Aggressive Maneuver Planning and Control of a Multi-UAV and Payload System after a Failure

Master Thesis Defense

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14 October 2025

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Introduction & Motivation

- UAVs (Unmanned Aerial Vehicles) are widely used in agriculture, delivery, surveillance, inspection, and rescue missions.
- Recent advances in autonomous control have enabled complex multi-UAV operations.
- Cooperative UAVs can share tasks, transport heavier payloads, and improve safety and efficiency.

Photo credits: James Gibson, DRONE EFT & Will Porada on Unsplash

Problem Statement & Motivation

When one UAV in a cooperative transport system fails, the sudden load redistribution creates an immediate and dangerous swinging motion of the payload. Without a specialized control strategy, these oscillations can escalate, leading to mission failure or collisions.

- How to rapidly suppress severe payload oscillations after a UAV failure?
- How to maintain coordinated and stable flight among the remaining UAVs?
- How to ensure the system can transition back to safe and continue the mission after stabilization?

Objectives & Research Contributions

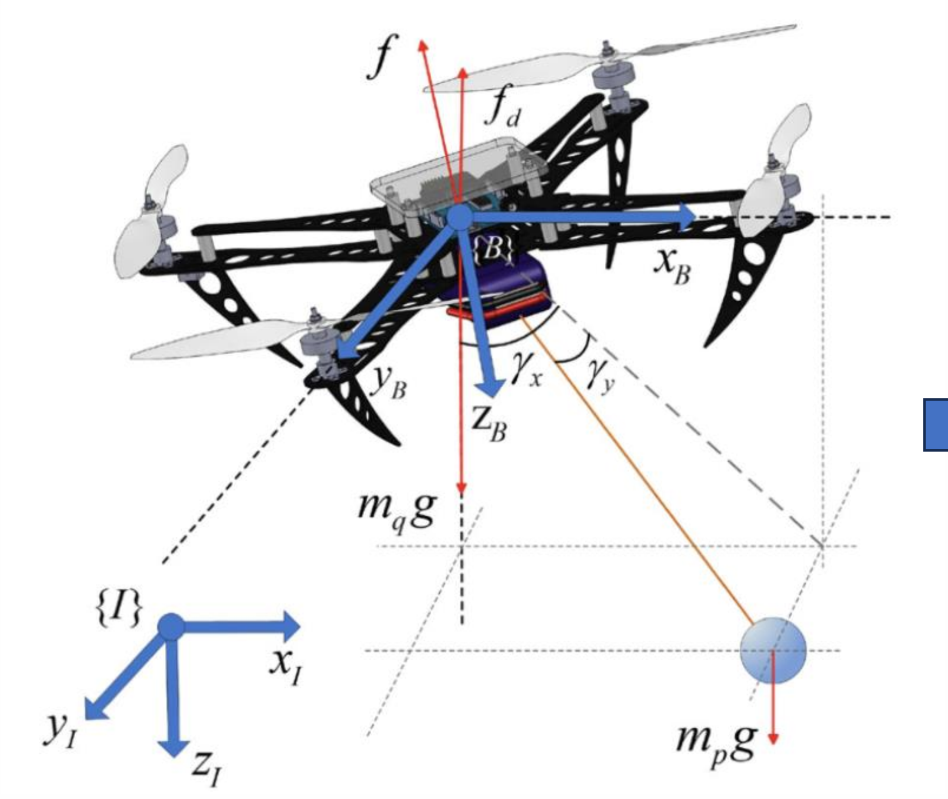
Objectives of the thesis

- Develop and test algorithms that allow the remaining UAVs to:
  - Reconfigure their formation to maintain control of the payload.
  - Dampen oscillations rapidly and restore stability through aggressive maneuvers.
  - Implement and validate these strategies in simulation like (ROS2/Gazebo and MATLAB)

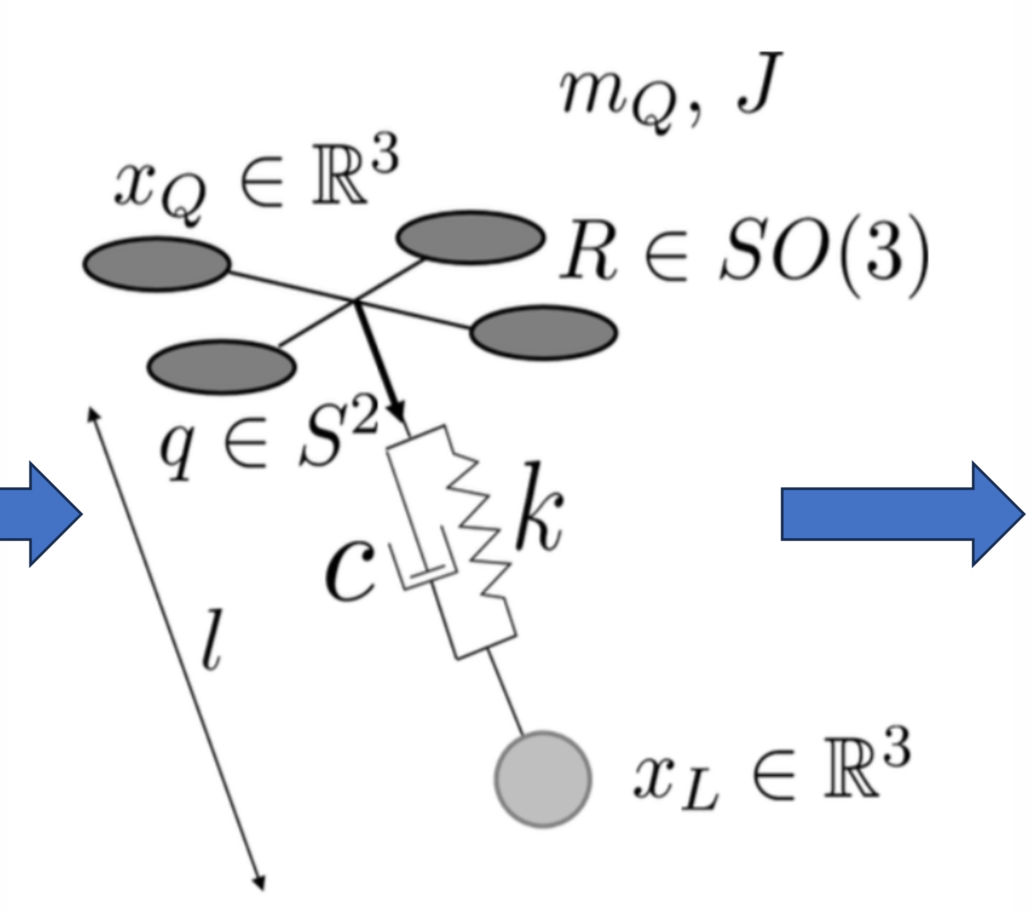
Main Contribution

- Proposed a two-phase control framework for post-failure stabilization and tracking with remaining UAV and payload system.
- Introduced a fault-tolerant optimization strategy that enables aggressive stabilization for quick recovery.
- Demonstrated through simulations that the approach achieves rapid oscillation damping and trajectory tracking after stabilization.

State of the Art



Single-UAV cable-suspended payload system



Elastic cable model for UAV payload system

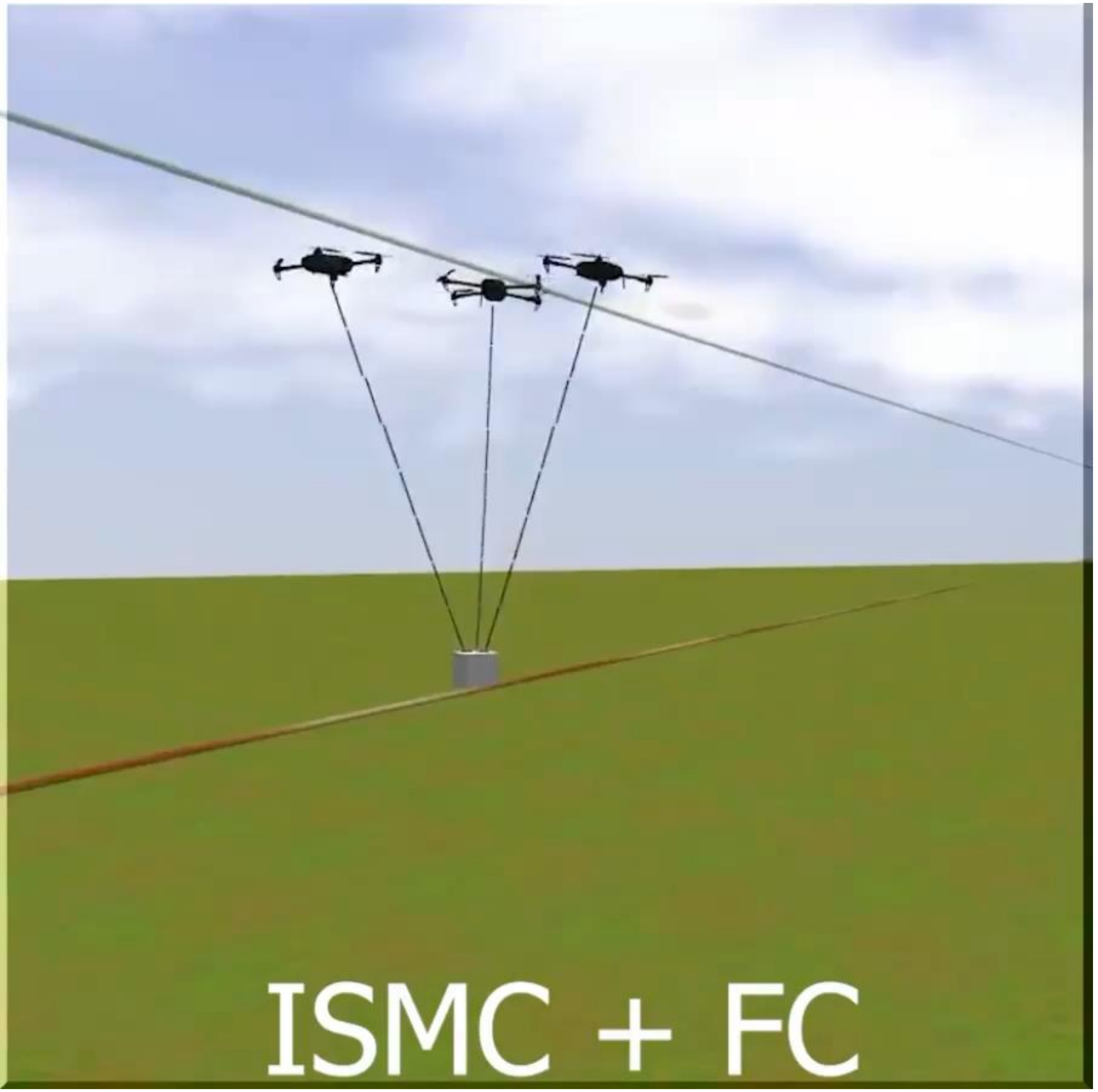
Multi UAVs payload system

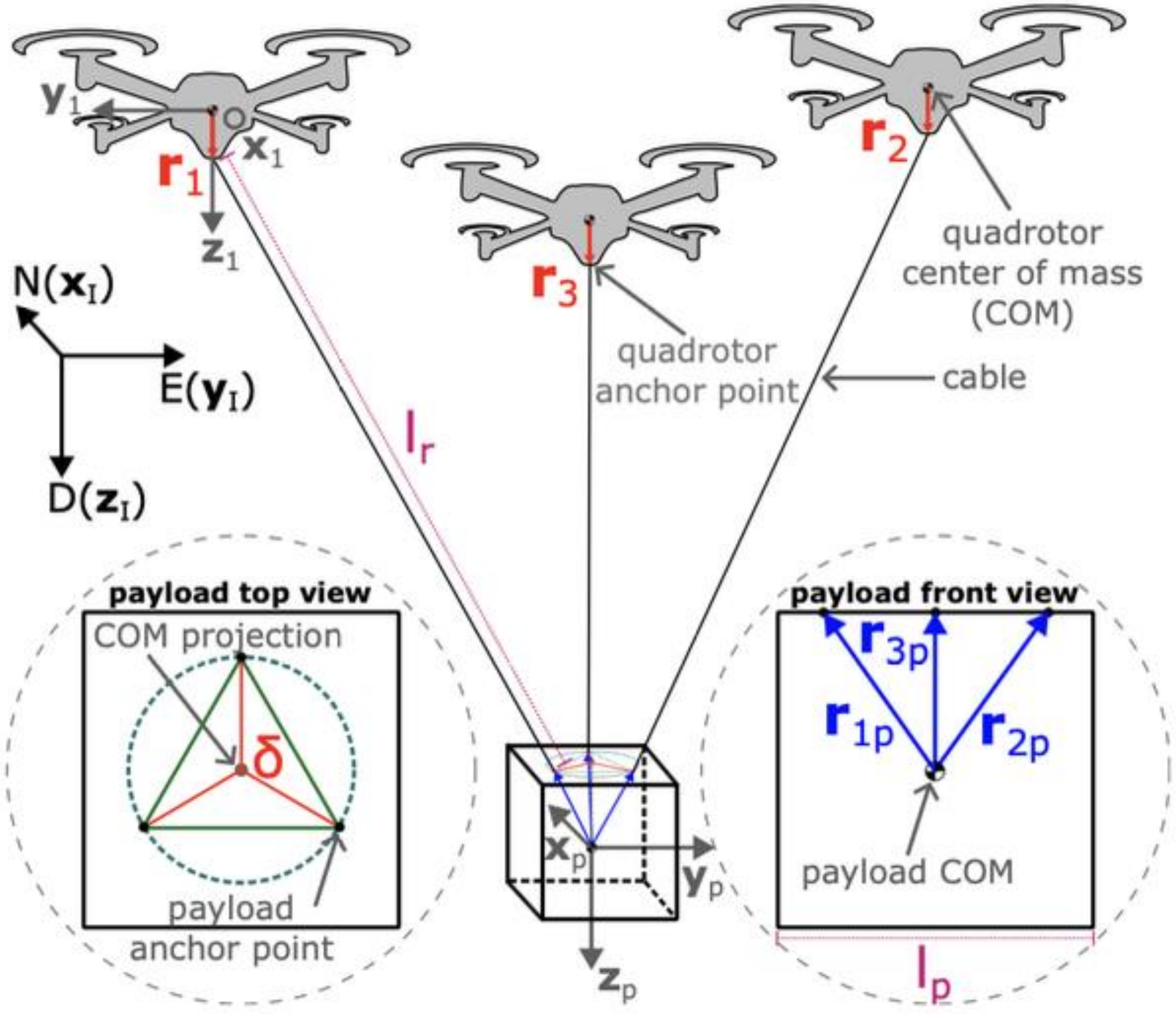
Xian, B., Wang, S. & Yang, S. (2019). Nonlinear adaptive control for an unmanned aerial payload transportation system: theory and experimental validation. Nonlinear Dynamics, 98, 1745–1760

Kotaru, P., Wu, G. & Sreenath, K. (2017). Dynamics and control of a quadrotor with a payload suspended through an elastic cable. In 2017 American Control Conference (ACC), 3906–3913, IEEE.

Alothman, Y.N. (2018). Optimal control of multiple quadrotors for transporting a cable suspended payload.

State of the Art





Delbene, A. & Baglietto, M. (2024). Recovery techniques for a multi-uav system transporting a payload. In 2024 IEEE 20th International Conference on Automation Science and Engineering (CASE), 559 – 566, IEEE.

Delbene, A. & Baglietto, M. (2024). Cables tension modeling for multi-uav payload transportation. In 2024 IEEE 20th International Conference on Automation Science and Engineering (CASE), 212–218, IEEE.

