Automation and Robotics Engineering

Field and Service Robotics: Final project

Aerial Robots: Quadrotor Control with External Disturbances Estimations and Ground and Ceiling Effects Simulation

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Contents

Aim of the project

Hypothesis:

- Perfect knowledge of current pose of the quadrotor in every time instant
- Well-known environment with several obstacles
- External disturbances and several physical effects

Goals:

- Simulate the flight control of a quadrotor with different approaches
- Analyze the performance for each approach
- Analyze advantages and drawbacks for each approach

1. Simulation Environment and Elements

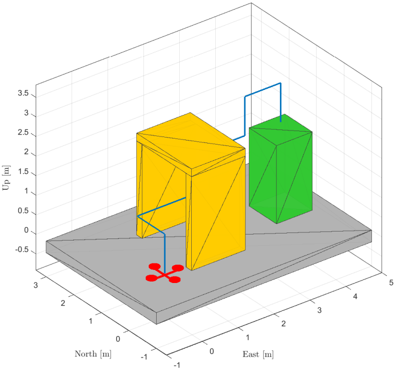
1.1. Simulation Tools and Environment

MATLAB R2024b & Simulink

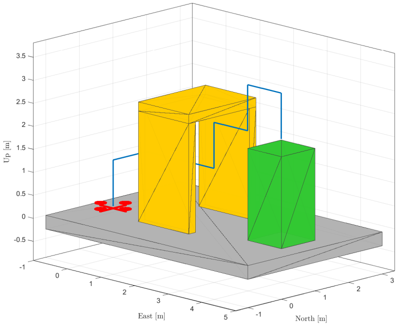
1.2. X3D-BL Quadrotor

Symbols	Definitions	Values	Units
m	Mass	0.5	kg
I_{xx}, I_{yy}	Moment of inertia about the x and y axis	0.0023	$kg \cdot m^2$
I_{zz}	Moment of inertia about the z axis	0.00509	$kg \cdot m^2$
h	Height	100	mm
ρ	Radius of blade propeller	100	mm
l	Distance between the axis of rotation of the rotors and the center of the mass	170	mm
d	Distance between adjacent propeller axis	240	mm
w	Maximum width with propeller	570	mm

1.3. Environment Scenario



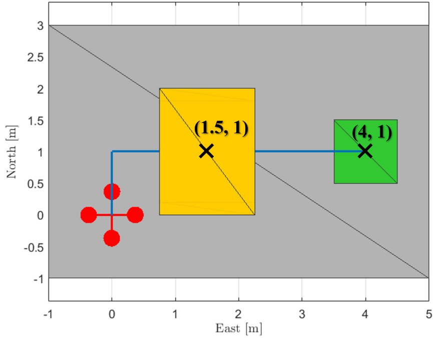
Diagonal - front view



Diagonal - back view

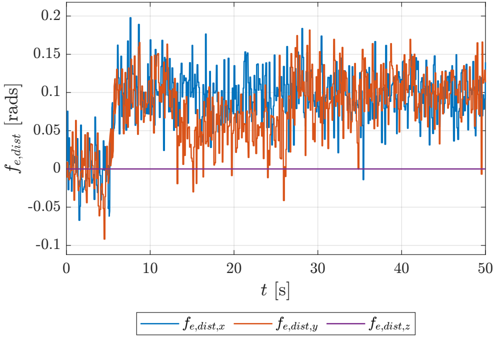
Click here to watch the video

1.3. Environment Scenario



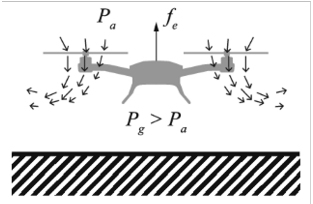
Top view

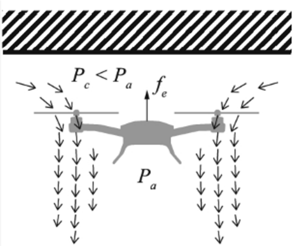
1.3. Environment Scenario: Wind external disturbance



After 5 s:**noisy wind effect** in the *xy* plane linearly increases to a mean value of $(f_{e,dist,x}, f_{e,dist,y}, f_{e,dist,z}) \approx (0.1, 0.1, 0)\,\mathrm{N}$, then remaining constant.

