Part 1

Modeling of Unmanned Aerial Vehicles

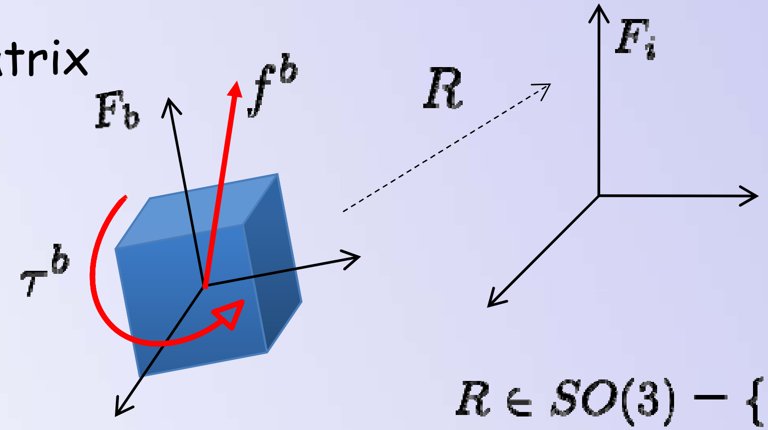
Overview

- Modeling in free-flight
  - Rigid body
  - Force/Torque generation mechanisms
    - Quadrotors, Helicopters
    - Ducted-fan, Coaxial (postponed)
  - Control of under-actuated vehicles
    - Inner-outer loop strategy
    - The linearized system
  - UNIBO research activity
- Modeling in presence of contact (R. Naldi)

Rigid Body

- Newton-Euler equations of motion

R Rotation matrix
M Mass
J Inertia



$$\vec{p} = p^i = \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

$$\vec{\omega} = \omega^b = \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix}$$

$$R \in SO(3) = \{R \in \mathbb{R}^{3\times 3} \; : \; R^T R = R R^T = I \\ \det(R) = 1\}$$

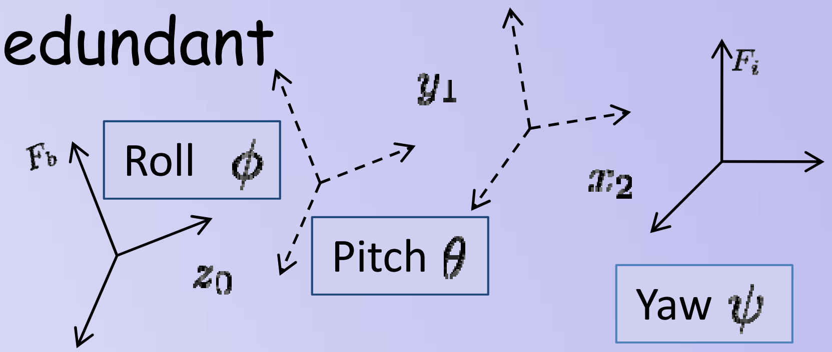
$$\begin{aligned} M\ddot{\vec{p}} &= R\, f^b \\ \dot{R} &= R\,\mathrm{Skew}(\vec{\omega}) \\ J\dot{\vec{\omega}} &= -\mathrm{Skew}(\vec{\omega})\; J\,\vec{\omega} + \tau^b \end{aligned}$$

$$(\vec{p}, R) \in SE(3) = \mathbb{R}^3 \times SO(3)$$

$$\vec{v} \times \vec{w} = \mathrm{Skew}(\vec{v})\vec{w} \qquad \mathrm{Skew}(\vec{v}) = \begin{pmatrix} 0 & -v_3 & v_2 \\ v_3 & 0 & -v_1 \\ -v_2 & v_1 & 0 \end{pmatrix}$$

Rigid Body

- R computationally nice but redundant
- Attitude parameterization
  - Roll/Pitch/Yaw



$$\Theta := \begin{pmatrix} \phi \\ \theta \end{pmatrix} \quad \Theta_\psi := \begin{pmatrix} \Theta \\ \psi \end{pmatrix}$$

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

$$\dot{R} = R\,\mathrm{Skew}(\vec{\omega})$$

$$\dot{\Theta}_\psi = Q(\Theta)\vec{\omega} \qquad Q(\Theta) = \begin{pmatrix} 1 & S_\phi T_\theta & C_\phi T_\theta \\ 0 & C_\phi & -S_\phi \\ 0 & S_\phi / C_\theta & C_\phi / C_\theta \end{pmatrix}.$$

Minimal ($\Theta_\psi \in \mathbb{R}^3$) but containing singularities

Rigid Body

- Attitude parameterization
  - Quaternions $\mathbf{q} = \begin{pmatrix} q_0 \\ q \end{pmatrix} \in S_4 := \{x \in \mathbb{R}^4 \ : \ \|x\| = 1\}$ $\quad q = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$

$$R(\mathbf{q}) = \begin{pmatrix} 1-2q_2^2-2q_3^2 & 2q_1q_2-2q_0q_3 & 2q_1q_3+2q_0q_2 \\ 2q_1q_2+2q_0q_3 & 1-2q_1^2-2q_3^2 & 2q_2q_3-2q_0q_1 \\ 2q_1q_3-2q_0q_2 & 2q_2q_3+2q_0q_1 & 1-2q_1^2-2q_2^2 \end{pmatrix}$$

- $R(\mathbf{q}) \in SO(3)$
- $\forall \ R^* \in SO(3)$
  $\exists \ \mathbf{q}^* \in S_4$
  s.t. $R(\mathbf{q}^*) = R^*$

$$\dot{R} = R \, \mathrm{Skew}(\vec{\omega})$$

$$\dot{\mathbf{q}} = \frac{1}{2} E(\mathbf{q})\vec{\omega} \, , \quad E(\mathbf{q}) = \begin{pmatrix} -q^T \\ q_0 I + \mathrm{Skew}(q) \end{pmatrix}$$

Non minimal ($\mathbf{q} \in \mathbb{R}^4$) but
non singular and …
nice algebra

Rigid Body

- Overall

$$\begin{aligned} M\ddot{\vec{p}} &= R\, f^b \\ \dot{R} &= R\, \mathrm{Skew}(\vec{\omega}) \\ J\dot{\vec{\omega}} &= -\mathrm{Skew}(\vec{\omega})\, J\, \vec{\omega} + \tau^b \end{aligned}$$

$$\mathbb{R}^6 \times SO(3) \times \mathbb{R}^3$$

– rpy

$$\begin{aligned} M\ddot{\vec{p}} &= R(\Theta_\psi)\, f^b \\ \dot{\Theta}_\psi &= Q(\Theta)\vec{\omega} \\ J\dot{\vec{\omega}} &= -\mathrm{Skew}(\omega) J\vec{\omega} + \tau^b \end{aligned}$$

