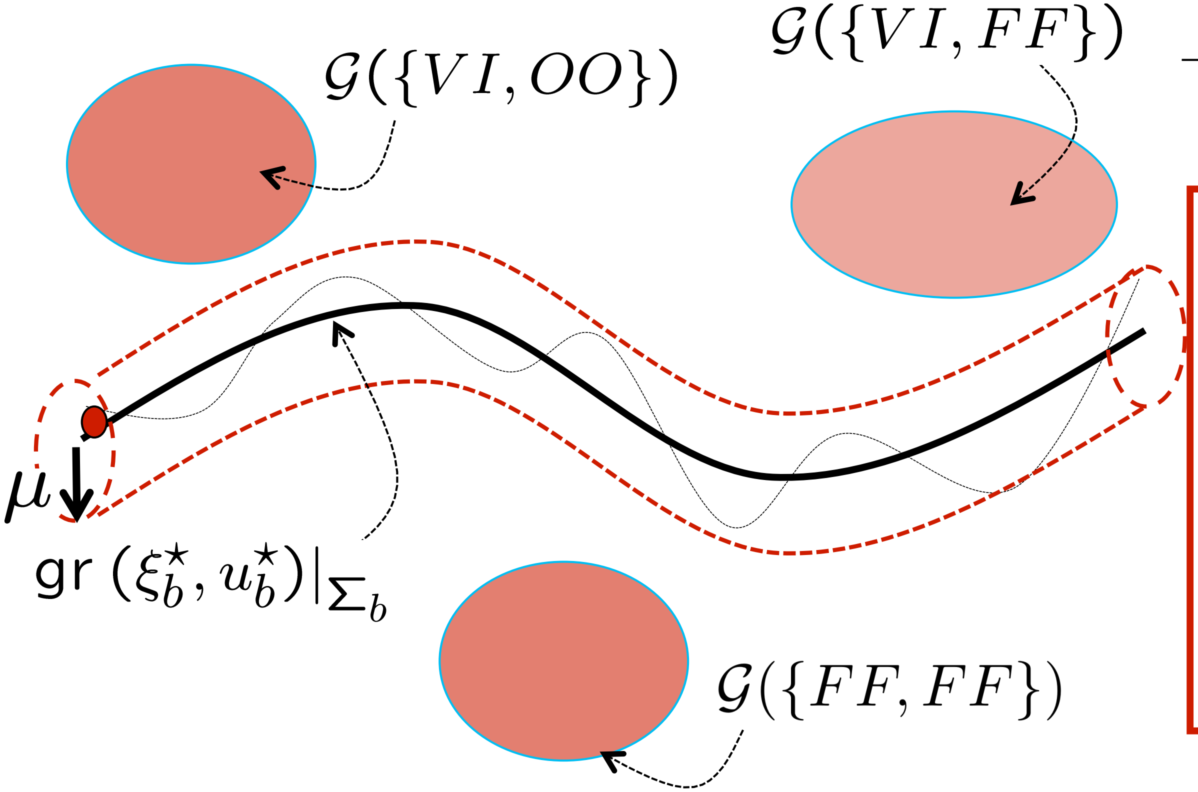
Robust reference maneuvers

Design $(\xi_b^\star(\varrho), u_b^\star(\varrho))$ s.t.

$$\frac{d\xi_b^\star(\varrho(t))}{d\varrho}\dot{\varrho} = f(VI, \xi_b^\star(\varrho), u_b^\star(\varrho))$$

$$\varrho(t) \in \Sigma_b$$





If $\varrho(t) \in \Sigma_b$ every maneuver that evolves μ-close to the geometric path remains in the vertical interaction mode

Robust reference maneuvers

“Concatenation condition” between the two maneuvers asking that the reset state value characterizing the docking phase is sufficiently close to the reference state maneuver for an appropriate choice of the time-law.

For all $(\xi, u) \in \left(\text{gr}\, (\xi_a^\star, u_a^\star)|_{\Sigma_a} + \mathcal{B}_\mu\right) \cap \mathcal{G}(\{FF, VI\})$