1.3. Environment Scenario: Ground and Ceiling Effects





Ground Effect: $$\frac{u_{T,\mathrm{IGE}}}{u_{T,\mathrm{OGE}}} = k_{GE} = \frac{1}{1 - \left(\frac{\rho}{4z}\right)^2 - \frac{z\rho^2}{\sqrt{(d^2+4z^2)^3}} - \frac{z\rho^2}{2\sqrt{(2d^2+4z^2)^3}}}$$

Ceiling Effect: $$\frac{u_{T,\mathrm{ICE}}}{u_{T,\mathrm{OCE}}} = k_{CE} = \frac{1}{2} + \frac{1}{2}\sqrt{1 + \frac{1}{8\hat{z}^2}}, \quad \text{where } \hat{z} = z/\rho.$$

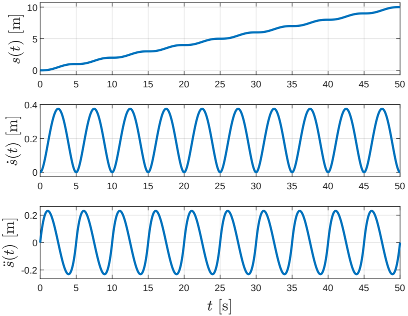
1.4. Trajectory planner: Time law

- Individual rectilinear trajectory:

$$s(t) = a_5 t^5 + a_4 t^4 + a_3 t^3 + a_2 t^2 + a_1 t + a_0, \qquad \text{s.t:}$$

$$\begin{aligned} s(t_0) &= s(0) = 0, & \dot{s}(t_0) &= 0, & \ddot{s}(t_0) &= 0, \\ s(t_f) &= s(5) = 1, & \dot{s}(t_f) &= 0, & \ddot{s}(t_f) &= 0. \end{aligned}$$

- Overall time law and its time derivatives:



1.4. Trajectory planner: Geometric path

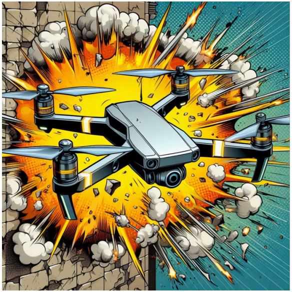
- Parametric representation of the individual rectilinear paths composing the overall trajectory, its velocity and acceleration:

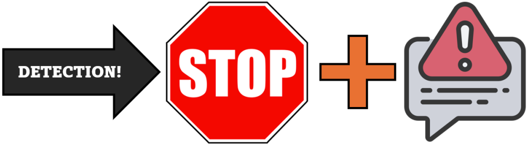
$$p(s) = p_i + \frac{s}{\|p_f - p_i\|}(p_f - p_i), \qquad \dot{p}(s) = \frac{\dot{s}}{\|p_f - p_i\|}(p_f - p_i),$$

$$\ddot{p}(s) = \frac{\ddot{s}}{\|p_f - p_i\|}(p_f - p_i)$$

- Overall positional trajectory $p_d(t)$ starting from $p_0 = (0,\, 0,\, 0.2)\,\mathrm{m}$ and ending at the top of the cylindrical column in $p_F = (4,\, 1,\, 2.2)\,\mathrm{m}$, remaining in hovering for further $5\,\mathrm{s}$

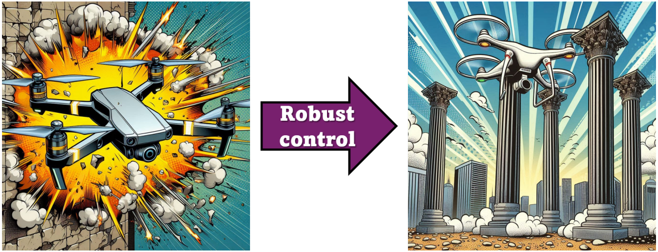
1.5. Collision detector



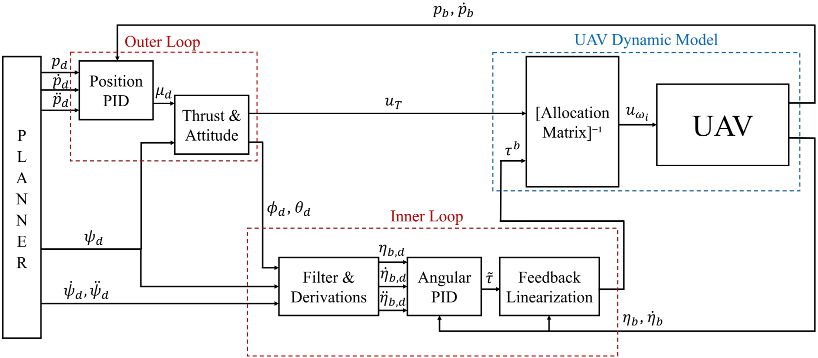


2. Controllers

- **Control approaches**:
  - Hierarchical
  - Geometric
  - Passivity-based
- **Common architecture**: Inner & Outer loops
- **Ideal conditions**: no external disturbances, physical effects