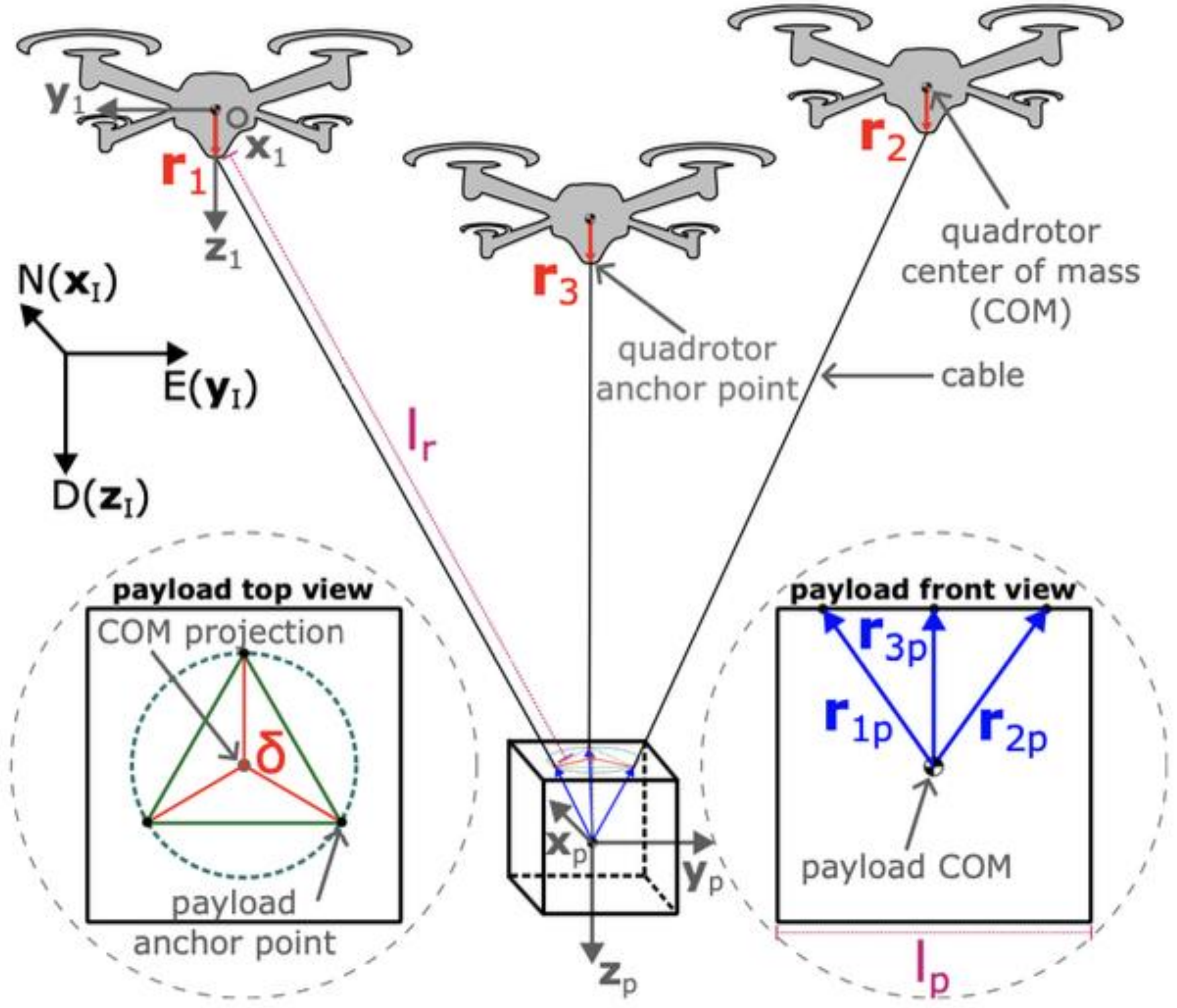
State of the Art

Architectural Similarities to Present Thesis:

- ➤ Spring-damper cable modeling approach
- ➤ Fault-tolerant controller
- ➤ Recovery methodology
- ➤ Dynamic formulation

Key Differences:

- Anchor points: Off-COM vs. COM-based present thesis.
- Control method: PID + ISMC + CB vs. NMPC optimization
- Recovery strategy: Rule-based vs. Aggressive Stabilization



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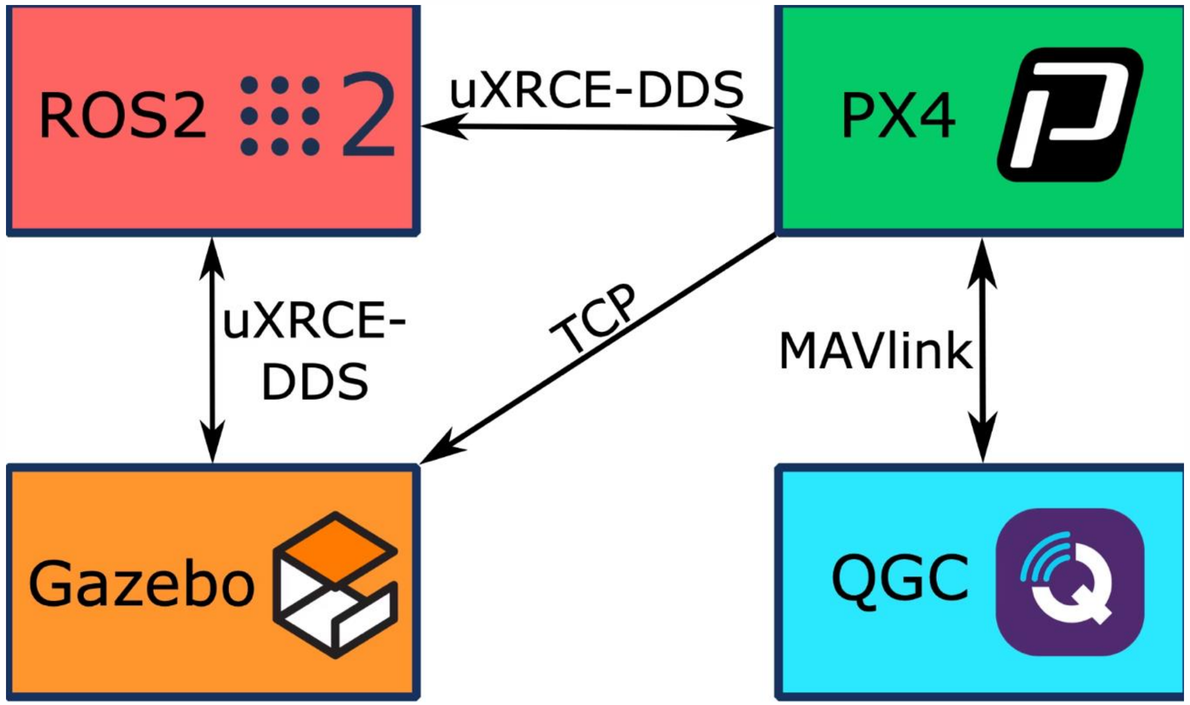
Delbene, A. & Baglietto, M. (2024). Cables tension modeling for multi-uav payload transportation. In 2024 IEEE 20th International Conference on Automation Science and Engineering (CASE), 212–218, IEEE.

Simulation Setup

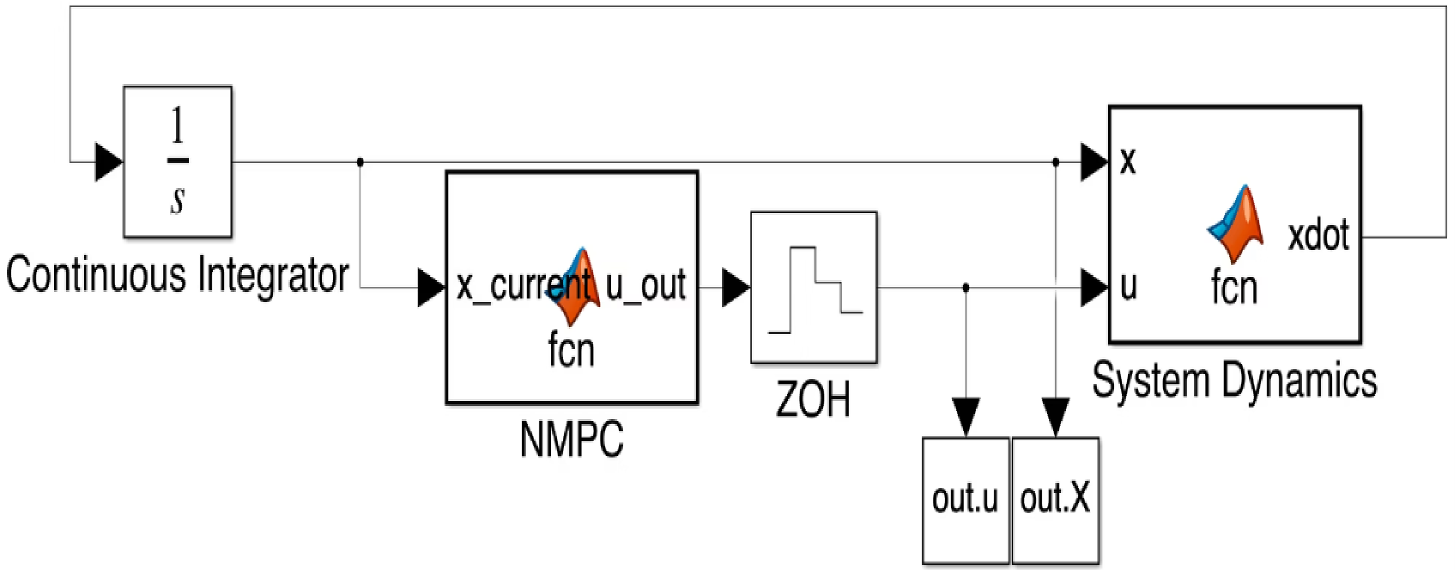
Dual-platform setup for prototyping and controller validation

ROS2/Gazebo



- PX4 autopilot integration
- ROS2 <--> PX4 communication via XRCE-DDS
- QGroundControl monitoring & telemetry
- High-fidelity physics simulation in Gazebo