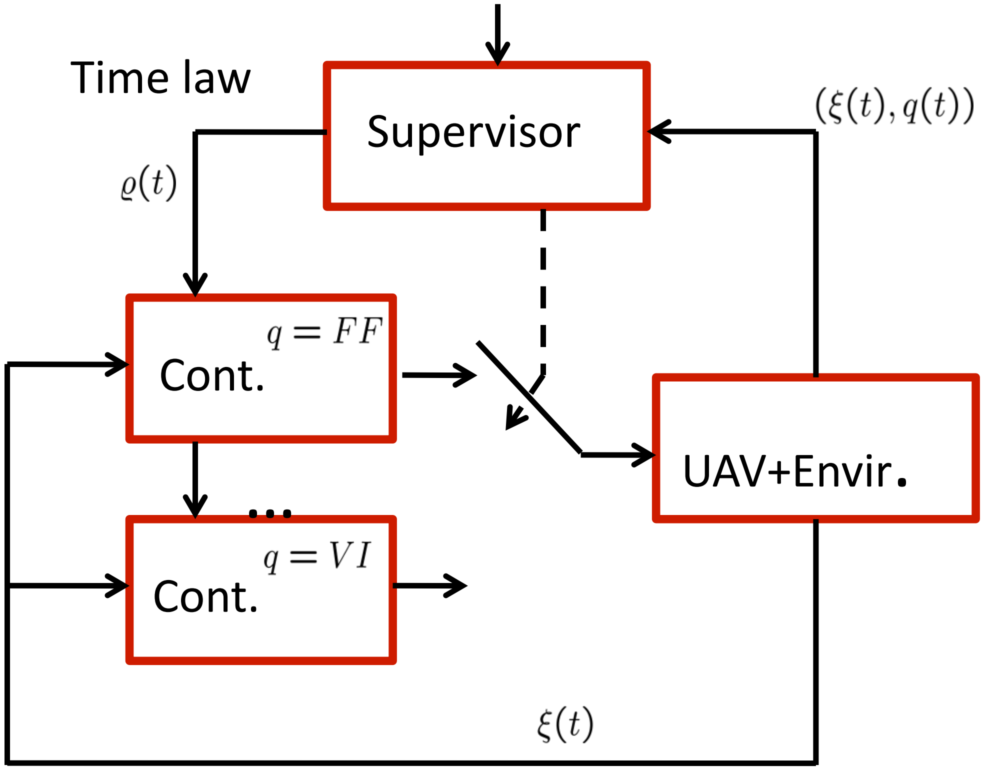
there exists $\varrho \in \Sigma_b$ such that

$|\mathcal{R}(\{FF, VI\}, (\xi, u)) - \xi_b^\star(\varrho)|$ sufficiently small

Control design

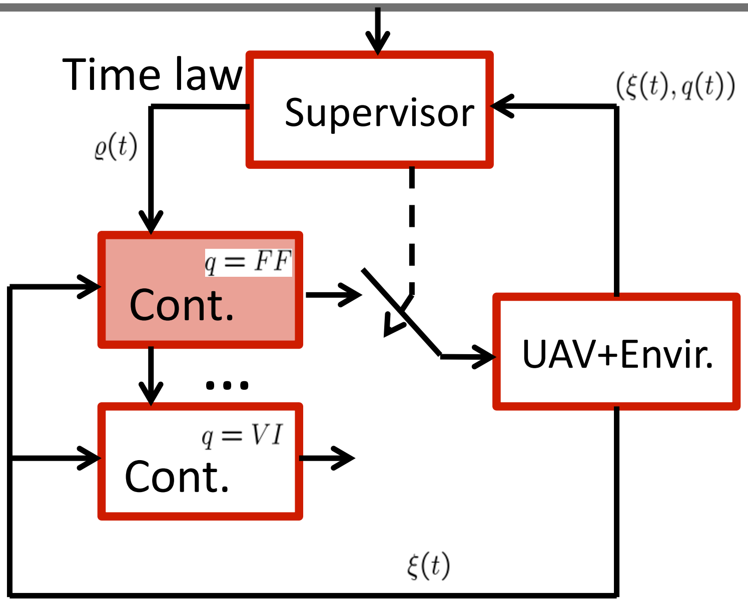
The "low-level" control laws depend on specific reference maneuvers and are parameterized by $\varrho(t)$

The stability properties of the controllers are "uniform" in $\varrho(t) \in \Sigma$ with Σ a given compact set.



➡ This allows, in the selection of the supervisor strategy, to freely choose the most appropriate $\varrho(t) \in \Sigma$ to accomplish the desired task without re-design of the controllers.

FF Control Design



Mix of feedforward and feedback terms

Inner-outer loop strategy

$$u_M(\varrho) = \frac{1}{\cos\theta}\left(u_M^\star(\varrho)\cos\theta^\star(\varrho) - k_1\tilde{z} + k_2\dot{\tilde{z}}\right)$$

$$u_F(\varrho) = \frac{1}{u_M(\varrho)}\left[u_M^\star(\varrho)u_F^\star(\varrho) + K_P\left(K_D\dot{\tilde{\theta}} + \tan(\tilde{\theta} + \theta^\star(\varrho)) - \tan\theta^\star(\varrho) + \theta_{\text{out}}\right)\right]$$

$$\tilde{z} := z - z^\star(\varrho)\,, \quad \dot{\tilde{z}} := \dot{z} - \dot{z}^\star(\varrho)\,, \quad \tilde{\theta} := \theta - \theta^\star(\varrho)\,, \quad \dot{\tilde{\theta}} := \dot{\theta} - \dot{\theta}^\star(\varrho)\,,$$

$$\theta_{\text{out}} = \lambda_2\sigma\left(\frac{K_2}{\lambda_2}\eta\right) \quad \eta := \dot{\tilde{x}} + \lambda_1\sigma\left(\frac{K_1}{\lambda_1}\tilde{x}\right) \quad \tilde{x} := x - x^\star(\varrho)\,, \ \dot{\tilde{x}} := \dot{x} - \dot{x}^\star(\varrho)$$

