Nonlinear MPC for Quadrotors in Close-Proximity Flight with Neural Network Downwash Prediction

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Open Source!
Scan here!

https://github.com/Li-Jinjie/ndp_nmpc_qd

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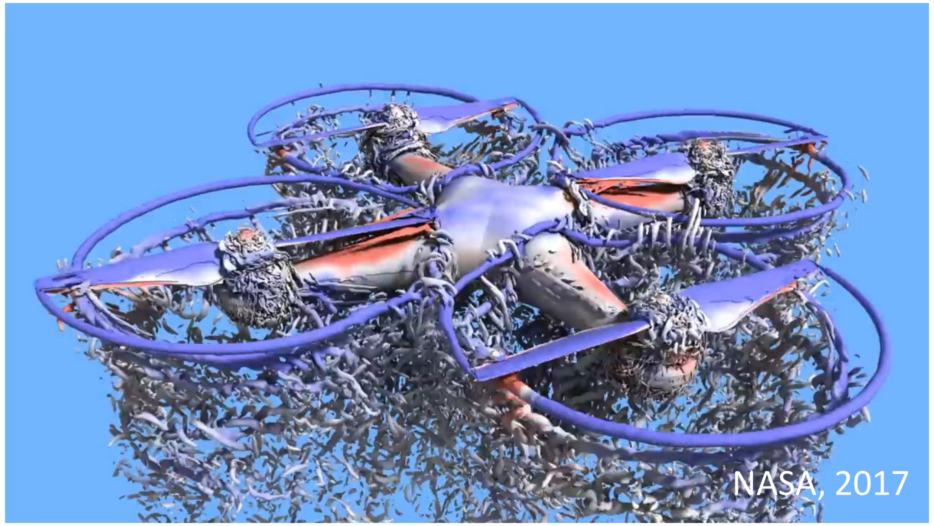
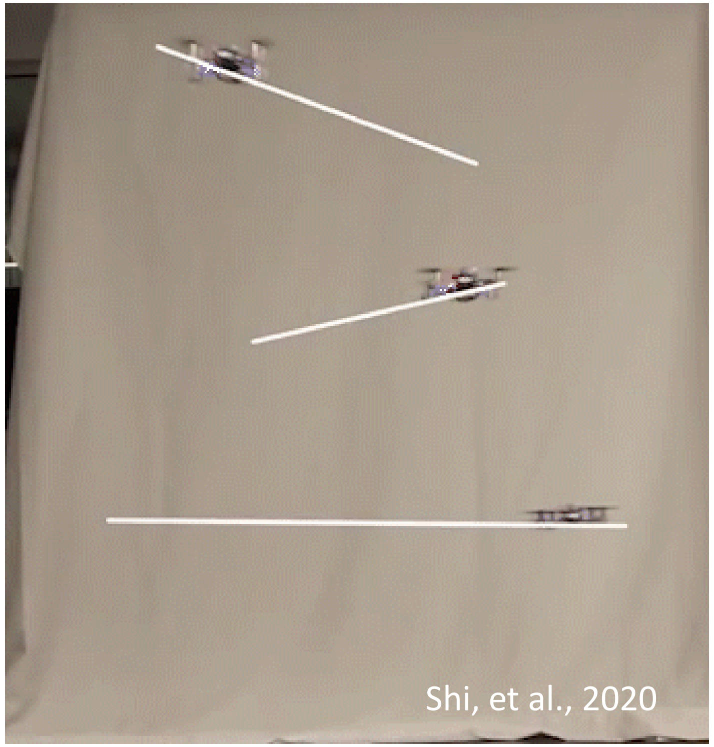
CDC 2023 SINGAPORE

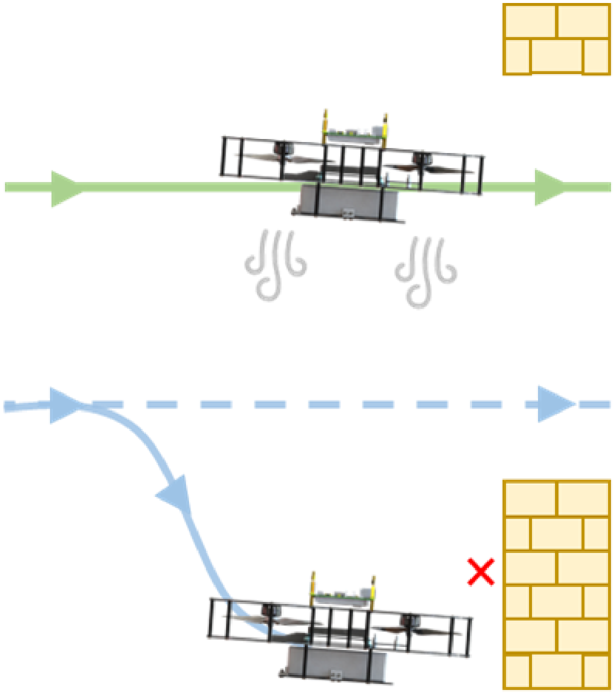
Introduction

Downwash effect?