$$\mathbb{R}^6 \times \mathbb{R}^3 \times \mathbb{R}^3$$

- quaternions

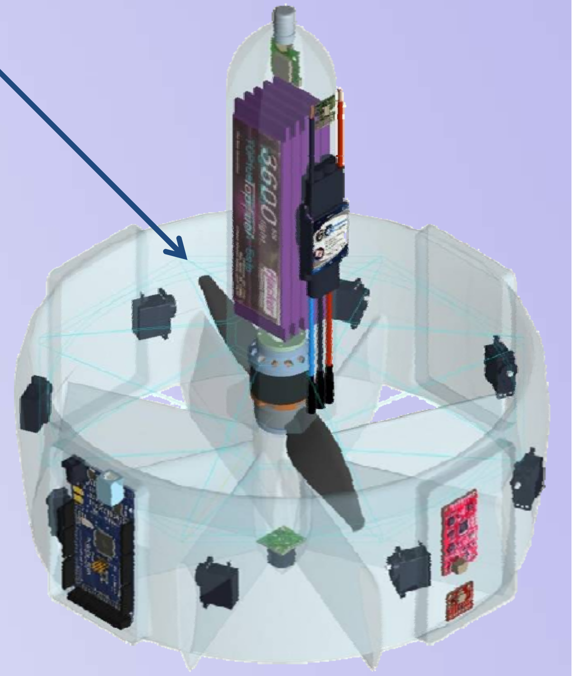
$$\begin{aligned} M\ddot{\vec{p}} &= R(\mathbf{q})\, f^b \\ \dot{\mathbf{q}} &= \tfrac{1}{2}\, E(\mathbf{q})\, \vec{\omega} \\ J\dot{\vec{\omega}} &= -\mathrm{Skew}(\omega) J\vec{\omega} + \tau^b \end{aligned}$$

$$\mathbb{R}^6 \times S_4 \times \mathbb{R}^3$$

(f^b, τ^b) wrench vector

Wrench generation mechanism

- Ducted-fan
  - ✓ 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



Wrench generation mechanism

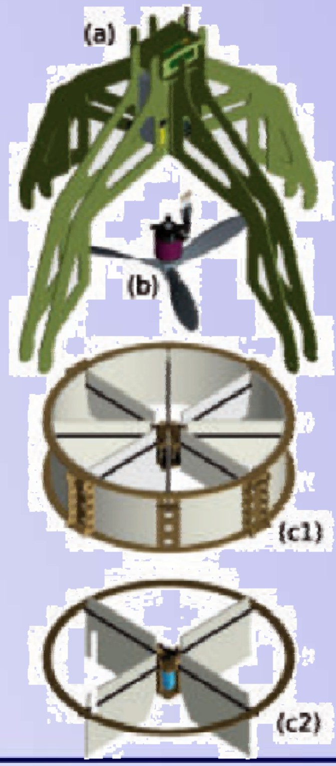
- Vanes architectures (3 dof, 3 motors in principle)

• Single level, "minimalistic" conf.

• Single level, "redundant" conf.

Control allocation policies

• Two levels, Yaw, Roll-Pitch



Wrench generation mechanism

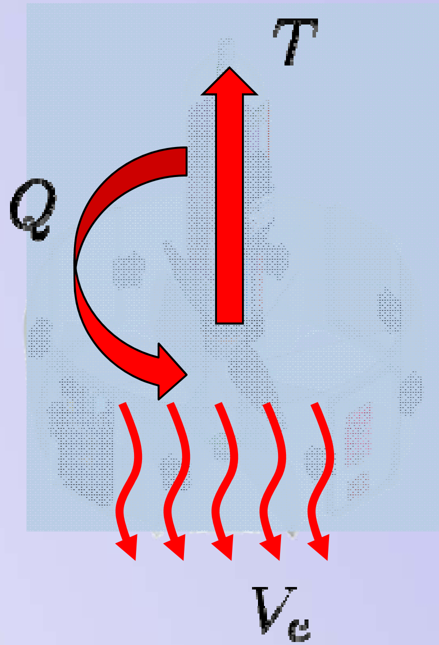
- Ducted-fan literature:
  - Project ARODhttp://www.dtic.mil/dtic/tr/fulltext/u2/a271957.pdf
  - Caltech Ducted-Fan [A. Jadbabaie et al., 1999] , [J. Yu et al, 1999]
  - iSTAR Micro Air Vehicle [L. Lipera et al, 2001], [I. Guerrero et al, 2001] , Allied Aerospace
  - GTSpy Ducted-Fan [E. N. Johnson and M. A. Turbe, 2004] Georgia tech
  - "Hovereye" [Pflimlin et al., 2004] (supported by BERTIN tech)
  - …

Wrench generation mechanism

- Modeling the propeller thrust

  - Two theories available to model a propeller disk:
    - Actuator disk theory (based on Bernoulli equations)
    - Blade element theory

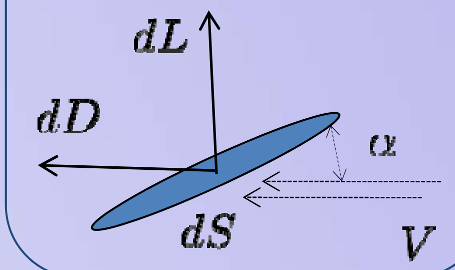
  - Thrust: $T \approx K_T w_e^2$
  - Reaction torque: $Q \approx K_Q w_e^2$
  - Downwash: $V_e \approx K_{V_e} w_e$
  - Propeller speed: w_e



Wrench generation mechanism

- Basic aerodynamic principles
  - Drag force (direction of the relative wind)
  - Lift force (perpendicular to the relative wind)

