Experimental Analysis of Advanced Control and Estimation Systems for Autonomous Ship Landing

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Introduction

- Landing rotorcraft during high sea states is difficult
- Lack of public domain experimental data on ship landing systems
  - Full scale testing is difficult, risky, and expensive
- Testing at model scale is desirable
  - Low risk and cost
  - Controllable environment
  - High volume testing
- Research goals:
  - Sensitivity of landing algorithms to aircraft response characteristics
  - Comparisons between different path planners
  - Vision based deck state estimation

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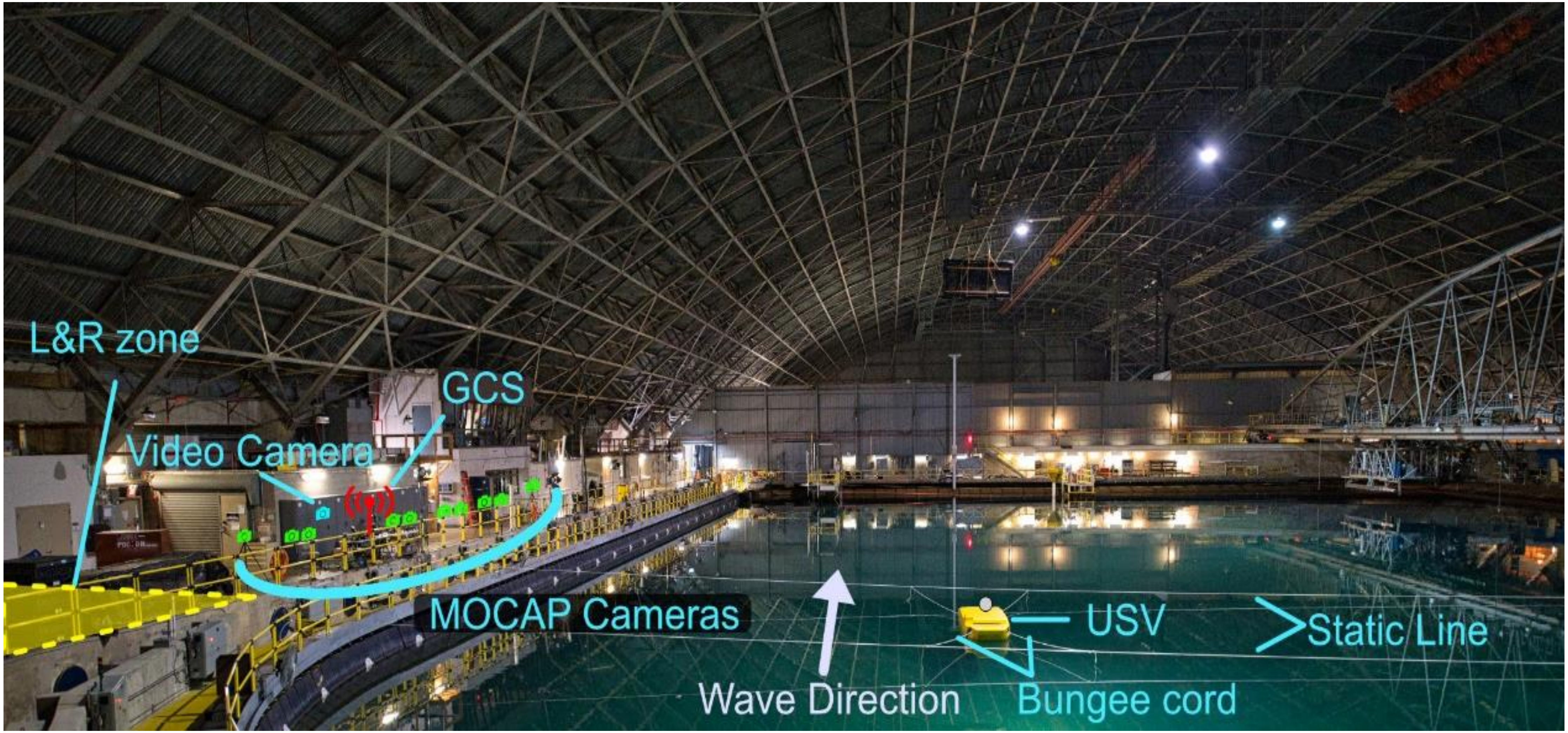
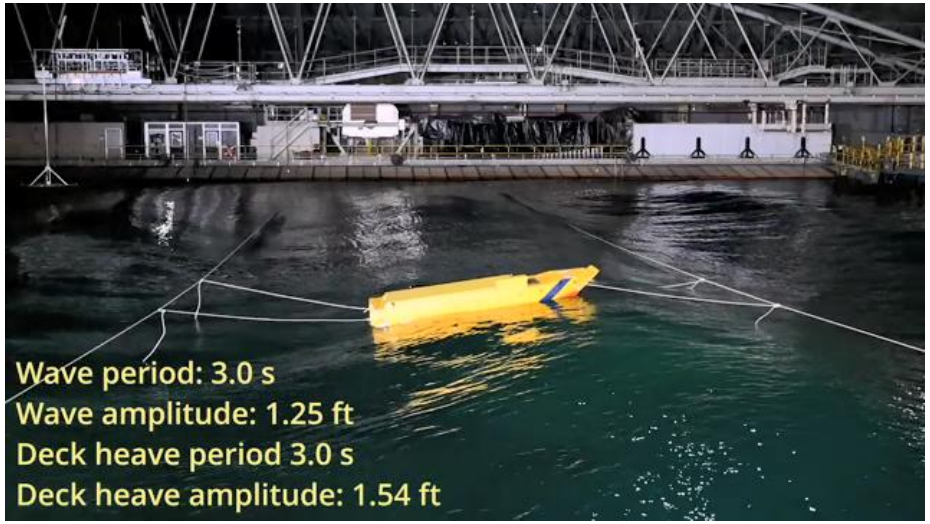
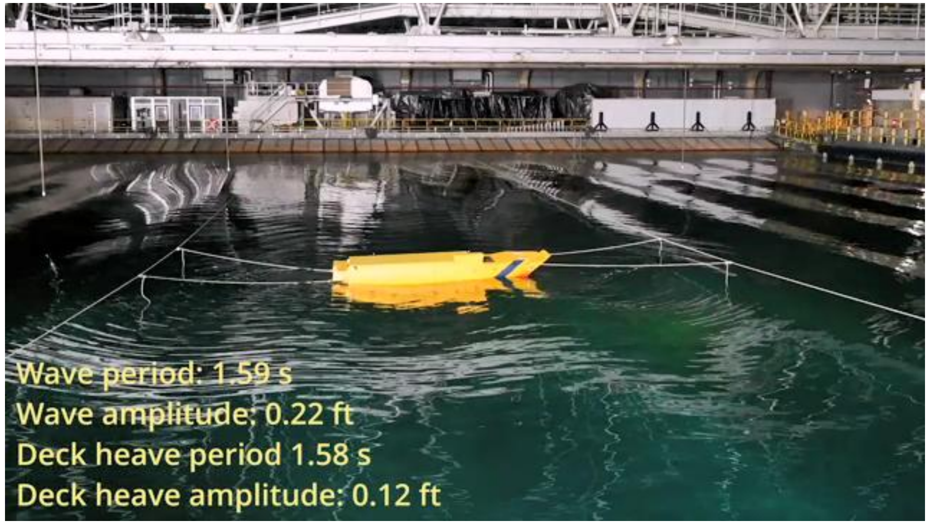
Experimental Setup

Maneuvering and Sea Keeping Basin



USV Platform





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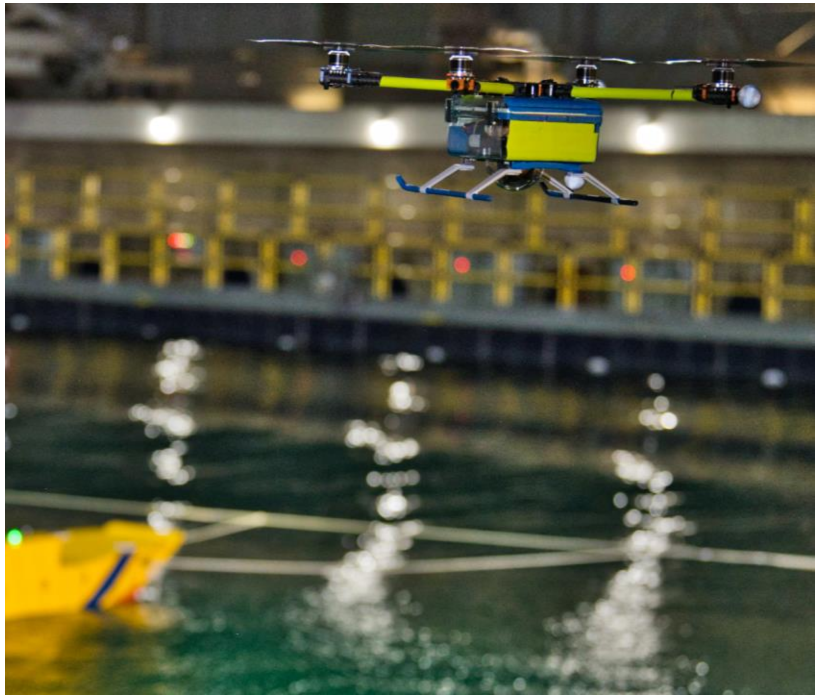
UAV Platforms

- 2 UAVs: hexacopter and quadcopter
  - Odroid XU4 single board computer
  - Jevios a33 camera
  - Pixhawk Cube Orange autopilot + PX4 Firmware



