GRIFFIN Seminars Presentation

Perception-Aware Perching on Powerlines with Multirotors (ICRA 2022 Submitted)

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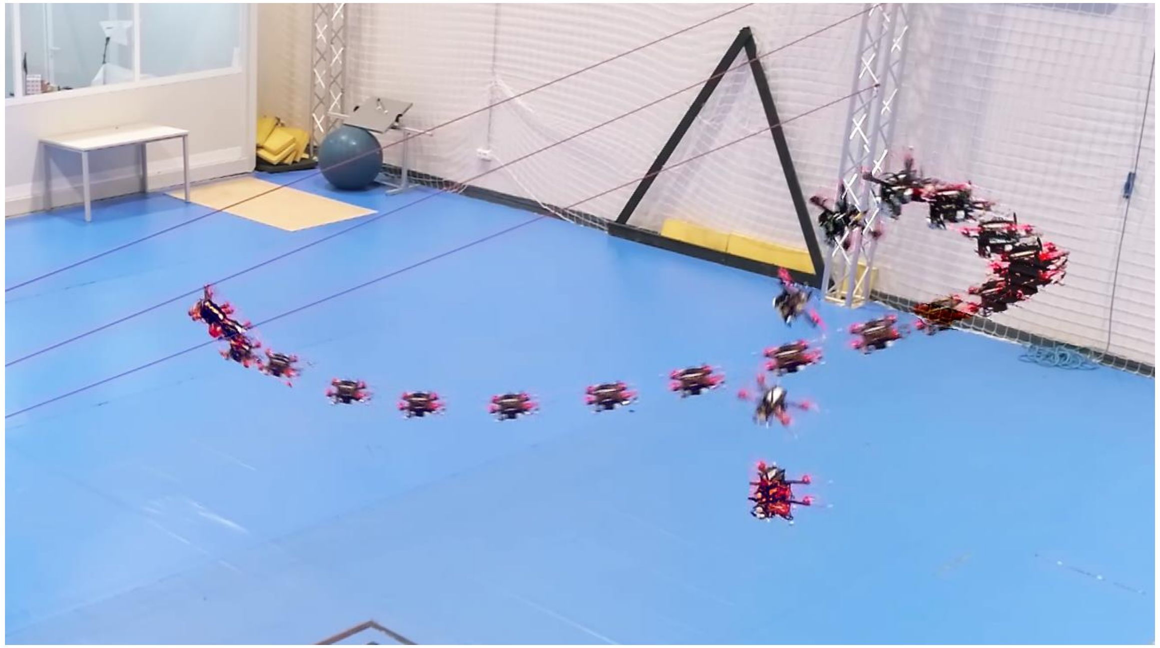
Objective

- Guide an aerial robot to a certain pose with (potentially) zero velocity
- Maximize visibility of the objective line during the maneuver
- Avoid collisions
- High versatility
  - Even for extreme cases
- Feasible maneuvers
- Missing piece: Trajectory Generator



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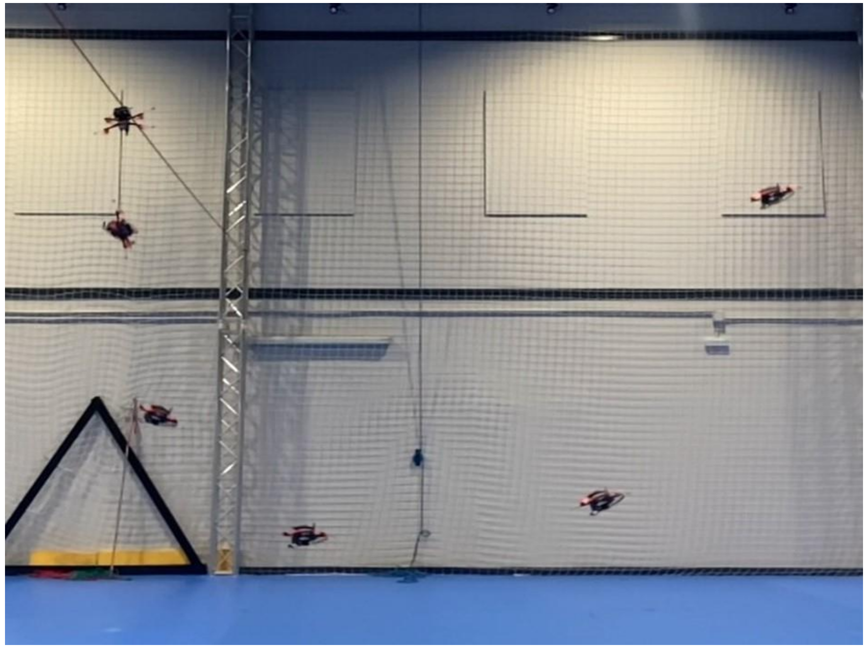


