Motor and Perception Constrained NMPC for Torque-controlled Generic Aerial Vehicles

Martin Jacquet

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Summary

Objectives

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- Extend previous work with a more complete version [1]
- Define a NMPC framework for generic UAVs
- Use motor-torque level controls
- Include actuation and perception constraints

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[1] Jacquet *et al.*, "Perception-constrained and Motor-level Nonlinear MPC for both Underactuated and Tilted-propeller UAVs."

Motivations

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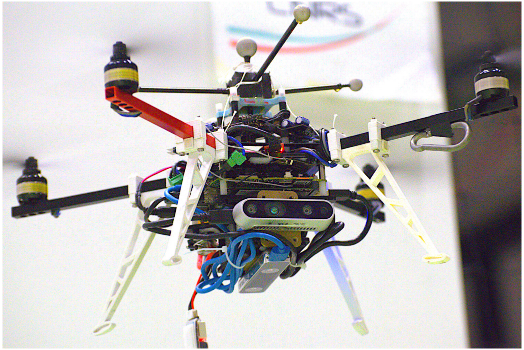
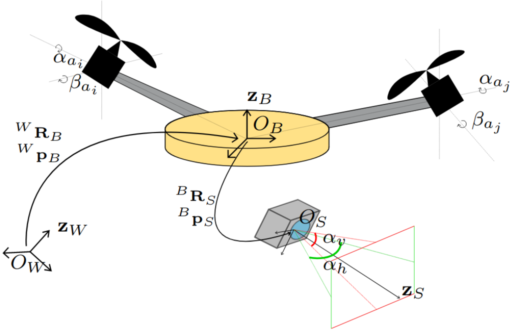
- Handle motion tasks with critical perception objectives
- Maintain visibility over a set of markers for localization
- Track a mobile phenomenon with maximum time coverage
- Maintain safety distance with the environment

Part I: System modeling

Generically Tilted Multi Rotor





System state

$$\mathbf{x}_{body} = [\mathbf{p}^\top \mathbf{q}^\top \mathbf{v}^\top \boldsymbol{\omega}^\top]^\top \in \mathbb{R}^3 \times \mathbb{S}^3 \times \mathbb{R}^3 \times \mathbb{R}^3, \tag{1a}$$

$$\mathbf{x}_{actuators} = \gamma, \text{ with } \gamma = [f_1 ... f_n]^\top, \tag{1b}$$

System input

$$\dot{\gamma} = \mathbf{u}, \tag{2}$$

The forces γ and their derivatives $\dot{\gamma}$ are linked to the rotors' speeds and accelerations doing a change of coordinates [2]

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[2] Bicego *et al.*, "Nonlinear model predictive control with enhanced actuator model for multi-rotor aerial vehicles with generic designs."

Kinematic and Dynamic equations

$$\dot{\mathbf{p}} = \mathbf{v} \tag{3a}$$

$$\dot{\mathbf{q}} = \frac{1}{2}\begin{bmatrix} 0 \\ \omega \end{bmatrix} \otimes \mathbf{q} \tag{3b}$$

$$\begin{bmatrix} \dot{\mathbf{v}} \\ \dot{\boldsymbol{\omega}} \end{bmatrix} = \begin{bmatrix} m\mathbf{I}_3 & \mathbf{O}_3 \\ \mathbf{O}_3 & \mathbf{J} \end{bmatrix}^{-1} \left(\begin{bmatrix} -mg\mathbf{z}_W \\ -\boldsymbol{\omega} \times \mathbf{J}\boldsymbol{\omega} \end{bmatrix} + \begin{bmatrix} \mathbf{q} \otimes \mathbf{G}_f\gamma \otimes \mathbf{q}^* \\ \mathbf{G}_\tau\gamma \end{bmatrix} \right) \tag{3c}$$

with $\mathbf{G}_f$ and $\mathbf{G}_\tau \in \mathbb{R}^{3\times n}$ respectively being the *force* and *torque allocation matrices* [3]

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[3] Michieletto *et al.*, "Fundamental Actuation Properties of Multirotors: Force-Moment Decoupling and Fail-Safe Robustness."