MATLAB/Simulink



Rapid NMPC tuning & prototyping

Realistic discrete–continuous system modeling

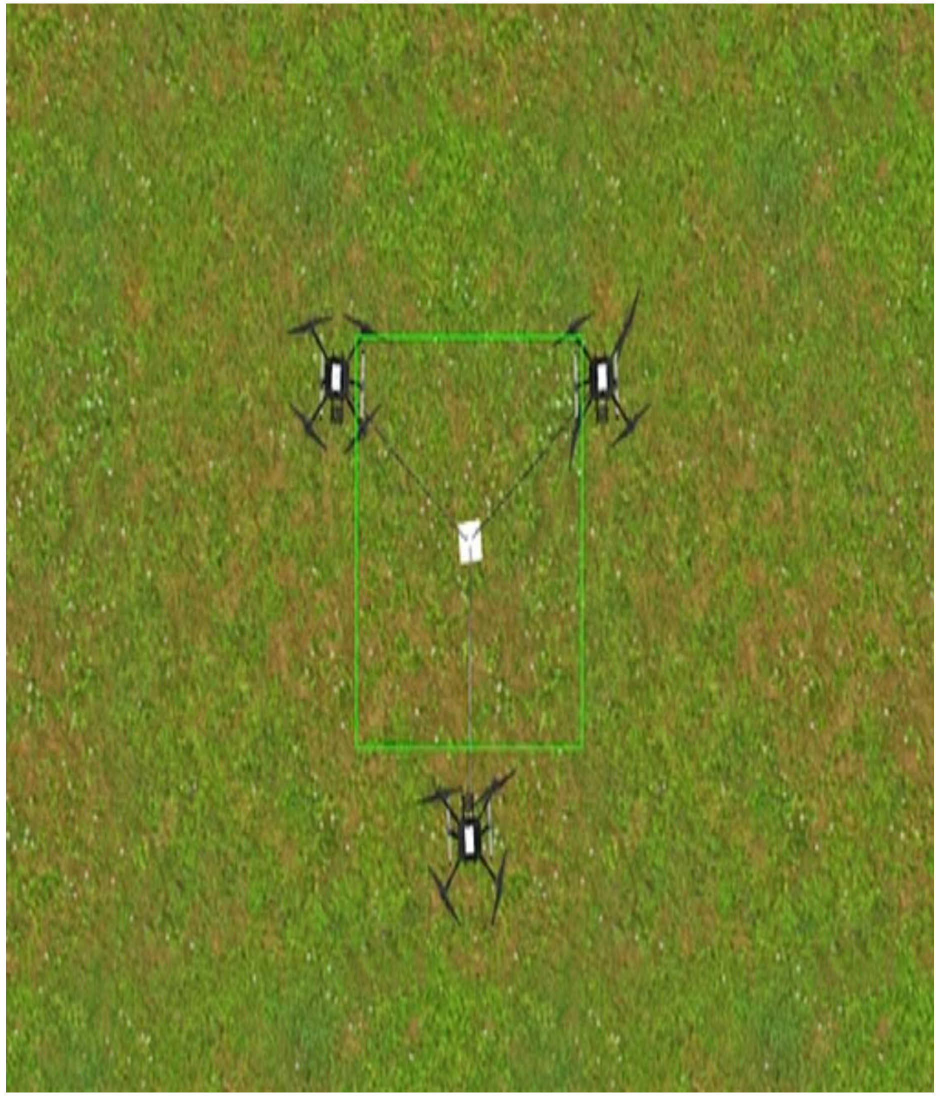
Fast cost & constraint iteration

Parameter sensitivity analysis

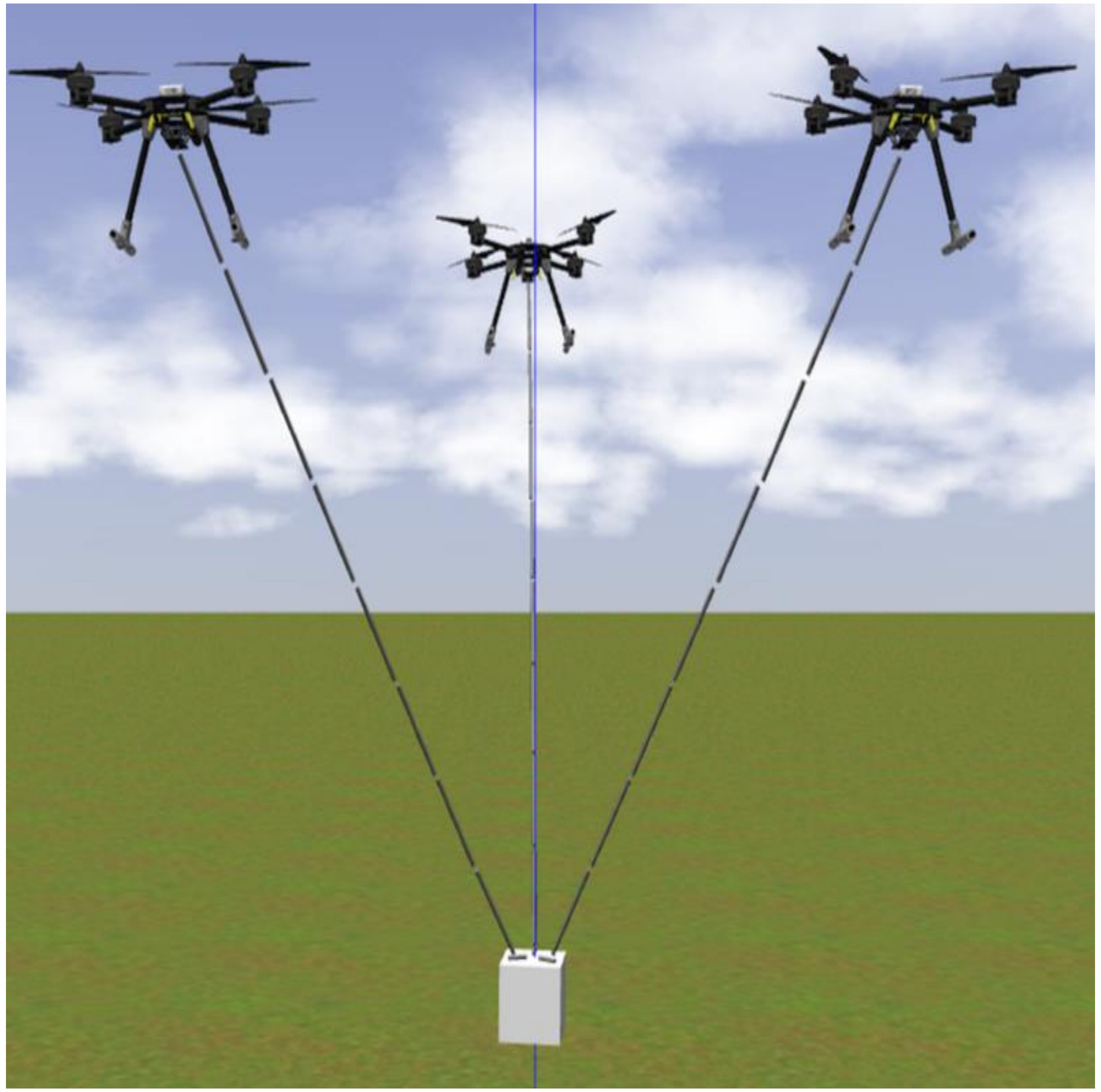
Stability and convergence testing

Transition testing before ROS2 integration

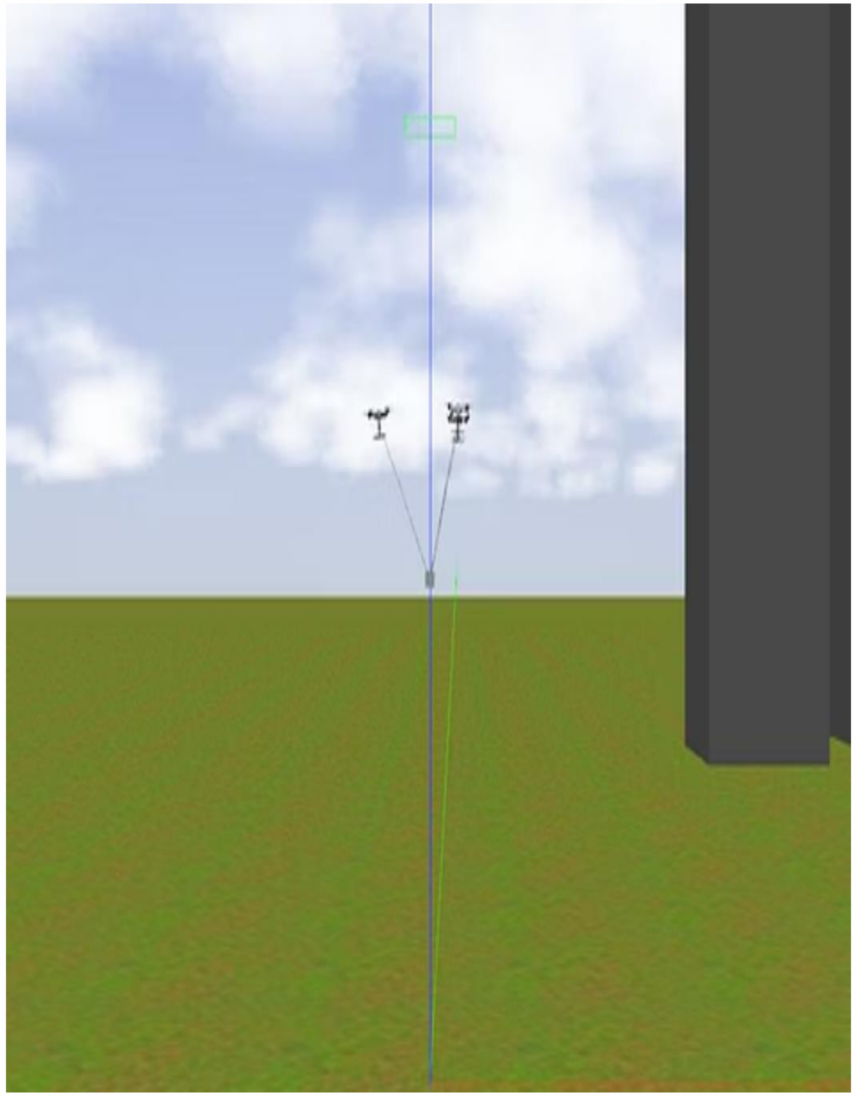
Core Idea behind the Control Approch



Top view

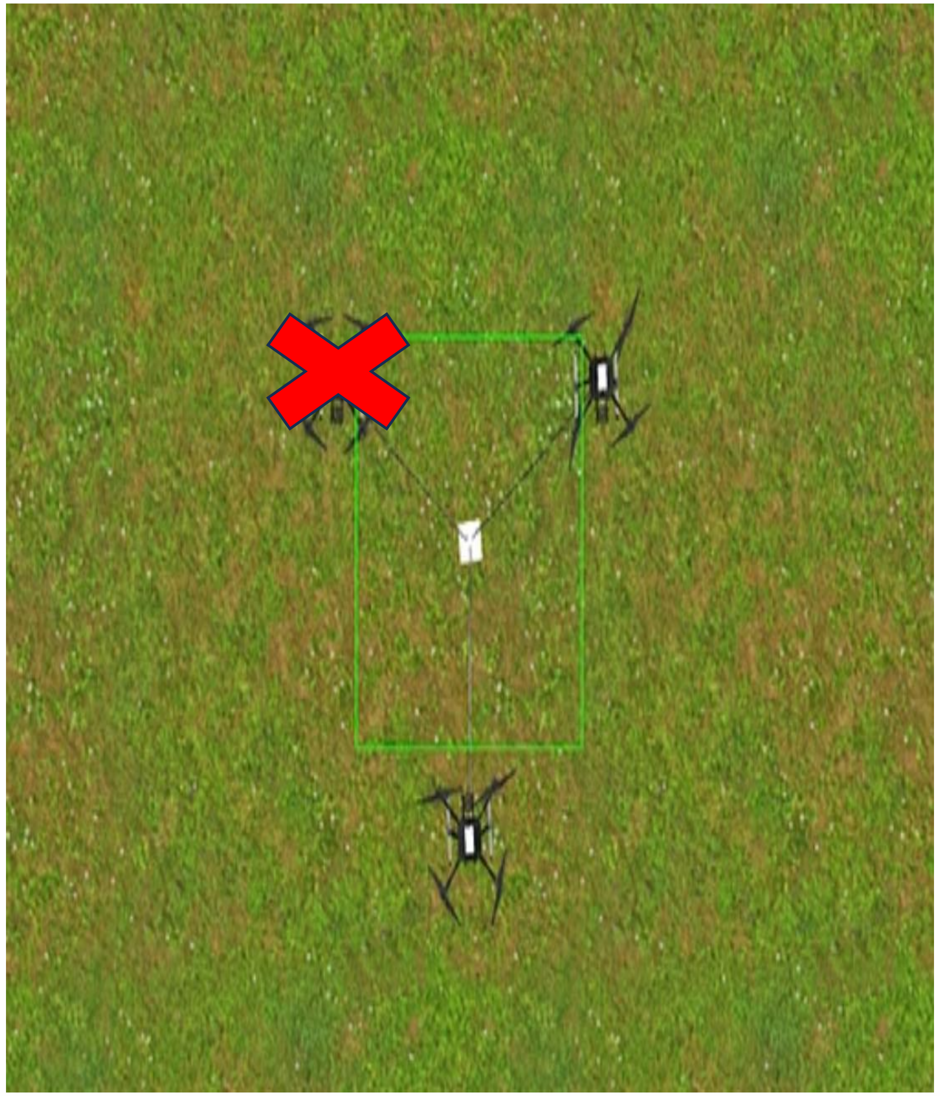


Front view

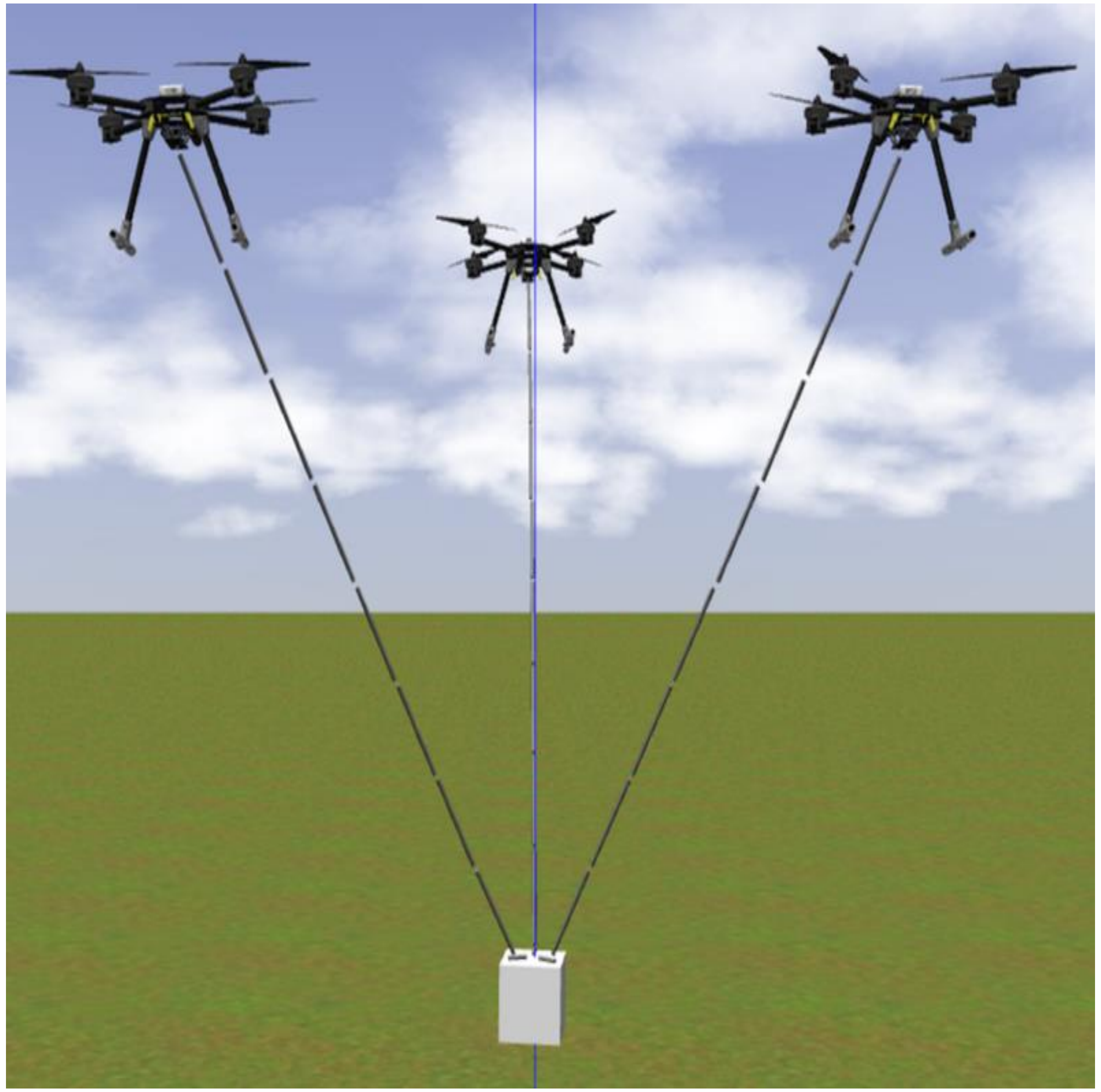


Side view

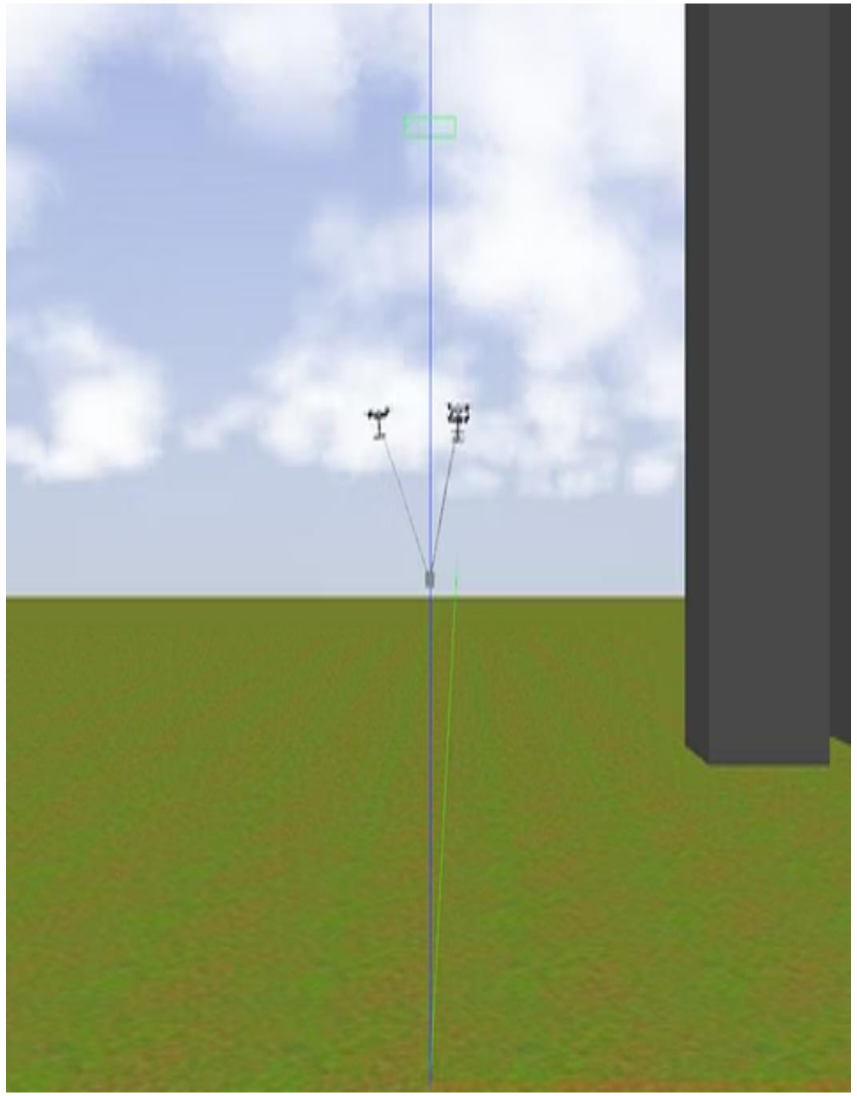
Core Idea behind the Control Approch



Top view



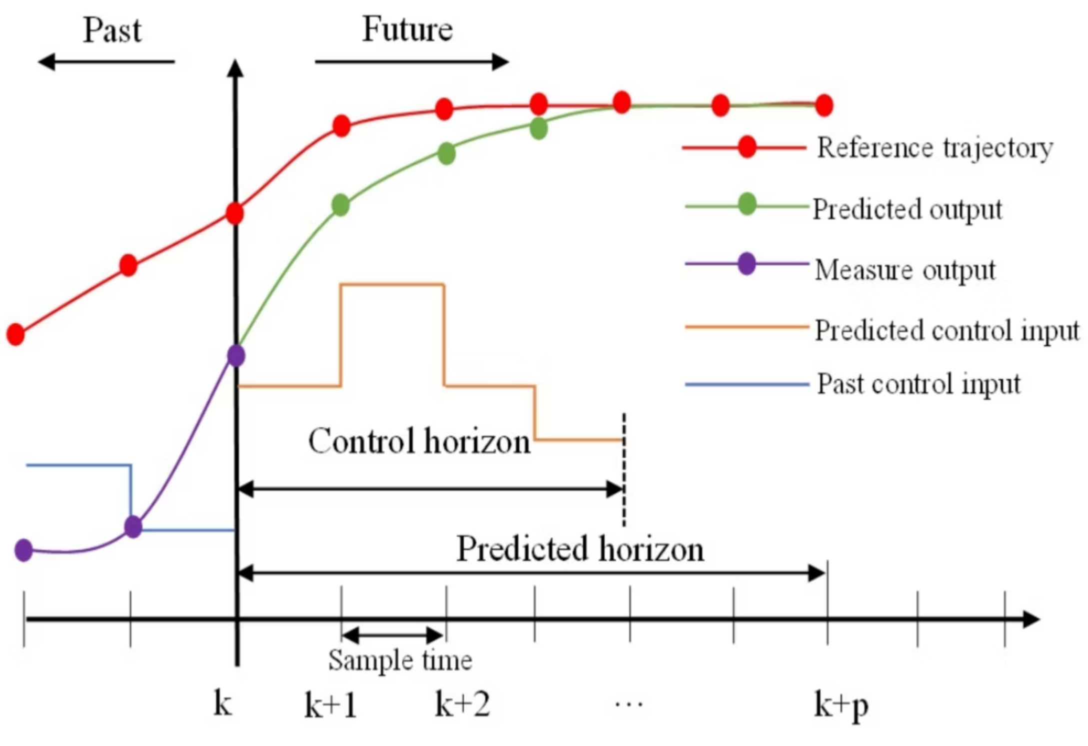
Front view



Side view

Controller Selection: NMPC

Nonlinear Model Predictive Control (NMPC) is an advanced control strategy that most Extensively Researched Control Framework for UAV Systems which is uniquely suited for this problem.



MPC Control Structure

Why NMPC why not other controllers?

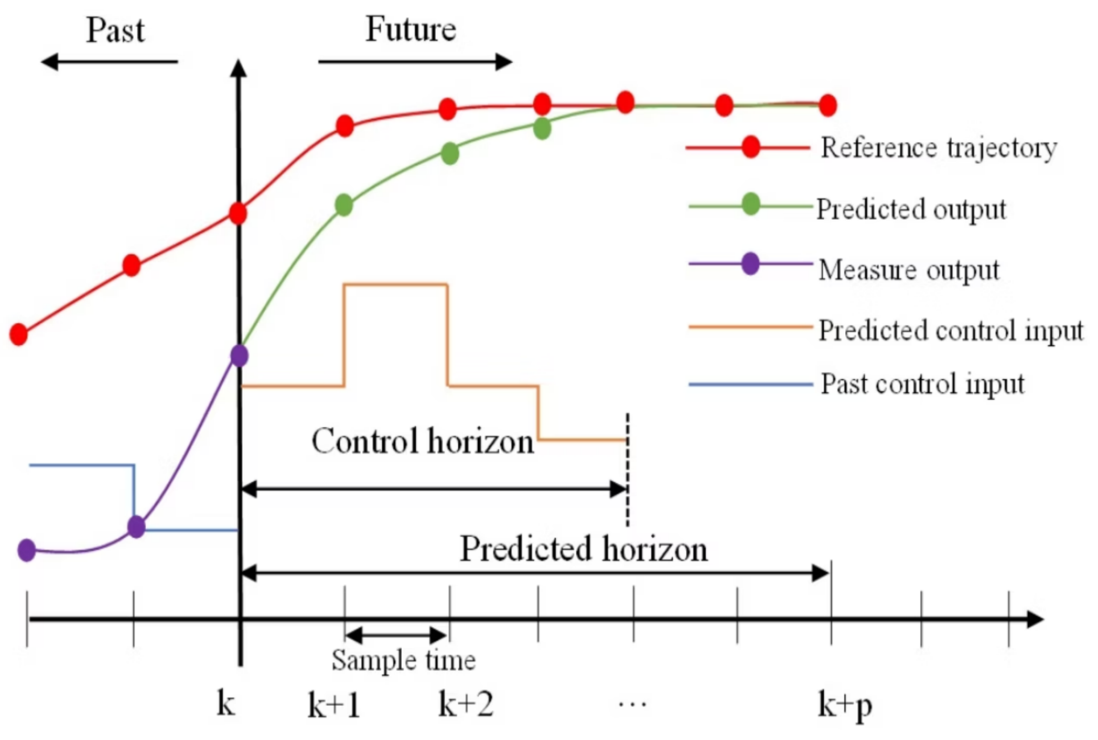
- Predictive Nature
- Constraint Handling
- Robust performance
- Multi-Objective Optimization
- Natively handles the complex dynamics

$$
\begin{aligned}
\min_{\mathbf{U}} \quad & \sum_{k=0}^{N-1} L(\mathbf{x}_k, \mathbf{u}_k) + V_f(\mathbf{x}_N) \\
\text{s.t.} \quad & \mathbf{x}_{k+1} = f(\mathbf{x}_k, \mathbf{u}_k) \\
& \mathbf{x}_0 = \mathbf{x}(t) \\
& \mathbf{u}_{\min} \leq \mathbf{u}_k \leq \mathbf{u}_{\max} \\
& \mathbf{x}_{\min} \leq \mathbf{x}_k \leq \mathbf{x}_{\max}
\end{aligned}
$$

NMPC Formulation

Chen, J., Tian, G. & Fu, Y. (2023). A novel multi-objective tuning strategy for model predictive control in trajectory tracking. Journal of MechanicalScience and Technology, 37, 6657–6667.