- CFD simulation for a DJI Phantom 3 quadrotor





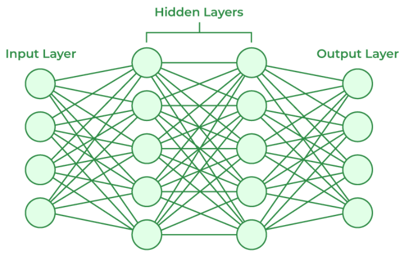
- Downwash in Swarm Robotics

Introduction

Downwash effect

- Caused by other quadrotors
- Difficult to describe

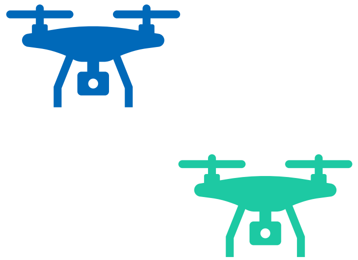
Neural Network



+

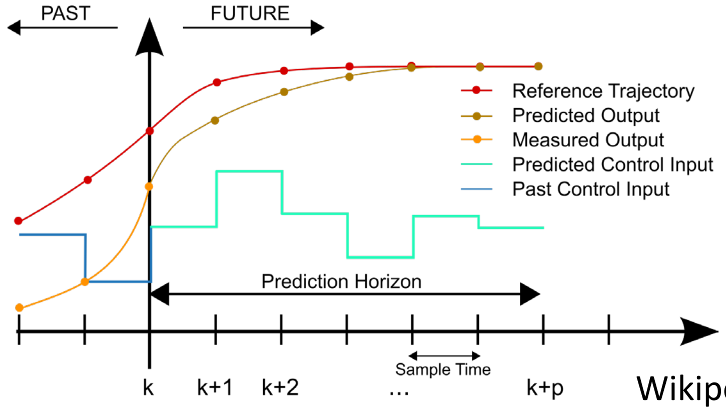
Control Problem

1. No prediction
2. No constraints



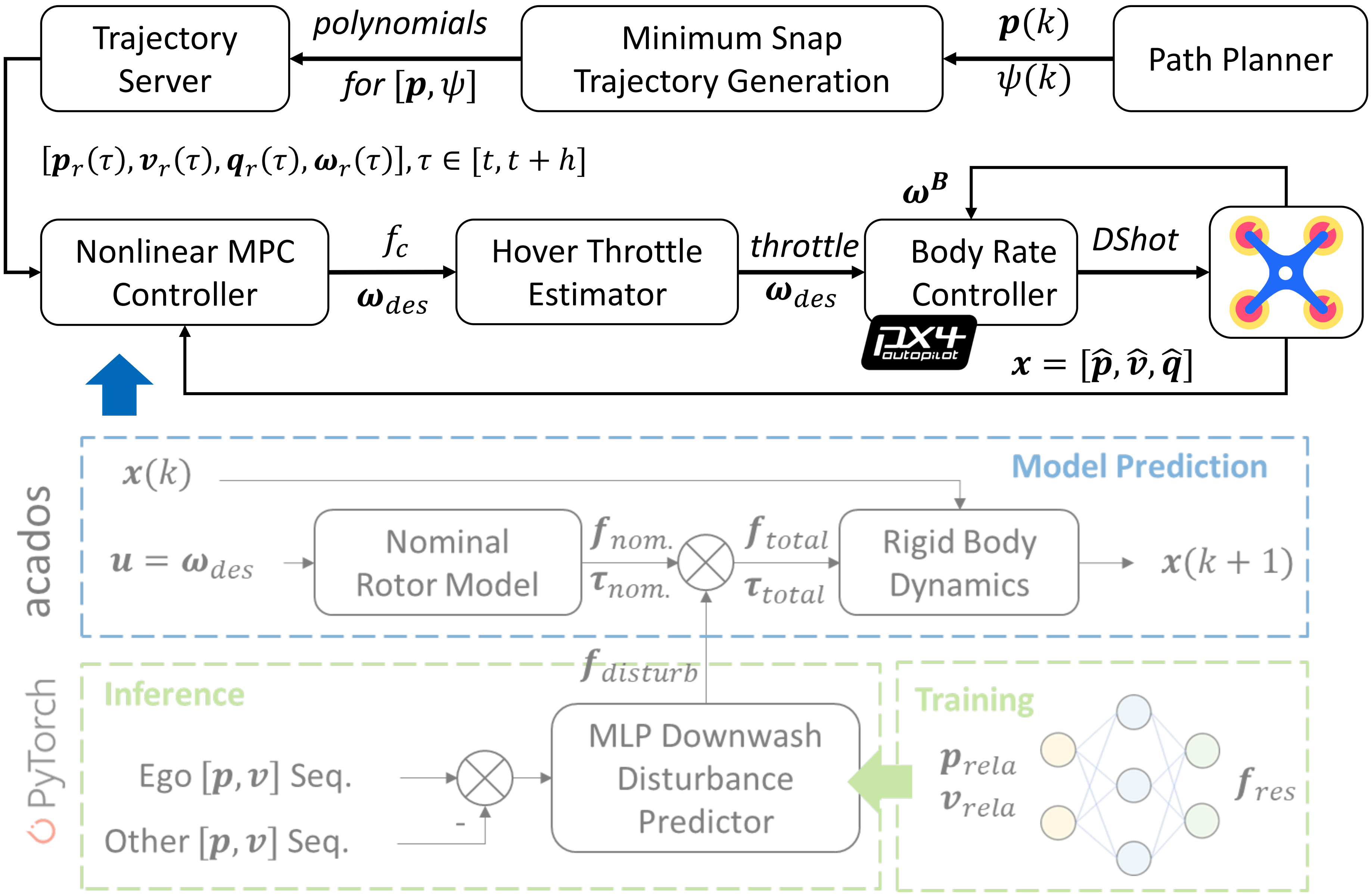
VS

Model Predictive Control



Wikipedia, 2023

System Overview



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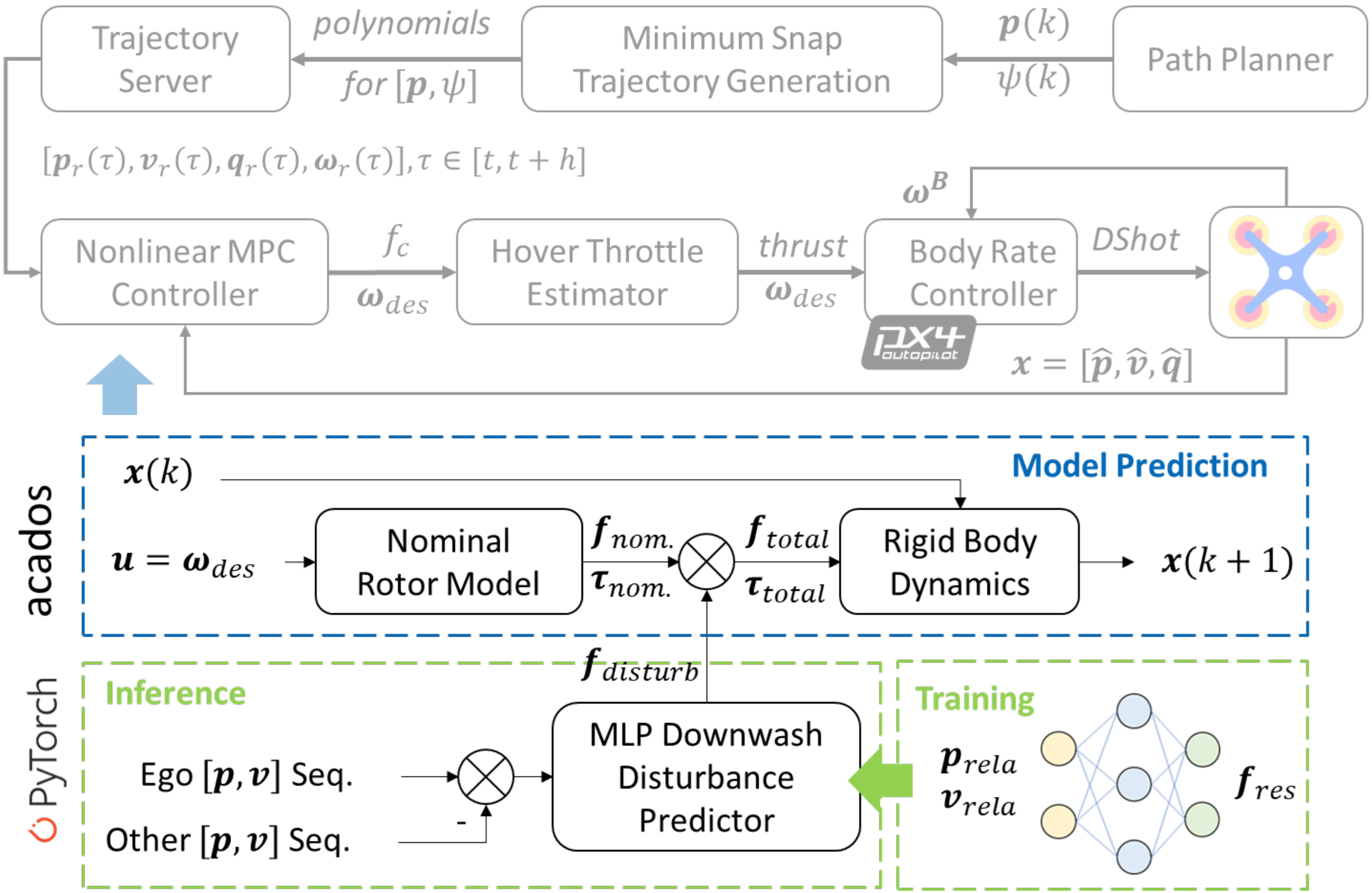
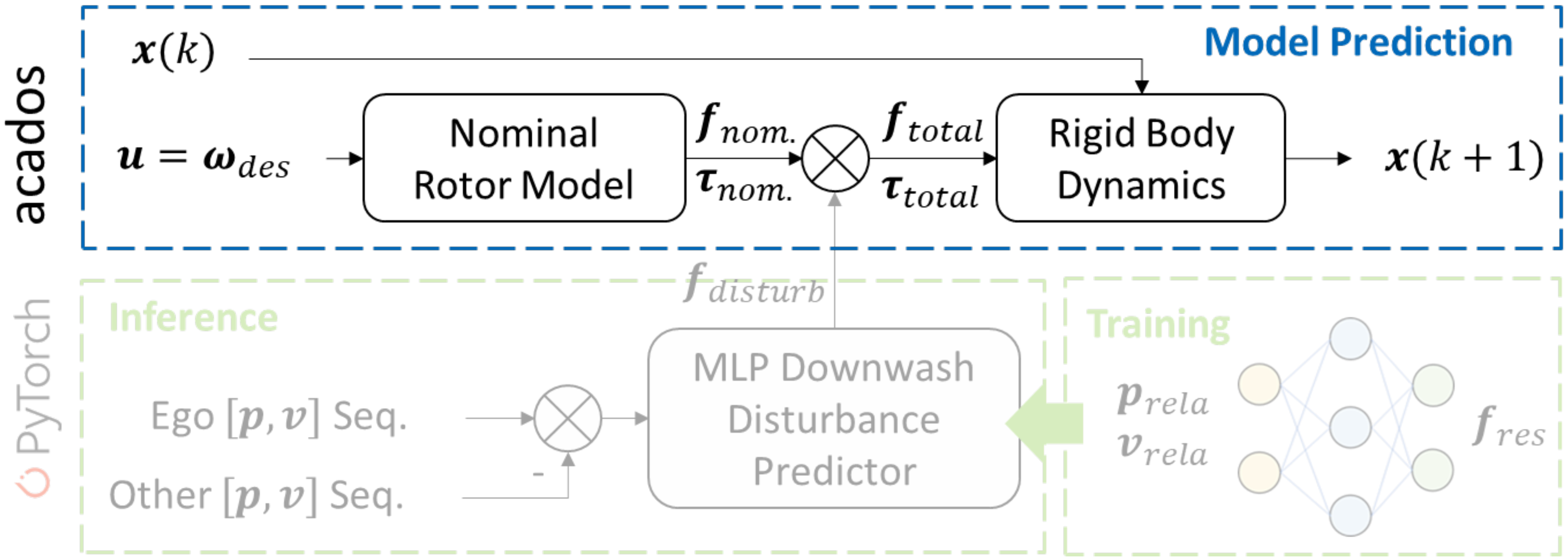