Actuation constraints

Realistic actuation constraints

$$\underline{\gamma} \leq \mathbf{x}_a \leq \overline{\gamma} \tag{4a}$$

$$\underline{\dot{\gamma}}(\gamma) \leq \mathbf{u} \leq \overline{\dot{\gamma}}(\gamma) \tag{4b}$$

Where $\underline{\dot{\gamma}}(\gamma)$ and $\overline{\dot{\gamma}}(\gamma)$ are known through an identification campaign [2]

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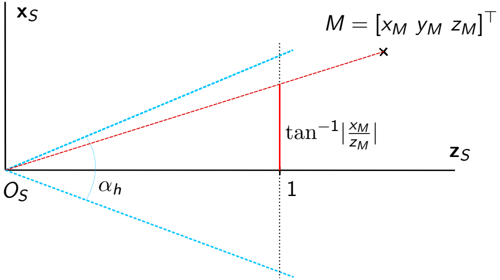
[2] Bicego *et al.*, "Nonlinear model predictive control with enhanced actuator model for multi-rotor aerial vehicles with generic designs."

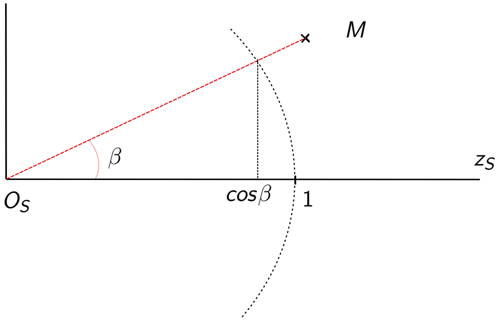
Field of View constraints



Decoupled vertical and horizontal FOV constraints:

$$|x_M/z_M| \leq \tan\frac{\alpha_h}{2}, \qquad |y_M/z_M| \leq \tan\frac{\alpha_v}{2}. \tag{5}$$

Feature tracking objective



Minimization of the angular distance between the feature and the sensor principal axis [4]

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[4] Penin *et al.*, “Vision-Based Reactive Planning for Aggressive Target Tracking While Avoiding Collisions and Occlusions.”

Optimal control problem

$$
\begin{aligned}
&\min_{\substack{\mathbf{x}_0 \dots \mathbf{x}_N \\ \mathbf{u}_0 \dots \mathbf{u}_{N-1}}} \sum_{k=0}^{N} \|\mathbf{y}_k - \mathbf{y}_{r,k}\|^2_{\mathbf{Q}} && && \text{(6a)}\\
&s.t. \quad \mathbf{x}_0 = \mathbf{x}(t) && && \text{(6b)}\\
&\qquad \mathbf{x}_{k+1} = \mathbf{f}(\mathbf{x}_k, \mathbf{u}_k), && {\scriptstyle k \in \{0, N-1\}} && \text{(6c)}\\
&\qquad \mathbf{y}_k = \mathbf{h}(\mathbf{x}_k, \mathbf{u}_k, \mathbf{p}_{M_k}), && {\scriptstyle k \in \{0, N\}} && \text{(6d)}\\
&\qquad \underline{\gamma} \leq \gamma_k \leq \overline{\gamma}, && {\scriptstyle k \in \{0, N\}} && \text{(6e)}\\
&\qquad \underline{\dot{\gamma}}_k \leq \mathbf{u}_k \leq \overline{\dot{\gamma}}_k, && {\scriptstyle k \in \{0, N-1\}} && \text{(6f)}\\
&\qquad |x_M/z_M|_k \leq \tan \alpha_h, && {\scriptstyle k \in \{0, N\}} && \text{(6g)}\\
&\qquad |y_M/z_M|_k \leq \tan \alpha_v, && {\scriptstyle k \in \{0, N\}} && \text{(6h)}
\end{aligned}
$$

with the objective vector $\mathbf{y} = [\mathbf{p}^\top \; \mathbf{q}^\top \; \dot{\mathbf{p}}^\top \; \boldsymbol{\omega}^\top \; \ddot{\mathbf{p}}^\top \; \dot{\boldsymbol{\omega}}^\top \; \cos\beta \; \dot{\cos\beta}]^\top$

Feature detection uncertainty estimation

Compute the feature position covariance $\mathbf{\Sigma}_M$ from the pixel covariance $\mathbf{\Sigma}_\mathbf{c} = \sigma^2 \mathbf{I}_8, \sigma \in \mathbb{R}^+$ of the 4 corners, using a 1st order approximation scheme [5]

$$\mathbf{\Sigma}_M = \sigma^2 (\mathbf{J}_M^\top \mathbf{J}_M)^{-1} \tag{7}$$

$\mathbf{J}_M \in \mathbb{R}^{8\times 6}$ is computed for each corner using the chain rule