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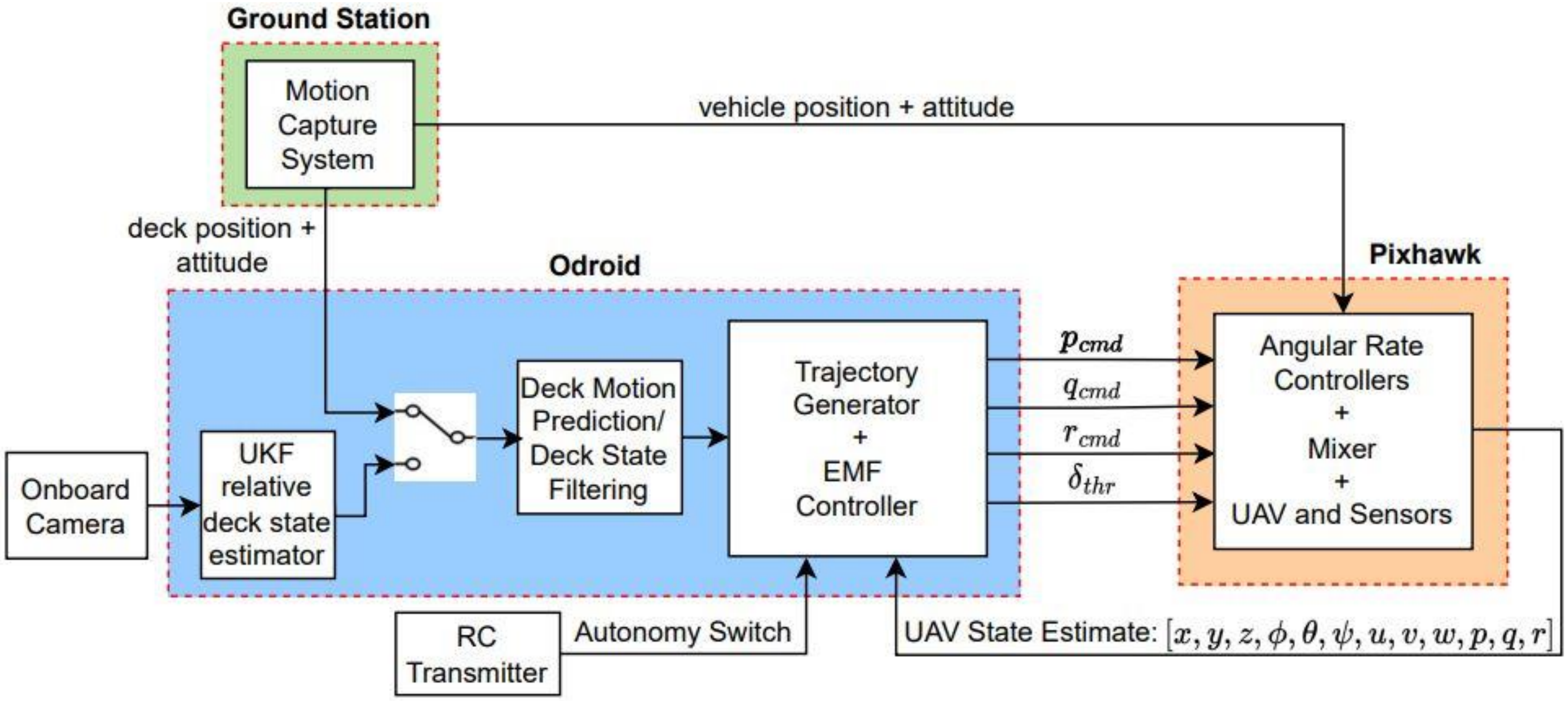
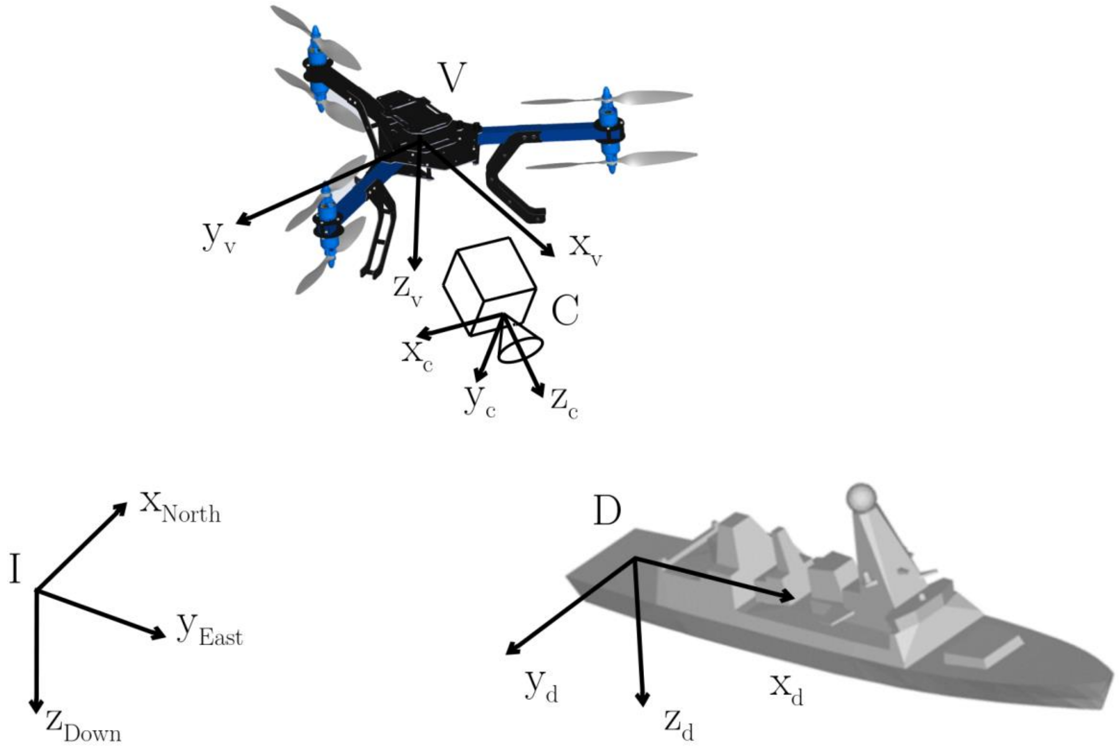
Hardware and Software Integration



Relative Deck State Estimator

Vision Based Unscented Kalman Filter



$$\hat{\mathbf{x}} = \begin{bmatrix} \mathbf{r}_d^v \\ \Phi_{d/v} \\ \mathbf{v}_d^v \\ \boldsymbol{\omega}_{d/i} \end{bmatrix}$$

- $\mathbf{r}_d^v$: Relative deck **position**
- $\Phi_{d/v}$: Relative deck **attitude**
- $\mathbf{v}_d^v$: Relative deck **velocity**
- $\boldsymbol{\omega}_{d/i}$: Deck **angular velocity**

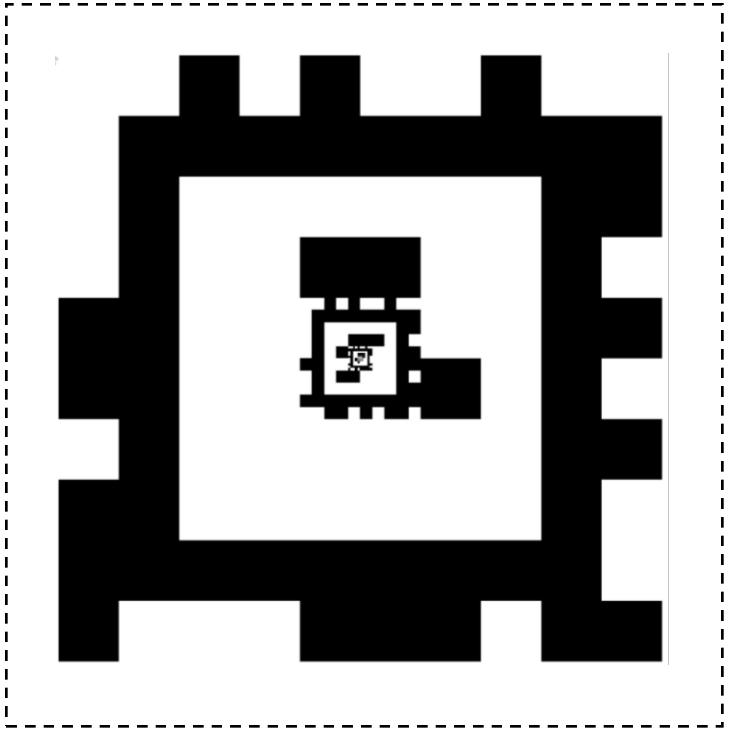
Process Model

$$\ddot{\mathbf{r}}^{\mathbf{h}}_{\mathbf{d/h}} = \ddot{\mathbf{r}}^{\mathbf{I}}_{\mathbf{d/h}} - \dot{\omega} \times \mathbf{r}_{\mathbf{d/h}} - \mathbf{2}\omega \times \dot{\mathbf{r}}_{\mathbf{d/h}} - \omega \times \left(\omega \times \mathbf{r}^{\mathbf{h}}_{\mathbf{d/h}}\right)$$