Nonlinear MPC



State: $\boldsymbol{p}, \boldsymbol{v}, \boldsymbol{q}$

Input: $\boldsymbol{\omega}$ + Collective Thrust

Nonlinear Model

$$\begin{cases} {}^{I}\dot{\boldsymbol{p}} = {}^{I}\boldsymbol{v} \\ {}^{I}\dot{\boldsymbol{v}} = {}^{I}_{B}\boldsymbol{R}(\boldsymbol{q}) \cdot {}^{B}\boldsymbol{f}_{u} / m + {}^{I}\boldsymbol{g} \\ {}^{B}_{I}\dot{\boldsymbol{q}} = 1/2 \cdot {}^{B}_{I}\boldsymbol{q} \circ \mathcal{V}^{*}\left({}^{B}\boldsymbol{\omega}\right) \end{cases}$$

Nonlinear Least Square Cost

$$\min_{\boldsymbol{u}_k} \left(\overline{\boldsymbol{x}}_N^T \boldsymbol{Q}_N \overline{\boldsymbol{x}}_N + \sum_{k=0}^{N-1} \left(\overline{\boldsymbol{x}}_k^T \boldsymbol{Q} \overline{\boldsymbol{x}}_k + \overline{\boldsymbol{u}}_k^T \boldsymbol{R} \overline{\boldsymbol{u}}_k \right) \right)$$

$$\boldsymbol{q}_e = \boldsymbol{q} \circ \boldsymbol{q}_r^{-1}$$

$$\overline{\boldsymbol{q}}_k^T \boldsymbol{Q}_q \overline{\boldsymbol{q}}_k = \|\mathrm{sgn}(q_{ew}) \cdot \mathcal{V}(\boldsymbol{q}_e)\|_Q^2 = \mathcal{V}(\boldsymbol{q}_e)^T \boldsymbol{Q}_q \mathcal{V}(\boldsymbol{q}_e),$$

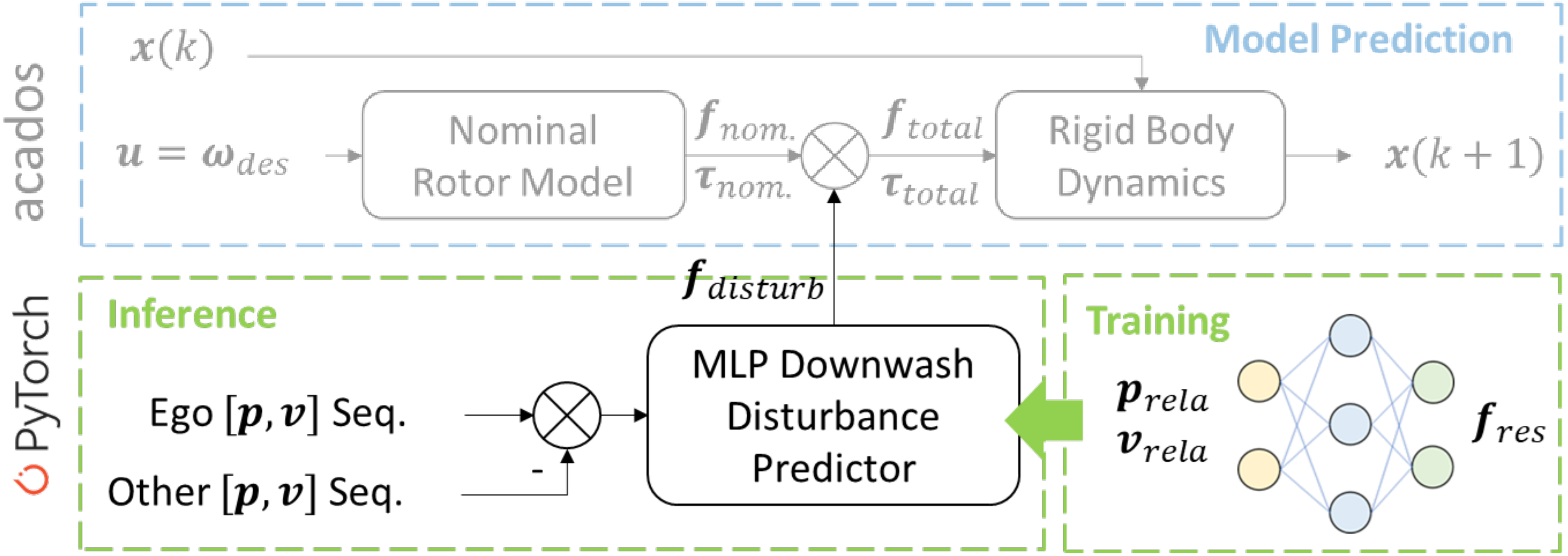
Linear Constraints

$$\boldsymbol{x}_0 = \boldsymbol{x}_{\text{init}},$$
$$\boldsymbol{u}_k \in [\boldsymbol{u}_{\min}, \boldsymbol{u}_{\max}],$$

Control Frequency:

50~60Hz

Nonlinear MPC



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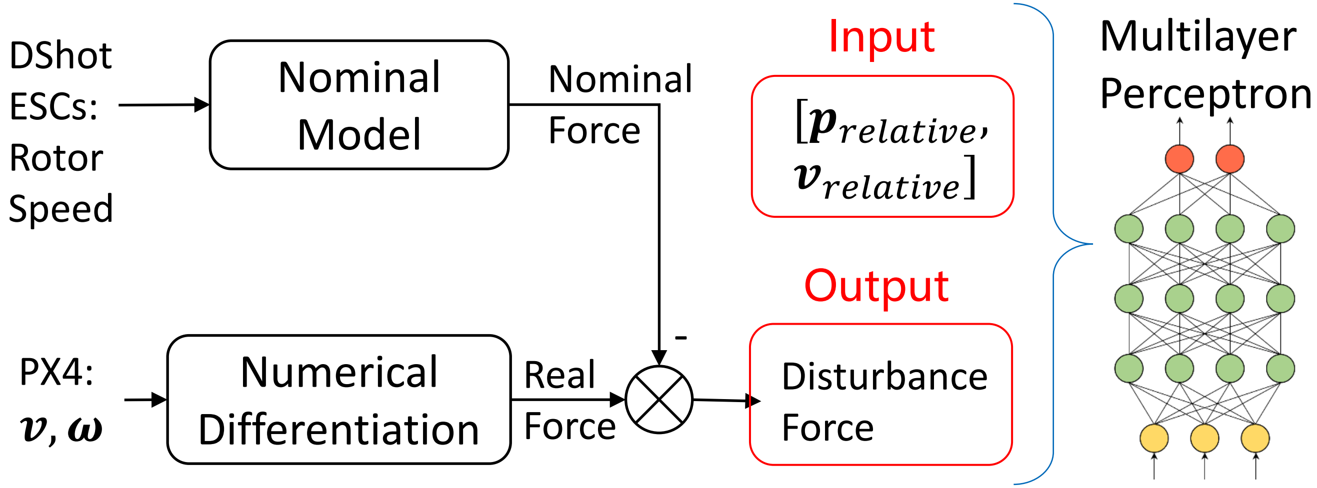
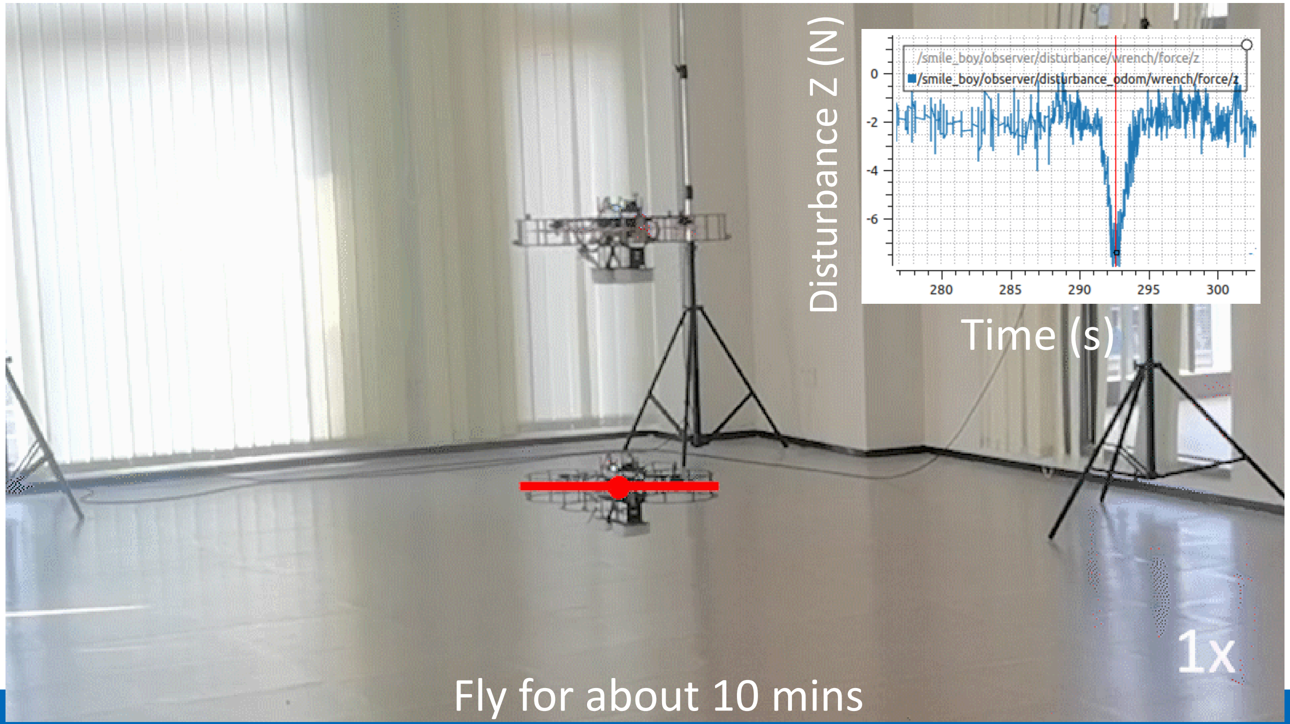
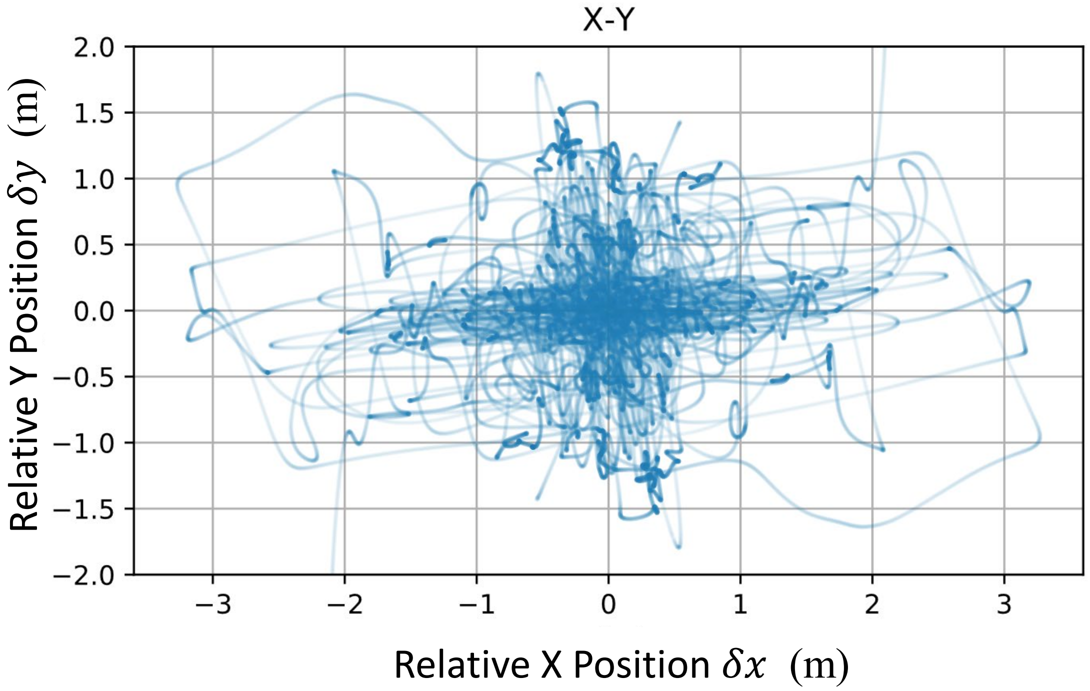
Control Frequency:

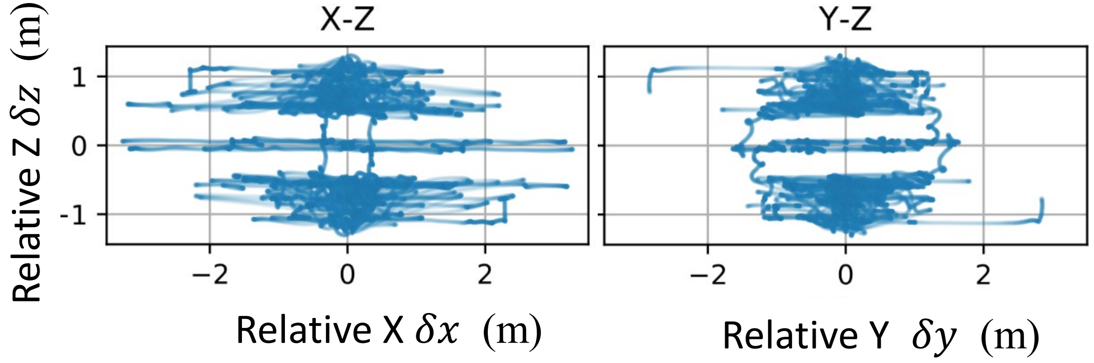
50~60Hz

Collection of Disturbance Data









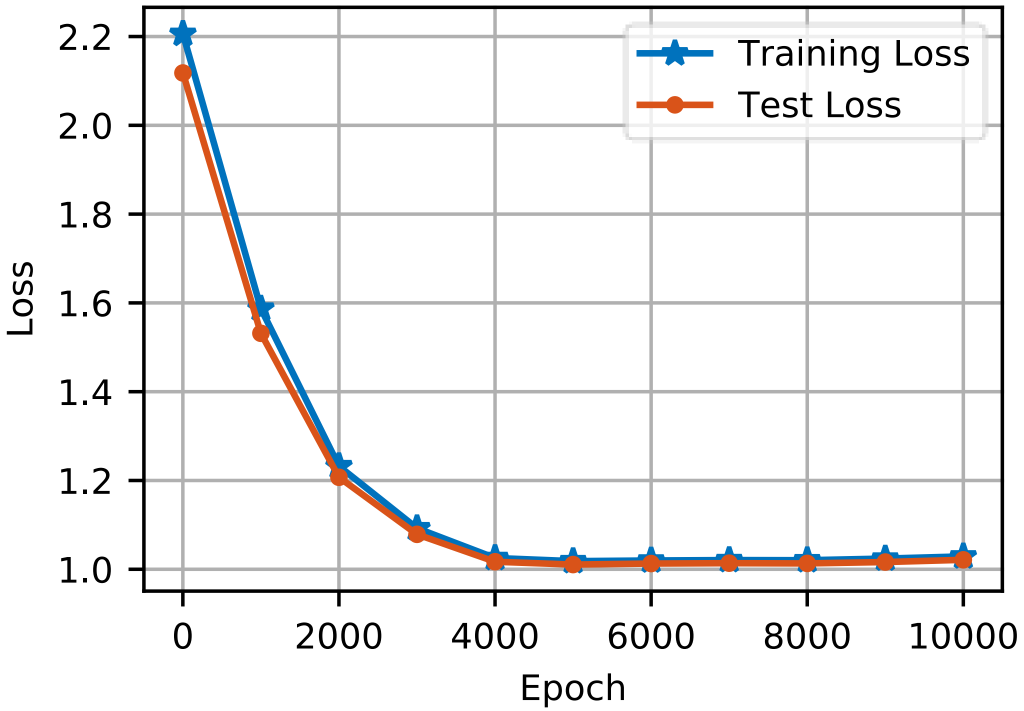
Total Data Number： 57,000 x 2

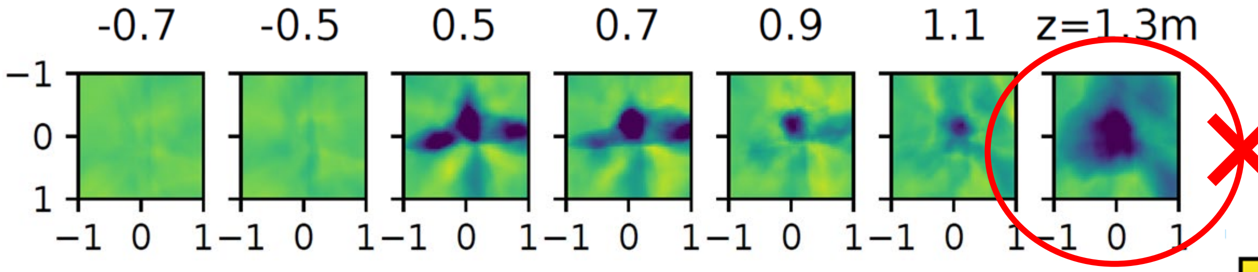
Training for Disturbance Network

Training Parameters

Layers	Initialization	Activation Function
6-128-64-128-3	normal	ReLU
Epoch	**Learning Rate**	**Loss Function**
20,000	1e-4	Mean Squared Error

Training Process when $\gamma = 4$



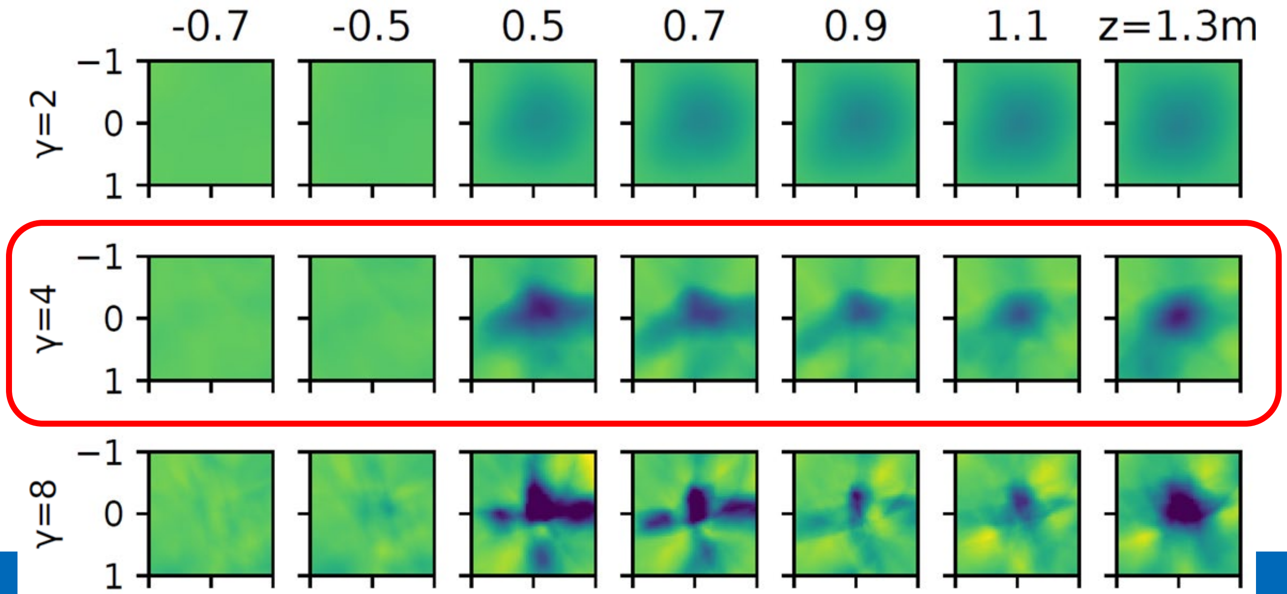


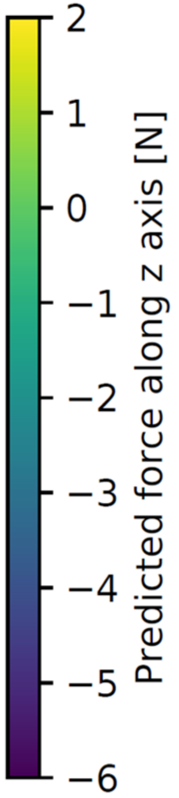
Spectral Normalization

$$\|f(\boldsymbol{x};\boldsymbol{\theta})\|_{\text{Lip}} \le \|\boldsymbol{W}^{H+1}\boldsymbol{x}+\boldsymbol{b}^{H+1}\|_{\text{Lip}} \cdot \|\phi\|_{\text{Lip}} \cdot \|\boldsymbol{W}^{H}\boldsymbol{x}+\boldsymbol{b}^{H}\|_{\text{Lip}} \cdots \|\boldsymbol{W}^{1}\boldsymbol{x}+\boldsymbol{b}^{1}\|_{\text{Lip}}$$

$$= \|\boldsymbol{W}^{H+1}\|\cdots\|\boldsymbol{W}^{1}\| = \sigma_{\max}(\boldsymbol{W}^{H+1})\cdots\sigma_{\max}(\boldsymbol{W}^{1}) = \prod_{l=1}^{H+1}\sigma_{\max}(\boldsymbol{W}^{l})$$

$$\overline{\boldsymbol{W}}^{l} := \gamma \cdot \boldsymbol{W}^{l} / \sigma_{\max}(\boldsymbol{W}^{l}) \longrightarrow \|f(\boldsymbol{x};\overline{\boldsymbol{\theta}})\|_{\text{Lip}} \le \gamma^{H+1}$$