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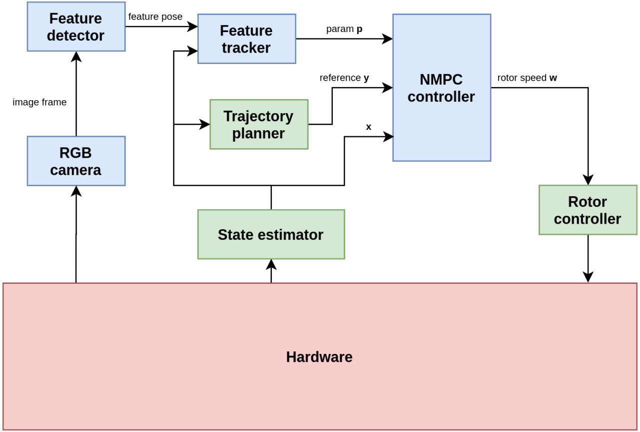
[5] Fourmy *et al.*, "Absolute humanoid localization and mapping based on IMU Lie group and fiducial markers."

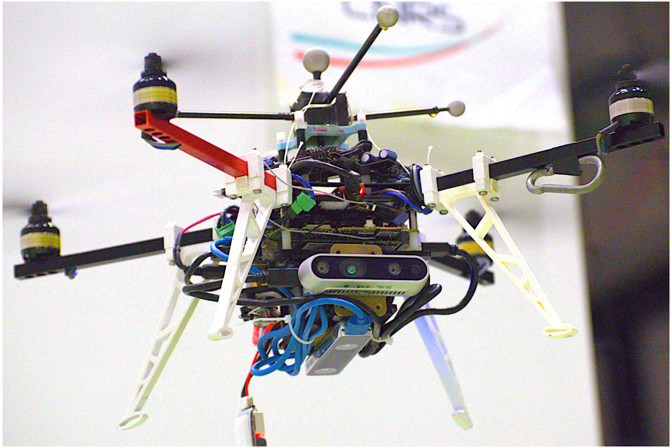
Part II: Results

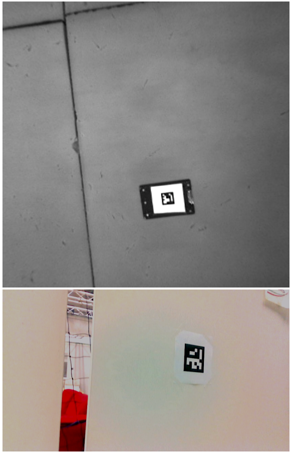
Software diagram



Open-source implementation available online: `https://redmine.laas.fr/projects/perceptive-torque-nmpc`

Hardware platform





Experiments

See video

Conclusion

Achievements

- Onboard NMPC implementation for several types of UAVs
- Actuation and perception realistic limitations
- Open source implementation
- Extended non-linear model using quaternions
- Uncertainty estimation of the feature 3D-pose from the camera measurements

Future works

- Extension to multi-robot systems
- NMPC failure handling, e.g. when constraints are not feasible
- Visual-Inertial state estimation
- Replace fiducial markers with object detection algorithms

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ANR

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ANR

AERIAL -CORE

European Commission
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Bibliography

[1] M. Jacquet, G. Corsini, D. Bicego, and A. Franchi, “Perception-constrained and motor-level nonlinear MPC for both underactuated and tilted-propeller UAVs,” in *2020 IEEE Int. Conf. on Robotics and Automation*, 2020, pp. 4301–4306.

[2] D. Bicego, J. Mazzetto, R. Carli, M. Farina, and A. Franchi, “Nonlinear model predictive control with enhanced actuator model for multi-rotor aerial vehicles with generic designs,” *Journal of Intelligent & Robotics Systems*, vol. 100, no. 3, pp. 1213–1247, 2020.

[3] G. Michieletto, M. Ryll, and A. Franchi, “Fundamental actuation properties of multirotors: Force-moment decoupling and fail-safe robustness,” *IEEE Trans. on Robotics*, vol. 34, no. 3, pp. 702–715, 2018.

[4] B. Penin, P. Robuffo Giordano, and F. Chaumette, “Vision-based reactive planning for aggressive target tracking while avoiding collisions and occlusions,” *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 3725–3732, 2018.

[5] M. Fourmy, D. Atchuthan, N. Mansard, J. Solà, and T. Flayols, “Absolute humanoid localization and mapping based on imu lie group and fiducial markers,” in *2019 IEEE-RAS 19th International Conference on Humanoid Robots*, 2019, pp. 237–243.