Scalable Fiducial Marker Arrays

- Robustly identify desired landing area
- Measure deck pose accurately from a wide range of distances

$$z_{cam} = \begin{bmatrix} r^{c}_{d/c} \\ q_{d/c} \end{bmatrix}$$



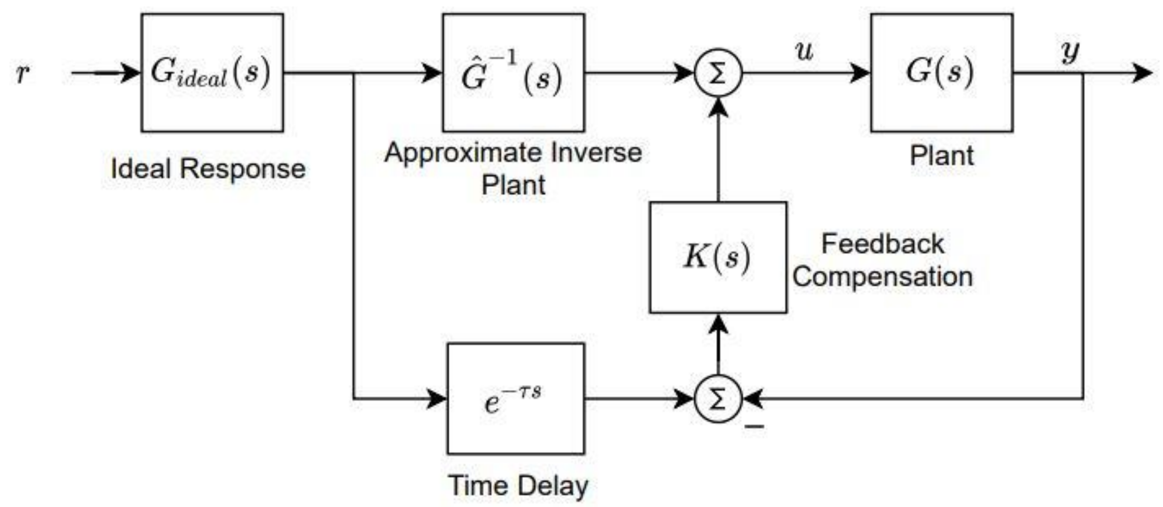
Flight Control and Autonomy Algorithms

Explicit Model Following Position Controllers

- Motivation – easily varied bandwidths
  - Reference tracking tuned through $G_{ideal}(s)$
  - DRB tuned through $K(s)$

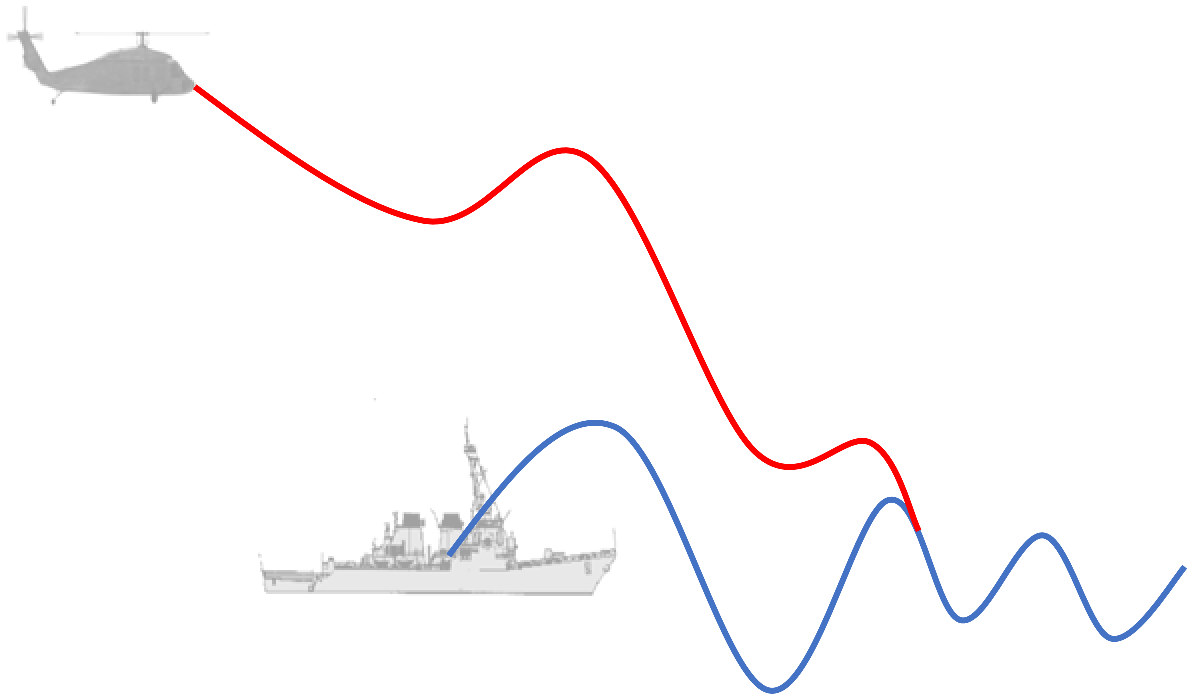
- Froude scaled control:

$$N_F = \left(\frac{M_{fs}}{M_{ms}}\right)^{1/3} \rightarrow \omega_{ms} = \omega_{fs}\sqrt{N_F}$$

