Aggressive deployment of a quadrotor aerial vehicle

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Drones applications

Nowadays, quadrotors are used in military, commercial, industrial, and scientific applications :

- Filming and aerial takes.
- Toys and entertainment.
- Cartography.
- Tropical diseases management.
- And many more...

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  - Natural disasters
- Search and rescue missions.





Emergency drones

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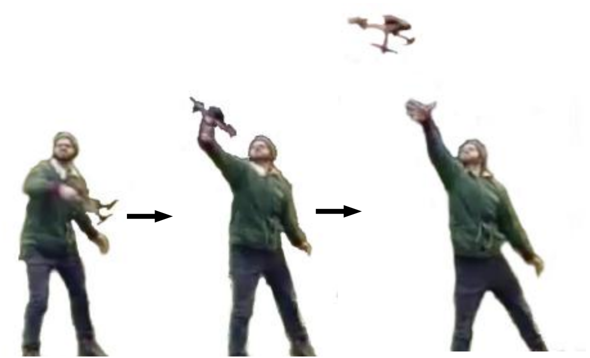
A different deployment strategy



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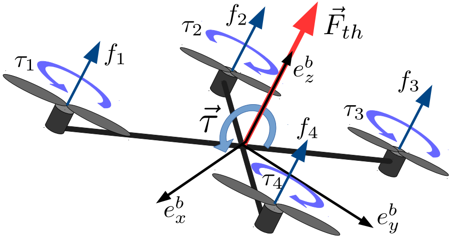
Quadrotor mechanical modeling



Blade element theory is used to compute the total torques and forces

$$\vec{F}_{th} = \begin{bmatrix} 0 \\ 0 \\ \sum_{i=1}^{4} k_T\,\omega_i^2 \end{bmatrix},$$

$$\vec{\tau} = \begin{bmatrix} l\left(k_T\,\omega_1^2 - k_T\,\omega_2^2 - k_T\,\omega_3^2 + k_T\,\omega_4^2\right) \\ l\left(k_T\,\omega_1^2 + k_T\,\omega_2^2 - k_T\,\omega_3^2 - k_T\,\omega_4^2\right) \\ \sum_{i=1}^{4} k_Q \omega_i^2 (-1)^i \end{bmatrix},$$

$$k_T \approxeq C_T \rho A_p\, r^2, \quad k_Q \approxeq C_Q \rho A_p r^3.$$

Quadrotor mechanical modeling

Classical approaches use Euler angles ϕ, θ, and ψ to describe rotations

Euler-Lagrange Methodology:

$$L(\mathbf{x}) = T_{trans} + T_{rot} - U, \\ = \frac{m}{2}\dot{\vec{p}}^T\dot{\vec{p}} + \frac{1}{2}\vec{\Omega}^T J\vec{\Omega} + m\vec{g}\cdot\vec{p},$$

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\mathbf{x}}} - \frac{\partial L}{\partial \mathbf{x}} = \begin{bmatrix} \vec{F}_p \\ \vec{\tau} \end{bmatrix}.$$

Newton-Euler Approach:

$$m\ddot{x} = -\sin\theta F_{th},$$
$$m\ddot{y} = \cos\theta\sin\phi F_{th},$$
$$m\ddot{z} = \cos\theta\cos\phi F_{th} - mg,$$

$$\begin{bmatrix} \ddot{\psi} \\ \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} = J^{-1}\left(\begin{bmatrix} \tau_z \\ \tau_y \\ \tau_x \end{bmatrix} - \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}\begin{bmatrix} \dot{\psi} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix}\right).$$

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Advantages:

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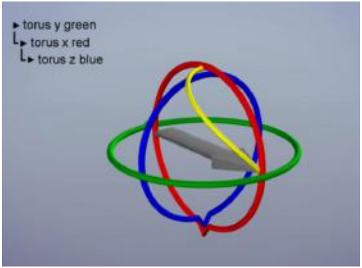
  - Also dealt by exact linearization: singularities are induced.
- Inherent Gimbal lock effect.