2.1. Hierachical controller



Advantages & Drawbacks

Advantages:

- Two PID sub-controllers (inner and outer loops): tuning the gains variable one can deduct easily the effects on control action

- Stability proved just employing PD+ sub-controllers (even if in practice, an integral term is required)

Drawbacks:

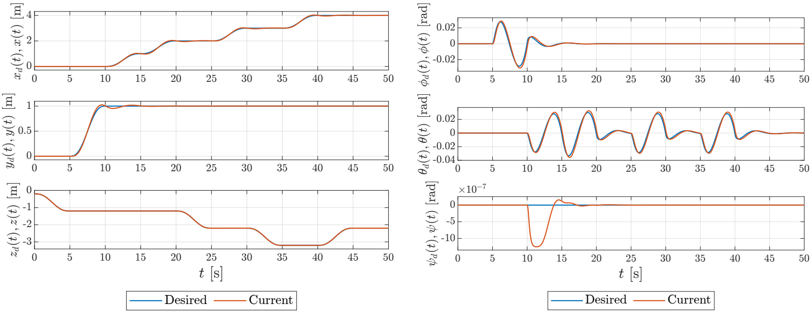
- Implementation of a "Filtering & derivation" operation of the angular references

- Partial Feedback linearization: the control system lacks robustness with respect to model uncertainties

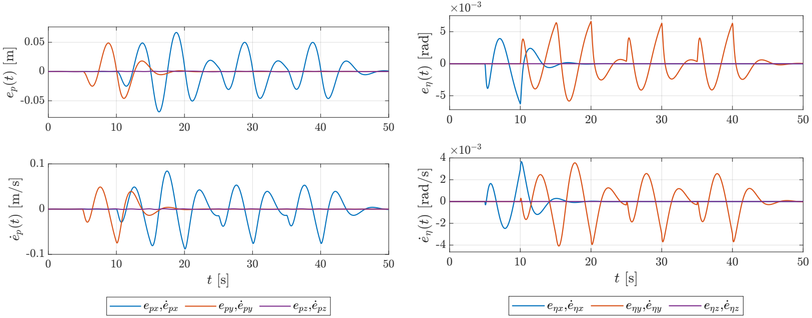
- Sensitivity to representation singularities

Desired & effective pose

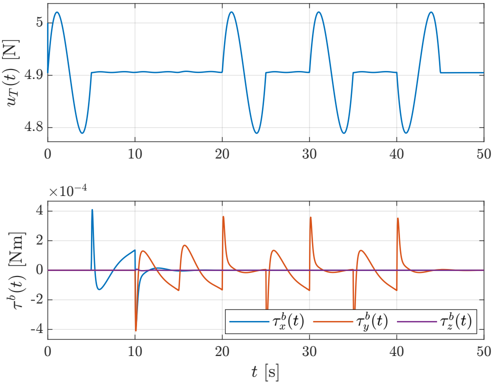
$K_p = K_e = \begin{bmatrix} I_3 & I_3 \end{bmatrix}$:



Linear & angular errors



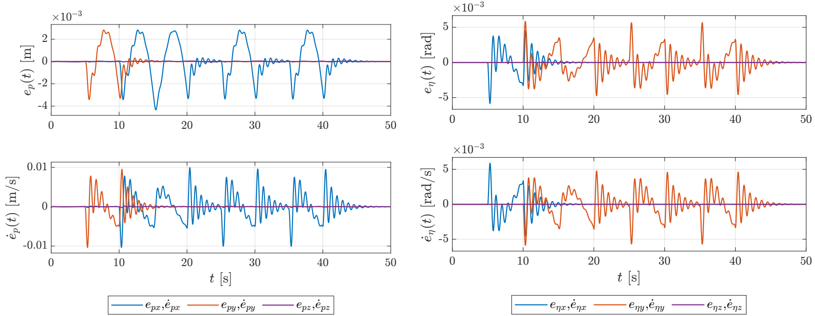
Total thrust & torques



Click here to watch the UAV animation

Linear & angular errors

$$K_p = 10\left[I_3 \quad I_3\right], \qquad K_e = 100\left[I_3 \quad I_3\right]:$$