FF Control Design

$$\dot{\xi} = f(FF, \xi, u) + \delta_{FF}(\varrho)$$

Effect of neglected Dynamics (drag forces)

Proposition. Let Σ be a given compact set and $|\theta(0)| \leq \bar{\theta} < \pi/2$. Then there exists a tuning of the control law and, for all $\mu > 0$, a $\Delta_{FF,0}, \Delta_{FF,d} > 0$ such that if

$$|\xi(0) - \xi^\star(\varrho(0))| \leq \Delta_{FF,0}\,, \qquad |\delta_{FF}(\cdot)|_\infty \leq \Delta_{FF,d}$$

Then

$$\left| \begin{pmatrix} \xi(t) \\ u(t) \end{pmatrix} - \begin{pmatrix} \xi^\star(\varrho(t)) \\ u^\star(\varrho(t)) \end{pmatrix} \right| \leq \mu$$

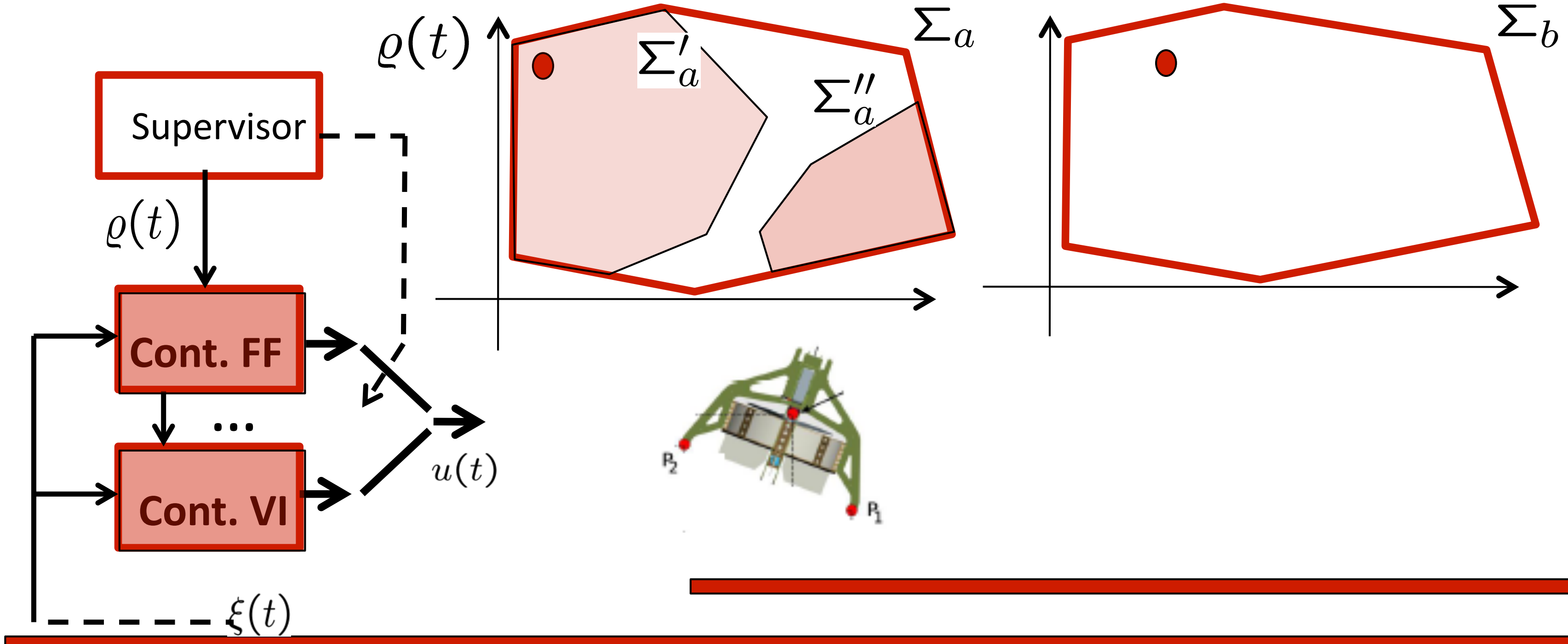
for all $t \geq 0$ and for all smooth $\varrho(t) \in \Sigma$.