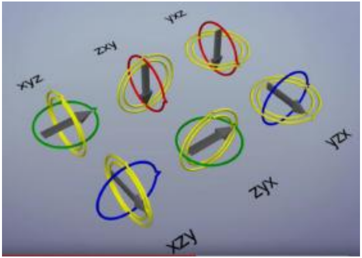
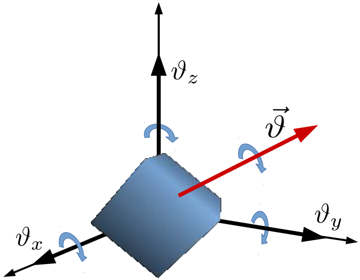


Figure source: GuerrillaCG, https://youtu.be/zc8b2Jo7mno

Quadrotor quaternion modeling



$$\boldsymbol{q} = e^{\frac{1}{2}\vec{\vartheta}} = \cos(\vartheta/2) + \vec{u}\sin(\vartheta/2)\,.$$

- Euler 1776
- Rodrigues 1815
- Hamilton 1843

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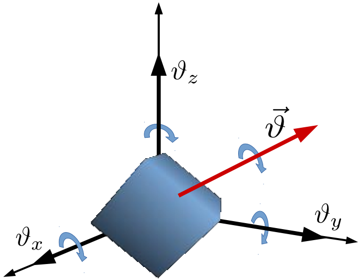

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The quadrotor quaternion dynamic model can be described as

$$\frac{d}{dt}\begin{bmatrix} \vec{p} \\ \dot{\vec{p}} \\ \boldsymbol{q} \\ \vec{\Omega} \end{bmatrix} = \begin{bmatrix} \dot{\vec{p}} \\ \frac{1}{m}\boldsymbol{q} \otimes \begin{bmatrix} 0 \\ 0 \\ F_{th} \end{bmatrix} \otimes \boldsymbol{q}^* + \vec{g} \\ \frac{1}{2}\boldsymbol{q} \otimes \vec{\Omega} \\ J^{-1}\left(\vec{\tau}_u - \vec{\Omega} \times J\,\vec{\Omega}\right) \end{bmatrix}.$$

Spherical chattering-free sliding mode controller

A sliding manifold for the translational subsystem can be defined as

$$\varsigma_t = K_1\,(\vec{p} - \vec{p}_d) + K_2(\dot{\vec{p}} - \dot{\vec{p}}_d),$$

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As for the rotational subsystem:

$$\varsigma_r = K_4 \ln \left(\boldsymbol{q}_z^* \otimes \boldsymbol{q}_t^* \otimes \boldsymbol{q} \right) + K_5 \vec{\Omega},$$

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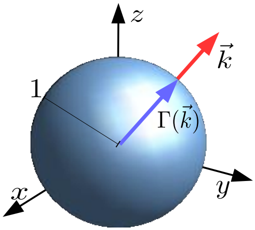
Using a vector direction instead of the sign of each one of its components:



$$\Gamma\left(\vec{k}\right) = \frac{\vec{k}}{||\vec{k}||}\frac{2}{\pi}\tan^{-1}||\vec{k}||.$$

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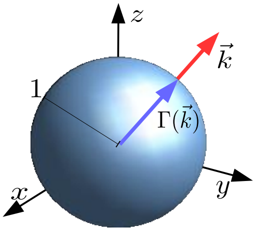

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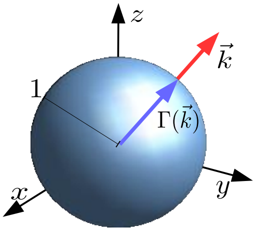

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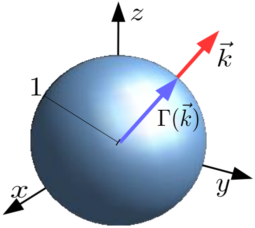

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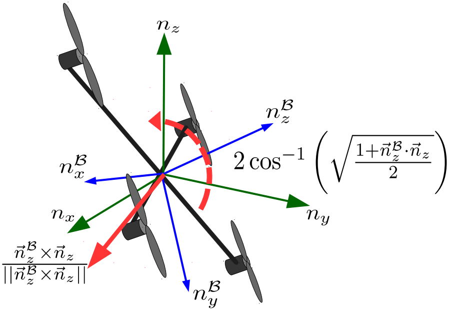
Quaternion-based recovery rotation