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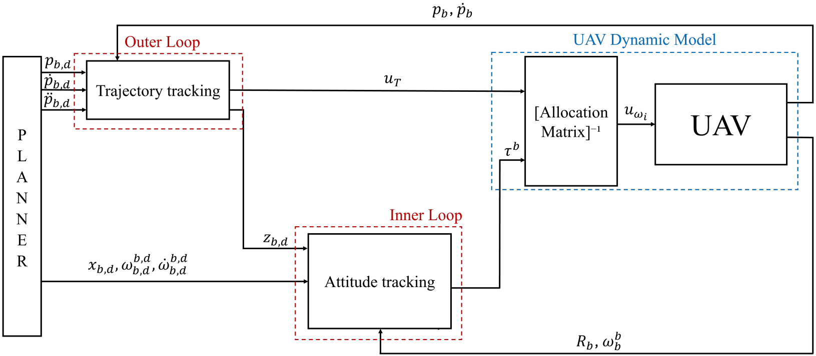
2.2. Geometric controller



Advantages & Drawbacks

Advantages:

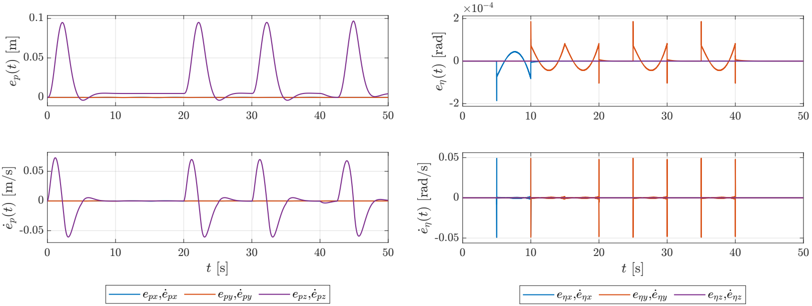
- Two linear sub-controllers advantages (already explained)
- No "Filtering & derivation" operation requested
- No representation singularities

Drawbacks:

- Lack of robustness due to Partial Feedback linearization (already explained)
- Exponential stability of the closed-loop system can be proven only if the initial attitude error is less than 90°

Linear & angular errors

$K_p = K_v = K_r = K_w = I_3$:



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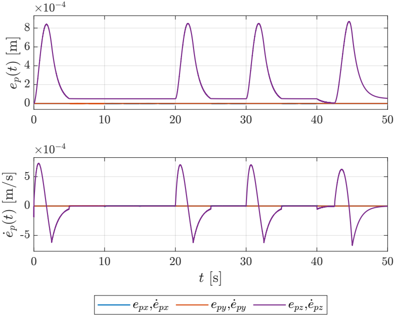
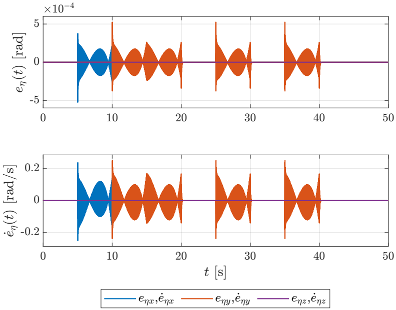
Linear & angular errors

$K_p = K_v = 100I_3, \qquad K_r = 10I_3, \qquad K_w = I_3$:





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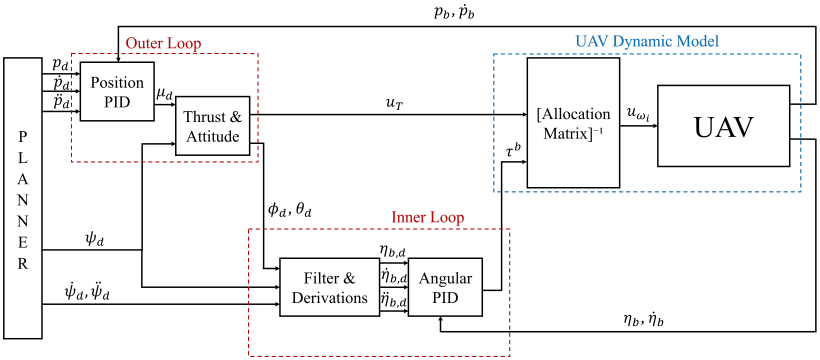
2.3. Passivity-based controller



Advantages & Drawbacks

Advantages:

- Two linear controllers advantages (already explained)

- Robustness with respect to model uncertainties, since feedback linearization is not involved

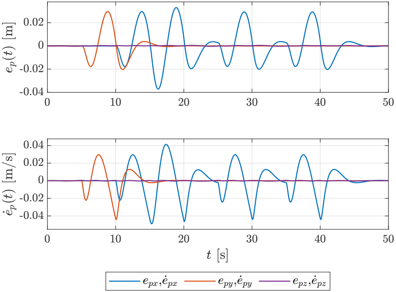
Drawbacks:

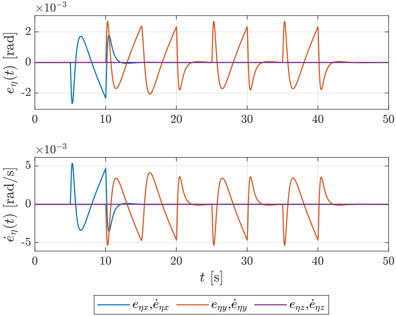
- Implementation of a "Filtering & derivation" operation of the angular references (already explained)

- Sensitivity to Representation singularities (already explained)

Linear & angular errors

$$K_p = \begin{bmatrix} I_3 & I_3 \end{bmatrix}, \qquad D_0 = I_3, \qquad K_0 = \sigma D_0 = I_3:$$

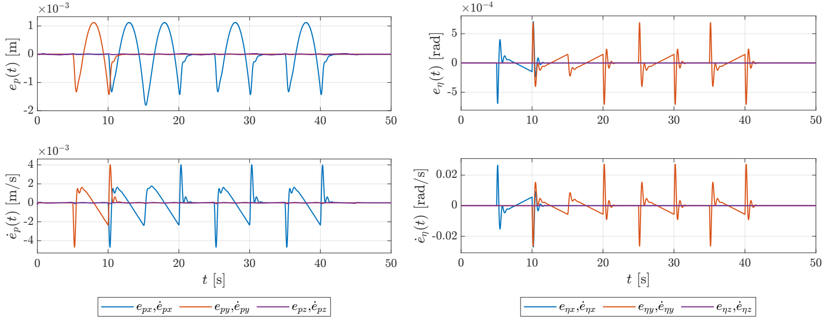




Click here to watch the UAV animation

Linear & angular errors

$$K_p = \begin{bmatrix} 20I_3 & 10I_3 \end{bmatrix}, \qquad D_0 = I_3, \qquad K_0 = \sigma D_0 = 20I_3:$$



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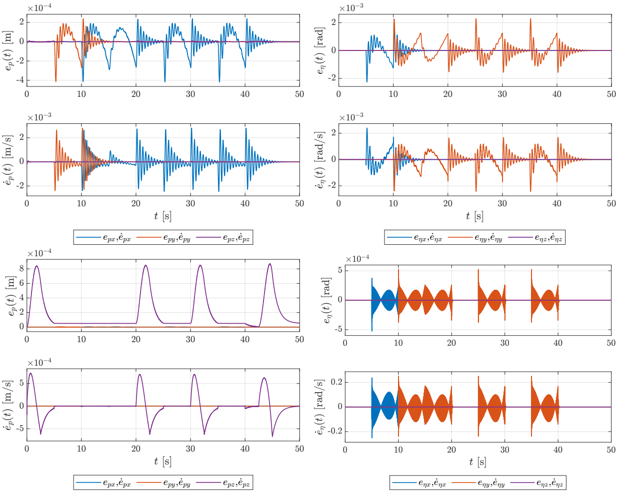
2.4. Impact of "Filter and Derivative" Block on system performance

- Hierarchical controller:
    - $w_c = 10\,\mathrm{rad/s} \rightarrow$ limit the control performance
    - $w_c = 30\,\mathrm{rad/s}$ allows finding new optimal gains ($K_p = \begin{bmatrix} 100I_3 & 10I_3 \end{bmatrix}$) and achieving performance comparable to the Geometric controller

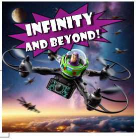
Enhanced Hierarchical control VS Geometric control

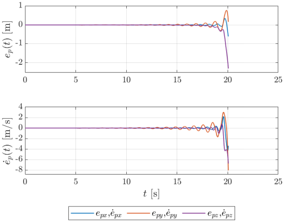


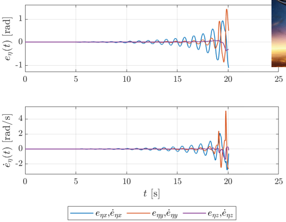
Click here to watch the Enhanced Hierarchical control