ISS and Lyapunov arguments

Similar results for the others operative modes

Supervisory design

With the notion of robust maneuvers and the previous result in hand, the design of the supervisor boils down to select appropriate smooth time-laws and to switch the appropriate controller according to the actual operative mode



Supervisory design

REMARKS

- The previous framework lends it self to handle possible uncertainties on the environment (guard sets, reset map, …)

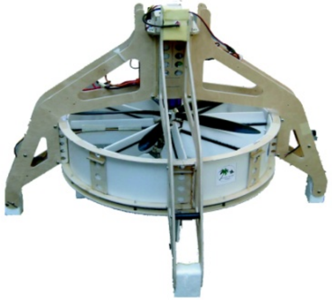
- The supervisor can handle possible rebounds while docking the surface (by properly selecting time-laws)

- L. Marconi, R. Naldi, L. Gentili, “Modeling and control of a flying robot interacting with the environment”, AUTOMATICA 2011

An overview of ongoing research activities in the field at CASY

Transition Hovering-Forward Flight

- V/STOL: Vertical/Short Take-Off and Landing
  - Combine the flight qualities of a VTOL aircraft (e.g. a helicopter) with the ones of a fixed-wing aircraft (e.g. an airplane)
    - maneuverability (VTOL)
    - flight endurance (FW)
    - hovering (VTOL)
    - high speed flight (FW)



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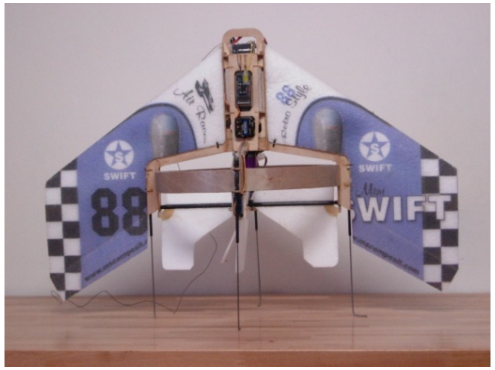
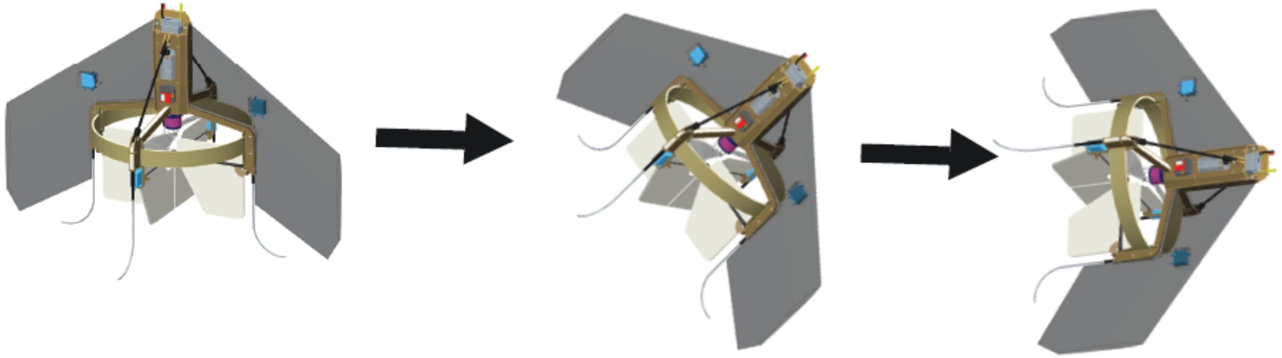


Transition Hovering-Forward Flight

- Goal: change of the attitude allows one to achieve more efficient level flight starting from a hovering (low speed) flight