Disadvantages of the NMPC?



MPC Control Structure

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& \mathbf{x}_0 = \mathbf{x}(t) \\
& \mathbf{u}_{\min} \leq \mathbf{u}_k \leq \mathbf{u}_{\max} \\
& \mathbf{x}_{\min} \leq \mathbf{x}_k \leq \mathbf{x}_{\max}
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NMPC Formulation

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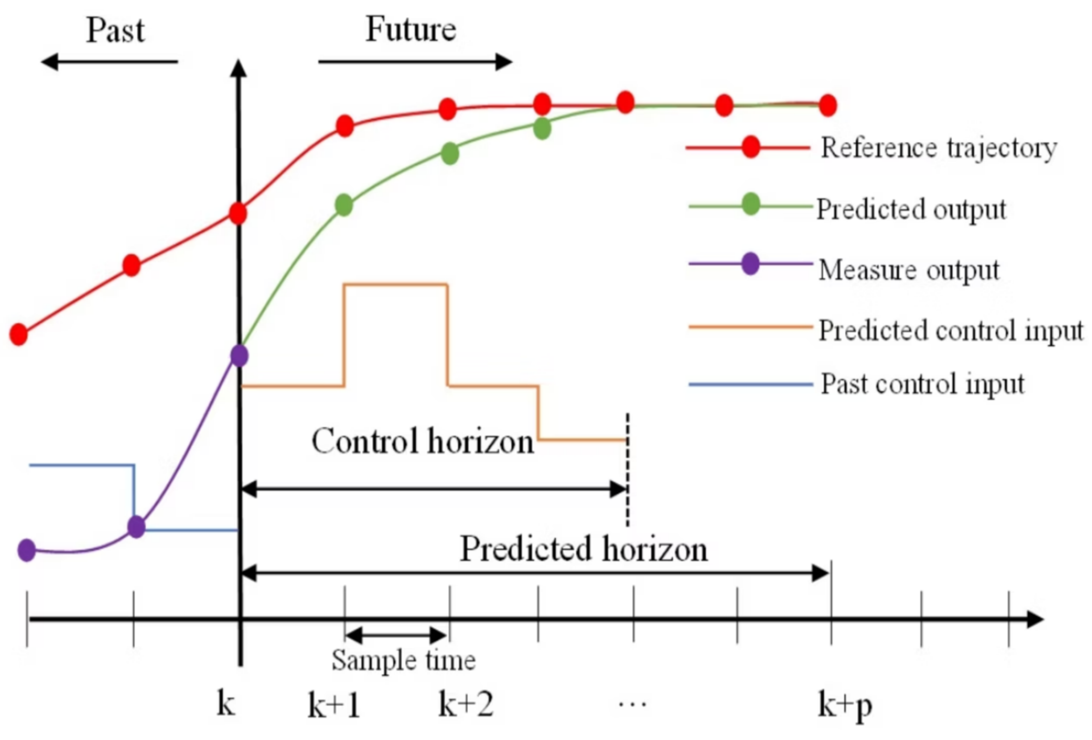
Disadvantages of the NMPC?

1. Model Sensitivity



MPC Control Structure

$$
\begin{aligned}
\min_{\mathbf{U}} \quad & \sum_{k=0}^{N-1} L(\mathbf{x}_k, \mathbf{u}_k) + V_f(\mathbf{x}_N) \\
\text{s.t.} \quad & \mathbf{x}_{k+1} = f(\mathbf{x}_k, \mathbf{u}_k) \\
& \mathbf{x}_0 = \mathbf{x}(t) \\
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& \mathbf{x}_{\min} \leq \mathbf{x}_k \leq \mathbf{x}_{\max}
\end{aligned}
$$

NMPC Formulation

Chen, J., Tian, G. & Fu, Y. (2023). A novel multi-objective tuning strategy for model predictive control in trajectory tracking. Journal of MechanicalScience and Technology, 37, 6657–6667.

Mathematical Model

The effectiveness of the NMPC controller heavily relies on an accurate mathematical model.

$$\ddot{x} = u_1((s_\phi s_\psi + c_\phi c_\psi s_\theta) - \underline{(mlc_\alpha\ddot{\alpha} + lms_\alpha\dot{\alpha}^2)})/(m+M);$$

$$\ddot{y} = u_1((c_\phi s_\theta s_\psi - c_\psi s_\phi) - \underline{(mlc_\beta\ddot{\beta} + lms_\beta\dot{\beta}^2)})/(m+M);$$

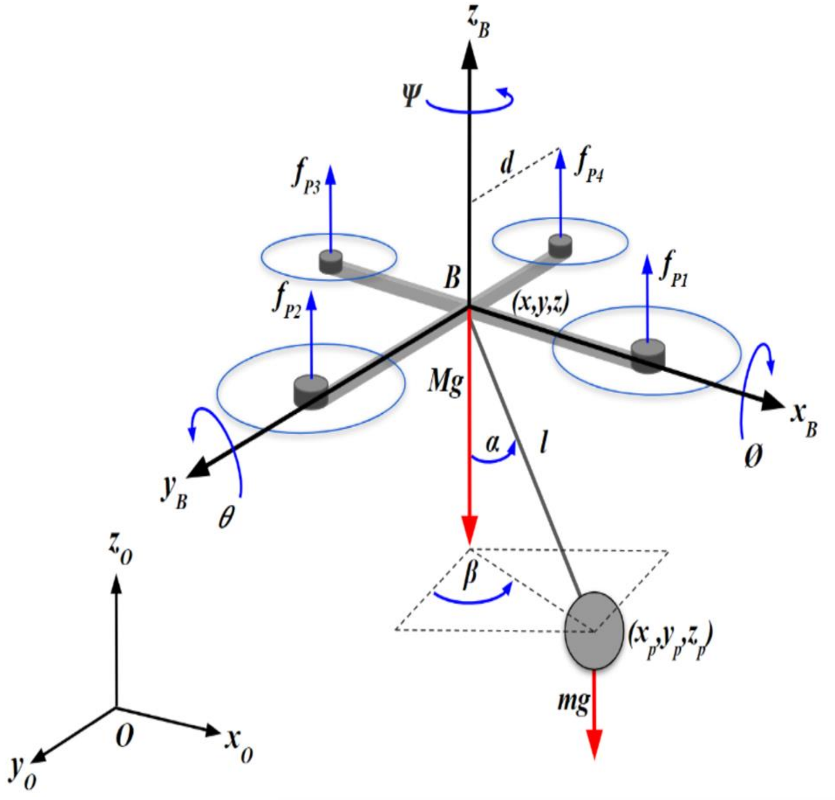
$$\ddot{z} = (u_1(c_\theta c_\phi) - (m+M)g - \underline{ml(s_\alpha c_\beta\ddot{\alpha} - ml(s_\beta c_\alpha\ddot{\beta} - ml\dot{\beta}^2 c_\alpha - ml\dot{\beta}^2 c_\beta + 2Mls_\beta s_\alpha\dot{\alpha}\dot{\beta})))}/(m+M);$$

$$\begin{aligned}\ddot{\psi} = {} & (\tau_\psi - \ddot{\theta}(I_y I_z c_\theta s_\phi c_\phi c_\theta s_\phi c_\phi) + I_x\ddot{\phi}s_\theta - \dot{\psi}(I_x\dot{\theta}s_\theta c_\theta + I_y(-\dot{\theta}s_\theta c_\theta s_\phi^2 + \dot{\phi}c_\theta^2 s_\phi c_\phi) - I_z(\dot{\theta}s_\theta c_\theta c_\phi^2 + \dot{\phi}s_\phi c_\phi c_\theta^2) \\ & - \dot{\theta}(I_x\dot{\psi}s_\theta c_\theta - I_y(\dot{\theta}s_\theta s_\phi c_\phi + \dot{\phi}c_\theta s_\phi^2 - \dot{\phi}c_\theta c_\phi^2 + \dot{\psi}s_\theta c_\theta s_\phi^2 + I_z(\dot{\phi}c_\theta s_\phi^2 - \dot{\phi}c_\theta c_\phi^2 - \dot{\psi}s_\theta c_\theta c_\phi^2 + \dot{\theta}s_\theta s_\phi c_\phi)) \\ & + \dot{\phi}(I_x\dot{\theta}c_\theta - I_y\dot{\psi}c_\theta^2 s_\phi c_\phi + I_z\dot{\psi}c_\theta^2 s_\phi c_\phi))/(I_x s_\theta^2 + I_y c_\theta^2 s_\phi^2 + I_z c_\theta^2 c_\phi^2);\end{aligned}$$

$$\begin{aligned}\ddot{\theta} = {} & (\tau_\theta - \ddot{\psi}(I_y c_\theta s_\phi c_\phi - I_z c_\theta s_\phi c_\phi) - \dot{\psi}(-I_x\dot{\psi}s_\theta c_\theta + I_y\dot{\psi}s_\theta c_\theta s_\phi^2 + I_z\dot{\psi}s_\theta c_\theta(c_\phi)^2) + \dot{\theta}(I_y\dot{\phi}s_\phi c_\phi - I_z\dot{\phi}s_\phi c_\phi) \\ & - \dot{\phi}(I_x\dot{\psi}c_\theta + I_y(-\dot{\theta}s_\phi c_\phi + \dot{\psi}c_\theta c_\phi^2 - \dot{\psi}c_\theta s_\phi^2) + I_z(\dot{\psi}c_\theta s_\phi^2 - \dot{\psi}c_\theta c_\phi^2) + \dot{\theta}s_\phi c_\phi) + \dot{\theta}(I_y\dot{\phi}s_\phi c_\phi - I_z\dot{\phi}s_\phi c_\phi))/(I_y c_\phi^2 + I_z s_\phi^2);\end{aligned}$$

$$\ddot{\phi} = (\tau_\phi + \ddot{\psi}I_x s_\theta + \dot{\psi}(I_y\dot{\psi}c_\theta^2 s_\phi c_\phi - I_z\dot{\psi}s_\phi c_\phi c_\theta^2 - \dot{\theta}(-I_x\dot{\psi}c_\theta + I_y(\dot{\theta}s_\phi c_\phi + \dot{\psi}c_\theta s_\phi^2 - \dot{\psi}c_\theta c_\phi^2) - I_z(\dot{\psi}c_\theta s_\phi^2 - \dot{\psi}c_\theta c_\phi^2 + \dot{\theta}s_\phi c_\phi)))/(I_x);$$

$$\boxed{\begin{aligned}\ddot{\alpha} = {} & (-mlc_\alpha\ddot{x} - mlc_\beta s_\alpha\ddot{z} - ml^2 c_\alpha c_\beta s_\alpha s_\beta\ddot{\beta} - gmls_\alpha c_\beta + ml^2\dot{\alpha}^2 c_\alpha s_\alpha - ml^2 c_\beta^2 s_\alpha c_\alpha\dot{\alpha}^2 \\ & + 2ml^2 s_\alpha^2 c_\beta s_\beta\dot{\alpha}\dot{\beta} - ml^2 c_\beta^2 s_\alpha c_\alpha\dot{\beta}^2)/(ml^2(c_\alpha^2 + c_\alpha^2 c_\beta^2) + I_p); \\ \ddot{\beta} = {} & (-mlc_\beta\ddot{y} - mlc_\alpha s_\beta\ddot{z} - ml^2 c_\alpha c_\beta s_\alpha s_\beta\ddot{\alpha} - gmls_\beta c_\alpha + ml^2\dot{\beta}^2 c_\beta s_\alpha - ml^2 c_\alpha^2 s_\beta c_\beta\dot{\beta}^2 \\ & + 2ml^2 s_\beta^2 c_\alpha s_\alpha\dot{\alpha}\dot{\beta} - ml^2 c_\alpha^2 s_\beta c_\beta\dot{\alpha}^2)/(ml^2(c_\beta^2 + c_\beta^2 c_\alpha^2) + I_p).\end{aligned}}$$

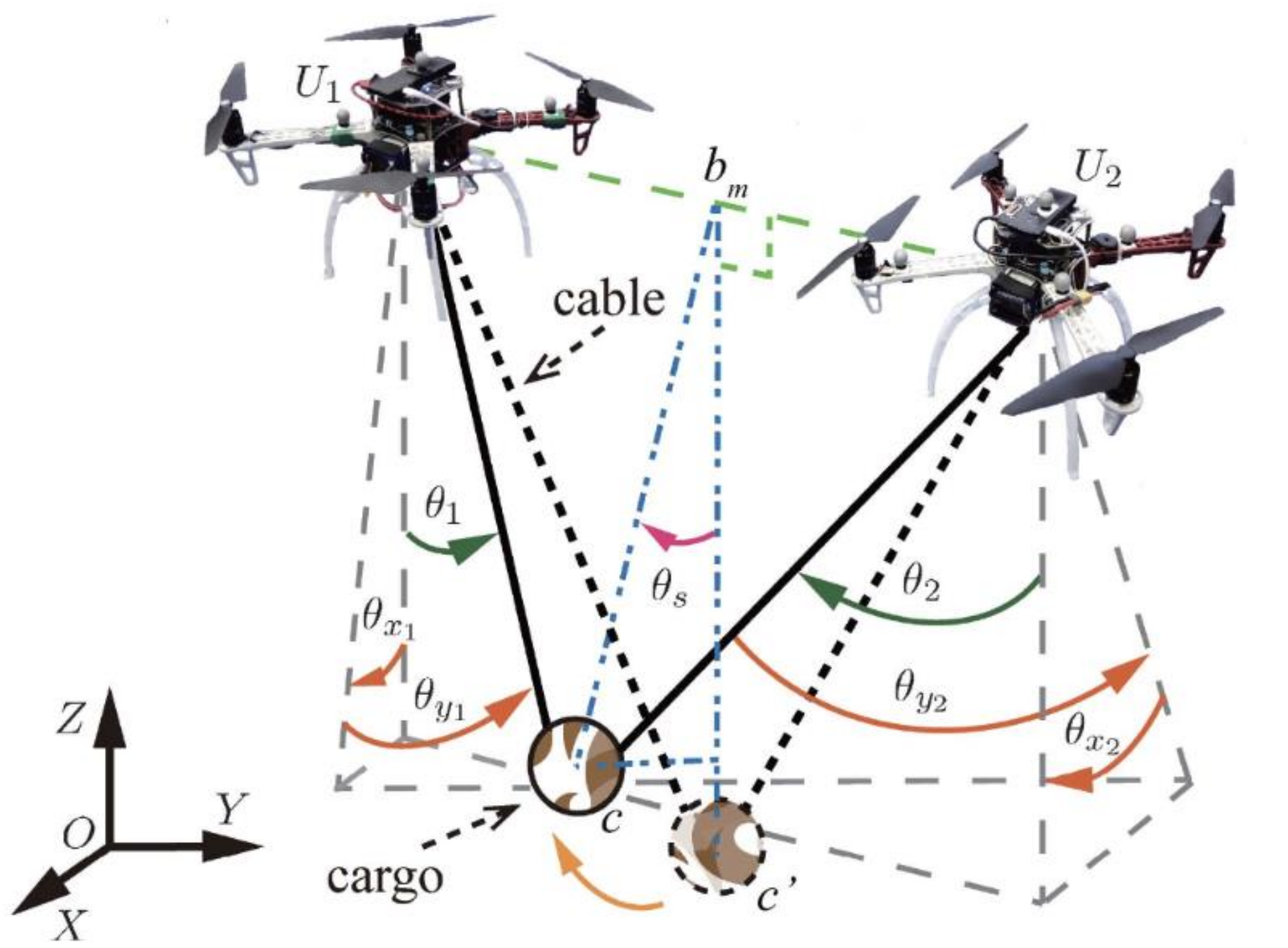


Quadrotor with a cable-suspended payload

Urbina-Brito, N., Guerrero-Sánchez, M.E., Valencia-Palomo, G., Hernández-González, O., López-Estrada, F.R., & Hoyo-Montaño, J.A. (2021). A predictive control strategy for aerial payload transport using an unmanned aerial vehicle. Mathematics, 9, 1822.