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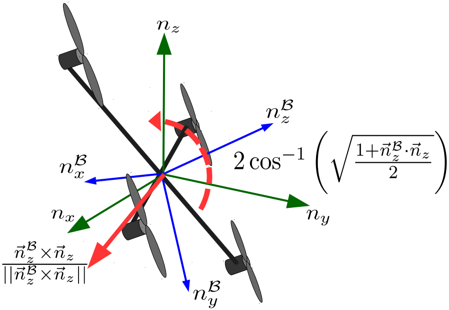

The minimal recovery rotation is computed:

$$\boldsymbol{q}_r = \boldsymbol{q} \otimes \left(\sqrt{\frac{1+\vec{n}_z^{\mathcal{B}}\cdot\vec{n}_z}{2}} - \frac{\vec{n}_z^{\mathcal{B}}\times\vec{n}_z}{||\vec{n}_z^{\mathcal{B}}\times\vec{n}_z||}\sqrt{\frac{1-\vec{n}_z^{\mathcal{B}}\cdot\vec{n}_z}{2}}\right).$$

Launching detection and identification

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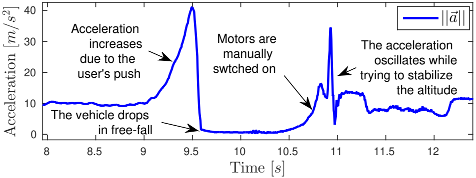

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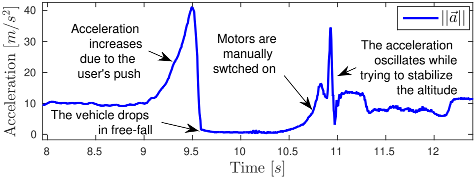

Autonomous launching detection:

$$\gamma_a := \frac{1}{2}\left(\tanh\left(\beta_a(||\vec{a}|| - \alpha_a)\right) + 1\right).$$

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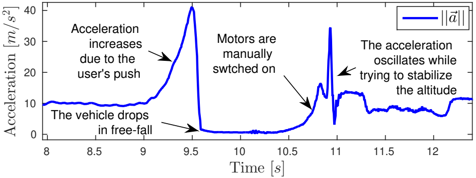

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Autonomous motor activation:

$$\gamma_\mu(t) = \tanh\left(\zeta_\mu \int_{t_0}^{t} \left(\tanh\left(\beta_\mu(||\vec{a}|| - \alpha_\mu)\right) + 1\right) dt\right),$$

$$\omega_i \approxeq \gamma_\mu(t)\sqrt{f_i/k_i}\,.$$

Switching control references

Attitude references are combined:

$$\vec{\tau}_u = -K_{d1}\vec{\Omega} - \Gamma\left(\gamma_a K_p 2\ln\left(\boldsymbol{q}_d^* \otimes \boldsymbol{q}\right) + K_{d2}\vec{\Omega}\right) + \vec{\Omega} \times J\vec{\Omega},$$

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With:

$$\boldsymbol{q}_j \coloneqq \operatorname{sign}(\pi - 2\ln(\boldsymbol{q}_{usr}^* \otimes \boldsymbol{q}))\boldsymbol{q}_{usr},$$

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The switching follows:

$$\gamma_\vartheta := \frac{1}{2}\left(\tanh\left(\beta_\vartheta(||2\ln(\boldsymbol{q}_{re})|| - \alpha_\vartheta)\right) + 1\right),$$
$$\gamma_\Omega := \frac{1}{2}\left(\tanh\left(\beta_\Omega(||\vec{\Omega}|| - \alpha_\Omega)\right) + 1\right),$$
$$\gamma_R(t) := \tanh\left(\beta_R \int_{t_0}^{t} \gamma_\vartheta \gamma_\Omega dt\right), \quad \gamma_R(t_0) = 0.$$