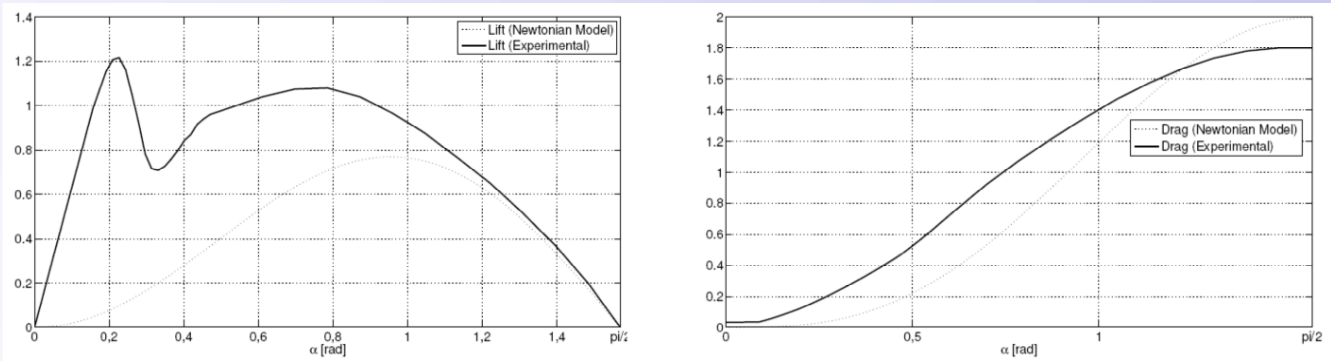
Infinitesimal airfoil profile



$$dL = \frac{1}{2}\rho V^2 C_L dS \qquad dD = \frac{1}{2}\rho V^2 C_D dS$$

- Lift and drag coefficients $C_L(\alpha), C_D(\alpha)$

$C_L(\alpha)$



$C_D(\alpha)$

α α

$C_L(\alpha) \approx K_L \alpha$

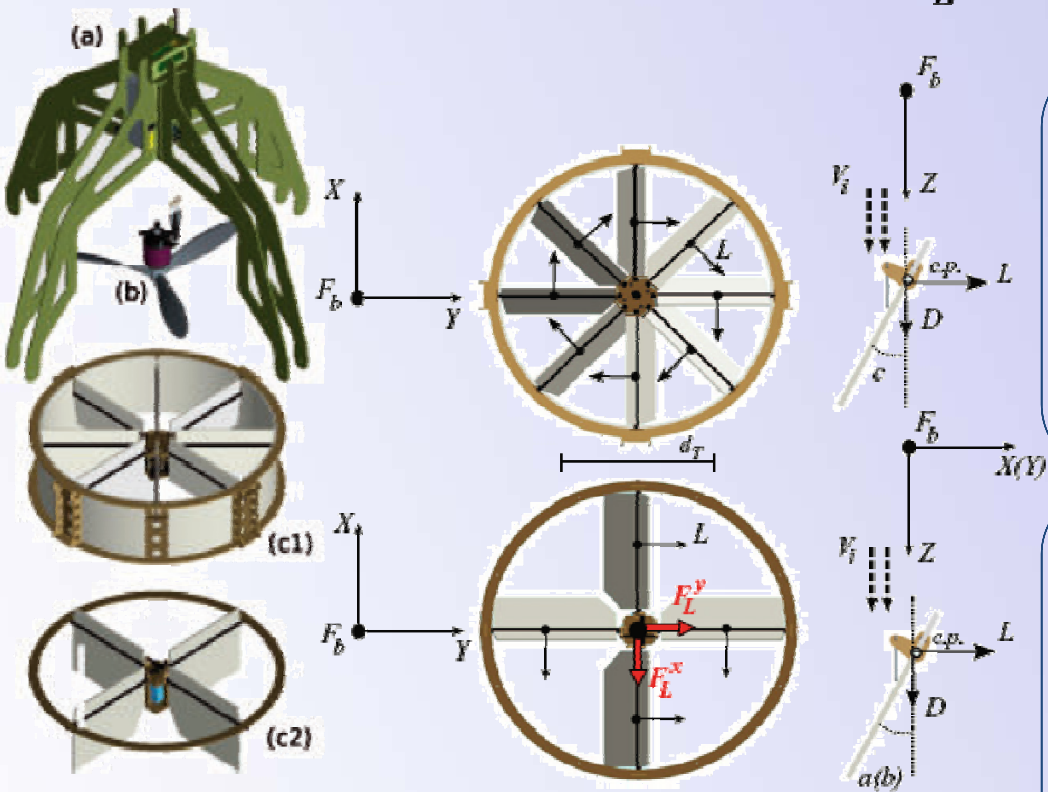
$C_D(\alpha) \approx K_D \alpha^2 + C_{D0}$

Wrench generation mechanism

- Aerodynamic forces

$$L = \frac{1}{2}\rho V_e^2 C_L S \qquad D = \frac{1}{2}\rho V_e^2 C_D S$$

$$C_L \approx K_L \alpha \qquad C_D \approx K_D \alpha^2 + C_{D0}$$



$$f^b = \begin{pmatrix} F_L^x \\ F_L^y \\ -T + F_D \end{pmatrix} + R^T \begin{pmatrix} 0 \\ 0 \\ Mg \end{pmatrix}$$

$$F_L^x = \kappa_x V_e^2 a \qquad F_L^y = \kappa_y V_e^2 b$$

$$V_e = K_{V_e} w_e^2 \qquad T = K_T w_e^2$$

F_D sum of the drag forces

$$\tau^b = \begin{pmatrix} -F_L^y d \\ F_L^x d \\ Q + Q_c \end{pmatrix} + R^T w_e G \vec{\omega}$$

$$Q = K_Q w_e^2 \qquad Q_c = \kappa_z V_e^2 c$$

$R^T w_e G \vec{\omega}$ Gyroscopic precession propeller

$$G = \mathrm{Skew}([0, 0, I_{\mathrm{rot}}])$$

Wrench generation mechanism

$$f^b = w_e^2 \begin{pmatrix} \epsilon_x a \\ \epsilon_y b \\ -K_T + F_D \end{pmatrix} + R^T \begin{pmatrix} 0 \\ 0 \\ Mg \end{pmatrix} \qquad f^b \approx w_e^2 \begin{pmatrix} 0 \\ 0 \\ -K_T \end{pmatrix} + R^T \begin{pmatrix} 0 \\ 0 \\ Mg \end{pmatrix}$$

Side forces (often neglected)

Drag forces (often neglected)

$$\tau^b = w_e^2 \begin{pmatrix} 0 & -a_1 & 0 \\ a_1 & 0 & 0 \\ 0 & 0 & a_2 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} + w_e^2 \begin{pmatrix} 0 \\ 0 \\ K_Q \end{pmatrix} + R^T w_e G \vec{\omega}$$