Mathematical Model

The effectiveness of the NMPC controller heavily relies on an accurate mathematical model.



Multi-UAV cooperative payload transport system

Liang, X., Zhang, Z., Yu, H., Wang, Y., Fang, Y. & Han, J. (2022). Antiswing control for aerial transportation of the suspended cargo by dual quadrotor uavs. IEEE/ASME Transactions on Mechatronics, 27, 5159–5172.

Mathematical Model

The effectiveness of the NMPC controller heavily relies on an accurate mathematical model.

$$
\begin{aligned}
f_1(\boldsymbol{x},\boldsymbol{u}) = {} & F_z^1 C(\phi^1)C(\psi^1)S(\theta^1) + F_z^2 C(\phi^2)C(\psi^2)S(\theta^2) + F_z^1 S(\phi^1)S(\psi^1) + \\
& F_z^2 S(\phi^2)S(\psi^2) + Lr(-2m_{Q2}S(\alpha^1)S(\beta^1)(\dot\alpha^1)(\dot\beta^1) + m_{Q1}C(\alpha^1)C(\beta^1) \\
& ((\dot\alpha^1)^2 + (\dot\beta^1)^2) - 2m_{Q2}S(\alpha^2)S(\beta^2)(\dot\alpha^2)(\dot\beta^2) + m_{Q2}C(\alpha^2)C(\beta^2)((\dot\alpha^2)^2 + (\dot\beta^2)^2)) \\
f_2(\boldsymbol{x},\boldsymbol{u}) = {} & -F_z^1 C(\psi^1)S(\phi^1) - F_z^2 C(\psi^2)S(\phi^2) + F_z^1 C(\phi^1)S(\theta^1)S(\psi^1) + \\
& F_z^2 C(\phi^2)S(\theta^2)S(\psi^2) + Lr(2m_{Q1}C(\alpha^1)S(\beta^1)(\dot\alpha^1)(\dot\beta^1) + m_{Q1}C(\beta^1) \\
& S(\alpha^1)((\dot\alpha^1)^2 + (\dot\beta^1)^2) + 2m_{Q2}C(\alpha^2)S(\beta^2)(\dot\alpha^2)(\dot\beta^2) + \\
& m_{Q2}C(\beta^2)S(\alpha^2)((\dot\alpha^2)^2 + (\dot\beta^2)^2)) \\
f_3(\boldsymbol{x},\boldsymbol{u}) = {} & -g(m_P + m_{Q1} + m_{Q2}) + F_z^1 C(\theta^1)C(\phi^1) + F_z^2 C(\theta^2)C(\phi^2) + Lrm_{Q1}S(\beta^1) \\
& (\dot\beta^1)^2 + Lrm_{Q2}S(\beta^2)(\dot\beta^2)^2
\end{aligned}
$$

$$
\begin{aligned}
f_4(\boldsymbol{x},\boldsymbol{u}) = {} & LrC(\beta^1)(-F_z^1(C(\alpha^1 - \psi^1)S(\phi^1) + C(\phi^1)S(\theta^1)S(\alpha^1 - \psi^1)) + \\
& 2Lrm_{Q1}S(\beta^1)(\dot\alpha^1)(\dot\beta^1)) \\
f_5(\boldsymbol{x},\boldsymbol{u}) = {} & -Lr(C(\beta^1)(gm_{Q1} - F_z^1 C(\theta^1)C(\phi^1)) + F_z^1 S(\beta^1)(C(\phi^1)C(\alpha^1 - \psi^1)) \\
& S(\theta^1) - S(\phi^1)S(\alpha^1 - \psi^1)) + Lrm_{Q1}C(\beta^1)S(\beta^1)(\dot\alpha^1)^2) \\
f_6(\boldsymbol{x},\boldsymbol{u}) = {} & M_x^1 + (-I_y^1 + I_z^1)C(\phi^1)S(\phi^1)(\dot\theta^1)^2 + C(\theta^1)(I_x^1 + (I_y^1 - I_z^1)C(2\phi^1)) \\
& (\dot\theta^1)(\dot\psi^1) + (I_y^1 - I_z^1)C(\theta^1)^2 C(\phi^1)S(\phi^1)(\dot\psi^1)^2
\end{aligned}
$$

$$
\begin{aligned}
f_7(\boldsymbol{x},\boldsymbol{u}) = {} & M_y^1 C(\phi^1) - M_z^1 S(\phi^1) + (I_y^1 - I_z^1)S(2\phi^1)(\dot\theta^1)(\dot\phi^1) + C(\theta^1) \\
& (\dot\psi^1)(-(I_x^1 + (I_y^1 - I_z^1)C(2\phi^1))(\dot\phi^1) + S(\theta^1)(I_x^1 - I_z^1 C(\phi^1)^2 - I_y^1 S(\phi^1)^2)(\dot\psi^1)) \\
f_8(\boldsymbol{x},\boldsymbol{u}) = {} & -M_x^1 S(\theta^1) + C(\theta^1)(M_z^1 C(\phi^1) + M_y^1 S(\phi^1)) + (I_y^1 - I_z^1)C(\phi^1)S(\theta^1) \\
& S(\phi^1)(\dot\theta^1)^2 + (-I_y^1 + I_z^1)C(\theta^1)^2 S(2\phi^1)(\dot\phi^1)(\dot\psi^1) + (\dot\theta^1)(C(\theta^1) \\
& (I_x^1 + (-I_y^1 + I_z^1)C(2\phi^1))(\dot\phi^1) + S(2\theta^1)(-I_x^1 + I_z^1 C(\phi^1)^2 + I_y^1 S(\dot\phi^1)^2)(\dot\psi^1)) \\
f_9(\boldsymbol{x},\boldsymbol{u}) = {} & LrC(\beta^2)(-F_z^2(C(\alpha^2 - \psi^2)S(\phi^2) + C(\phi^2)S(\theta^2)S(\alpha^2 - \psi^2)) + 2Lrm_{Q2}S(\beta^2)(\dot\alpha^2)(\dot\beta^2)) \\
f_{10}(\boldsymbol{x},\boldsymbol{u}) = {} & -Lr(C(\beta^2)(gm_{Q2} - F_z^2 C(\theta)^2)C(\phi^2)) + F_z^2 S(\beta^2)(C(\phi^2)C(\alpha^2 - \psi^2) \\
& S(\theta^2) - S(\phi^2)S(\alpha^2 - \psi^2)) + Lrm_{Q2}C(\beta^2)S(\beta^2)(\alpha^2)^2) \\
f_{11}(\boldsymbol{x},\boldsymbol{u}) = {} & M_x^2 + (-I_y^2 + I_z^2)C[\phi^2]S(\phi^2)](\dot\theta^2)^2 + C(\theta^2)(I_x^2 + (I_y^2 - I_z^2)C(2\phi^2)) \\
& (\dot\theta^2)(\dot\psi^2) + (I_y^2 - I_z^2)C(\theta^2)^2 C(\phi^2)S(\phi^2)(\dot\psi^2)^2 \\
f_{12}(\boldsymbol{x},\boldsymbol{u}) = {} & M_y^2 C(\phi^2) - M_z^2 S(\phi^2) + (I_y^2 - I_z^2)S(2\phi^2)(\dot\theta^2)(\dot\phi^2) + C(\theta^2) \\
& (\dot\psi^2)(-(I_x^2 + (I_y^2 - I_z^2)C(2\phi^2)(\dot\phi^2) + S(\theta^2)(I_x^2 - I_z^2 C(\phi^2)^2 - I_y^2 S(\phi^2)^2)(\dot\psi^2)) \\
f_{13}(\boldsymbol{x},\boldsymbol{u}) = {} & -M_x^2 S(\theta^2) + C(\theta^2)(M_z^2 C(\phi^2) + M_y^2 S(\phi^2) + (I_y^2 - I_z^2)C(\phi^2)S(\theta^2) \\
& S(\phi^2)(\dot\theta^2)^2 + (-I_y^2 + I_z^2)C(\theta^2)^2 S(2\phi^2)(\dot\phi^2)(\dot\psi^2) + (\dot\theta^2)(C(\theta^2) \\
& (I_x^2 + (-I_y^2 + I_z^2)C(2\phi^2)(\dot\phi^2) + S(2\theta^2)(-I_x^2 + I_z^2 C(\phi^2)^2 + I_y^2 S(\phi^2)^2)(\dot\psi^2))
\end{aligned}
$$

Alothman, Y. & Gu, D. (2018). Using constrained nmpc to control a cable-suspended payload with two quadrotors. In 2018 24th International Conference on Automation and Computing, 1−6, IEEE.

Alothman, Y.N. (2018). Optimal control of multiple quadrotors for transporting a cable suspended payload.

Mathematical Model

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f_1(\boldsymbol{x},\boldsymbol{u}) = {} & F_z^1 C(\phi^1)C(\psi^1)S(\theta^1) + F_z^2 C(\phi^2)C(\psi^2)S(\theta^2) + F_z^1 S(\phi^1)S(\psi^1) + \\
& F_z^2 S(\phi^2)S(\psi^2) + Lr(-2m_{Q2}S(\alpha^1)S(\beta^1)(\dot{\alpha}^1)(\dot{\beta}^1) + m_{Q1}C(\alpha^1)C(\beta^1) \\
& ((\dot{\alpha}^1)^2 + (\dot{\beta}^1)^2) - 2m_{Q2}S(\alpha^2)S(\beta^2)\dot{(\alpha^2)}\dot{(\beta^2)} + m_{Q2}C(\alpha^2)C(\beta^2)((\dot{\alpha}^2)^2 + (\dot{\beta}^2)^2)) \\
f_2(\boldsymbol{x},\boldsymbol{u}) = {} & -F_z^1 C(\psi^1)S(\phi^1) - F_z^2 C(\psi^2)S(\phi^2) + F_z^1 C(\phi^1)S(\theta^1)S(\psi^1) + \\
& F_z^2 C(\phi^2)S(\theta^2)S(\psi^2) + Lr(2m_{Q1}C(\alpha^1)S(\beta^1)(\dot{\alpha}^1)(\dot{\beta}^1) + m_{Q1}C(\beta^1) \\
& S(\alpha^1)((\dot{\alpha}^1)^2 + (\dot{\beta}^1)^2) + 2m_{Q2}C(\alpha^2)S(\beta^2)(\dot{\alpha}^2)(\dot{\beta}^2) + \\
& m_{Q2}C(\beta^2)S(\alpha^2)((\dot{\alpha}^2)^2 + (\dot{\beta}^2)^2)) \\
f_3(\boldsymbol{x},\boldsymbol{u}) = {} & -g(m_P + m_{Q1} + m_{Q2}) + F_z^1 C(\theta^1)C(\phi^1) + F_z^2 C(\theta^2)C(\phi^2) + Lrm_{Q1}S(\beta^1) \\
& (\dot{\beta}^1)^2 + Lrm_{Q2}S(\beta^2)(\dot{\beta}^2)^2
\end{aligned}
$$

$$
\begin{aligned}
f_4(\boldsymbol{x},\boldsymbol{u}) = {} & LrC(\beta^1)(-F_z^1(C(\alpha^1 - \psi^1)S(\phi^1) + C(\phi^1)S(\theta^1)S(\alpha^1 - \psi^1)) + \\
& 2Lrm_{Q1}S(\beta^1)(\dot{\alpha}^1)(\dot{\beta}^1)) \\
f_5(\boldsymbol{x},\boldsymbol{u}) = {} & -Lr(C(\beta^1)(gm_{Q1} - F_z^1 C(\theta^1)C(\phi^1)) + F_z^1 S(\beta^1)(C(\phi^1)C(\alpha^1 - \psi^1)) \\
& S(\theta^1) - S(\phi^1)S(\alpha^1 - \psi^1)) + Lrm_{Q1}C(\beta^1)S(\beta^1)(\dot{\alpha}^1)^2)
\end{aligned}
$$

$$
\begin{aligned}
f_6(\boldsymbol{x},\boldsymbol{u}) = {} & M_x^1 + (-I_y^1 + I_z^1)C(\phi^1)S(\phi^1)(\dot{\theta}^1)^2 + C(\theta^1)(I_x^1 + (I_y^1 - I_z^1)C(2\phi^1)) \\
& (\dot{\theta}^1)(\dot{\psi}^1) + (I_y^1 - I_z^1)C(\theta^1)^2 C(\phi^1)S(\phi^1)(\dot{\psi}^1)^2 \\
f_7(\boldsymbol{x},\boldsymbol{u}) = {} & M_y^1 C(\phi^1) - M_z^1 S(\phi^1) + (I_y^1 - I_z^1)S(2\phi^1)(\dot{\theta}^1)(\dot{\phi}^1) + C(\theta^1) \\
& (\psi^1)(-(I_x^1 + (I_y^1 - I_z^1)C(2\phi^1))(\dot{\phi}^1) + S(\theta^1)(I_x^1 - I_z^1 C(\phi^1)^2 - I_y^1 S(\phi^1)^2)(\dot{\psi}^1)) \\
f_8(\boldsymbol{x},\boldsymbol{u}) = {} & -M_x^1 S(\theta^1) + C(\theta^1)(M_z^1 C(\phi^1) + M_y^1 S(\phi^1)) + (I_y^1 - I_z^1)C(\phi^1)S(\theta^1) \\
& S(\phi^1)(\dot{\theta}^1)^2 + (-I_y^1 + I_z^1)C(\theta^1)^2 S(2\phi^1)(\dot{\phi}^1)(\dot{\psi}^1) + (\dot{\theta}^1)(C(\theta^1) \\
& (I_x^1 + (-I_y^1 + I_z^1)C(2\phi^1))(\dot{\phi}^1) + S(2\theta^1)(-I_x^1 + I_z^1 C(\phi^1)^2 + I_y^1 S(\dot{\phi}^1)^2)(\dot{\psi}^1))
\end{aligned}
$$

$$
\begin{aligned}
f_9(\boldsymbol{x},\boldsymbol{u}) = {} & LrC(\beta^2)(-F_z^2(C(\alpha^2 - \psi^2)S(\phi^2) + C(\phi^2)S(\theta^2)S(\alpha^2 - \psi^2)) + 2Lrm_{Q2}S(\beta^2)(\dot{\alpha}^2)(\dot{\beta}^2)) \\
f_{10}(\boldsymbol{x},\boldsymbol{u}) = {} & -Lr(C(\beta^2)(gm_{Q2} - F_z^2 C(\theta)^2)C(\phi^2)) + F_z^2 S(\beta^2)(C(\phi^2)C(\alpha^2 - \psi^2) \\
& S(\theta^2) - S(\phi^2)S(\alpha^2 - \psi^2)) + Lrm_{Q2}C(\beta^2)S(\beta^2)(\alpha^2)^2)
\end{aligned}
$$

$$
\begin{aligned}
f_{11}(\boldsymbol{x},\boldsymbol{u}) = {} & M_x^2 + (-I_y^2 + I_z^2)C[\phi^2]S(\phi^2)](\dot{\theta}^2)^2 + C(\theta^2)(I_x^2 + (I_y^2 - I_z^2)C(2\phi^2)) \\
& (\dot{\theta}^2)(\dot{\psi}^2) + (I_y^2 - I_z^2)C(\theta^2)^2 C(\phi^2)S(\phi^2)(\dot{\psi}^2)^2 \\
f_{12}(\boldsymbol{x},\boldsymbol{u}) = {} & M_y^2 C(\phi^2) - M_z^2 S(\phi^2) + (I_y^2 - I_z^2)S(2\phi^2)(\dot{\theta}^2)(\dot{\phi}^2) + C(\theta^2) \\
& (\dot{\psi}^2)(-(I_x^2 + (I_y^2 - I_z^2)C(2\phi^2)(\dot{\phi}^2) + S(\theta^2)(I_x^2 - I_z^2 C(\phi^2)^2 - I_y^2 S(\phi^2)^2)(\dot{\psi}^2)) \\
f_{13}(\boldsymbol{x},\boldsymbol{u}) = {} & -M_x^2 S(\theta^2) + C(\theta^2)(M_z^2 C(\phi^2) + M_y^2 S(\phi^2) + (I_y^2 - I_z^2)C(\phi^2)S(\theta^2) \\
& S(\phi^2)(\dot{\theta}^2)^2 + (-I_y^2 + I_z^2)C(\theta^2)^2 S(2\phi^2)(\dot{\phi}^2)(\dot{\psi}^2) + (\dot{\theta}^2)(C(\theta^2) \\
& (I_x^2 + (-I_y^2 + I_z^2)C(2\phi^2)(\dot{\phi}^2) + S(2\theta^2)(-I_x^2 + I_z^2 C(\phi^2)^2 + I_y^2 S(\phi^2)^2)(\dot{\psi}^2))
\end{aligned}
$$

Alothman, Y. & Gu, D. (2018). Using constrained nmpc to control a cable-suspended payload with two quadrotors. In 2018 24th International Conference on Automation and Computing, 1−6, IEEE.