  - Computation of a transition maneuver: trajectory of system state and input

    R. Naldi, L. Marconi, AUTOMATICA, 2010

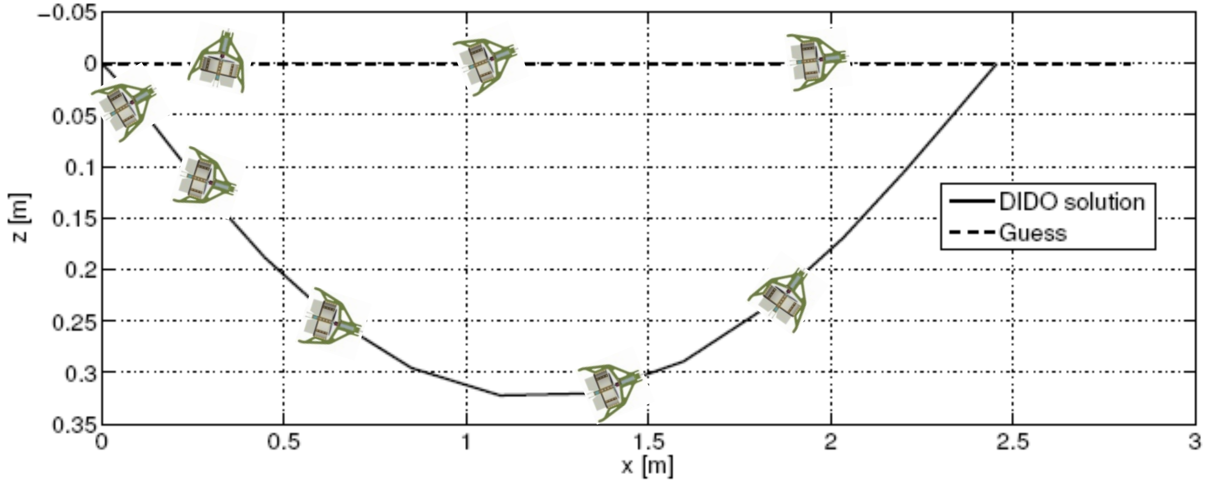
  - Design of a robust control law

    R. Naldi, L. Marconi, AUTOMATICA, second review round

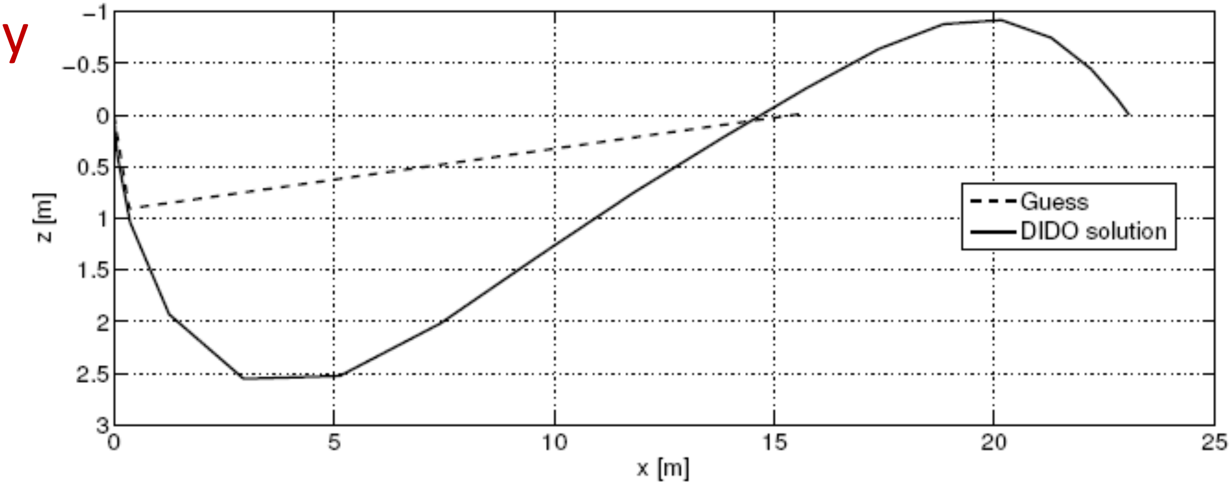
Transition Hovering-Forward Flight

Numerical results

Minimum time

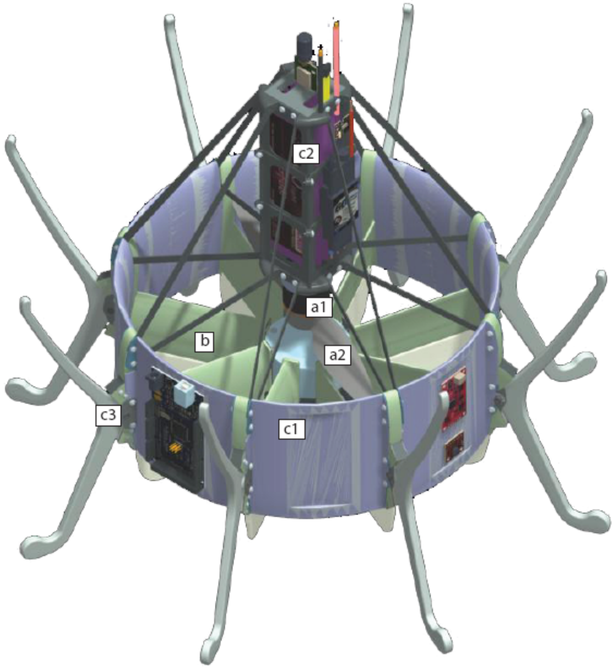


Minimum energy



Control Allocation for a Ducted-Fan UAV