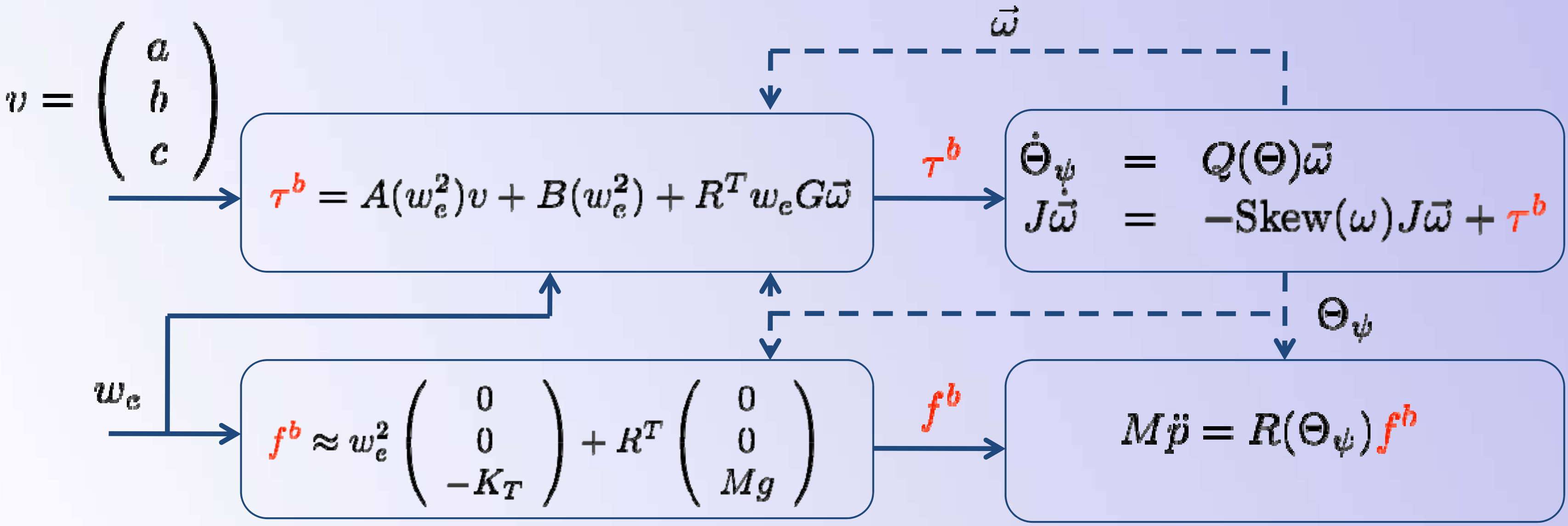
Aerodynamic drag forces neglected

Side forces relevant in output feedback (zero dynamics)

Wrench generation mechanism

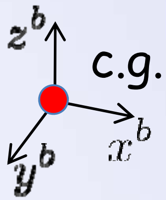
$$f^b \approx w_e^2 \begin{pmatrix} 0 \\ 0 \\ -K_T \end{pmatrix} + R^T \begin{pmatrix} 0 \\ 0 \\ Mg \end{pmatrix}$$

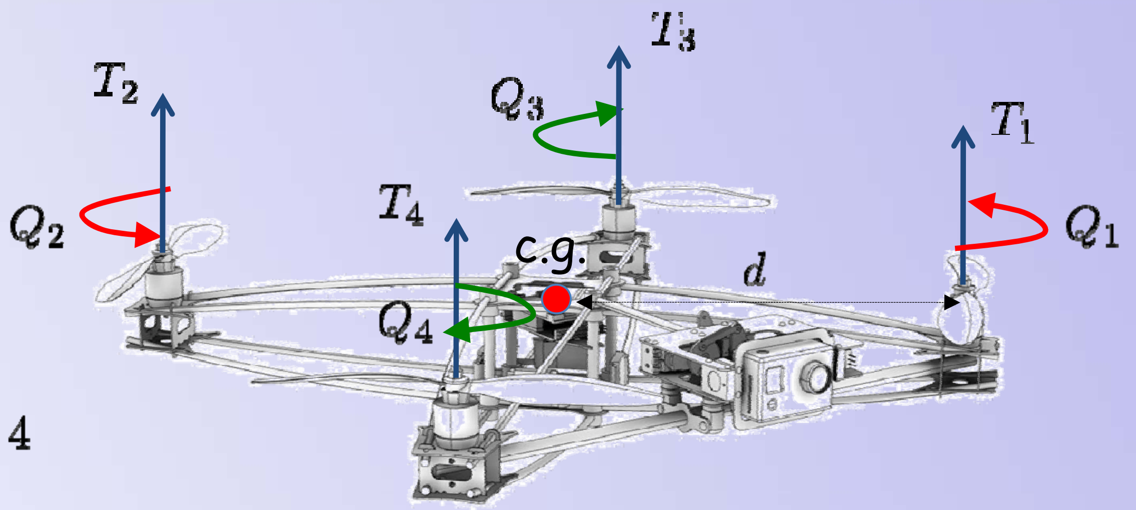
$$\tau^b = w_e^2 \begin{pmatrix} 0 & -a_1 & 0 \\ a_1 & 0 & 0 \\ 0 & 0 & a_2 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} + \omega_e^2 \begin{pmatrix} 0 \\ 0 \\ K_Q \end{pmatrix} + R^T w_e G \vec{\omega}$$



Wrench generation mechanism

- Quadrotor





$$Q_i = K_Q\, w_{ei}^2,\ i = 1, .., 4$$

$$T_i = K_T\, w_{ei}^2,\ i = 1, .., 4$$

$$f^b = \begin{pmatrix} 0 \\ 0 \\ \sum_{i=1}^{4} T_i \end{pmatrix} + R^T \begin{pmatrix} 0 \\ 0 \\ Mg \end{pmatrix} \qquad \tau^b = \begin{pmatrix} T_3\, d - T_4\, d \\ T_1\, d - T_2\, d \\ Q_1 + Q_2 - Q_3 - Q_4 \end{pmatrix}$$

$$w_e^2 = \sum_{i=1}^{4} w_{ei}^2$$

$$a = (w_{e3}^2 - w_{e4}^2)/w_e^2$$

$$b = (w_{e1}^2 - w_{e2}^2)/w_e^2$$

$$c = (w_{e2}^2 - w_{e3}^2)/w_e^2$$

$$f^b = w_e^2 \begin{pmatrix} 0 \\ 0 \\ K_T \end{pmatrix} + R^T \begin{pmatrix} 0 \\ 0 \\ Mg \end{pmatrix}$$

$$\tau^b = w_e^2 \begin{pmatrix} K_T d & 0 & 0 \\ 0 & K_T d & 0 \\ K_Q & K_Q & -2K_Q \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix}$$

Wrench generation mechanism

- Helicopter (Gravilets, 2003)

$$f^b = \begin{pmatrix} X_M \\ Y_M + Y_T \\ Z_M \end{pmatrix} + R^T \begin{pmatrix} 0 \\ 0 \\ Mg \end{pmatrix}$$

$$\tau^b = \begin{pmatrix} \tau_{f_1} \\ \tau_{f_2} \\ \tau_{f_3} \end{pmatrix} + \begin{pmatrix} R_M \\ M_M \\ N_M \end{pmatrix}$$