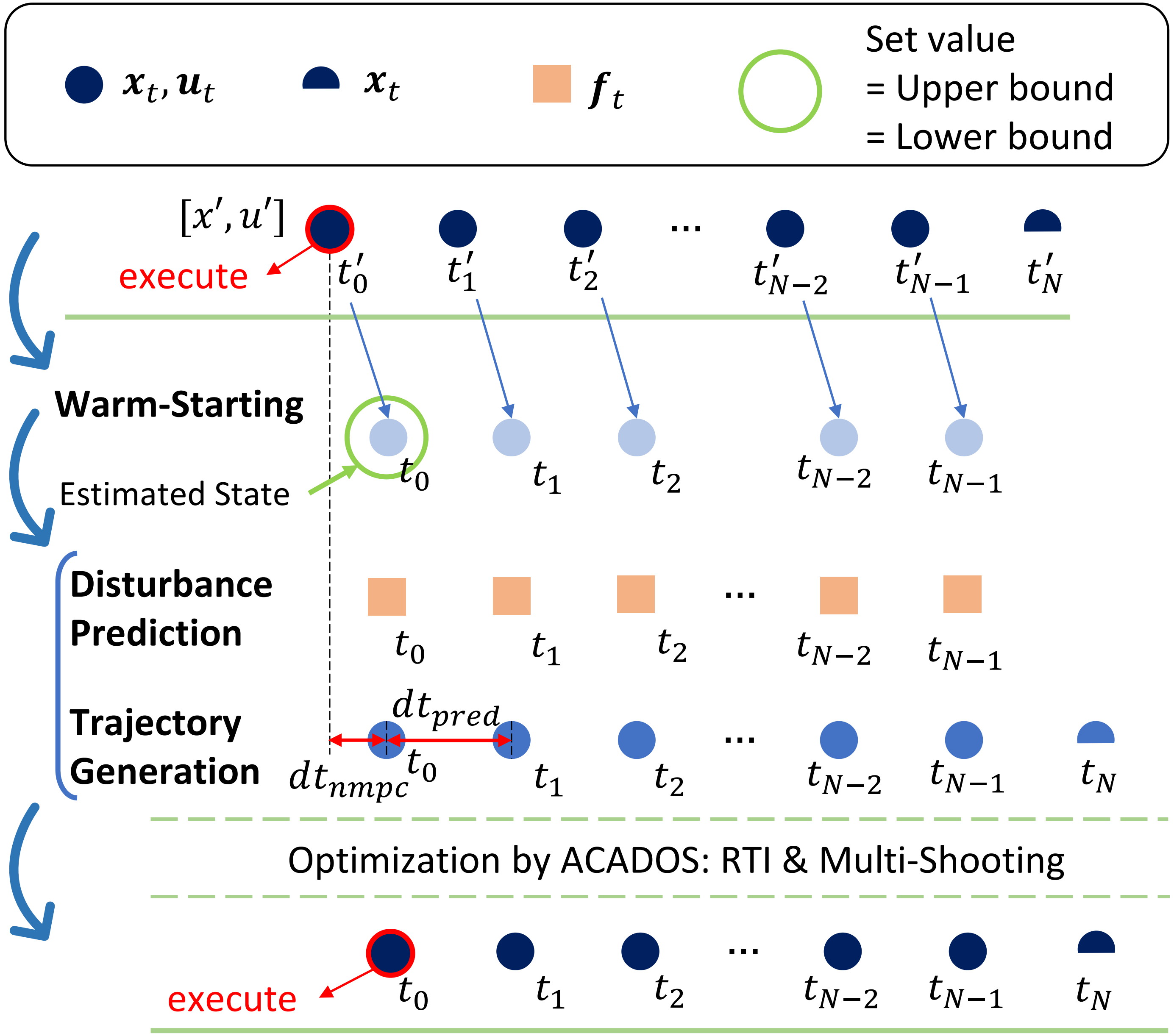


Network Downwash Prediction NMPC (NDP-NMPC)

$$\begin{cases} {}^{I}\dot{\boldsymbol{p}} = {}^{I}\boldsymbol{v} \\ {}^{I}\dot{\boldsymbol{v}} = {}^{I}_{B}\boldsymbol{R}(\boldsymbol{q}) \cdot {}^{B}\boldsymbol{f}_{u} / m + {}^{I}\boldsymbol{g} \\ {}^{B}_{I}\dot{\boldsymbol{q}} = 1/2 \cdot {}^{B}_{I}\boldsymbol{q} \circ \mathcal{V}^{*}\left({}^{B}\boldsymbol{\omega}\right) \end{cases}$$

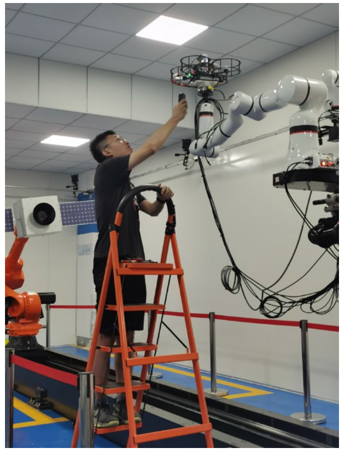
$$\begin{cases} {}^{I}\dot{\boldsymbol{p}} = {}^{I}\boldsymbol{v} \\ {}^{I}\dot{\boldsymbol{v}} = \left({}^{I}_{B}\boldsymbol{R}(\boldsymbol{q}) \cdot {}^{B}\boldsymbol{f}_{u} + {}^{I}\boldsymbol{f}_{d}\right) / m + {}^{I}\boldsymbol{g} \\ {}^{B}_{I}\dot{\boldsymbol{q}} = 1/2 \cdot {}^{B}_{I}\boldsymbol{q} \circ \mathcal{V}^{*}\left({}^{B}\boldsymbol{\omega}\right) \end{cases}$$

Disturbance Force

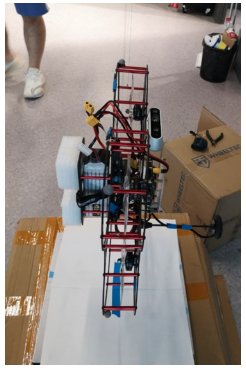


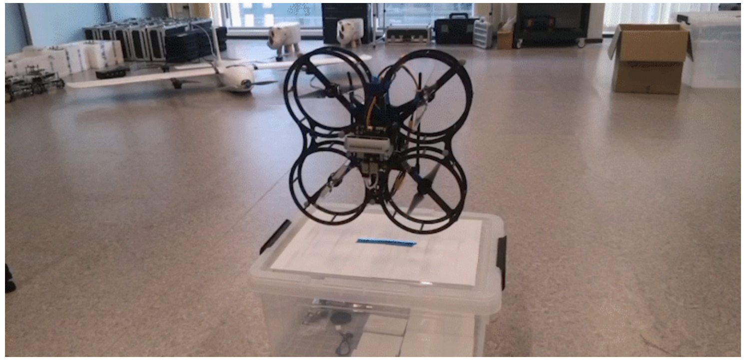
System Identification

Rotor Parameters



Inertial Parameters (Bifilar Pendulum)





Parameter(s)	Value(s)	Unit
L	0.1372	m
α	45	deg
m	1.5344	kg
g	9.81	m/s^2
I_{xx}	0.0094	$kg \cdot m^2$
I_{yy}	0.0134	$kg \cdot m^2$
I_{zz}	0.0145	$kg \cdot m^2$
k_q	3.7611 E-4	$N \cdot m/kRPM^2$
k_t	2.8158 E-2	$N/kRPM^2$
$[\Omega_{min}, \Omega_{max}]$	[2.6, 24.0]	kRPM
thrust/weight	4.3100	—
flight time	705	s