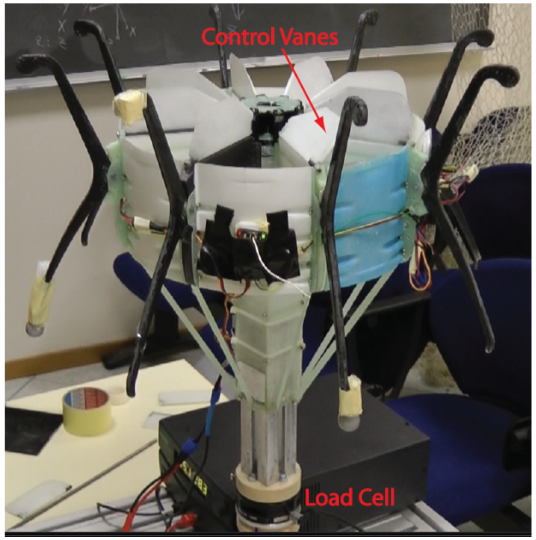
- **CASY ducted-fan UAV:**
  - 9 independent actuators (8 control vanes and 1 fixed pitch propeller driven by an electric motor)

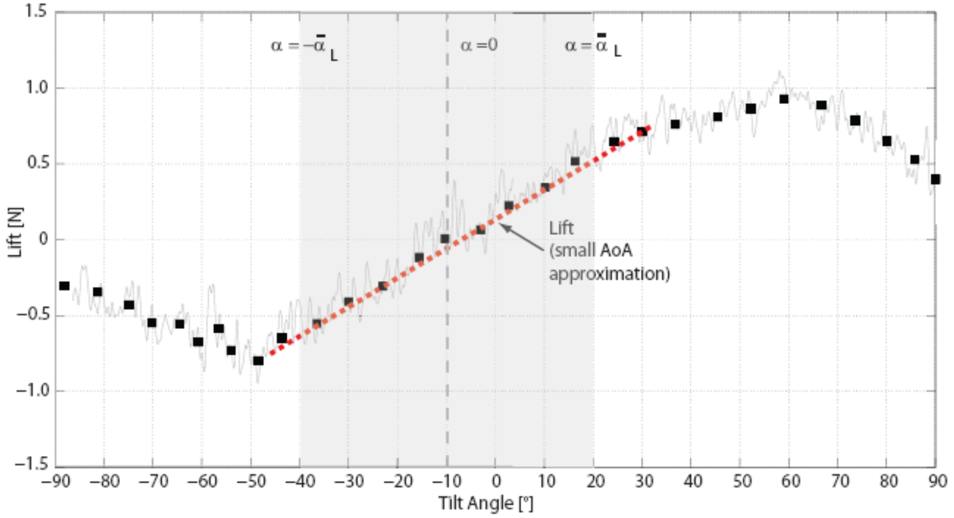


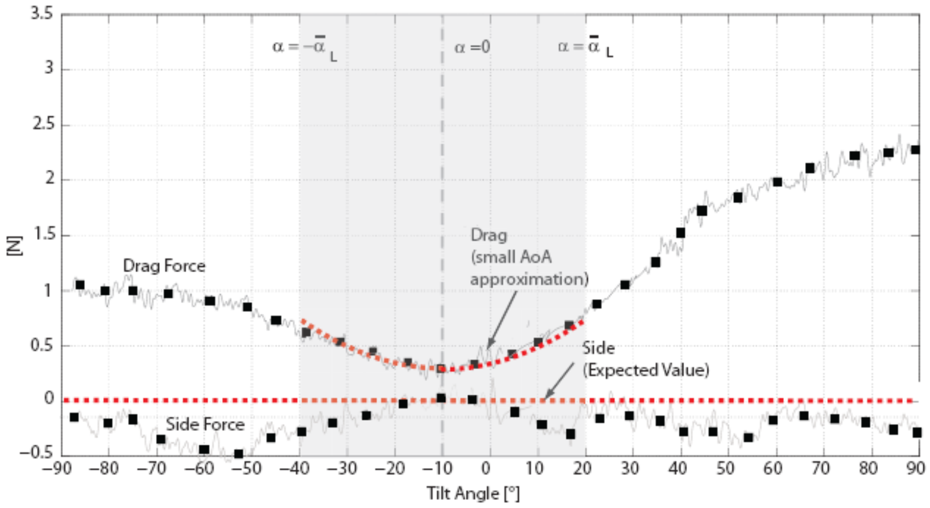
Problem:
design a control allocation policy in order to obtain a desired control wrench vector

Control vanes aerodynamic characteristics

- Experimental investigation of the aerodynamic characteristics of each control vane