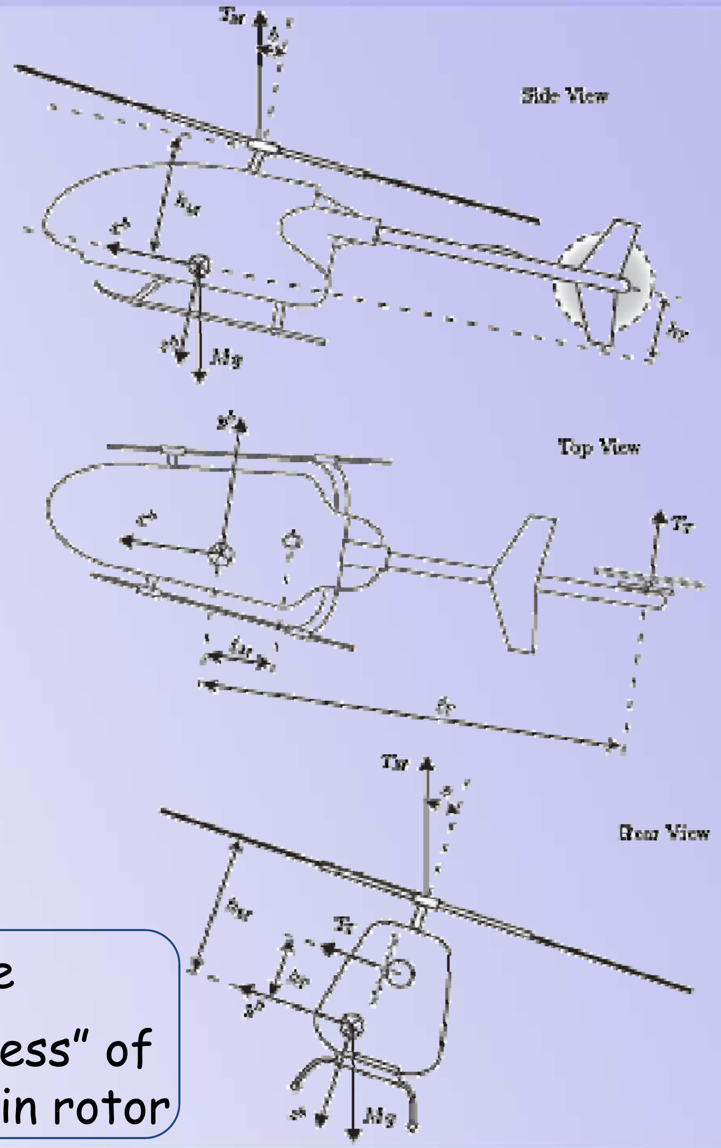
$$X_M = -T_M \sin a \qquad Y_M = T_M \sin b,$$
$$Z_M = -T_M \cos a \cos b \qquad Y_T = -T_T$$

$$\begin{aligned} \tau_{f_1} &= Y_M h_M + Z_M y_M + Y_T h_T \\ \tau_{f_2} &= -X_M h_M + Z_M \ell_M \\ \tau_{f_3} &= -Y_M \ell_M - Y_T \ell_T \end{aligned}$$

$$R_M = c_b^M b - Q_M \sin a$$
$$M_M = c_a^M a + Q_M \sin b$$
$$N_M = -Q_M \cos a \cos b$$

Q_M rotor torque

(C_a^M, C_b^M) "stiffness" of the main rotor



Wrench generation mechanism

- Helicopter

(a, b) Lateral/longitudinal inclination of the tip path plane of the main rotor (cyclic pitch)

$$T_M = K_{T_M} P_M w_e^2$$
$$T_T = K_{T_T} P_T w_e^2$$

(P_M, P_T) Collective main/tail rotor pitches

$$J_{\text{rot}} \dot{w}_e = k_e T_h + Q_M(w_e, P_M)$$

T_h Throttle of the main engine

Control inputs: $v = \begin{pmatrix} a \\ b \\ P_T \end{pmatrix}$, P_M, and T_h (to control w_e at a desired setpoint)

By neglecting side forces and $\sin\alpha \approx \alpha$, $\cos\alpha \approx 1$

$$f^b \approx P_M \begin{pmatrix} 0 \\ 0 \\ K_{T_M} w_e^2 \end{pmatrix} + R^T \begin{pmatrix} 0 \\ 0 \\ Mg \end{pmatrix} \qquad \tau^b \approx A(T_M)v + B(T_M)$$

Control of under-actuated vehicles

$$M\begin{pmatrix}\ddot{x}\\ \ddot{y}\\ \ddot{z}\end{pmatrix}=\begin{pmatrix}C_\psi C_\theta & -S_\psi C_\phi + C_\psi S_\theta S_\phi & S_\phi S_\psi + C_\phi S_\theta C_\psi\\ S_\psi C_\theta & C_\phi C_\psi + S_\phi S_\theta S_\psi & -C_\psi S_\phi + S_\psi S_\theta C_\phi\\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi\end{pmatrix}\begin{pmatrix}0\\ 0\\ -K_T\end{pmatrix}w_e^2+\begin{pmatrix}0\\ 0\\ Mg\end{pmatrix}$$

$$\begin{pmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{pmatrix}=\begin{pmatrix}1 & S_\phi T_\theta & C_\phi T_\theta\\ 0 & C_\phi & -S_\phi\\ 0 & S_\phi/C_\theta & C_\phi/C_\theta\end{pmatrix}\begin{pmatrix}\omega_x\\ \omega_y\\ \omega_z\end{pmatrix}$$