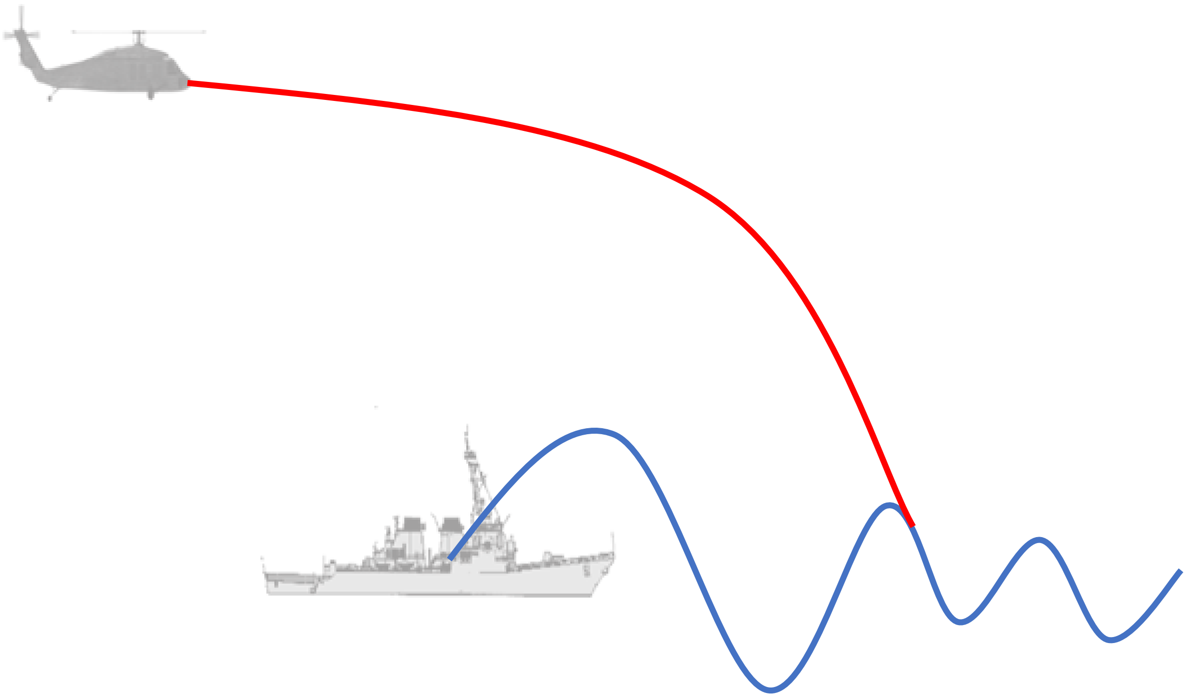


Path Planning Algorithms

Deck Relative Commands

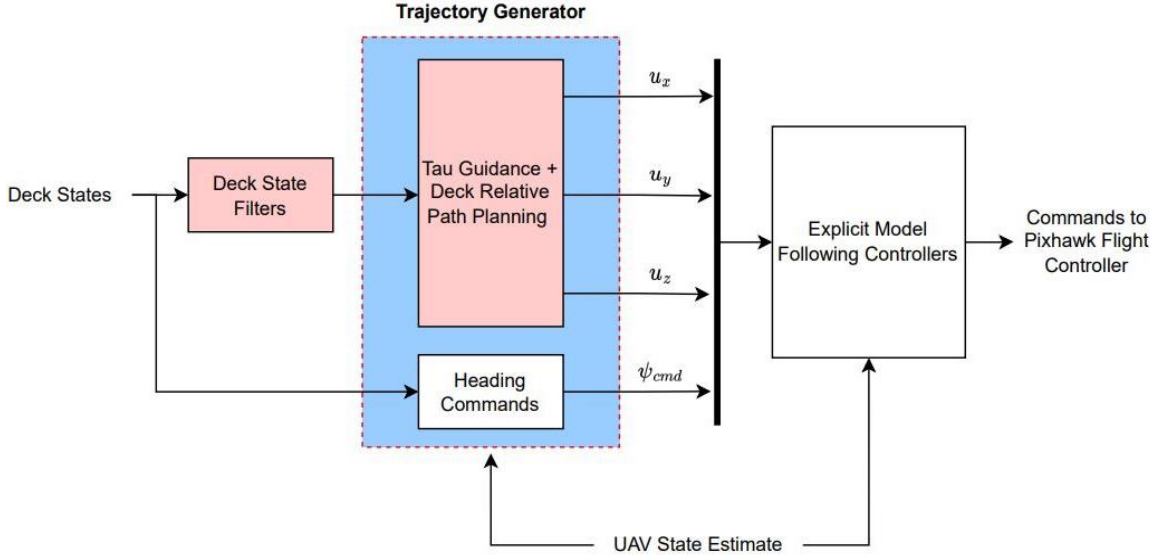


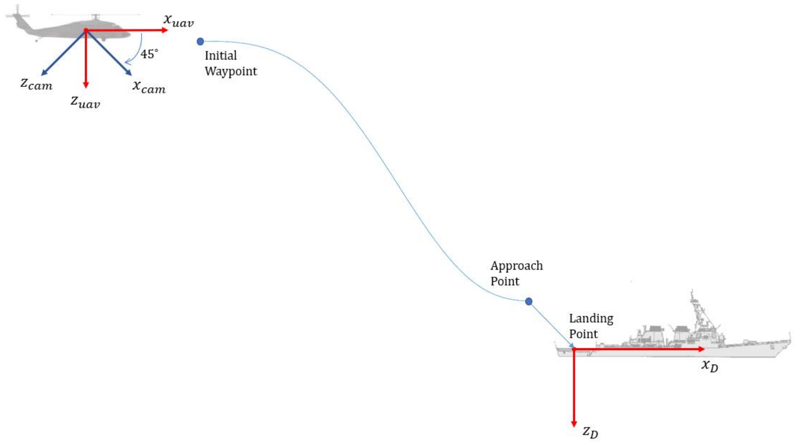
Planning to Predictions



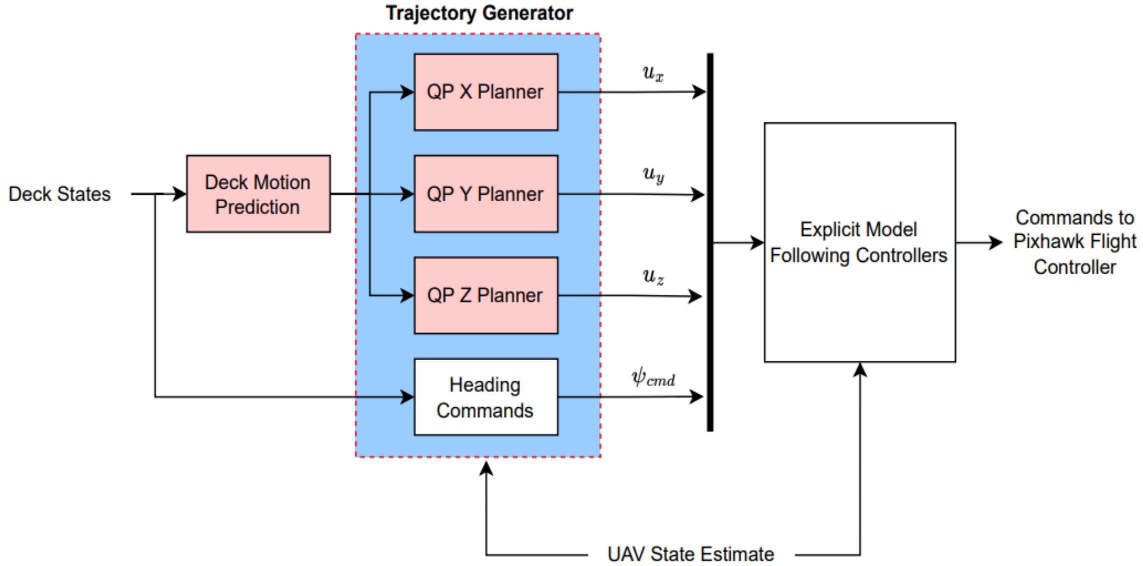
Baseline and QP Landing Algorithms

Baseline Path Planner





Quadratic Programming Path Planner



Discrete Model

$$\vec{x}_{k+1} = A\vec{x}_k + Bu_{k-\tau_d}$$
$$\vec{y}_{k+1} = A\vec{x}_k + Bu_{k-\tau_d}$$

→

Cost Function

$$J = \overbrace{\sum_{k=0}^{N-1} \left[\left(\vec{y}_{ref,k} - \vec{y}_k \right)^T Q \left(\vec{y}_{ref,k} - \vec{y}_k \right) + u_k^T R u_k \right]}^{\text{reference trajectory and control input}} \underbrace{+ u_N^T R u_N + N \left[\left(\vec{y}_{ref,N} - \vec{y}_N \right)^T S \left(\vec{y}_{ref,N} - \vec{y}_N \right) + j_N^T S_\Delta j_N \right]}_{\text{terminal cost}}$$

Constraints

$$\vec{y}_{low,k} \leq \vec{y}_k \leq \vec{y}_{up,k}$$

→

Standard QP Form

$$J = \frac{1}{2} \bar{U}^T H \bar{U} + F^T \bar{U}$$
$$s.t.\ \ A_c \bar{U} \leq b_0$$

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Autoregressive Models For Deck Forecasting

Define Output Vectors

$$\vec{y}_{long} = \left[X_d^{dhf} \quad \dot{X}_d^{dhf} \quad \theta_d \quad Z_d^I \quad \dot{Z}_d^I\right]^T$$

$$\vec{y}_{lat} = \left[Y_d^{dhf} \quad Y_d^{dhf} \quad \phi_d \quad \psi_d\right]^T$$

↓

AR Model

$$\vec{y}_k = \underline{\alpha}_1 \vec{y}_{k-1} + \underline{\alpha}_2 \vec{y}_{k-2} + \cdots + \underline{\alpha}_{N_{lag}} \vec{y}_{k-N_{lag}} + \vec{v}_k$$

↓

Estimate

$$\underline{\alpha}_1 \ \ldots \ \underline{\alpha}_{N_{lag}}$$

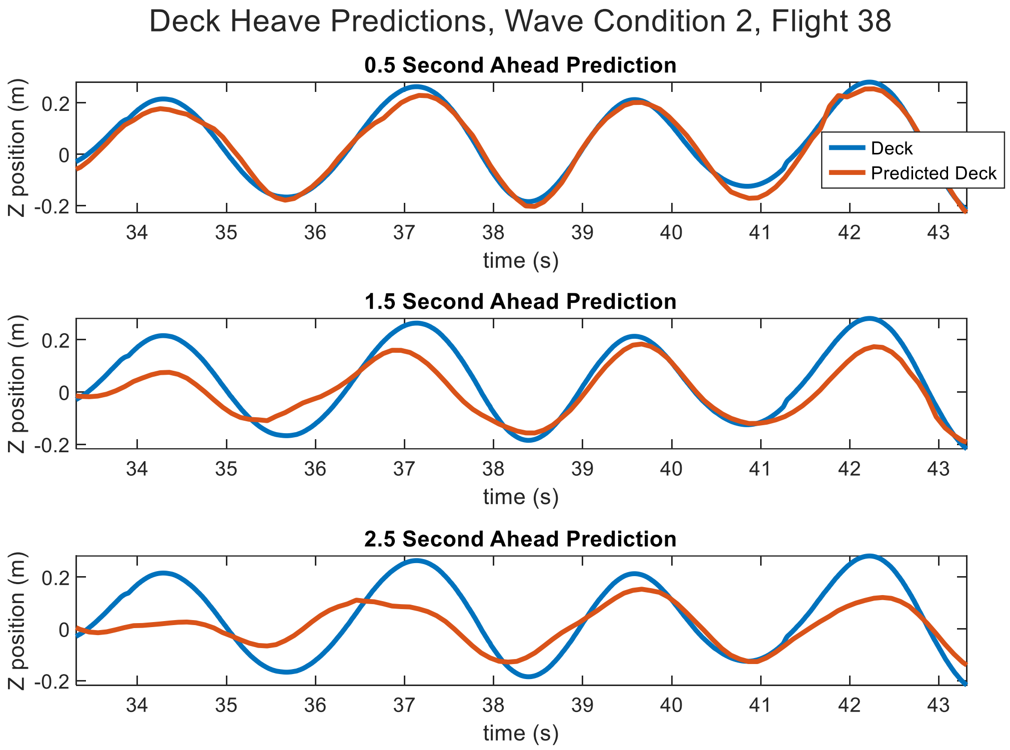
↓

Propagate

$$\vec{y}_{k+1} = \underline{\alpha}_1 \vec{y}_k + \underline{\alpha}_2 \vec{y}_{k-1} + \cdots + \underline{\alpha}_{N_{lag}} \vec{y}_{k-N_{lag}+1}$$

$$\vdots$$

$$\vec{y}_{k+N} = \underline{\alpha}_1 \vec{y}_{k-1+N} + \underline{\alpha}_2 \vec{y}_{k-2+N} + \cdots + \underline{\alpha}_{N_{lag}} \vec{y}_{k-N_{lag}+N}$$