Alothman, Y.N. (2018). Optimal control of multiple quadrotors for transporting a cable suspended payload.

Mathematical Model

The effectiveness of the NMPC controller heavily relies on an accurate mathematical model.

Cable Tension Modeling

$$\mathbf{l}_i = \boldsymbol{\xi}^a_{ip} - \boldsymbol{\xi}^a_i$$

$$\Downarrow$$

$$l_{0,i} = \|\mathbf{l}_i\|$$

$$\Downarrow$$

$$\hat{\mathbf{l}}_i = \frac{\mathbf{l}_i}{\|\mathbf{l}_i\|}$$

$$\Downarrow$$

$$\mathbf{T}_i = \begin{cases} k_i(L_i - l_{0,i})\hat{\mathbf{l}}_i + b_i\dot{\mathbf{l}}_i \\ \mathbf{0} & \text{if } L_i \leq l_{0,i} \end{cases}$$

Quadrotor Dynamics

Quadrotor Translational Dynamics:

(where $i = 1, 2$)

$$\ddot{x}_i = \frac{F_{T,i}}{m}(\cos\phi_i \sin\theta_i \cos\psi_i + \sin\phi_i \sin\psi_i) - \frac{T_{i,x}}{m}$$

$$\ddot{y}_i = \frac{F_{T,i}}{m}(\cos\phi_i \sin\theta_i \sin\psi_i - \sin\phi_i \cos\psi_i) - \frac{T_{i,y}}{m}$$

$$\ddot{z}_i = \frac{F_{T,i}}{m}\cos\phi_i \cos\theta_i - g - \frac{T_{i,z}}{m}$$

Quadrotor Rotational Dynamics:

$$\dot{p}_i = \frac{\tau_{\phi,i} - (I_{yy} - I_{zz})q_i r_i}{I_{xx}}$$

$$\dot{q}_i = \frac{\tau_{\theta,i} - (I_{zz} - I_{xx})p_i r_i}{I_{yy}}$$

$$\dot{r}_i = \frac{\tau_{\psi,i} - (I_{xx} - I_{yy})p_i q_i}{I_{zz}}$$

Payload Dynamics

Payload Translational Dynamics:

$$\ddot{x}_p = \frac{1}{m_p}\sum_{i=1}^{N} T_{i,x}$$

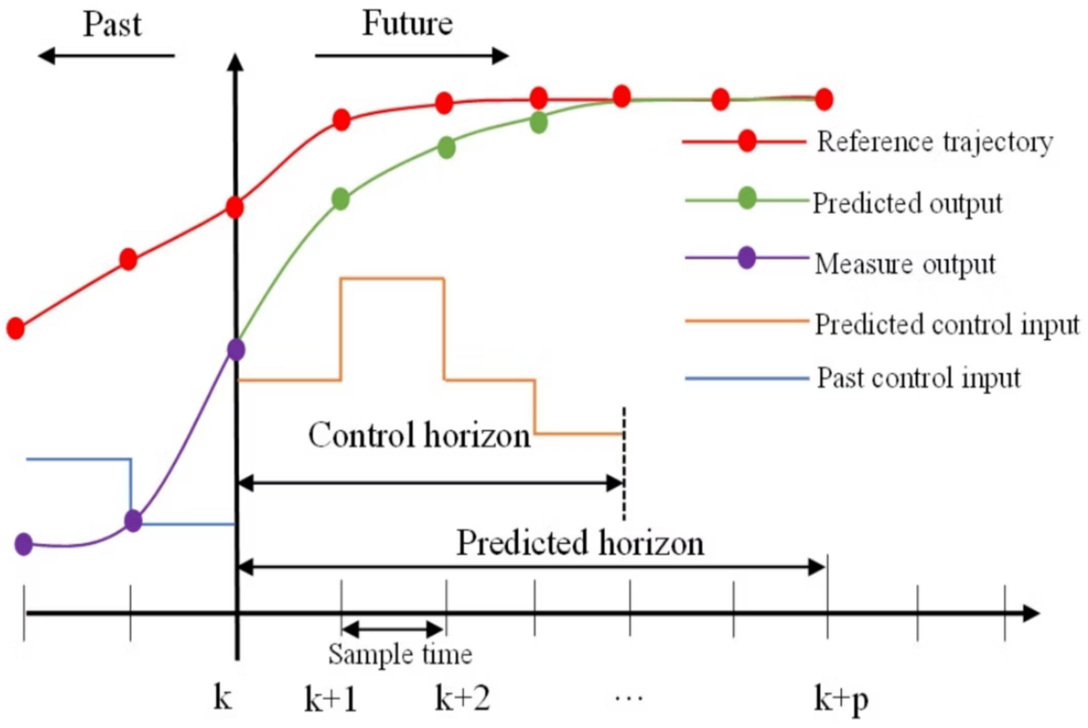
$$\ddot{y}_p = \frac{1}{m_p}\sum_{i=1}^{N} T_{i,y}$$

$$\ddot{z}_p = \frac{1}{m_p}\sum_{i=1}^{N} T_{i,z} - g$$

Delbene, A. & Baglietto, M. (2024). Recovery techniques for a multi-uav system transporting a payload. In 2024 IEEE 20th International Conference on Automation Science and Engineering (CASE), 559–566, IEEE.

Disadvantages of the NMPC?

1. MODEL SENSITIVITY
2. COMPUTATIONAL RESOURCES



MPC Control Structure

$$\min_{\mathbf{U}} \sum_{k=0}^{N-1} L(\mathbf{x}_k, \mathbf{u}_k) + V_f(\mathbf{x}_N)$$

$$\begin{aligned} \text{s.t.} \quad & \mathbf{x}_{k+1} = f(\mathbf{x}_k, \mathbf{u}_k) \\ & \mathbf{x}_0 = \mathbf{x}(t) \\ & \mathbf{u}_{\min} \leq \mathbf{u}_k \leq \mathbf{u}_{\max} \\ & \mathbf{x}_{\min} \leq \mathbf{x}_k \leq \mathbf{x}_{\max} \end{aligned}$$

NMPC Formulation

Chen, J., Tian, G. & Fu, Y. (2023). A novel multi-objective tuning strategy for model predictive control in trajectory tracking. Journal of MechanicalScience and Technology, 37, 6657–6667.

NMPC Implementation Setup

Optimization Framework

Several toolchains are used in real-time NMPC reseach: CasAdi, ACADO, Forces Pro, FiMCON etc.

We selected CasADi because it provides:

- ➢ Easy Prototyping
- ➢ Large and active community support
- ➢ Programming interface Python / MATLAB / C++
- ➢ Enables real-time NMPC computation

Discretization Method

Forward Euler

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \Delta t \cdot f(\mathbf{x}_k, \mathbf{u}_k)$$

Fourth Order Runge–Kutta Method

$$\begin{aligned} k_1 &= f(x_k, u), \\ k_2 &= f\left(x_k + \tfrac{\Delta t}{2} k_1, u\right), \\ k_3 &= f\left(x_k + \tfrac{\Delta t}{2} k_2, u\right), \\ k_4 &= f\left(x_k + \Delta t\, k_3, u\right), \\ x_{k+1} &= x_k + \tfrac{\Delta t}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right). \end{aligned}$$

Trade-off: RK4 provides higher accuracy but 4 times higher computational cost. While Euler is faster, easier to implement, and provides sufficient accuracy.

Workineh, Y., Mekonnen, H., & Belete, B. (2024). Numerical methods for solving second-order initial value problems of ordinary differential equations using Euler and fourth-order Runge–Kutta methods. Frontiers in Applied Mathematics and Statistics, 10.

Andersson, J.A.E., Gillis, J., Horn, G., Rawlings, J.B., & Diehl, M. (2018). CasADi: a software framework for nonlinear optimization and optimal control. Mathematical Programming Computation

NMPC Configuration & Parameters

Parameter values were optimized through iterative simulation and experimental validation.

- Prediction Horizon
- Control Horizon (Nc)
- Sampling / Discretization Time (Δt)
- Constraint violation tolerance
- Maximum solver iterations
- Maximum step tolerance
- Input constraint tolerance

$$T_{\min} \leq T_i \leq T_{\max}$$
$$\tau_{\phi,\min} \leq \tau_{\phi_i} \leq \tau_{\phi,\max}$$
$$\tau_{\theta,\min} \leq \tau_{\theta_i} \leq \tau_{\theta,\max}$$
$$\tau_{\psi,\min} \leq \tau_{\psi_i} \leq \tau_{\psi,\max}$$

Control Input Constraints

$$\phi_{\min} \leq \phi_i \leq \phi_{\max}$$
$$\theta_{\min} \leq \theta_i \leq \theta_{\max}$$
$$\psi_{\min} \leq \psi_i \leq \psi_{\max}$$

State Constraints

$$\mathbf{U}_{k+1}^{\text{init}} = \begin{bmatrix} \mathbf{u}_{1|k}^* \\ \mathbf{u}_{2|k}^* \\ \vdots \\ \mathbf{u}_{N-1|k}^* \\ \mathbf{u}_{N-1|k}^* \end{bmatrix}$$

Warm Starter Formulation

Phase 1: Aggressive Stabilization

1. Payload Velocity:

$$J_{\text{vel,p}} = w_{\text{vel,p}} \cdot (\dot{x}_p^2 + \dot{y}_p^2 + \dot{z}_p^2)$$

2. Payload Centering:

$$J_{\text{center}} = w_{\text{center}} \cdot [(x_p - \bar{x})^2 + (y_p - \bar{y})^2]$$

$$\text{where } \bar{x} = \tfrac{x_1+x_2}{2} \text{ and } \bar{y} = \tfrac{y_1+y_2}{2}$$

3. Payload Acceleration:

$$J_{\text{accel}} = w_{\text{accel}} \cdot [(\ddot{x}_p)^2 + (\ddot{y}_p)^2 + (\ddot{z}_p)^2]$$

4. UAV Velocity Coordination:

$$J_{\text{coord}} = w_{\text{coord}} \cdot [(\dot{x}_1 - \dot{x}_2)^2 + (\dot{y}_1 - \dot{y}_2)^2 + (\dot{z}_1 - \dot{z}_2)^2]$$

5. Distance Maintenance:

$$J_{\text{dis,h}} = w_{\text{dis,h}} \cdot [((x_1 - x_2)^2 - d_{\text{des}}^2)^2 + ((y_1 - y_2)^2 - d_{\text{des}}^2)^2]$$

Terminal cost:

$$V_{\text{stab}}(\mathbf{x}_N) = w_{\text{term,vel}} \|\mathbf{v}_p\|^2 + w_{\text{term,uav}}(\|\mathbf{v}_1\|^2 + \|\mathbf{v}_2\|^2) + w_{\text{term,center}} \|\mathbf{p}_p - \mathbf{p}_{\text{center}}\|^2$$

Cost Component	Weight	Purpose
Payload Velocity ($w_{\text{vel,p}}$)	50.0	Primary oscillation suppression
Payload Centering (w_{center})	15.0	Follow payload motion
Payload Acceleration (w_{accel})	5.0	Smooth movement
UAV Coordination (w_{coord})	2.0	Synchronized movement
Distance Maintenance ($w_{\text{dis,h}}$)	1.0	Collision avoidance
Terminal Weights		
Terminal Payload Velocity	100.0	Final stabilization guarantee
Terminal UAV Velocities	35.0	Complete system damping
Terminal Payload Centering	30.0	Final coordination

Phase 2: Precision Tracking

1. Formation Center Position Tracking:

$$J_{\text{pos}} = w_{\text{pos}} \cdot (1.0 + 1.5e^{-1.5 d_{\text{target}}}) \cdot [(x_{\text{center}} - x_{\text{des}})^2 + (y_{\text{center}} - y_{\text{des}})^2 + (z_{\text{center}} - z_{\text{des}})^2]$$

2. UAV Horizontal Separation Maintenance:

$$J_{\text{sep}} = w_{\text{sep}} \cdot [(\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} - d_{\text{des}})^2]$$

3. UAV Altitude Coordination:

$$J_{\text{alt}} = w_{\text{alt}} \cdot (z_1 - z_2)^2$$

4. Individual UAV Velocity Limiting:

$$J_{\text{vel,ind}} = w_{\text{vel,ind,soft}} \cdot (\|\mathbf{v}_1\|^2 + \|\mathbf{v}_2\|^2) + w_{\text{vel,ind,hard}} \cdot [\max(0, \|\mathbf{v}_1\| - v_{\max})^2 + \max(0, \|\mathbf{v}_2\| - v_{\max})^2]$$

5. UAV Velocity Coordination:

$$J_{\text{vel,coord}} = w_{\text{vel,coord}} \cdot [(\dot{x}_1 - \dot{x}_2)^2 + (\dot{y}_1 - \dot{y}_2)^2 + (\dot{z}_1 - \dot{z}_2)^2]$$

6. Formation Velocity Shaping:

$$J_{\text{vel,form}} = w_{\text{vel,form}} \cdot [(\bar{v}_x - v_{x,\text{des}})^2 + (\bar{v}_y - v_{y,\text{des}})^2 + (\bar{v}_z - v_{z,\text{des}})^2]$$

7. Payload Oscillation Damping:

$$J_{\text{payload}} = w_{\text{payload,vel}} \cdot (\dot{x}_p^2 + \dot{y}_p^2 + \dot{z}_p^2) + w_{\text{payload,accel}} \cdot (\ddot{x}_p^2 + \ddot{y}_p^2 + \ddot{z}_p^2) + w_{\text{payload,center}} \cdot [(x_p - x_{\text{center}})^2 + (y_p - y_{\text{center}})^2]$$

8. Attitude Stability:

$$J_{\text{attitude}} = w_{\text{attitude}} \cdot (\phi_1^2 + \theta_1^2 + \phi_2^2 + \theta_2^2) + w_{\text{angular}} \cdot (p_1^2 + q_1^2 + r_1^2 + p_2^2 + q_2^2 + r_2^2)$$

9. Control Effort:

$$J_{\text{control}} = w_{\text{control}} \cdot (\mathbf{u}_1^T \mathbf{W}_u \mathbf{u}_1 + \mathbf{u}_2^T \mathbf{W}_u \mathbf{u}_2)$$

Terminal cost:

$$V_{\text{track}}(\mathbf{x}_N) = w_{\text{term,pos}} \|\mathbf{p}_{\text{center}} - \mathbf{p}_{\text{des}}\|^2 + w_{\text{term,sep}} J_{\text{sep,term}} + w_{\text{term,alt}} (z_1 - z_2)^2 + w_{\text{term,vel,coord}} \|\mathbf{v}_1 - \mathbf{v}_2\|^2 + w_{\text{term,vel,ind}} (\|\mathbf{v}_1\|^2 + \|\mathbf{v}_2\|^2) + w_{\text{term,payload}} \|\mathbf{v}_p\|^2 + w_{\text{term,attitude}} (\phi_1^2 + \theta_1^2 + \phi_2^2 + \theta_2^2)$$

The Two-Phase NMPC Strategy

A single controller is not optimal for both emergency recovery and normal flight. We developed a two-phase strategy that switches the NMPC's objective (cost function) based on the system's stability.