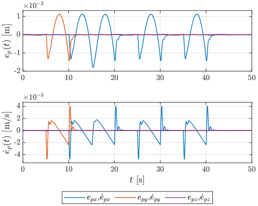
2.5. Robustness comparison

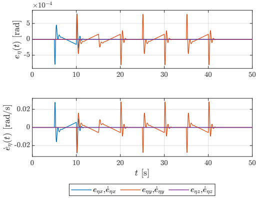
- Test: $I_b \times 5 \rightarrow$ animations: Hierarchical, Passivity-based controls
- Test: $I_b \times 50 \rightarrow$ animations: Passivity-based control











3. Momentum-based Estimator

Linear relationship between the external wrench and its estimation in the Laplace domain:

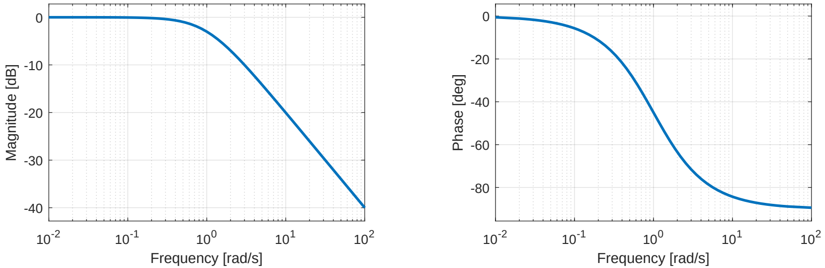
$$\mathcal{L}\left[\begin{bmatrix}\hat{f}_e \\ \hat{\tau}_e\end{bmatrix}\right] = G(s)\,\mathcal{L}\left[\begin{bmatrix}f_e \\ \tau_e\end{bmatrix}\right] = \mathrm{diag}(G_1, G_2, \ldots, G_6)\,\mathcal{L}\left[\begin{bmatrix}f_e \\ \tau_e\end{bmatrix}\right]$$

with $G(s) \in \mathbb{C}^{6\times 6}$ diagonal matrix of transfer functions $G_i(s)$, first-order low-pass filters:

$$G_i(s) = \frac{w_c}{s + w_c}, \qquad i = 1, \ldots, 6$$

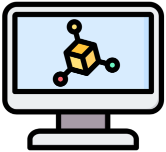
where $w_c = 1$ is the chosen cut-off frequency.

- Bode diagrams of $G_i(s)$:



4. Simulations and considerations

All the elements introduced previously are taken into account for the purpose of the simulations.