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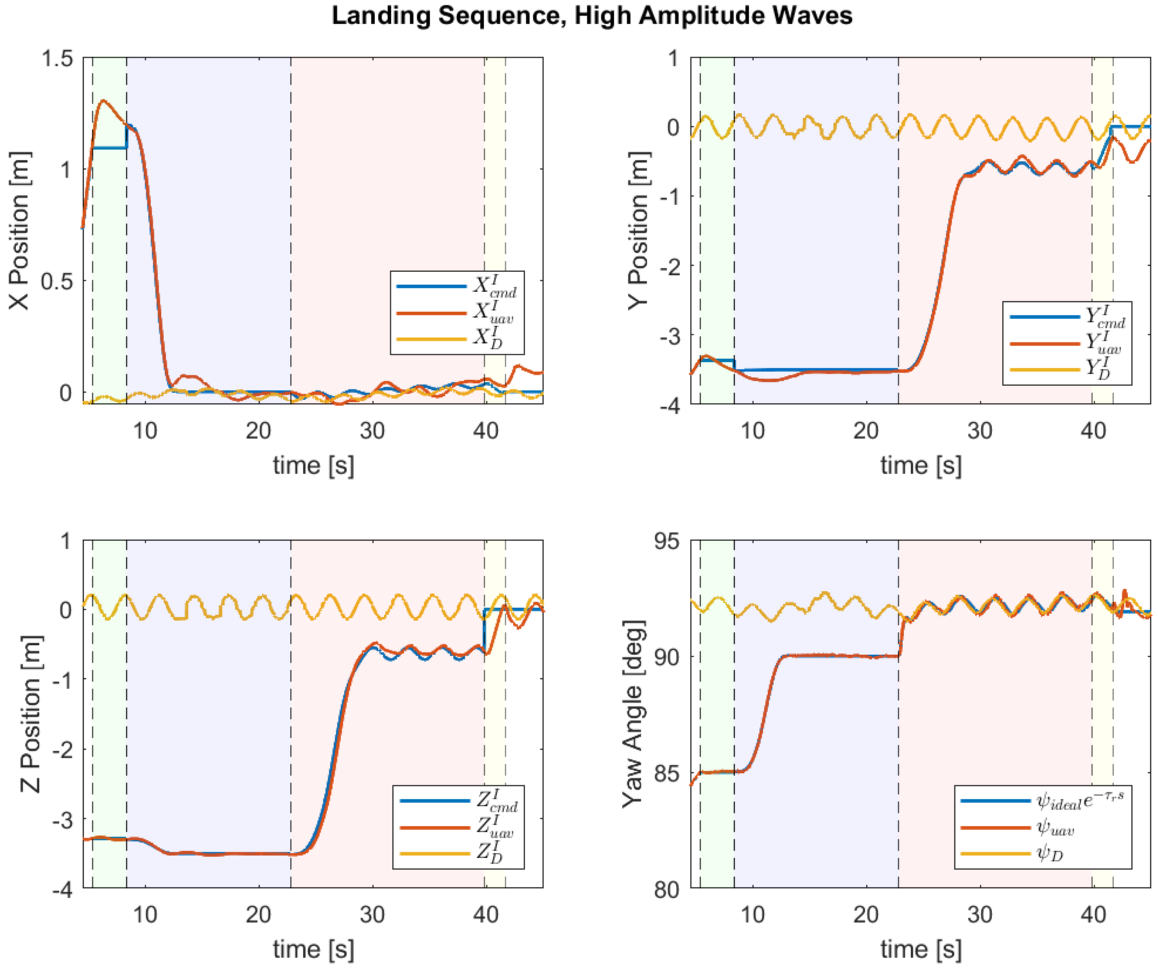
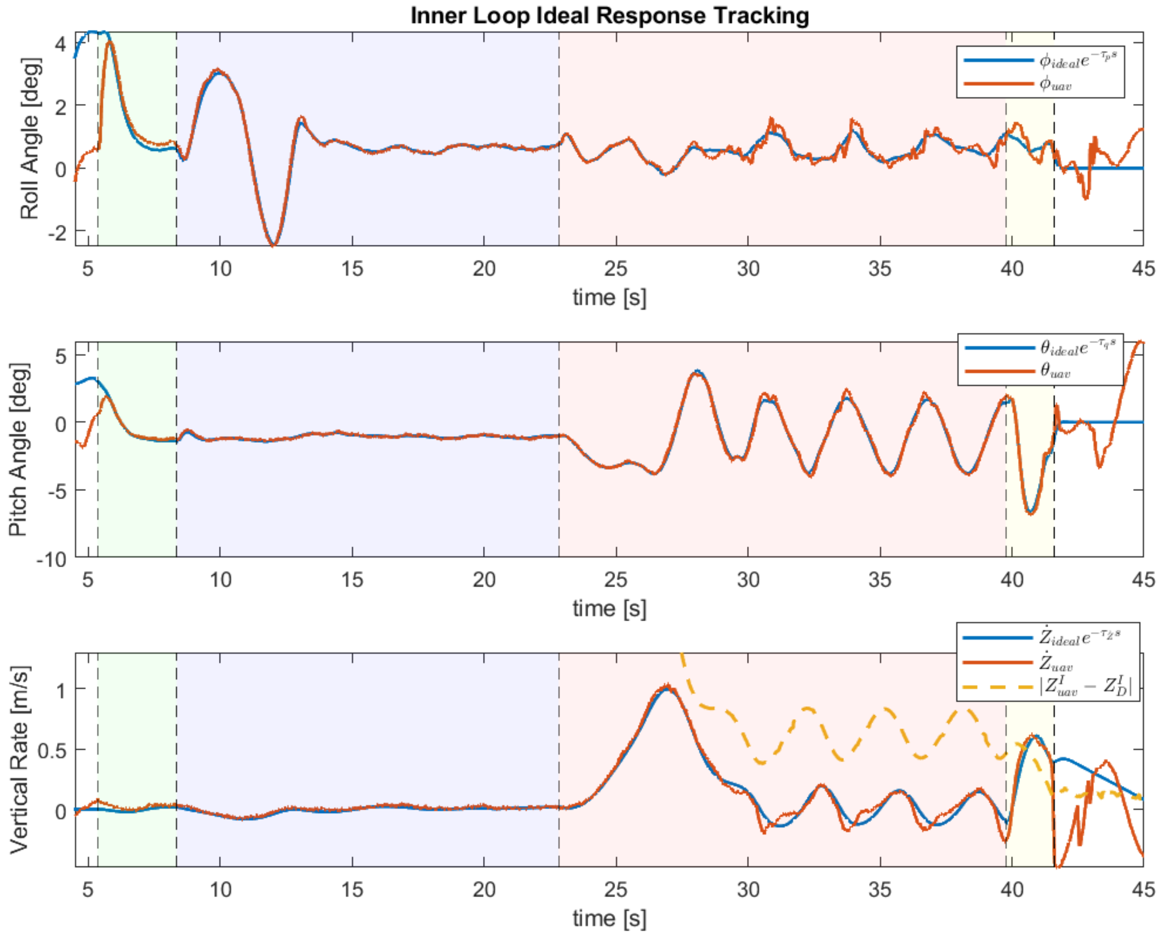
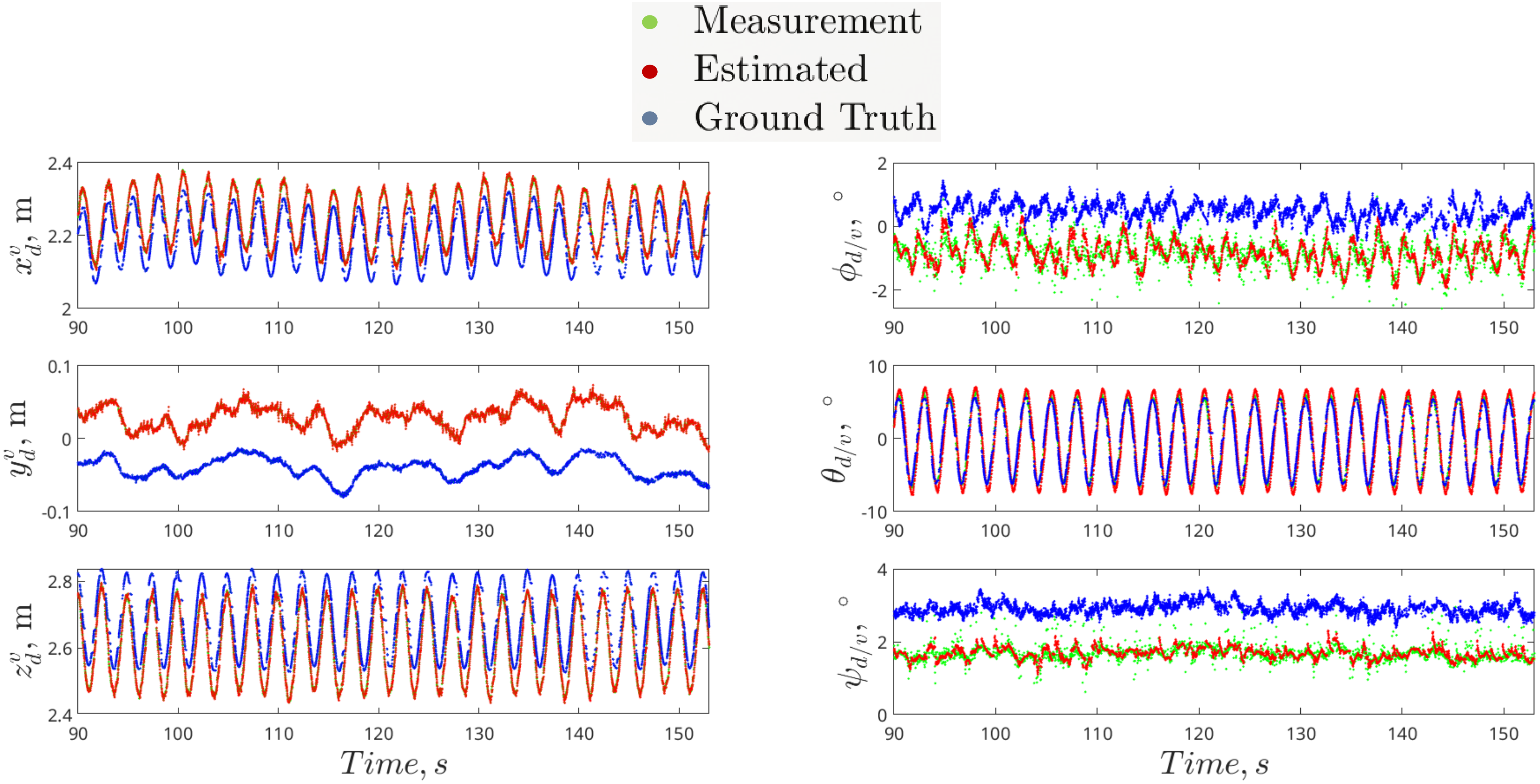
First Tests at the MASK