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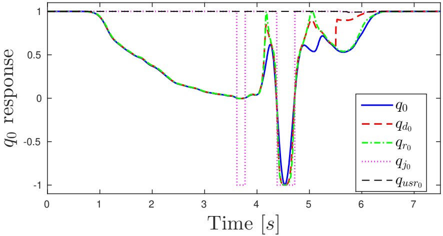

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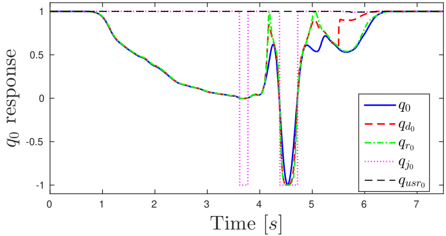

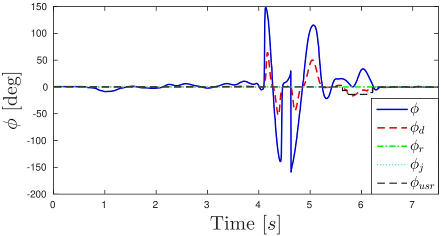

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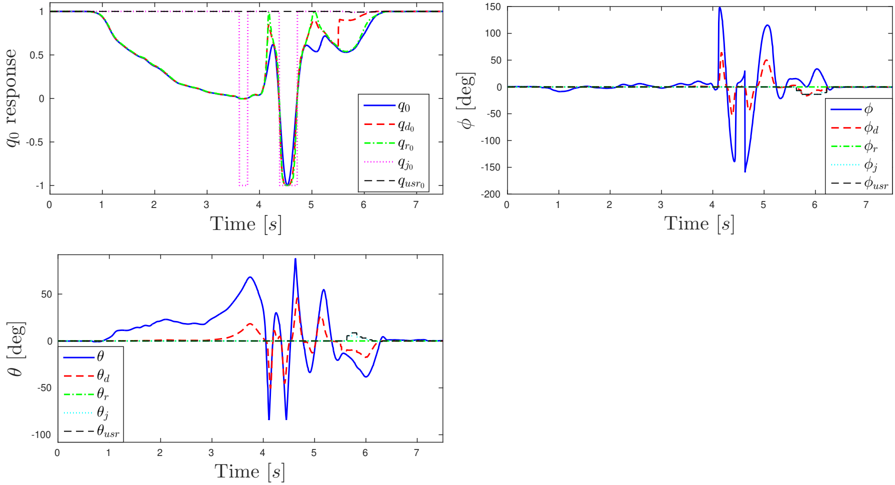

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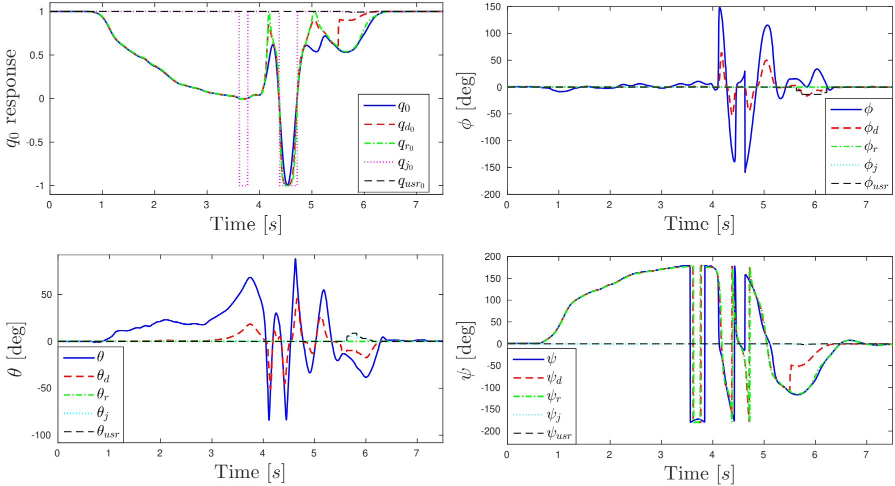

Quadrotor unconventional deployment: Experimental validation

Thank you for your attention.

Questions?