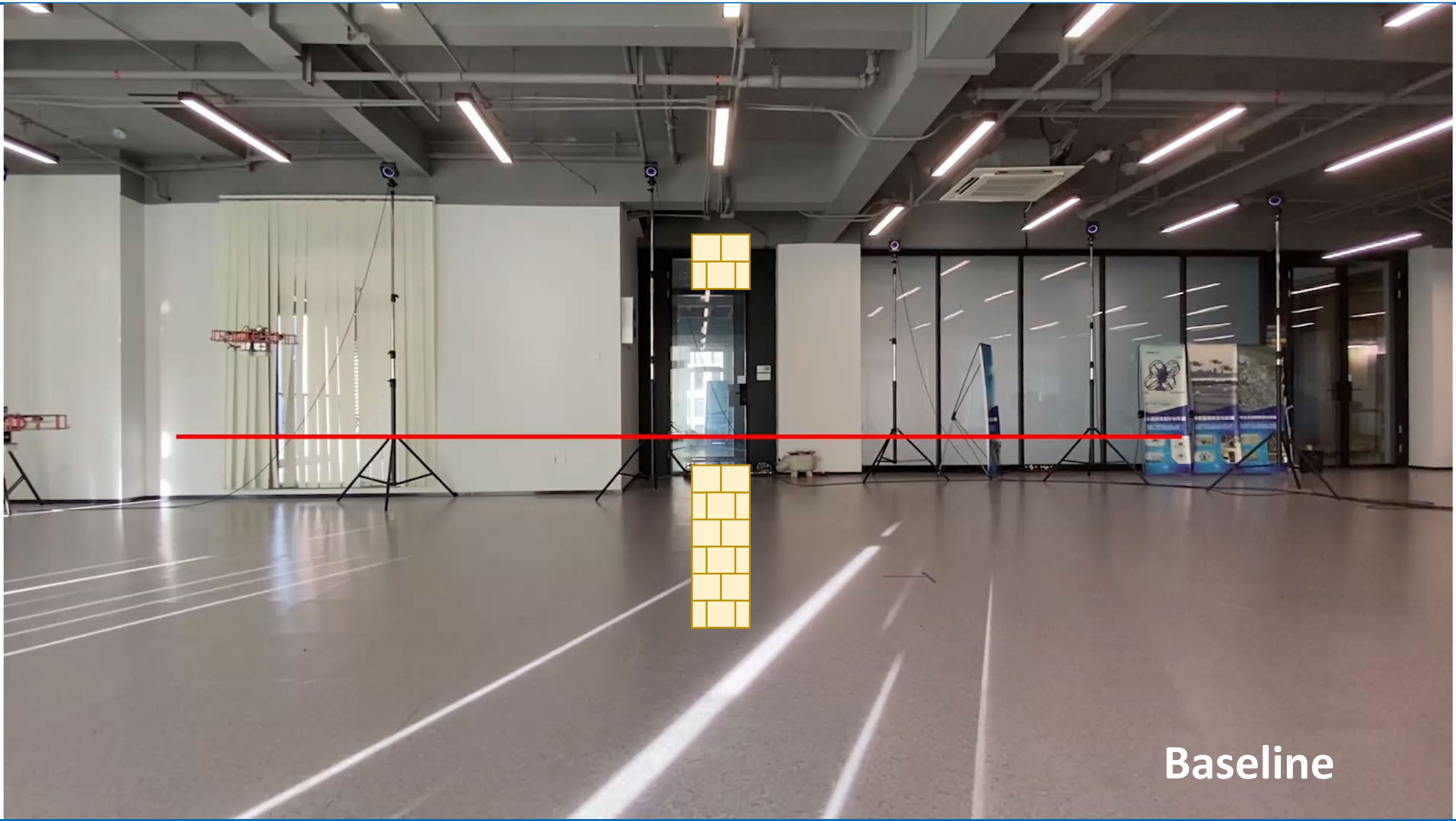
Onboard Computer TX2 NX

Jetson OS (Ubuntu 18.04)