Phase 1: Aggressive Stabilization

Algorithm 1: Phase 1: Aggressive Stabilization

Input : System state $\mathbf{x}_0$
Output: Optimal control inputs $\mathbf{u}^*$

while $\|\mathbf{v}_p\| > \epsilon$ **do**
  Initialize optimization variables
  $X \in \mathbb{R}^{30\times(N+1)}$, $U \in \mathbb{R}^{8\times N}$
  Set initial condition: $X(:,1) \leftarrow \mathbf{x}_{\text{current}}$
  for $k \leftarrow 1$ **to** N **do**
    Apply dynamics: $X(:,k+1) \leftarrow f(X(:,k), U(:,k))$
    Enforce input constraints: $\mathbf{u}_{\min} \leq U(:,k) \leq \mathbf{u}_{\max}$
    Enforce state constraints: $\mathbf{x}_{\min} \leq X(:,k) \leq \mathbf{x}_{\max}$
  Minimize cost: $J \leftarrow \sum_{k=1}^{N} L_{\text{stab}}(X(:,k), U(:,k)) + V_f(X(:,N+1))$ (Eq. 5.23)
  if *SOLVER converged* **then**
    Extract solution: $U^* \leftarrow \text{sol.value}(U)$
  else
    Use warm start fallback
  Apply control: $\mathbf{u}_0^* \leftarrow U^*(:,1)$
  Update state: $\mathbf{x}_{\text{new}} \leftarrow f(\mathbf{x}_{\text{current}}, \mathbf{u}_0^*)$
  Shift horizon: $U_{\text{init}} \leftarrow [U^*(:,2\!:\!N),\ U^*(:,N)]$

Phase 2: Precision Tracking

Algorithm 2: Phase 2: Precision Tracking

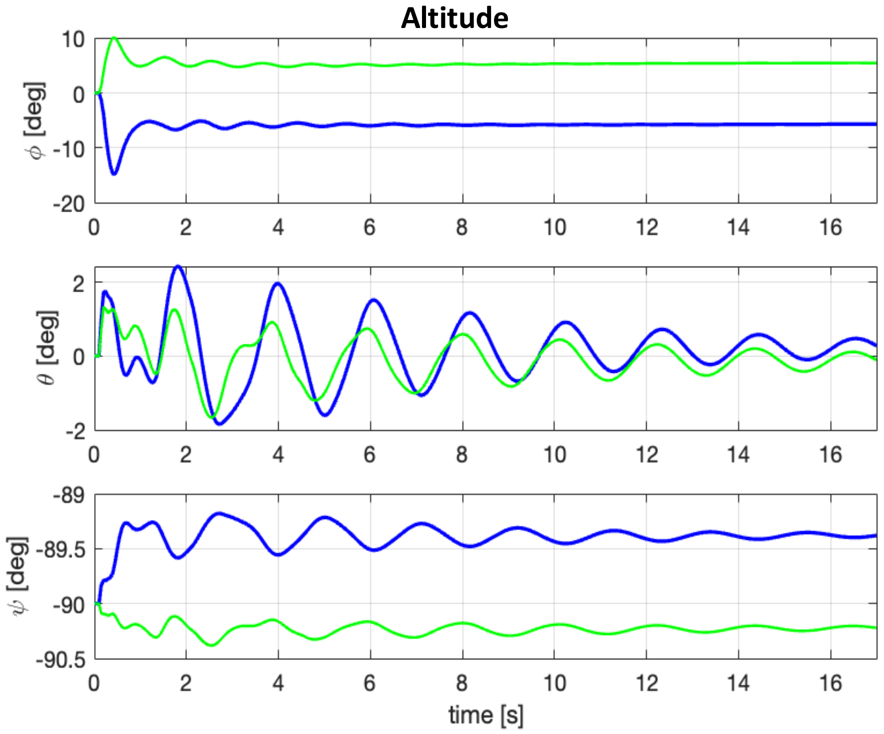
Input : System state $\mathbf{x}_0$, target position $\mathbf{p}_{\text{des}}$
Output: Optimal control inputs $\mathbf{u}^*$

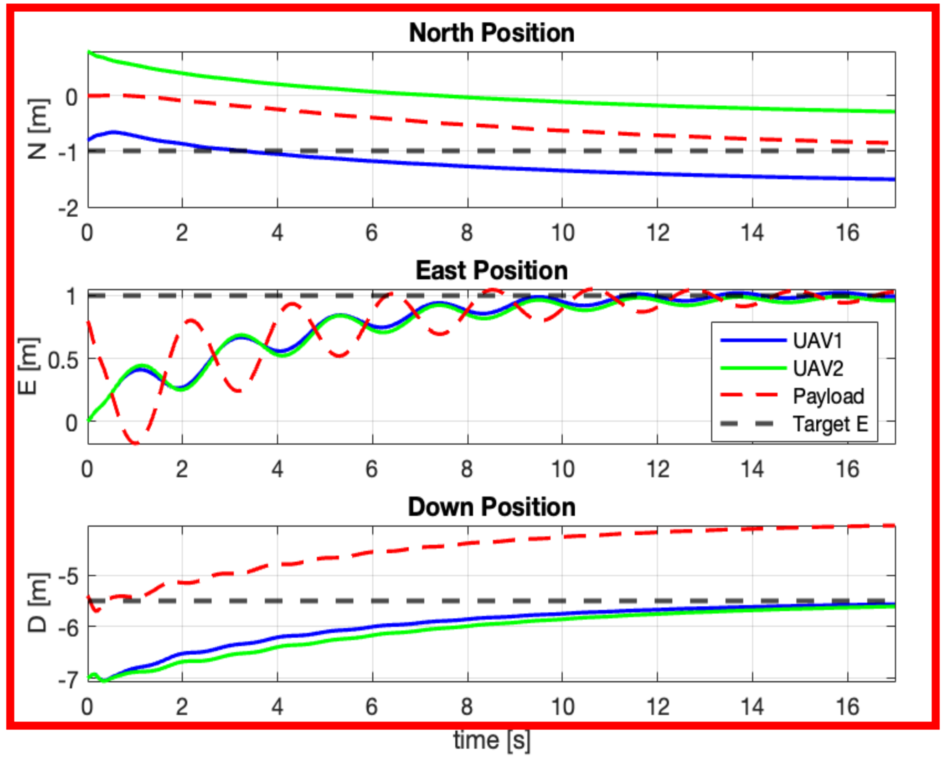
while $\|\mathbf{p}_{center} - \mathbf{p}_{des}\| > \epsilon_{pos}$ **do**
  Initialize optimization variables
  $X \in \mathbb{R}^{30\times(N+1)}$, $U \in \mathbb{R}^{8\times N}$
  Set initial condition: $X(:,1) \leftarrow \mathbf{x}_{\text{current}}$
  for $k \leftarrow 1$ **to** N **do**
    Apply dynamics: $X(:,k+1) \leftarrow f(X(:,k), U(:,k))$
    Enforce input constraints: $\mathbf{u}_{\min} \leq U(:,k) \leq \mathbf{u}_{\max}$
    Enforce state constraints: $\mathbf{x}_{\min} \leq X(:,k) \leq \mathbf{x}_{\max}$
    Compute formation center: $\mathbf{p}_{\text{center},k} \leftarrow \frac{\mathbf{p}_{1,k}+\mathbf{p}_{2,k}}{2}$
    Calculate distance to target: $d_{\text{target},k} \leftarrow \|\mathbf{p}_{\text{center},k} - \mathbf{p}_{\text{des}}\|$
    Compute desired formation velocities:
    $v_{x,\text{des}} \leftarrow v_{\max,\text{form}} \cdot \tanh(k_{\text{pos}} \cdot (x_{\text{des}} - x_{\text{center},k}))$
    $v_{y,\text{des}} \leftarrow v_{\max,\text{form}} \cdot \tanh(k_{\text{pos}} \cdot (y_{\text{des}} - y_{\text{center},k}))$
    $v_{z,\text{des}} \leftarrow v_{\max,\text{form}} \cdot \tanh(k_{\text{pos}} \cdot (z_{\text{des}} - z_{\text{center},k}))$
  Min cost: $J \leftarrow \sum_{k=1}^{N} L_{\text{track}}(X(:,k), U(:,k)) + V_{\text{track}}(X(:,N+1))$ (Eq. 5.31)
  if *SOLVER converged* **then**
    Extract solution: $U^* \leftarrow \text{sol.value}(U)$
  else
    Use warm start fallback
  Apply control: $\mathbf{u}_0^* \leftarrow U^*(:,1)$
  Update state: $\mathbf{x}_{\text{new}} \leftarrow f(\mathbf{x}_{\text{current}}, \mathbf{u}_0^*)$
  Shift horizon: $U_{\text{init}} \leftarrow [U^*(:,2\!:\!N),\ U^*(:,N)]$
  Check convergence criteria:
  Compute position error: $\epsilon_{\text{pos,current}} \leftarrow \|\mathbf{p}_{\text{center}} - \mathbf{p}_{\text{des}}\|$

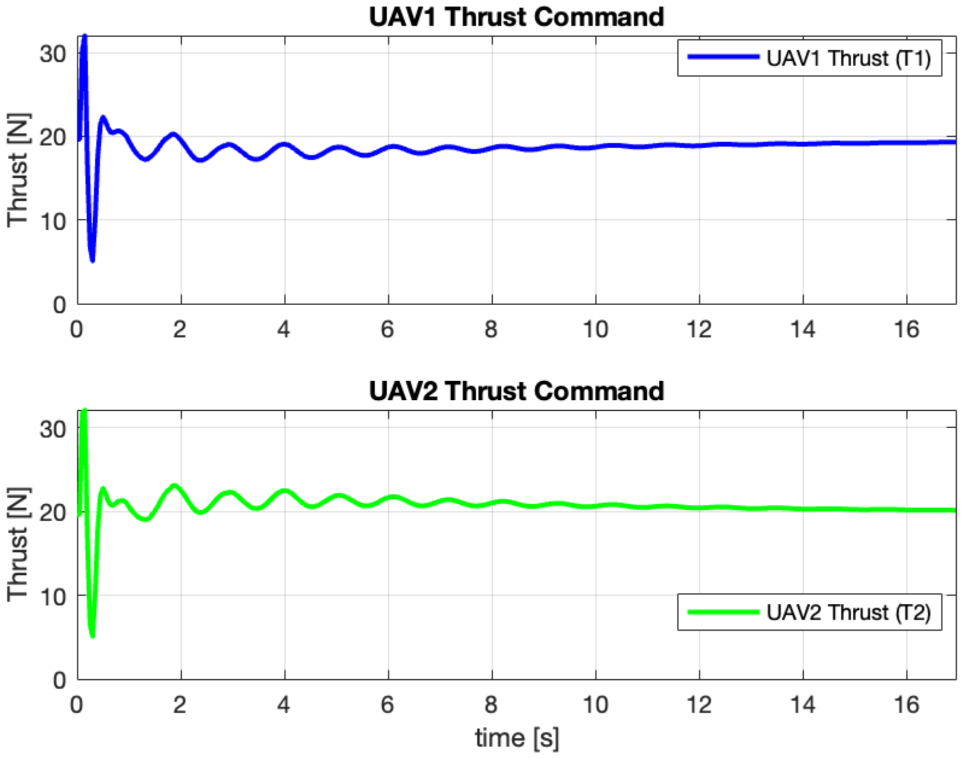
Phase Switching Logic

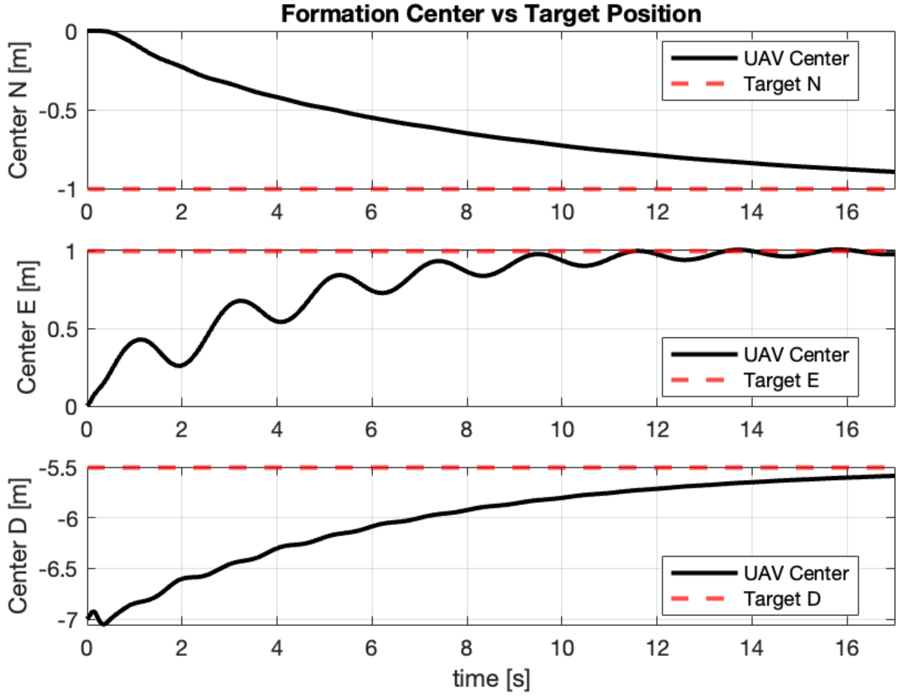
The controller transitions from Phase 1 to Phase 2 when the payload and UAV velocities fall below a predefined threshold (e.g., < 0.05 m/s), indicating the system is stable.

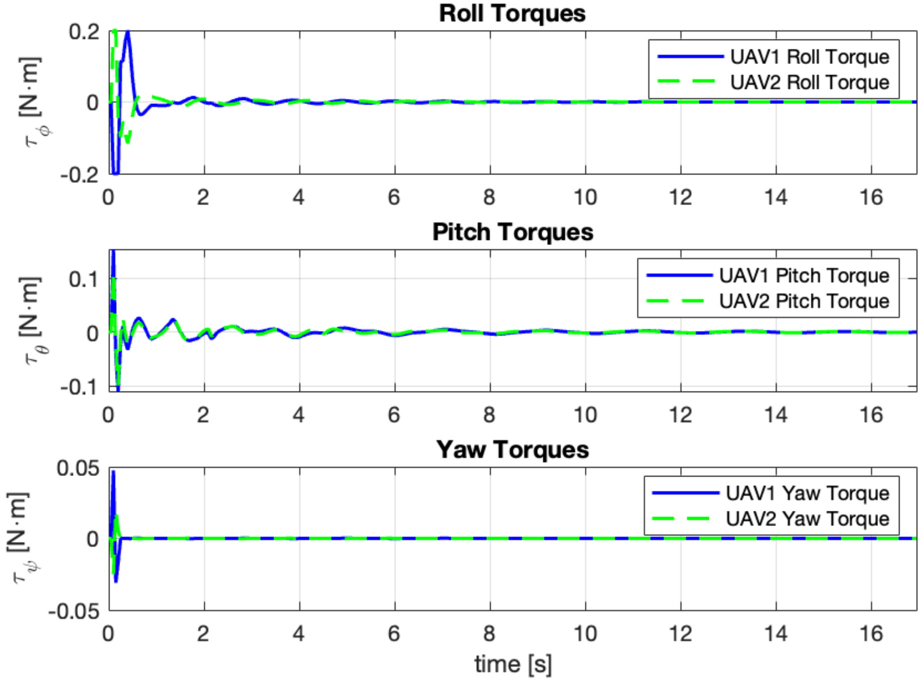
Results: Scenario 1 – Tracking without Stabilization