Structure of the presentation

- Mathematical modelling for the powerlines
  - For collision avoidance
  - For perception awareness
- Multirotor dynamics model
- Optimization problem formulation
- Experiments

Mathematical modelling

- Powerlines can be approximated as collections of segments
  - 185 meters -> 15 segments with 1.5cm mean error
- Line-ellipsoid distance models the collision

$$\mathbf{o}_{\breve{B}} = \mathbf{\Delta}_B \mathbf{q}_{BW} \odot (\mathbf{o}_W - \mathbf{p}_{WB}) \qquad \mathbf{l}_{\breve{B}} = \mathbf{\Delta}_B \mathbf{q}_{BW} \odot \mathbf{l}_W$$

$$\left(\left\|\mathbf{o}_{\breve{B}}\right\| - 1\right) \left\|\mathbf{l}_{\breve{B}}\right\| - (\mathbf{o}_{\breve{B}} \cdot \mathbf{l}_{\breve{B}})^2 > 0$$

- It can be extended to segments summing the following term:

$$k(\mathbf{p}_{WB}) = \lambda_1^2(\mathbf{\Delta}_B)\,\mathrm{sigm}((\|\mathbf{p}_{WB} - \mathbf{o}_W\|)))$$

Mathematical modelling

- To center the line in the image, we minimize its reprojection error

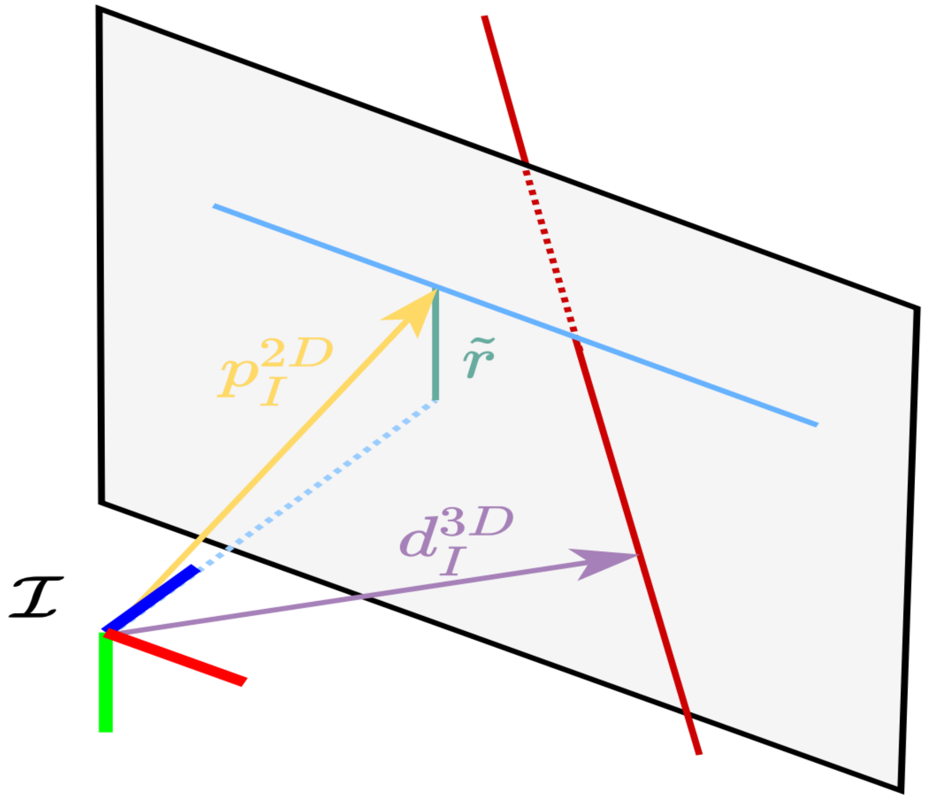
$$\mathbf{n}_C = \mathbf{o}_C \times \mathbf{l}_C \qquad \tilde{r} = \frac{\mathbf{m}^T \mathbf{n}_I}{\sqrt{n_{I,x}^2 + n_{I,y}^2}}$$

- The line is also constrained to be in front of the camera

$$d_{I,z}^{3D} > 0$$

- Finally, an additional constraint allows to work with finite segments

$$\left(\mathbf{p}_I^{3D} - \mathbf{e1}_I\right) \cdot \left(\mathbf{p}_I^{3D} - \mathbf{e2}_I\right) < 0$$



$$\mathbf{p}_I^{2D} = \mathbf{n}_I \times \left(\mathbf{e}_z \times \mathbf{n}_I\right), \quad \mathbf{d}_I^{3D} = \mathbf{l}_I \times \mathbf{n}_I$$

$$\mathbf{p}_I^{3D} = \frac{\mathbf{p}_I^{2D}}{d_{I,z}^{3D}}, \quad p_{I,z}^{3D} = \frac{n_{I,x}^2 + n_{I,y}^2}{d_{I,z}^{3D}}$$