Lift based control allocation

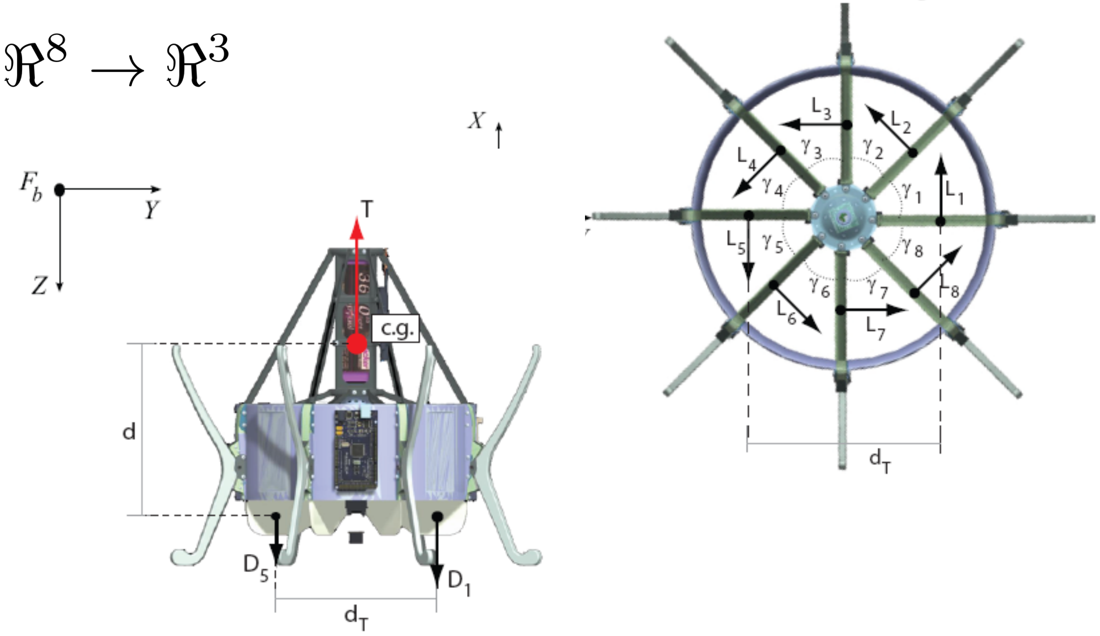
Produce three desired torque components by combining the lift forces produced by the control vanes

$$\min \sum_{i=1}^{8} \alpha_i^2 \quad \text{s.t.}$$

use the redundancy to minimize the total drag

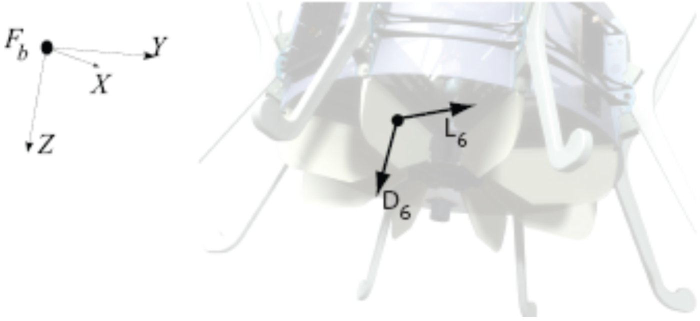
$$\tau_V(\alpha_1, \ldots, \alpha_8) = \tau^\star \qquad \tau_V : \Re^8 \to \Re^3$$

$$\tau^\star = (\tau_x^\star, \tau_y^\star, \tau_z^\star)^T$$

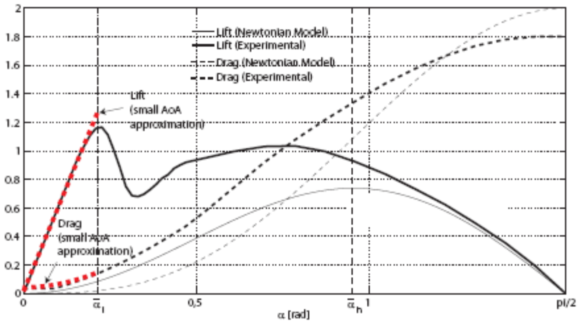


More advanced strategies

Lift and drag forces



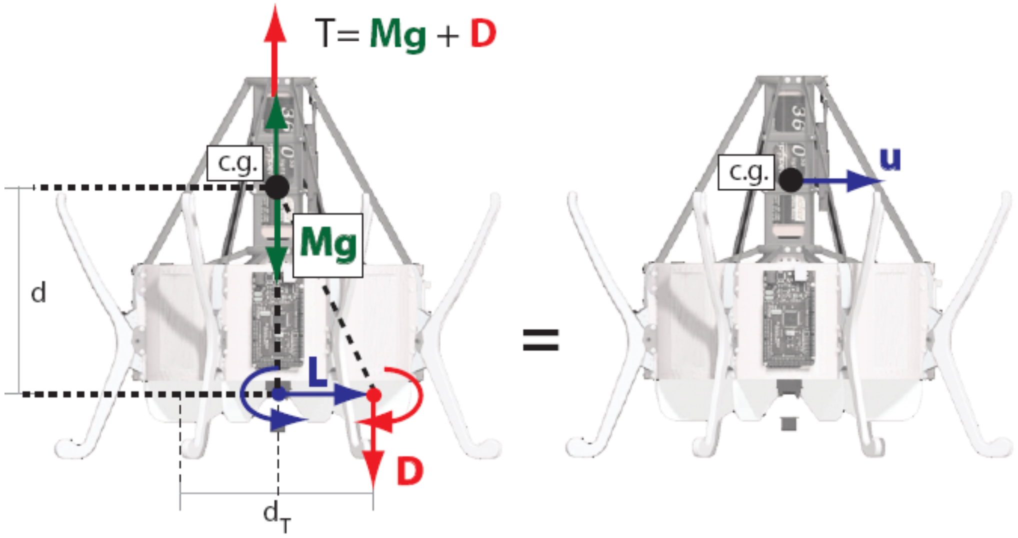
- drag forces are small at low AoA values while on the other side are non negligible at high AoA values