Simulation Environment & Elements

+

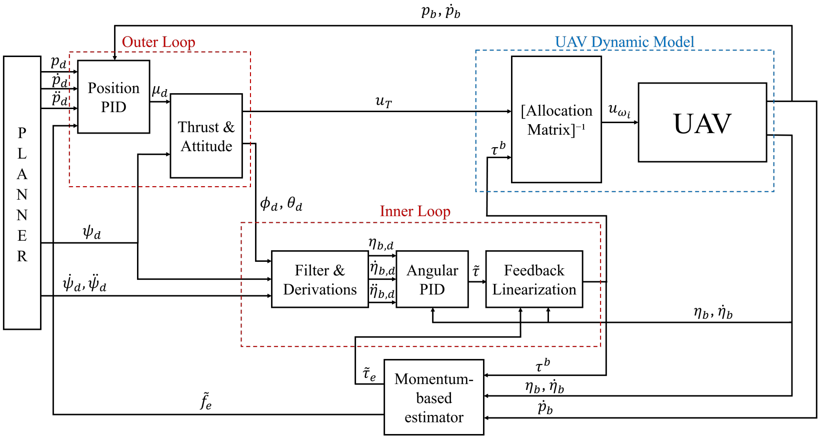
Position/Angular PID

Controllers

+

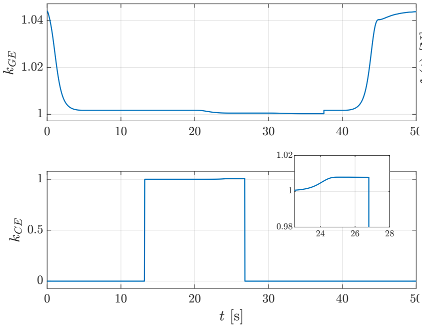
Moment-based Estimator

4.1. Hierarchical estimator-based control

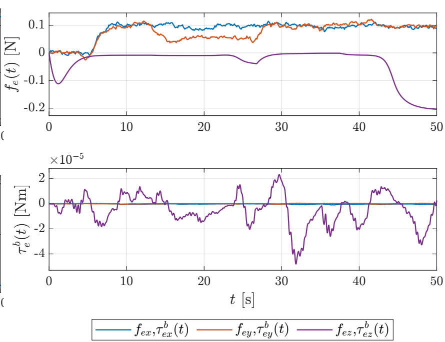


Ground and Ceiling effects Ratios & External Forces Estimation

$$K_p = 10 \begin{bmatrix} I_3 & I_3 \end{bmatrix}, \qquad K_e = 100 \begin{bmatrix} I_3 & I_3 \end{bmatrix}:$$

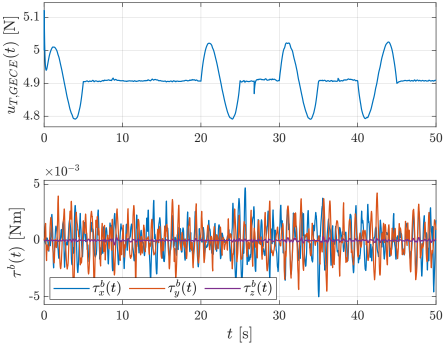


(a) Ground and ceiling effects ratios

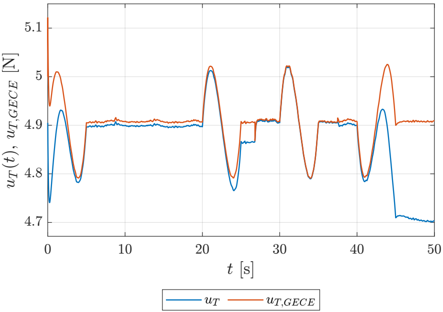


(b) External generalized forces estimate

Total thrust & torques

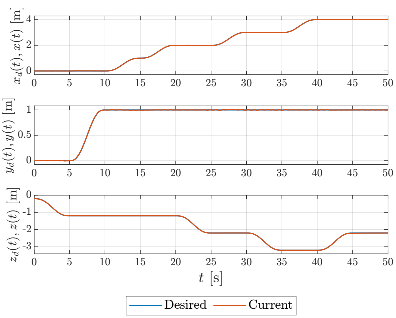


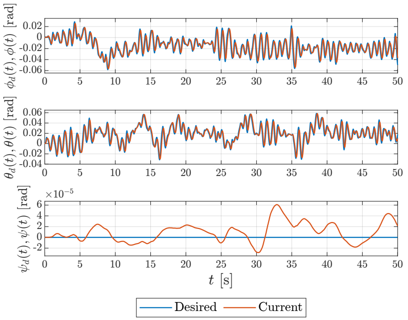
(a) Total thrust and torques.



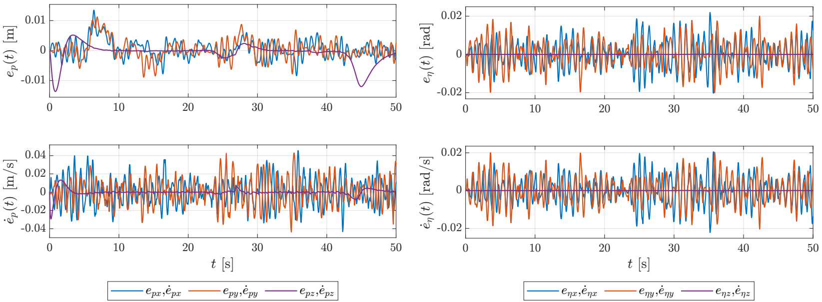
(b) Total thrusts: generated solely by the control input and acting on the drone