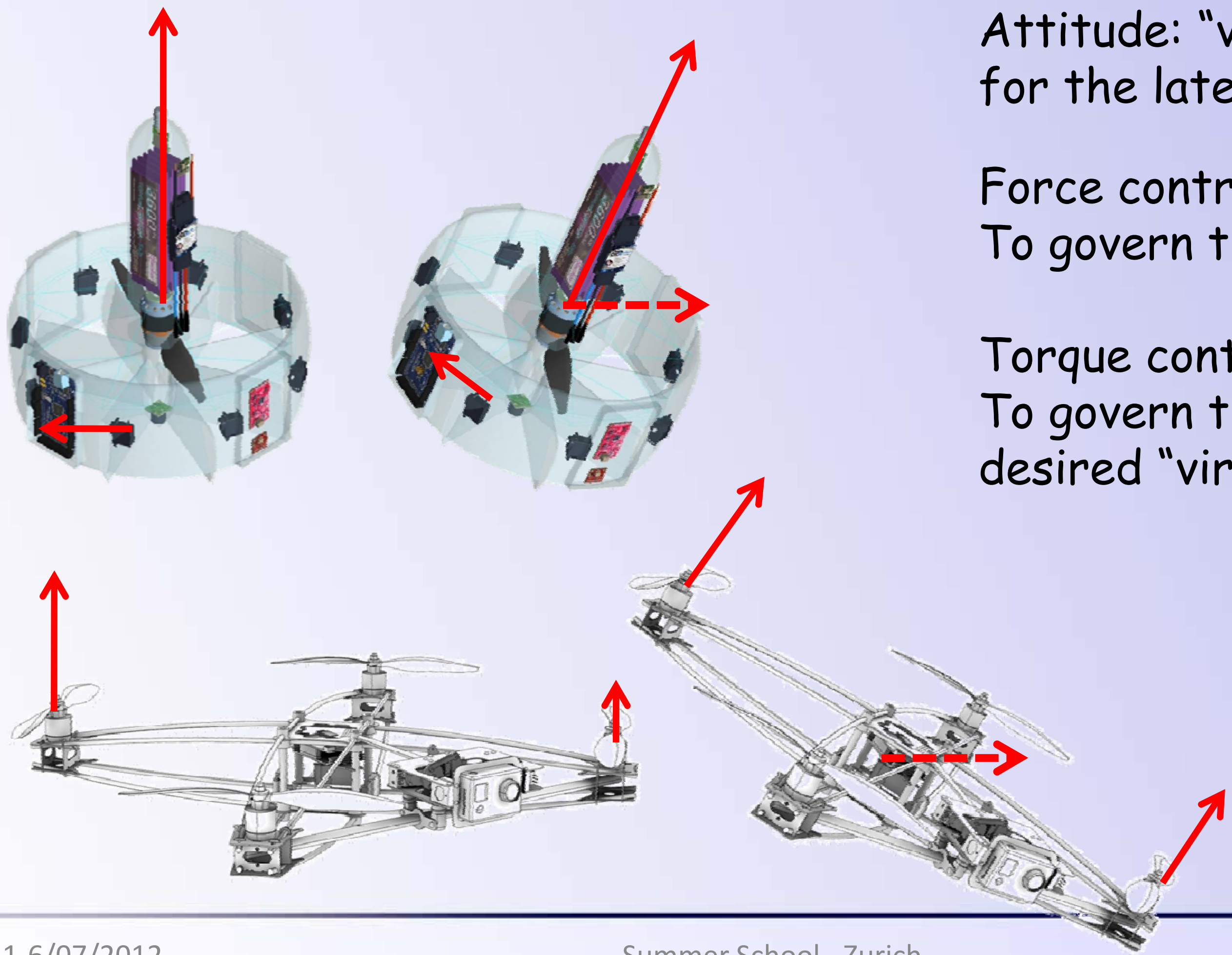
$$J\begin{pmatrix}\dot{\omega}_x\\ \dot{\omega}_y\\ \dot{\omega}_z\end{pmatrix}=\begin{pmatrix}0 & -\omega_z & \omega_y\\ \omega_z & 0 & -\omega_x\\ -\omega_y & \omega_x & 0\end{pmatrix}J\begin{pmatrix}\omega_x\\ \omega_y\\ \omega_z\end{pmatrix}+w_e^2\begin{pmatrix}0 & -a_1 & 0\\ a_1 & 0 & 0\\ 0 & 0 & a_2\end{pmatrix}\begin{pmatrix}a\\ b\\ c\end{pmatrix}+w_e^2\begin{pmatrix}0\\ 0\\ K_Q\end{pmatrix}$$
$$+R^T w_e G\vec{\omega}$$

Under-actuated system:
fewer inputs than dof

Four inputs used to control (p,ψ)

Control of under-actuated vehicles

- Roll/pitch attitude as virtual input for the lateral/longitudinal dynamics



Attitude: “virtual control input“ for the lateral and long. dyn.

Force control authority:
To govern the vertical dynamics

Torque control authority:
To govern the yaw and to assign desired “virtual control inputs”

Control of under-actuated vehicles

$$M\begin{pmatrix}\ddot{x}\\ \ddot{y}\\ \ddot{z}\end{pmatrix}=\begin{pmatrix}C_\psi C_\theta & -S_\psi C_\phi + C_\psi S_\theta S_\phi & S_\phi S_\psi + C_\phi S_\theta C_\psi\\ S_\psi C_\theta & C_\phi C_\psi + S_\phi S_\theta S_\psi & -C_\psi S_\phi + S_\psi S_\theta C_\phi\\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi\end{pmatrix}\begin{pmatrix}0\\0\\-K_T\end{pmatrix}w_e^2+\begin{pmatrix}0\\0\\Mg\end{pmatrix}$$

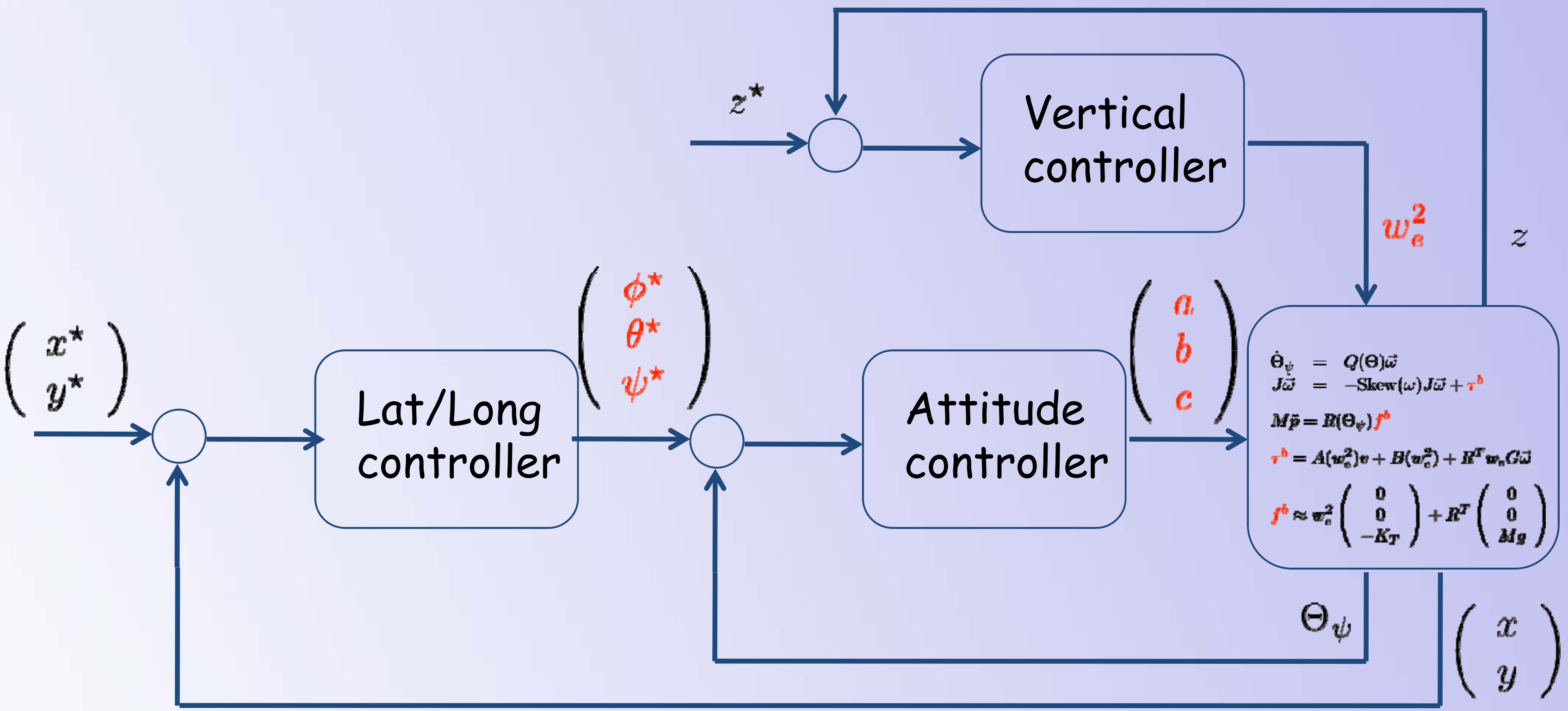
$$w_e^2=\frac{1}{C_\theta\, C_\phi\, K_T}\left[Mg+\kappa_1(z-z^\star)+\kappa_2\dot{z}\right]$$