Control Verification

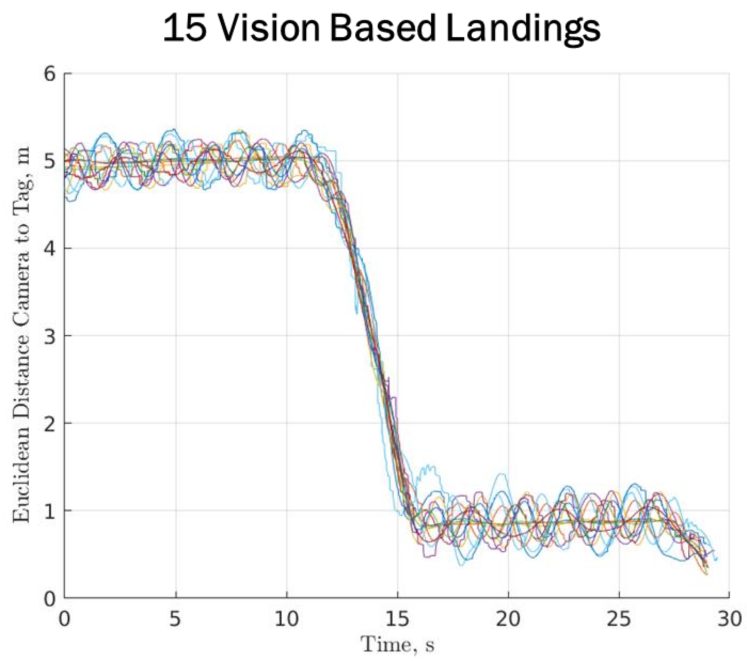


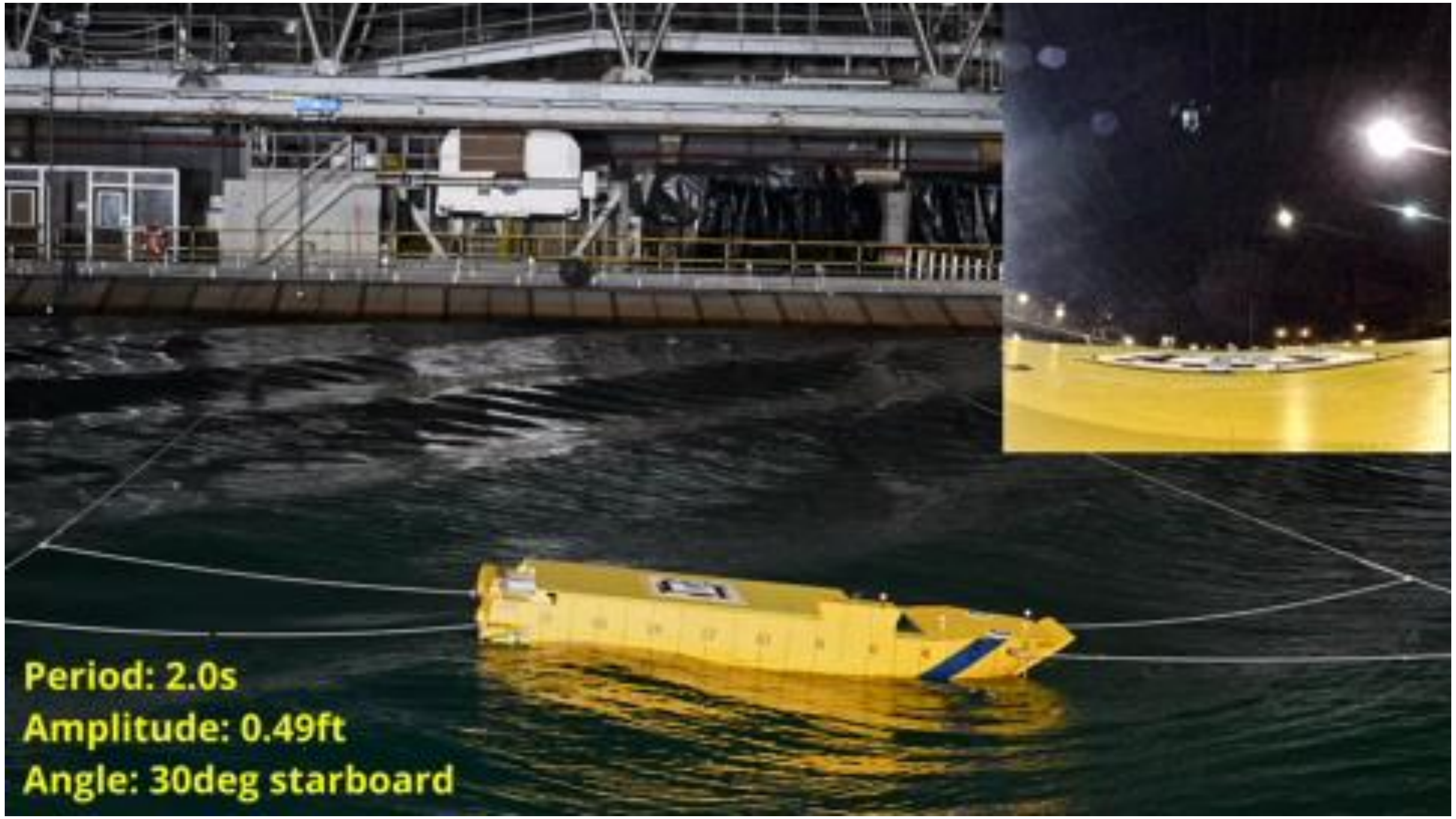


Estimator Verification in Hover

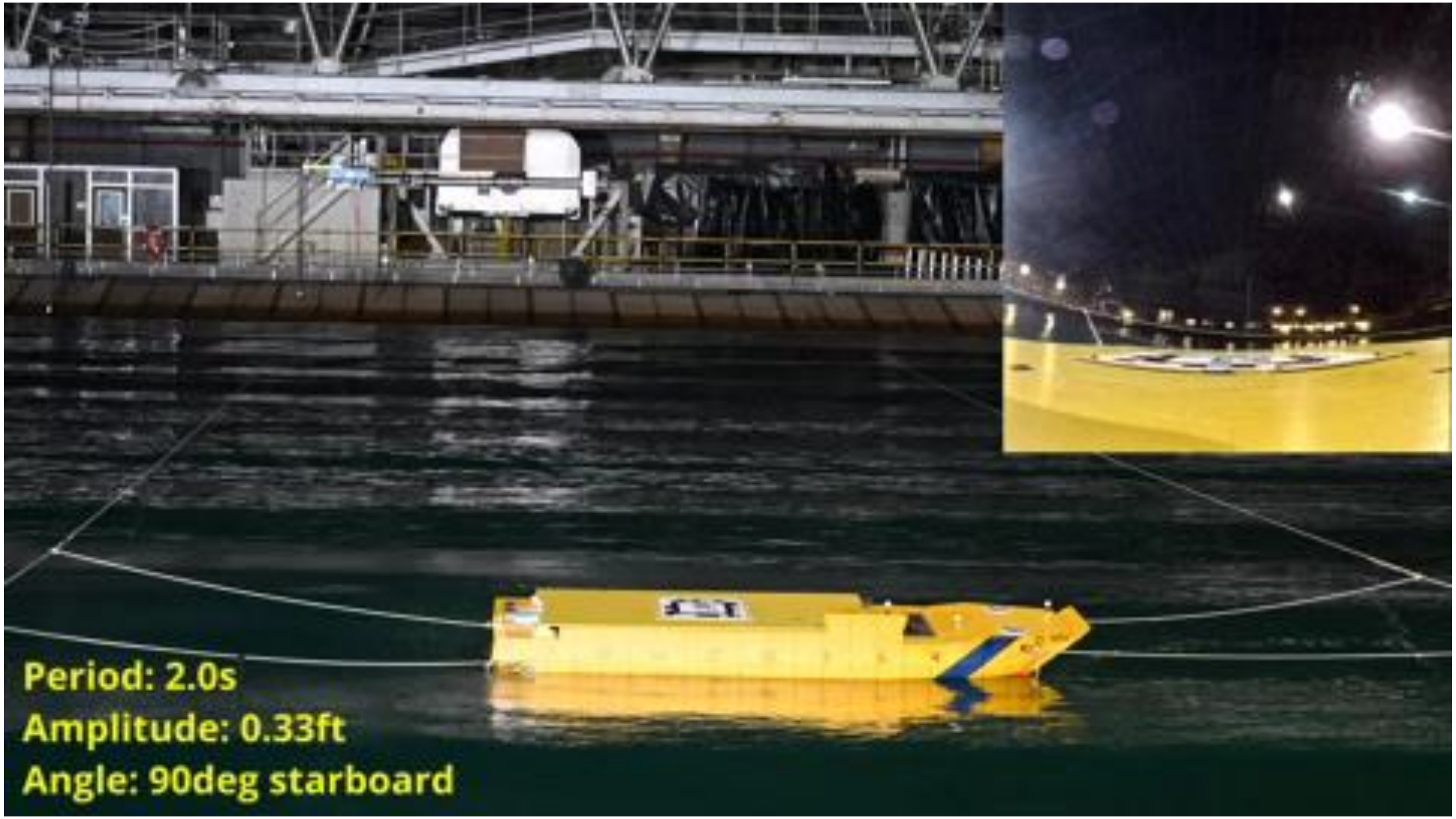


Vision Based Landings





Vision Based Landings



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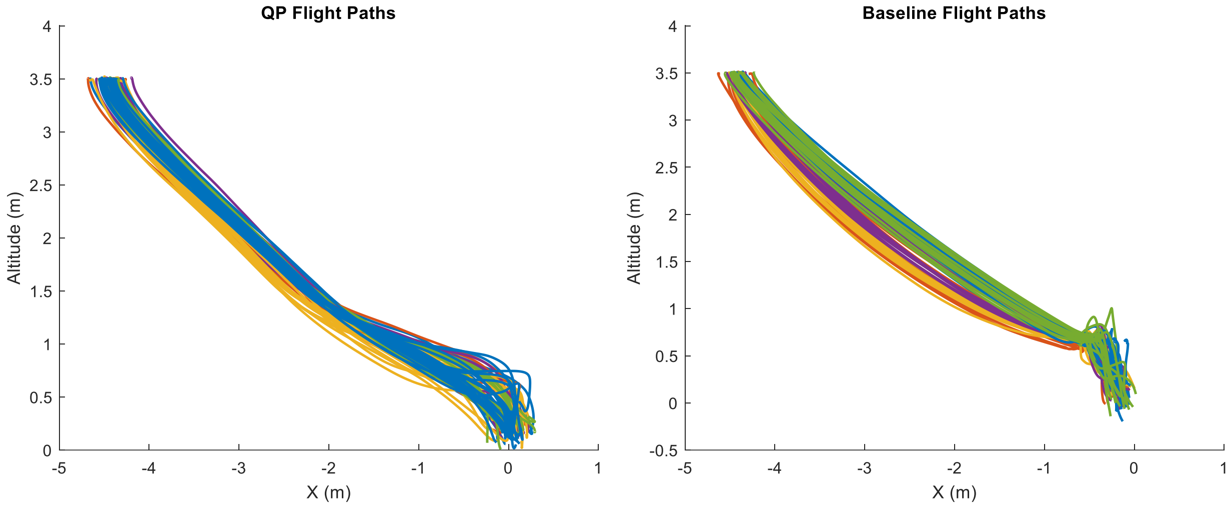