- the lift force produced at high values of AoA is lower or equal than the one that can be produced at lower AoA values

Fully actuated control allocation policy

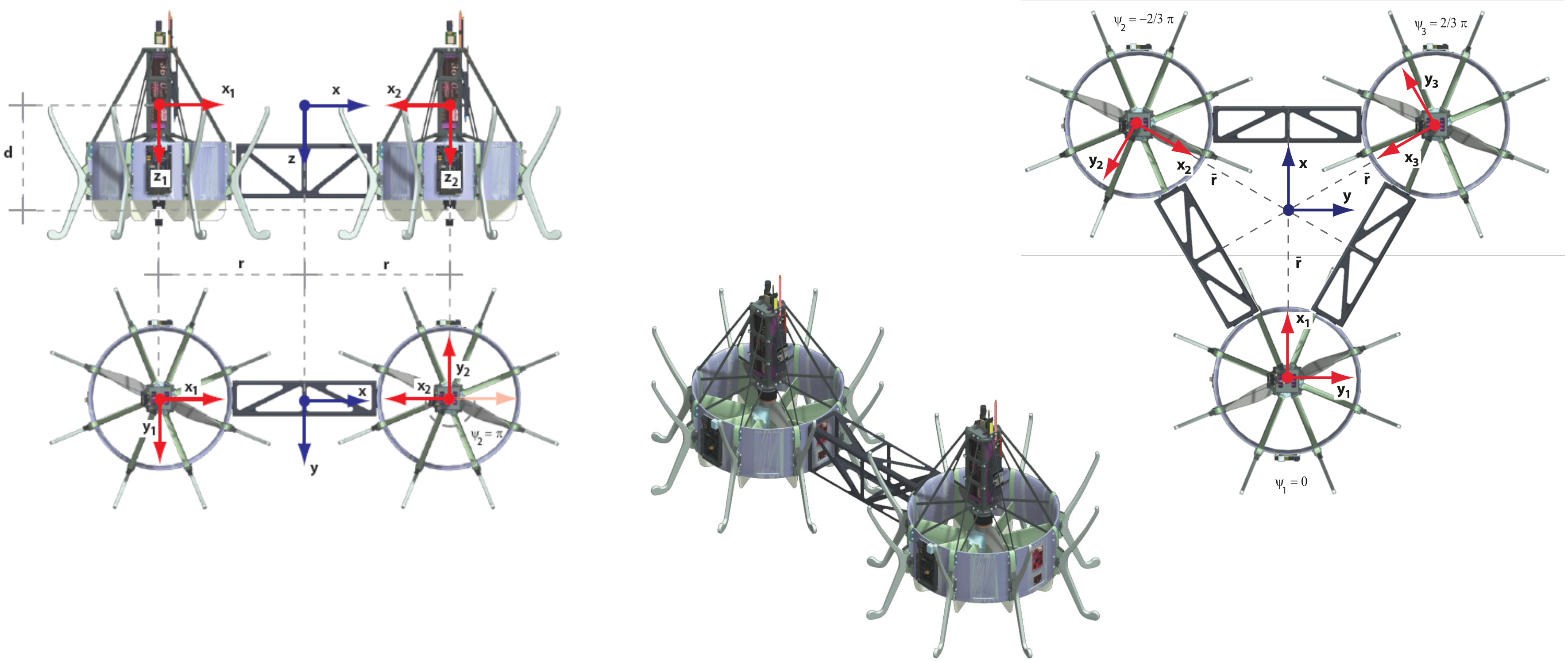
Idea:



- the torque produced by the drag force (large AoA) is compensated by using a lift force (small AoA)
- as a consequence an additional force control input is produced

R. Naldi, L. Marconi, ACC 2011

- # Ducted-fan: multi-UAVs configuration



Forte, R. Naldi, A. Serrani, L. Marconi, CDC 2012

Conclusions

- The Ducted-fan suitable for developing flying robots and for efficient fast forward-flight

- The European project AIRobots

- Modeling and controlling the UAV interacting with the environment

- Ongoing research activities