$$M\begin{pmatrix}\ddot{x}\\ \ddot{y}\end{pmatrix}=A(\Theta_\psi)\begin{pmatrix}\tan\phi\\ \tan\theta\end{pmatrix}+B(\Theta_\psi)(\kappa_1(z-z^\star)+\kappa_2\dot{z})$$

$$A(\Theta_\psi)=\begin{pmatrix}T_\psi\, C_\phi\,/\,C_\theta & C_\phi\\ -C_\phi\,/\,C_\theta & T_\psi\, C_\phi\end{pmatrix}$$

$$\begin{pmatrix}\phi^\star\\ \theta^\star\end{pmatrix}=\operatorname{atan}\left(A(\Theta_\psi)^{-1}\begin{pmatrix}\kappa_1(x-x^\star)+\kappa_2\dot{x}\\ \kappa_1(y-y^\star)+\kappa_2\dot{y}\end{pmatrix}\right)$$

Control of under-actuated vehicles



Inner-Outer (cascade) control strategy

Control of under-actuated vehicles

- Attitude controller (backstepping)

$$\dot{\Theta}_\psi = Q(\Theta)\omega$$

$|\phi| < \frac{\pi}{4}, |\theta| < \frac{\pi}{4} \quad \Rightarrow \quad Q(\Theta)$ non singular

$$J\dot{\omega} = -\mathrm{Skew}(\omega)J\omega + A(w_e^2)v + B(w_e^2) + R^T w_e G\omega$$

$$\omega^\star = -Q(\Theta)^{-1}\left[\kappa_\Theta\left(\Theta_\psi - \Theta_\psi^\star\right) + \dot{\Theta}_\psi^\star\right]$$

$$\tilde{\omega} := \omega - \omega^\star$$

$$\tilde{\Theta}_\psi := \Theta_\psi - \Theta_\psi^\star$$

$$\dot{\tilde{\Theta}}_\psi = -\kappa_\Theta \tilde{\Theta}_\psi + Q(\theta)\tilde{\omega}$$

$$J\dot{\tilde{\omega}} = -\mathrm{Skew}(\tilde{\omega} + \omega^\star)J(\tilde{\omega} + \omega^\star) + A(w_e^2)v + B(w_e^2) + R^T w_e G(\tilde{\omega} + \omega^\star) - \dot{\omega}^\star$$

$$v = A(w_e^2)^{-1}\left[-\kappa_\omega\tilde{\omega} + \dot{\omega}^\star - B(w_e^2) - R^T w_e G(\tilde{\omega} + \omega^\star) + \mathrm{Skew}(\tilde{\omega} + \omega^\star)J(\tilde{\omega} + \omega^\star)\right]$$

Control of under-actuated vehicles

- Robustness?

$$v = A_0(w_e^2)^{-1}\left[-\kappa_\omega\tilde{\omega} + \dot{\omega}^\star - B_0(w_e^2) - R^T w_e G\omega^\star + \mathrm{Skew}(\omega^\star)J_0\omega^\star\right]$$

with κ_ω large succeeds as long as $A(w_e^2)A_0(w_e^2)^{-1} > 0$

[Isidori, Marconi, Serrani, Springer Verlag, 2003]

- Singularities
  - Quaternions
  - Nested saturated control laws

Control of under-actuated vehicles

- Linear approximation

Equilibrium point: $$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x^\star \\ y^\star \\ z^\star \end{pmatrix} \quad \begin{pmatrix} \theta \\ \phi \\ \psi \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \psi^\star \end{pmatrix} \quad \dot{p} = \omega = 0$$

$$w_e^2 = \frac{Mg}{K_T} := w_e^{\star 2} \quad \begin{pmatrix} a \\ b \end{pmatrix} = 0 \quad c = -\frac{K_Q}{a_2} := c^\star$$

$$\delta x = x - x^\star \quad \delta y = y - y^\star$$

$$\begin{pmatrix} \ddot{\delta x} \\ \ddot{\delta y} \end{pmatrix} = g \begin{pmatrix} S_{\psi^\star} & -C_{\psi^\star} \\ C_{\psi^\star} & S_{\psi^\star} \end{pmatrix} \begin{pmatrix} \phi \\ \theta \end{pmatrix}$$

$$(\phi, \theta)$$

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \omega_x \\ \omega_y \end{pmatrix}$$

$$(\omega_x, \omega_y)$$

$$\delta z = z - z^\star$$

$$M \ddot{\delta z} = \delta w_e^2$$

$$\delta w_e^2 = w_e^2 - w_e^{\star 2}$$

$$\delta \psi = \psi - \psi^\star$$

$$\dot{\delta \psi} = \omega_z$$

$$\omega_z$$

$$J_z \dot{\omega}_z = w_e^{\star 2} a_2 \, \delta c$$

$$\delta c = c - c^\star$$

$$J_{xy} \begin{pmatrix} \dot{\omega}_x \\ \dot{\omega}_y \end{pmatrix} = w_e^\star \begin{pmatrix} 0 & -a_1 \\ a_1 & 0 \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} + I_{rot} w_e^\star \begin{pmatrix} S_{\psi^\star} & -C_{\psi^\star} \\ C_{\psi^\star} & S_{\psi^\star} \end{pmatrix} \begin{pmatrix} \omega_x \\ \omega_y \end{pmatrix}$$