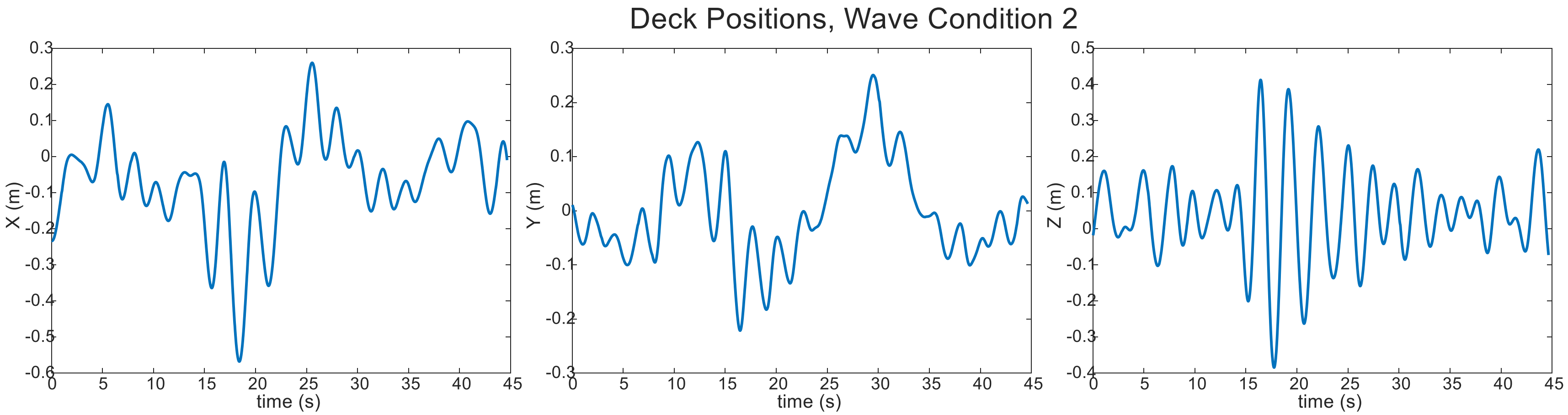
Recent Tests at the MASK

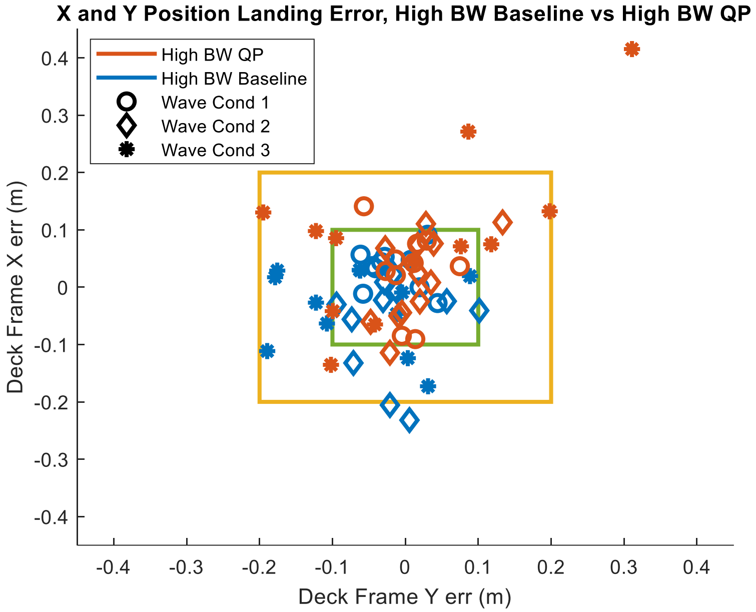
More Recent Tests

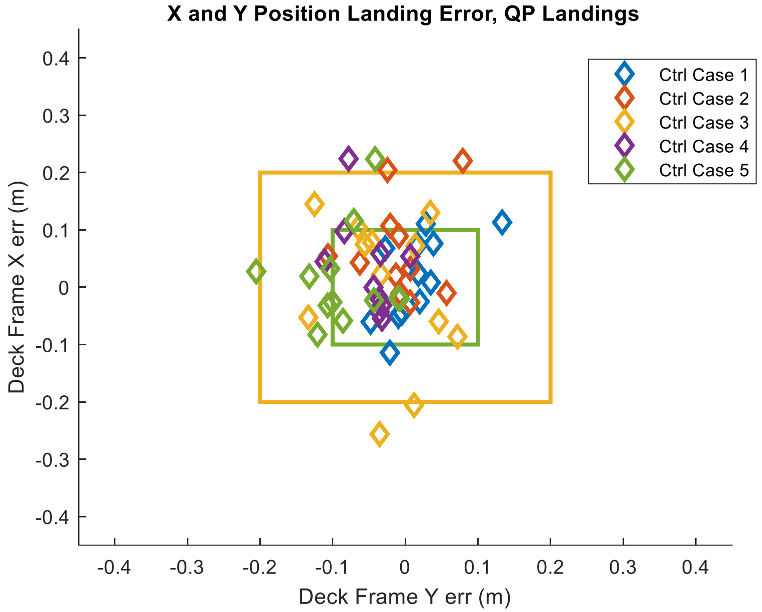
- 162 recorded landings
- Focus on path planning and control
  - QP vs baseline
  - Varied tracking bandwidths
  - 3 different stochastic wave conditions