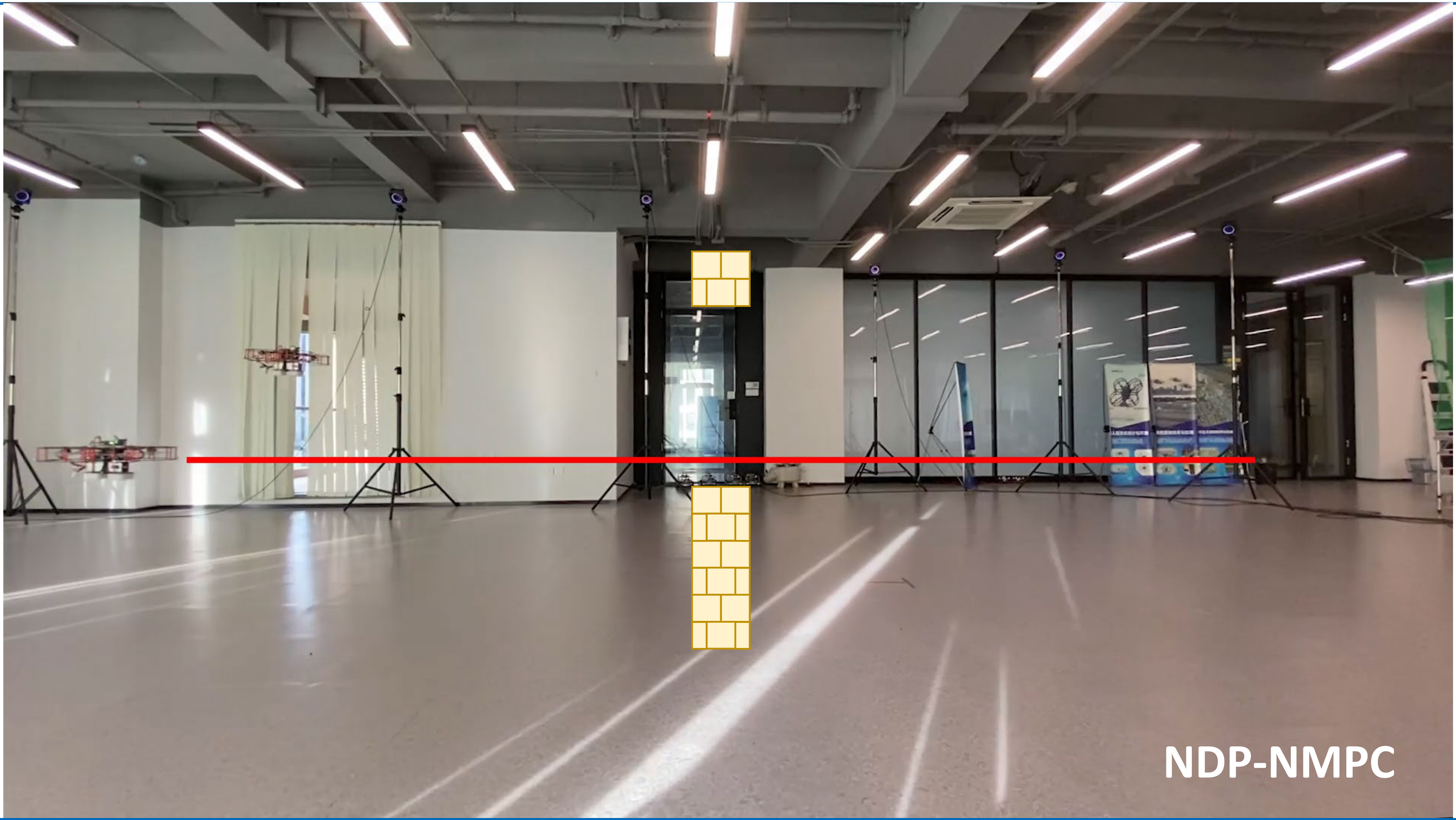
Pixhawk 4

PX4

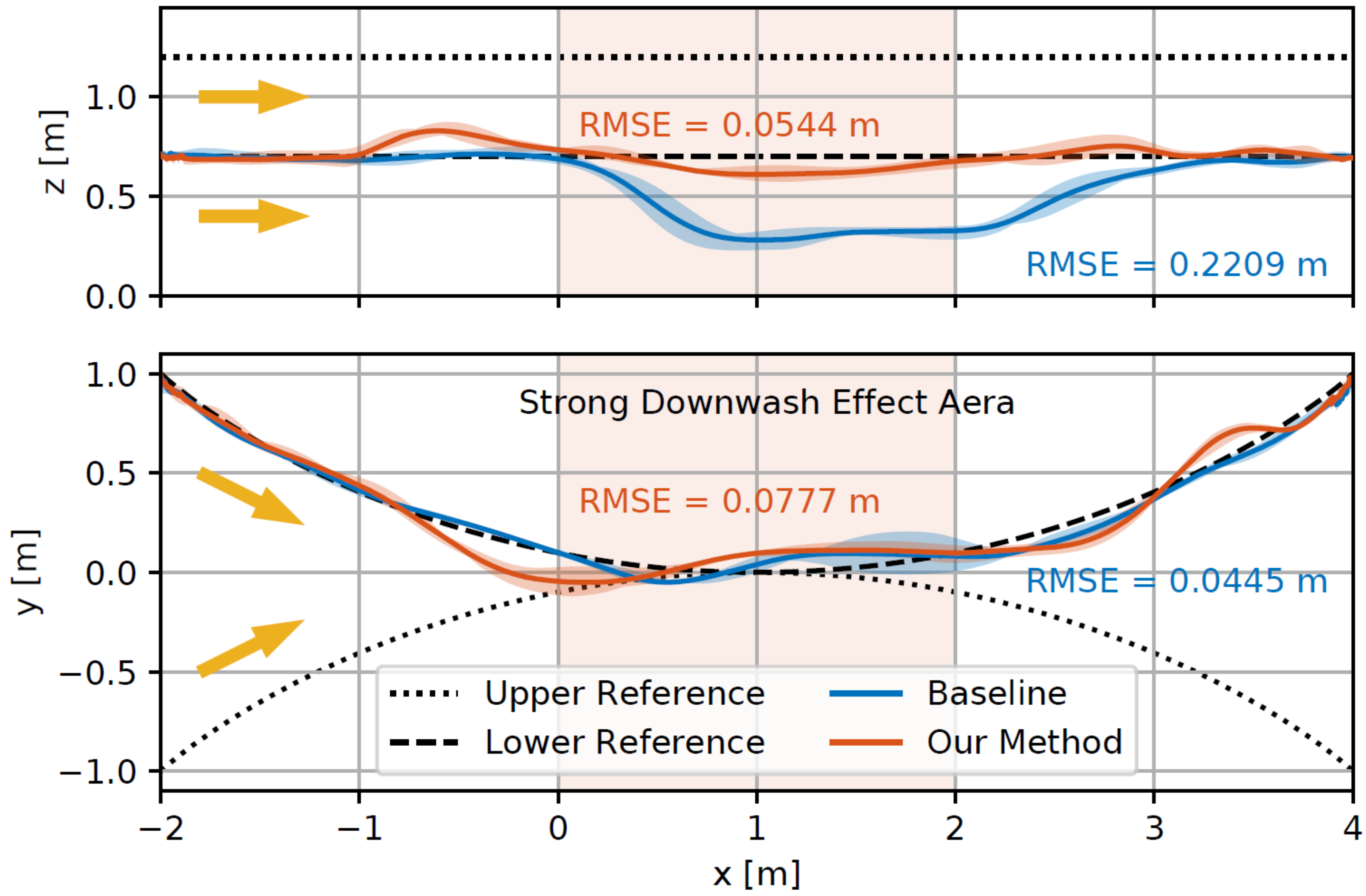
Flight Experiment --- Baseline



Flight Experiment --- NDP-NMPC



Comparison of Results



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Conclusion

Nonlinear MPC for Quadrotors in Close-Proximity Flight with Neural Network Downwash Prediction

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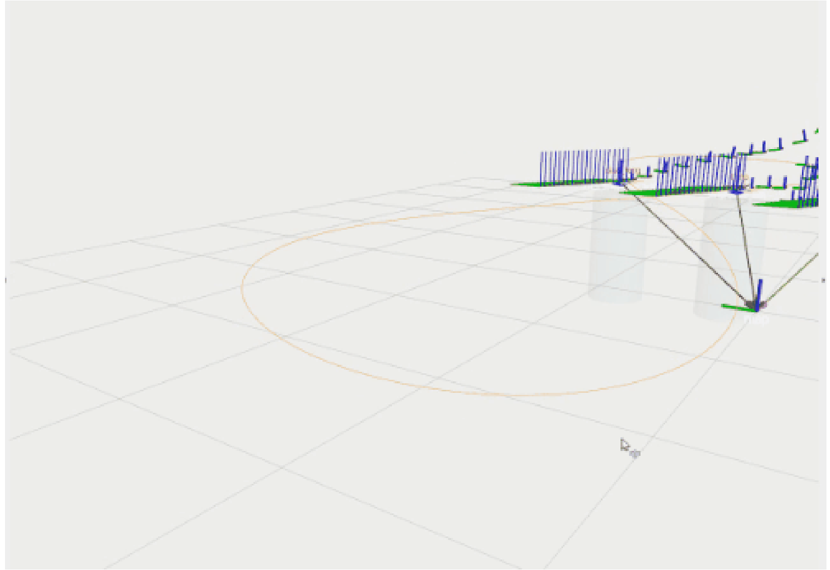
- Problem: downwash effect in two quadrotors
- Method: neural network + Nonlinear Model Predictive Control (NMPC)
- Achievement: two quadrotors, 0.5m close-proximity flight

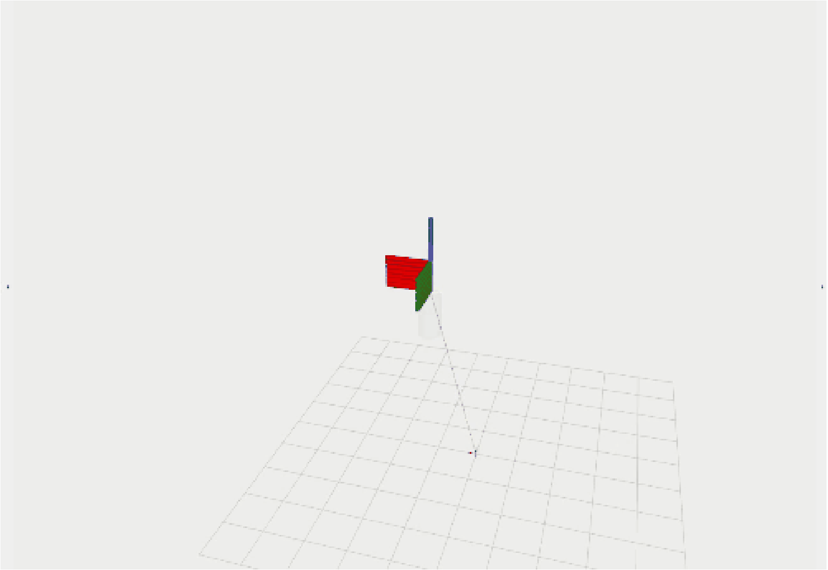
Future Work

- Extend to more drones (Graph Neural Network, etc.....)
- Considering closed-loop disturbance estimation
- More extensive comparison with other control methods

Thanks for listening!

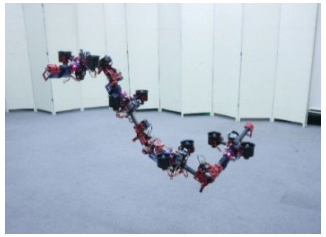
Scan here and try simulation!





Learn more about my research!

About me now: Doctoral Student, University of Tokyo, Supervised by Dr. Moju ZHAO, who created the DRAGON robot →



Homepage: https://jinjie.li/