$$(a, b)$$

UNIBO research activity

- 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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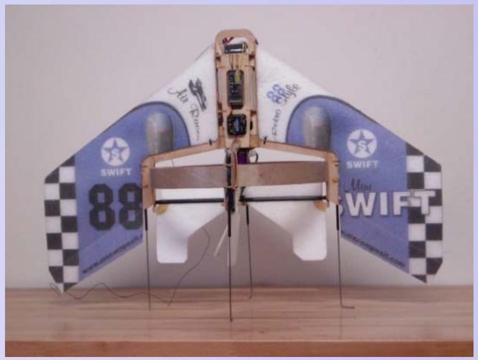
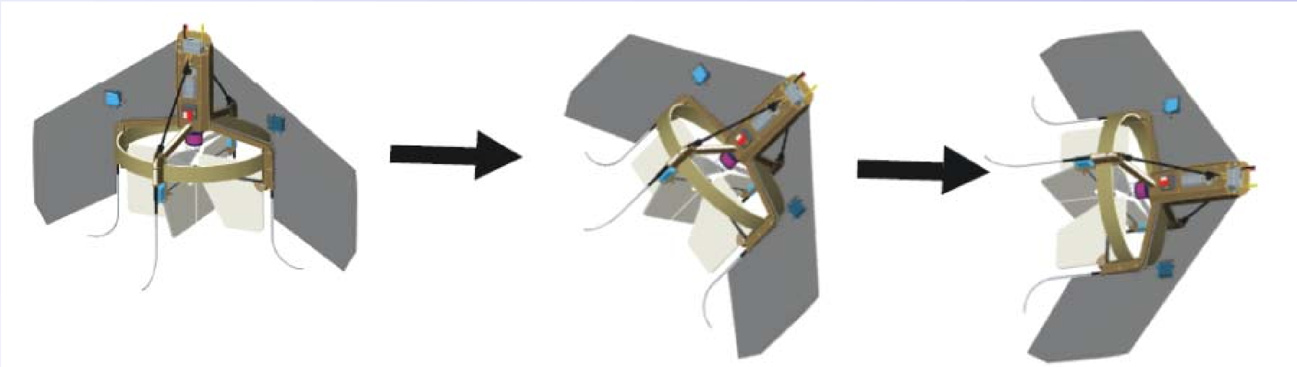


UNIBO research activity

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

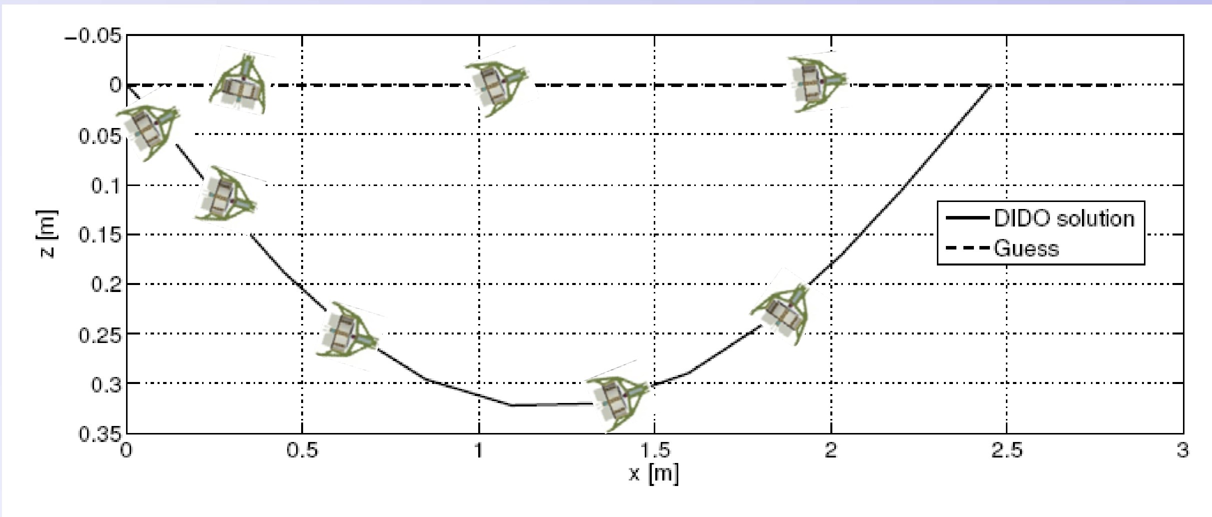


  - Computation of a transition maneuver: trajectory of system state and input

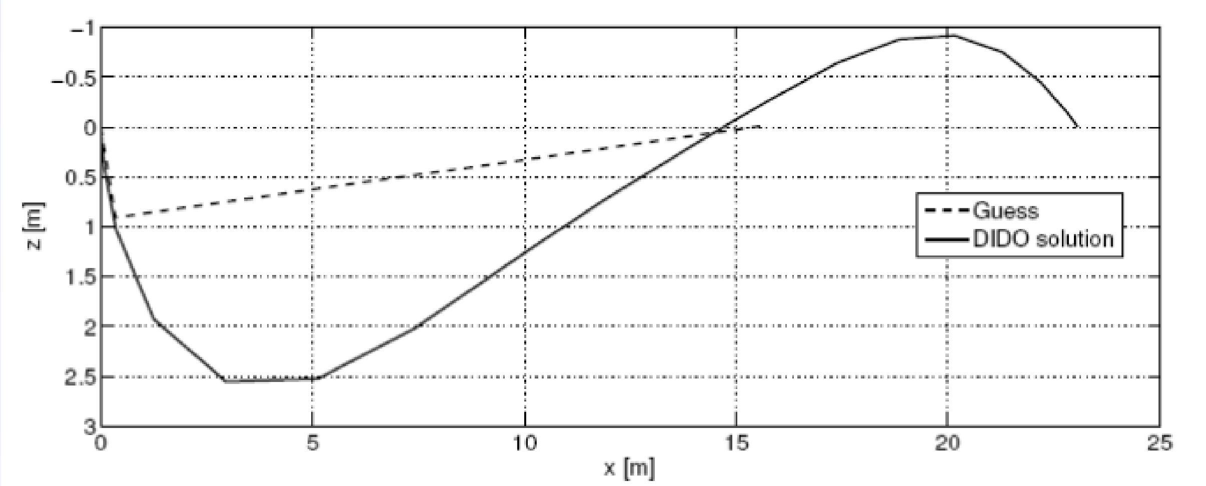
UNIBO research activity

Numerical results (R. Naldi, L. Marconi, AUTOMATICA, 2010)

Minimum time

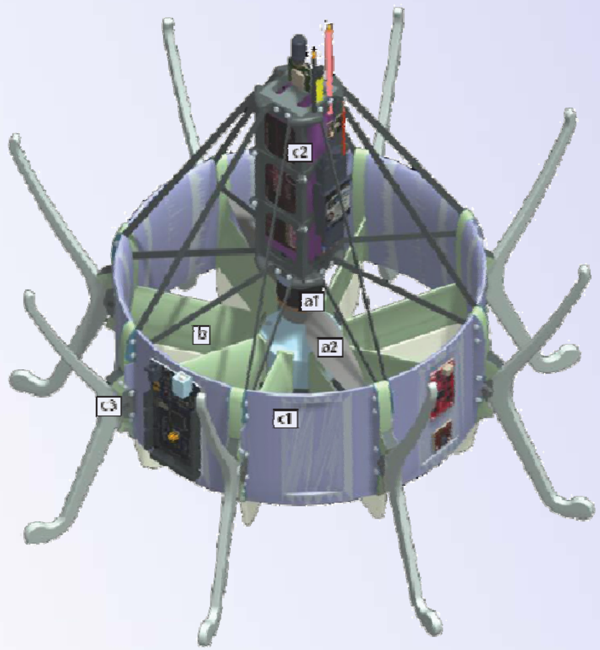


Minimum energy



UNIBO research activity

- **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

UNIBO research activity

- Modular aerial robotics