Desired & effective pose





Linear & angular errors



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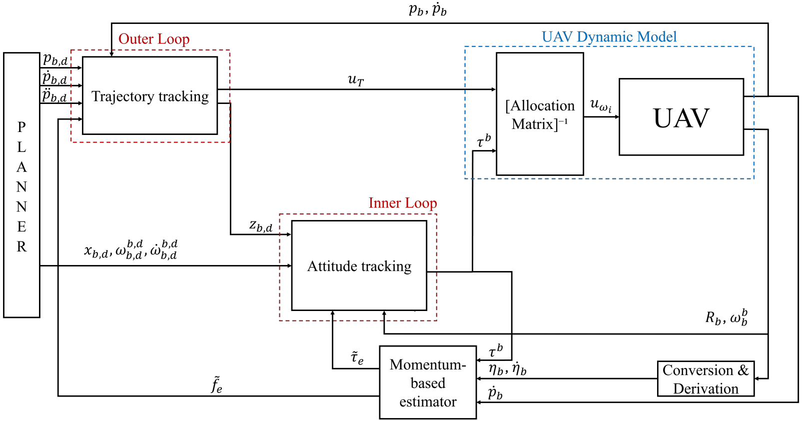
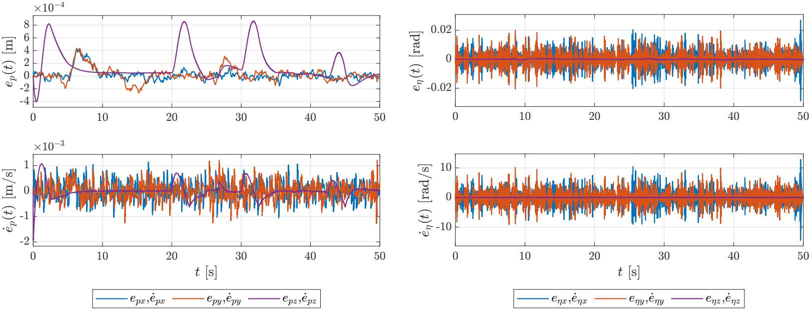
4.2. Geometric estimator-based control



Linear & angular errors

$K_p = K_v = 100 I_3, \qquad K_r = 10 I_3, \qquad K_w = I_3$:



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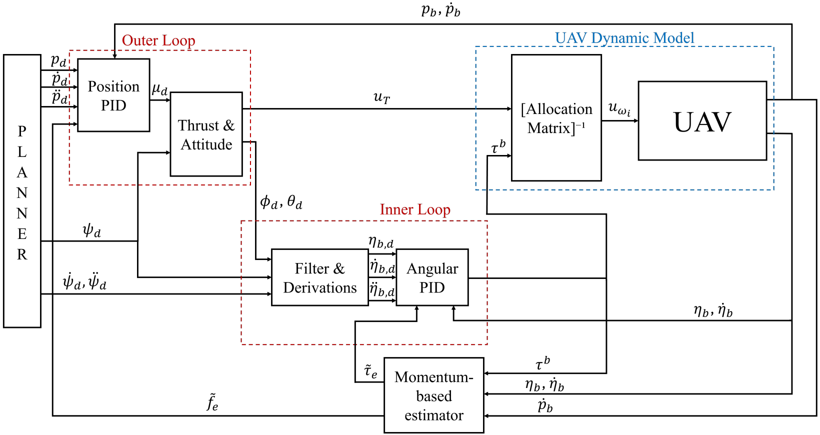
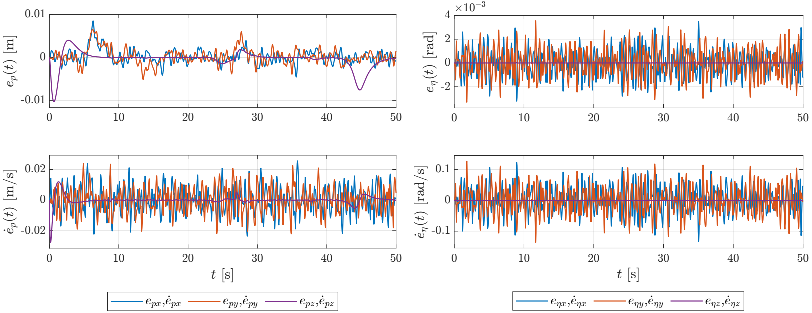
4.3. Passivity-and-estimator-based control



Linear & angular errors

$$K_p = \begin{bmatrix} 20I_3 & 10I_3 \end{bmatrix}, \qquad D_0 = I_3, \qquad K_0 = \sigma D_0 = 20I_3:$$



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5. Conclusions

Which controller delivers the best performance?

- In an ideal scenario $\rightarrow$ **Geometric controller**
- In a realistic scenario:

  $\rightarrow$ **Geometric controller** for positional control

  $\rightarrow$ **Passivity-based controller** for angular control

What if model uncertainty is considered?

Both theory and the analysis under ideal conditions clearly indicate that the **Passivity-based controller** consistently achieves superior performance.


THANK YOU
FOR YOUR
ATTENTION