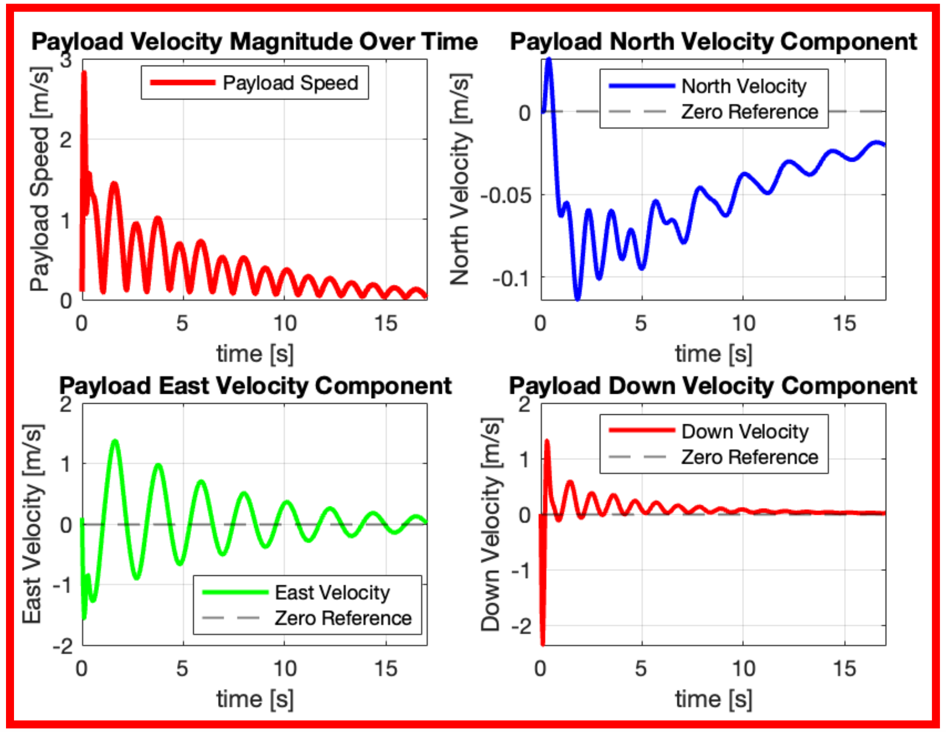




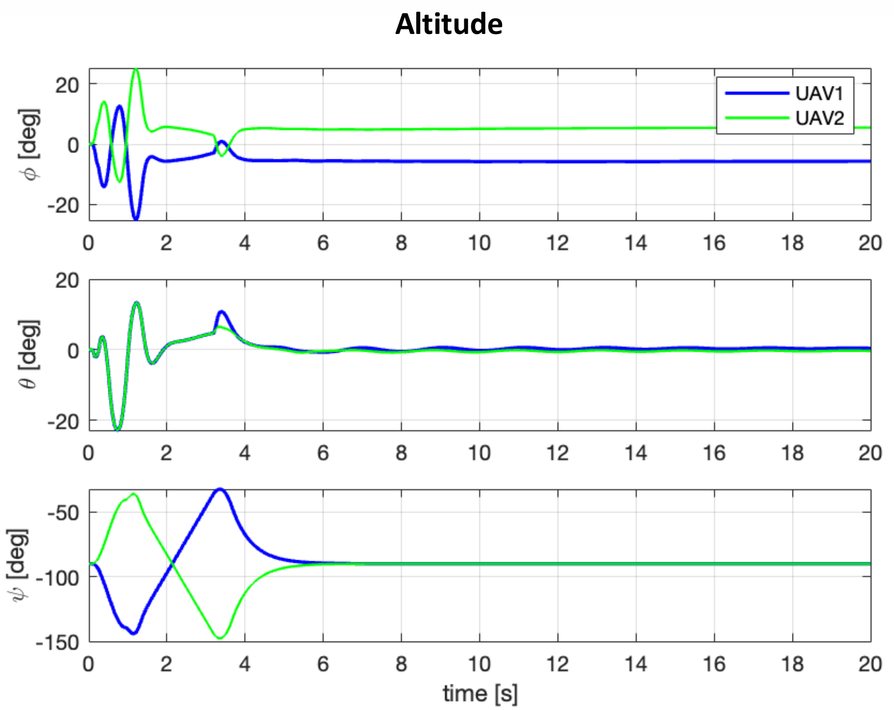


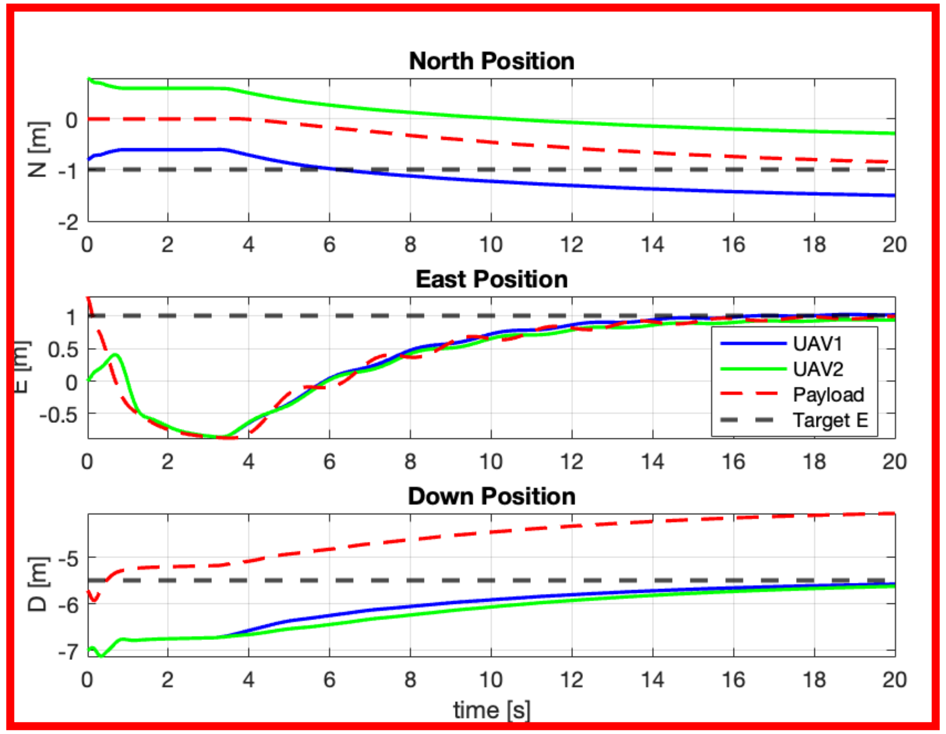


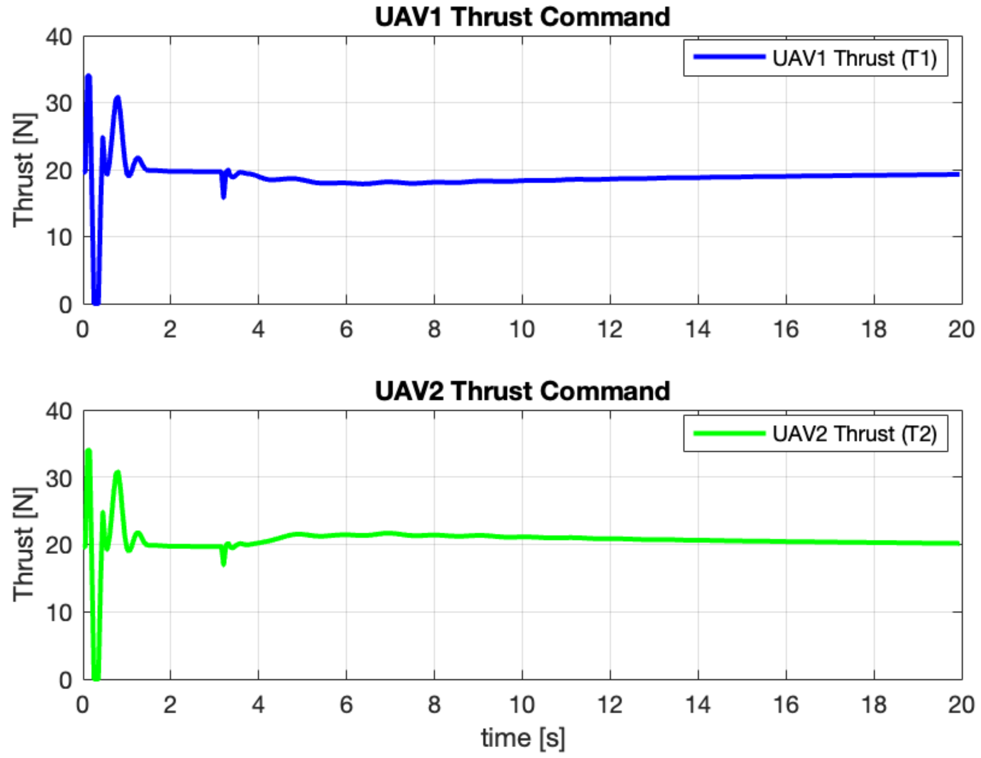


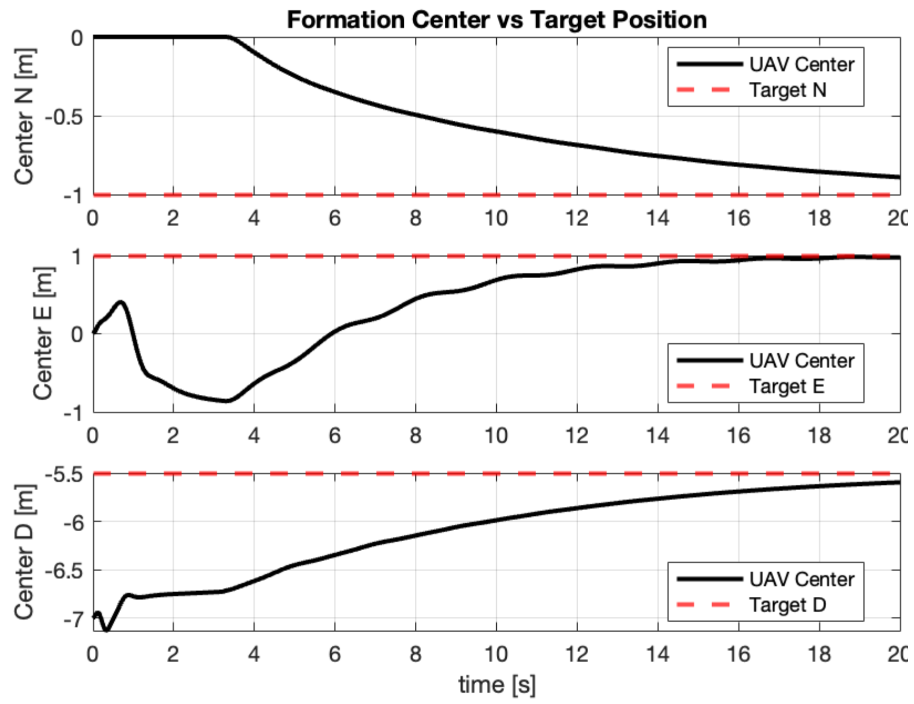


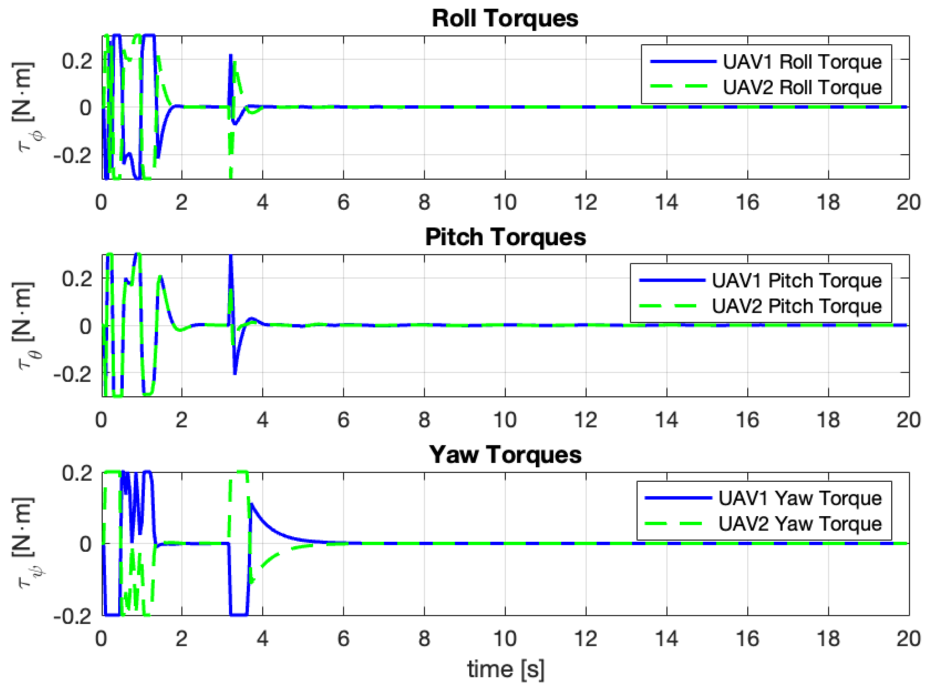
Results: Scenario 2 – Stabilization then Tracking

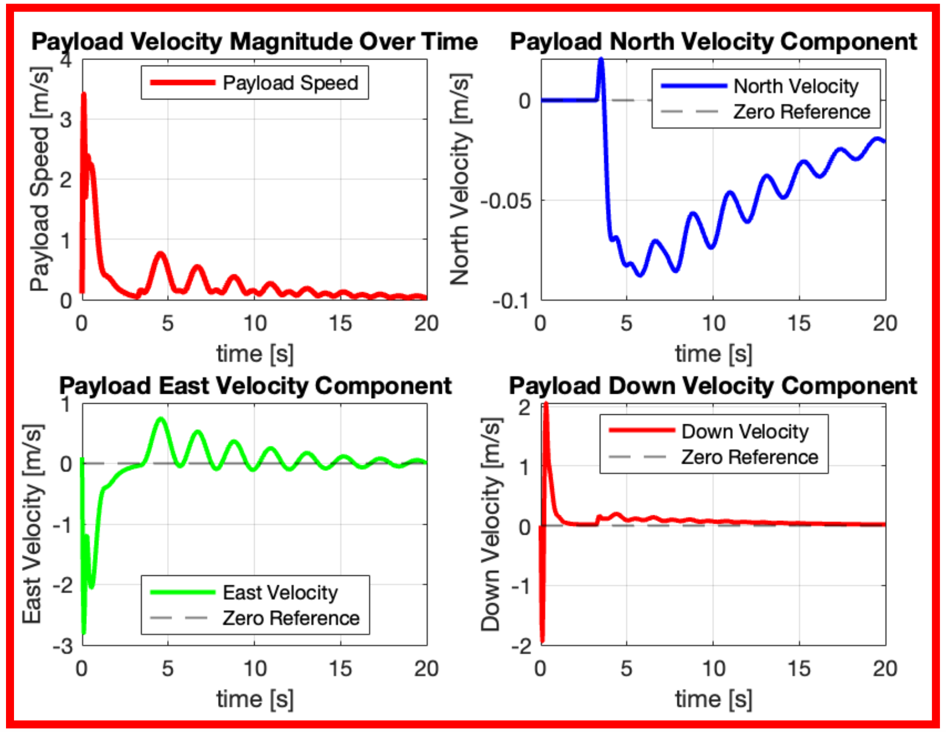










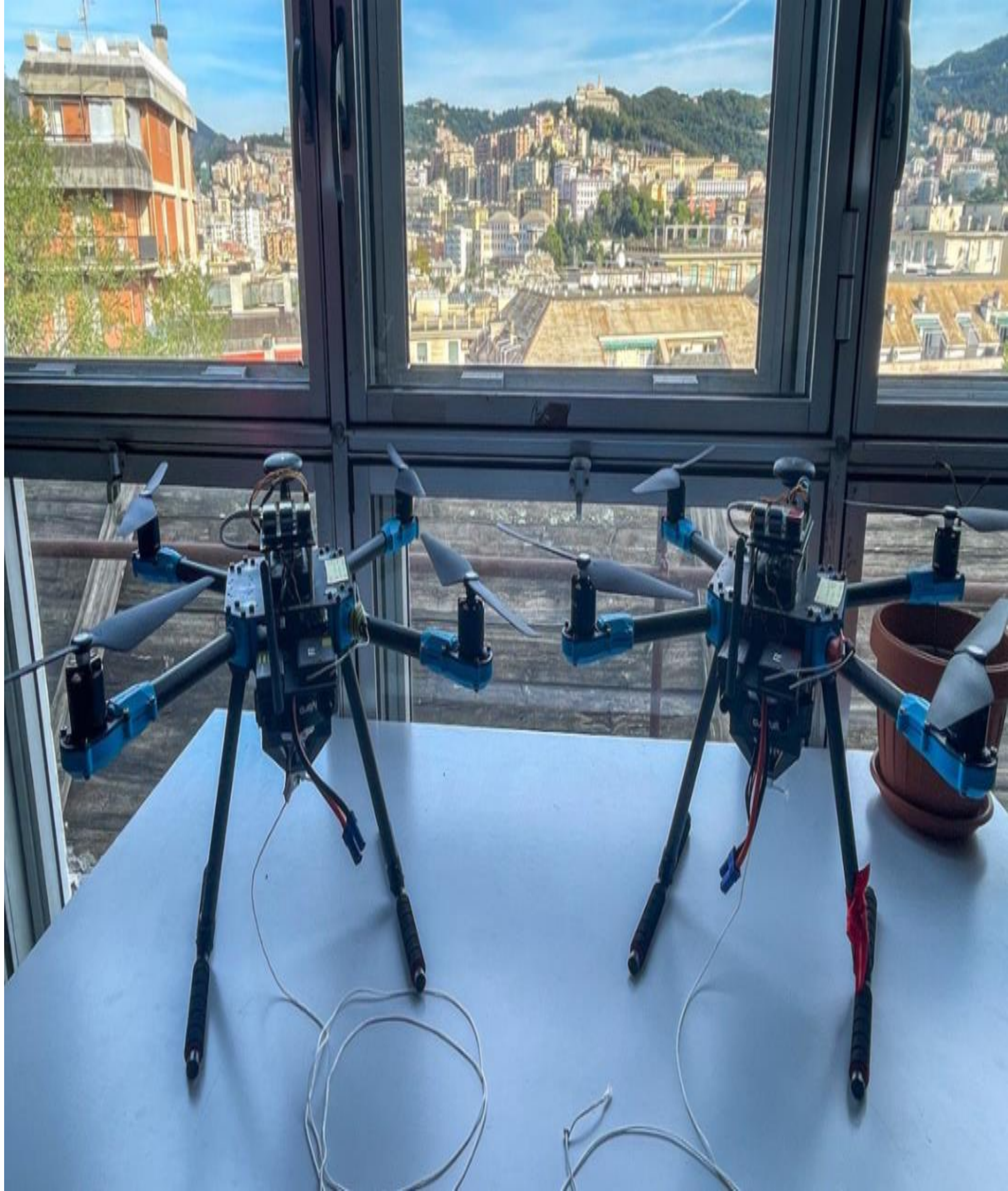


Conclusion

- We successfully developed and validated a two-phase NMPC framework for fault-tolerant control of a multi-UAV payload system.
- The dedicated aggressive stabilization phase is proven to be critical for safety, rapidly suppressing dangerous post-failure oscillations.
- The framework demonstrates a seamless transition to a precision tracking phase, allowing the mission to continue after recovery.
- Unfortunately, due to a communication error/bug between ROS2 and PX4, we were not able to fully test the controller performance in the Gazebo simulation. However, this limitation was related to the ROS interface, not the proposed NMPC algorithm itself.

Future Work

- Finalize ROS2/Gazebo Integration
- Enhanced Simulation Testing
- Advanced NMPC Methodologies
- Laboratory Experimental
- Onboard Implementation



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Thank you for attending this thesis defense. Your presence and engagement are greatly appreciated.

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Questions are welcome