Multirotor dynamics model

- Rigid body with mass and inertia
- The actuations are ramps in the different single rotor thrusts
  - This allows to account for dynamics of the motors
- No drag modelling since it is compensated online

$$\dot{\mathbf{x}} = \begin{bmatrix} \dot{\mathbf{p}}_{WB} \\ \dot{\mathbf{q}}_{WB} \\ \dot{\mathbf{v}}_{W} \\ \dot{\boldsymbol{\omega}}_{B} \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} \mathbf{v}_W \\ \mathbf{q}_{WB} \odot \left[0, {\boldsymbol{\omega}_B}^T/2\right]^T \\ \frac{1}{m}\mathbf{q}_{WB} \odot \boldsymbol{\Gamma}_B + \mathbf{g}_W \\ \mathbf{J}^{-1}(\mathbf{M}\boldsymbol{\gamma} - \boldsymbol{\omega}_B \times \mathbf{J}\boldsymbol{\omega}_B) \\ \boldsymbol{u} \end{bmatrix} \in \mathbb{R}^{17}$$

$$\boldsymbol{\Gamma}_B = \begin{bmatrix} 0 \\ 0 \\ \sum \boldsymbol{\gamma} \end{bmatrix}$$

$$\mathbf{M} = \begin{bmatrix} {\mathbf{r_y}}^T \\ -{\mathbf{r_x}}^T \\ \kappa {\mathbf{r_d}}^T \end{bmatrix}$$

Optimization problem formulation

- Time is also an optim. Variable
- Reach final spot
- Avoid collisions
- Maintain minimum height
- Maximize line visibility

$$\tilde{\mathbf{y}}_k = \begin{cases} \left[\left(\boldsymbol{\gamma}_k \frac{T}{N} + \mathbf{u}_k \frac{T^2}{2N^2}\right) \mathbf{w}_k \, \widetilde{r}_k\right]^T & k \in [0, N-1] \\ \left[\widetilde{\mathbf{p}}_k \, \widetilde{\mathbf{q}}_k \, \widetilde{\mathbf{v}}_k \, \widetilde{\mathbf{w}}_k\right]^T & k = N \end{cases}$$

$$\begin{aligned}
\min_{\substack{\boldsymbol{u}_0 \ldots \boldsymbol{u}_{N-1} \\ T}} \quad & \sum_{k=0}^{N} \|\tilde{\mathbf{y}}_k\|^2_{\mathbf{Q}_k} \\
\text{s.t.} \quad & \mathbf{x}_0 = \mathbf{x}_{init} \\
& T_{min} \leq T \leq T_{max} \\
& \mathbf{x}_{k+1} = \mathbf{f}(\mathbf{x}_k, \boldsymbol{u}_k) & \forall k \in [0, N-1] \\
& z_{min} \leq p_{WB,z} & \forall k \in [0, N] \\
& 0 \leq \boldsymbol{\gamma} \leq \gamma_{max} & \forall k \in [0, N] \\
& u_{min} \leq \boldsymbol{u} \leq u_{max} & \forall k \in [0, N-1] \\
& 0 < lc & \forall k \in [0, N] \\
& sv < 0 & \forall k \in [0, N] \\
& 0 \leq ca_i & \forall k \in [0, N] \\
& & \forall i \in [0, N_L - 1]
\end{aligned}$$

Optimization problem formulation

- Practical considerations
  - Perception constraints are soft constraints
  - Perception terms have an exponential decay to not impede the maneuver
  - Time variable optimization problems suffer from bad linearization
    - Still can be treated with modern solvers as ForcesPro
  - The same NLP can be used to compute a posterior recovery trajectory
    - Only trajectories with a valid recovery are considered safe to follow
  - Typically, 30 shooting nodes were enough to compute the maneuvers
    - Trajectories can be computed onboard (0.6-5 s)

Experiments

- Control of the quadrotor is done with NMPC+L1 adaptation (t.b.r)
  - Same model as before, but fixed time horizon
  - 100 Hz
- Two kinds of experiments
  - Inspection experiments to validate the modelling inside a controller
  - Perching guidance experiments to validate the whole scheme

Experiments

(Video)

Conclusions

- Lessons learnt
  - The starting point of the maneuver is of high importance
    - How do we include it in the optimization problem?
  - Perception awareness requires some freedom in the control
    - Gimbal, multiple cameras, non-fixed perching mechanism, etc.
- How can this be applied to ornithopters?
  - NMPC control for trajectory following
  - Biggest challenge: Aerodynamic effects
  - Positive outcomes: can model actuator delays, can anticipate for the whole horizon, can reward gliding vs flapping, etc.

Questions