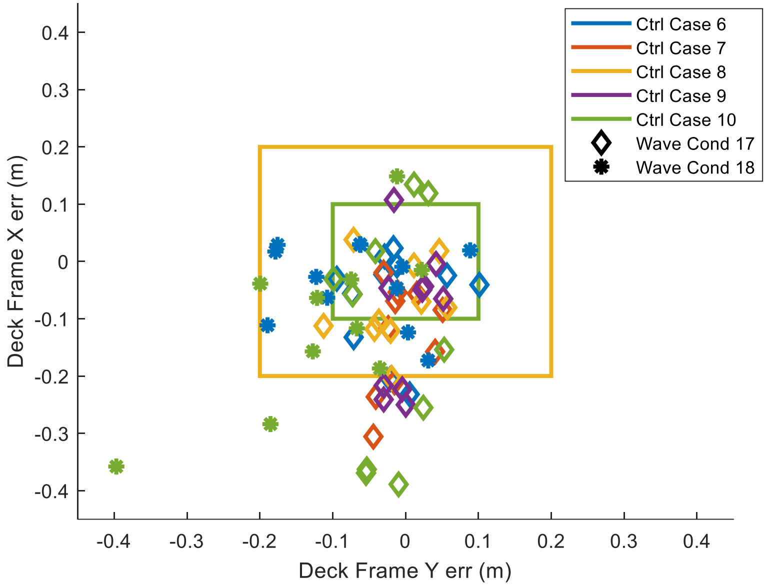




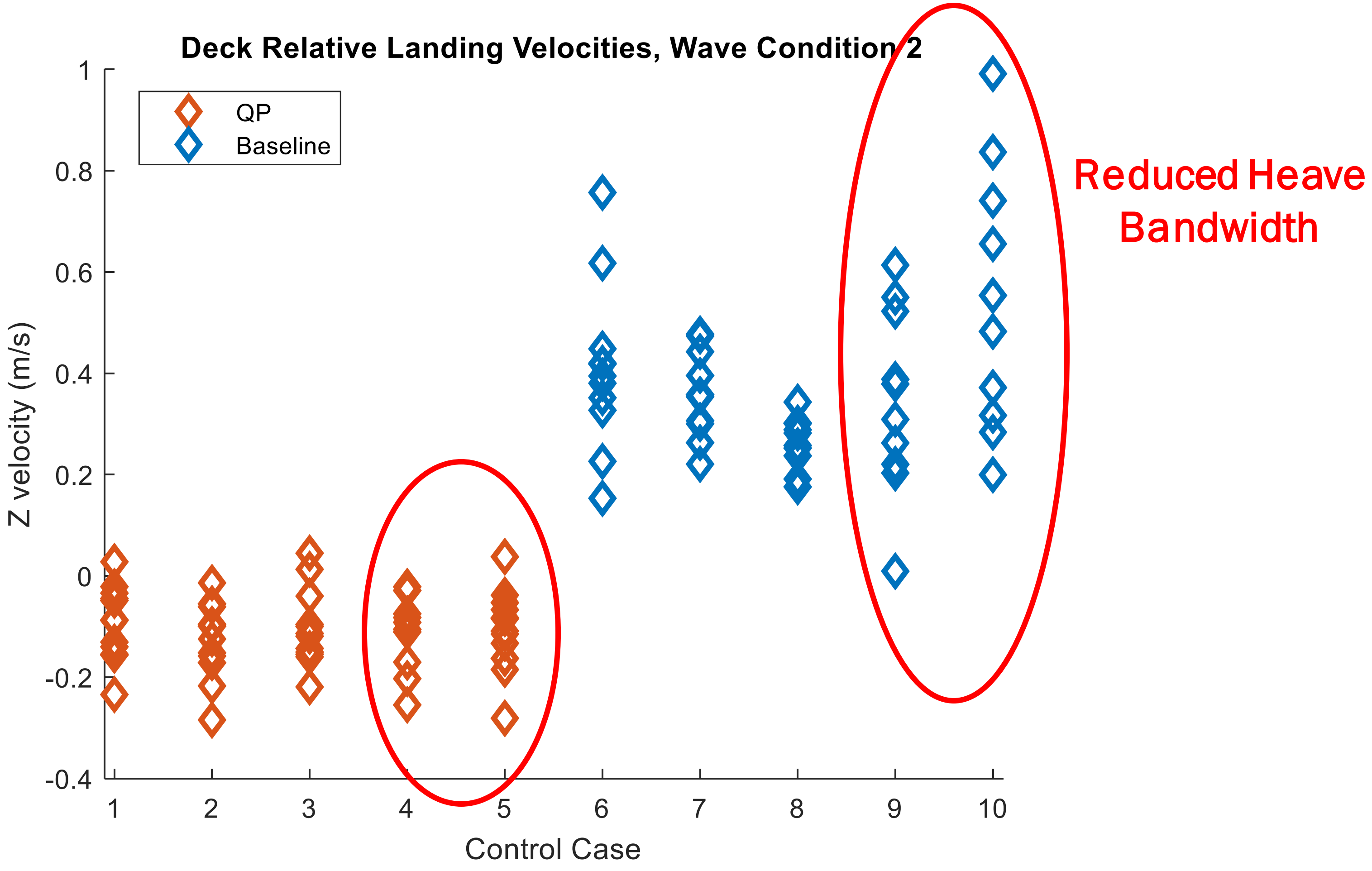
X and Y Landing Errors



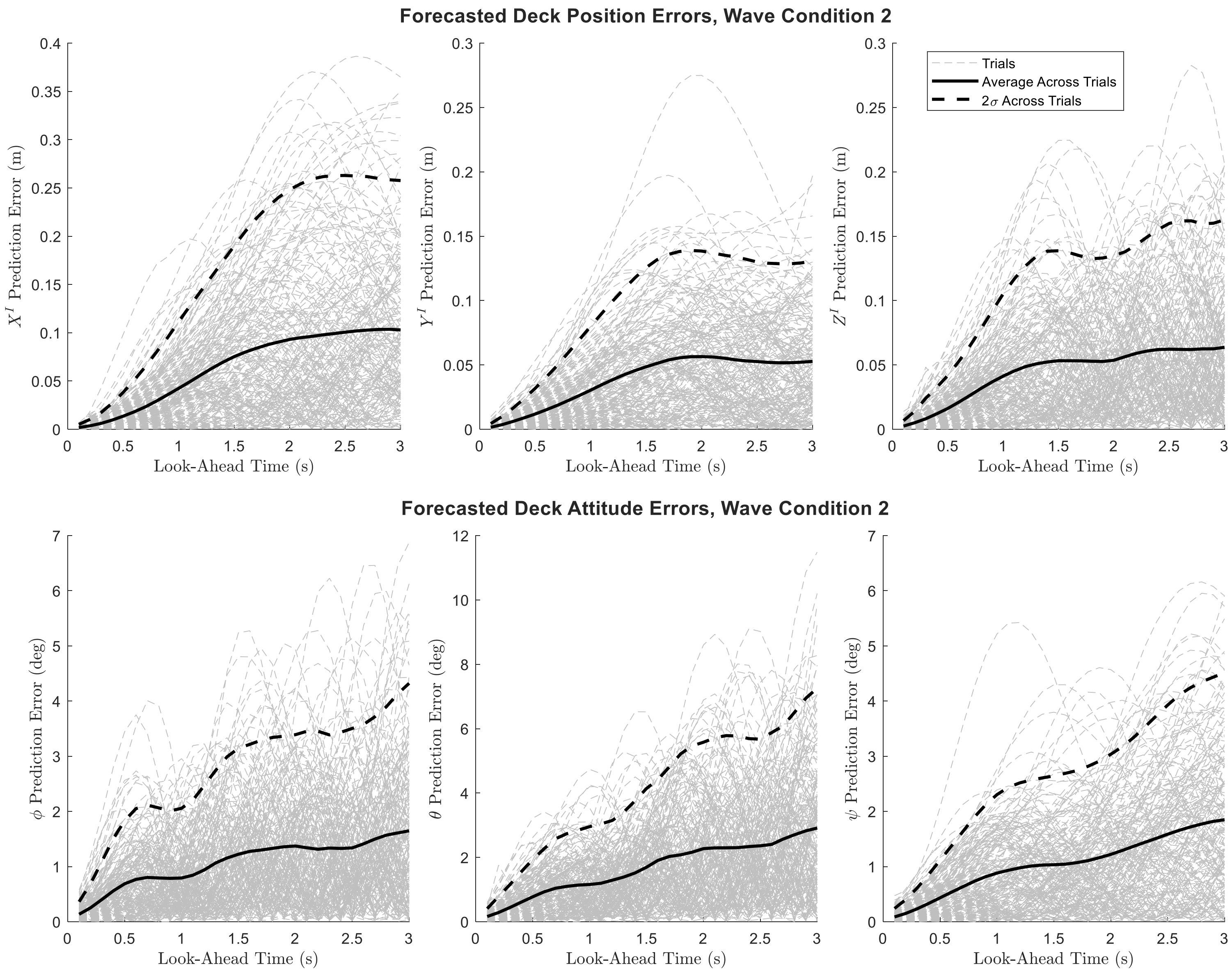




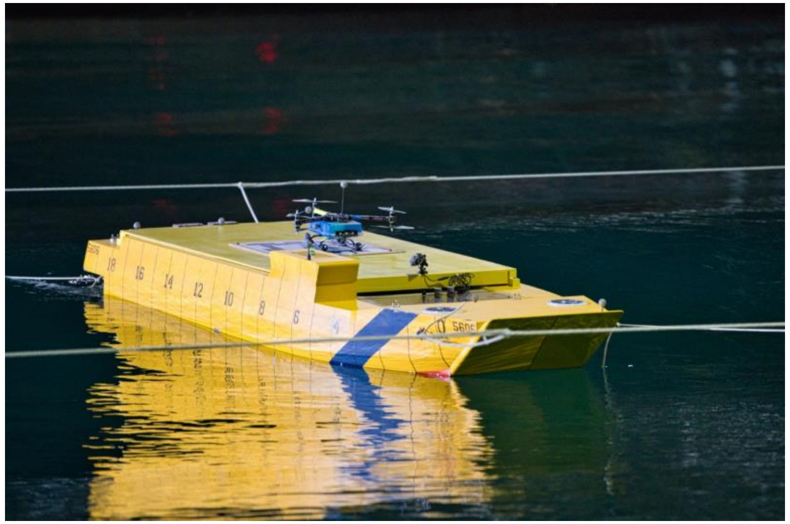
X and Y Landing Errors

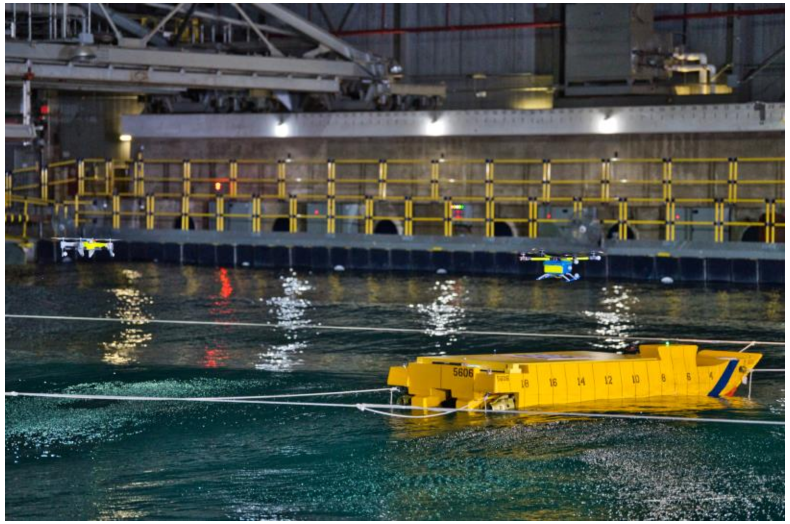


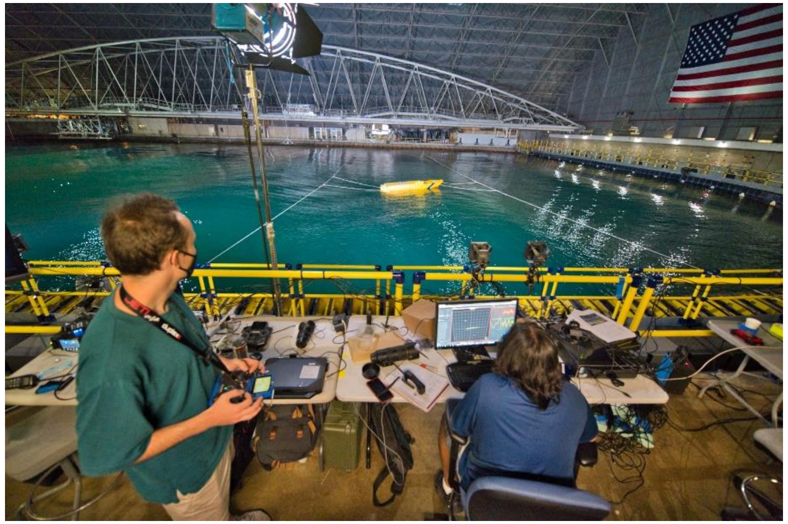
Deck Prediction Accuracy



Questions







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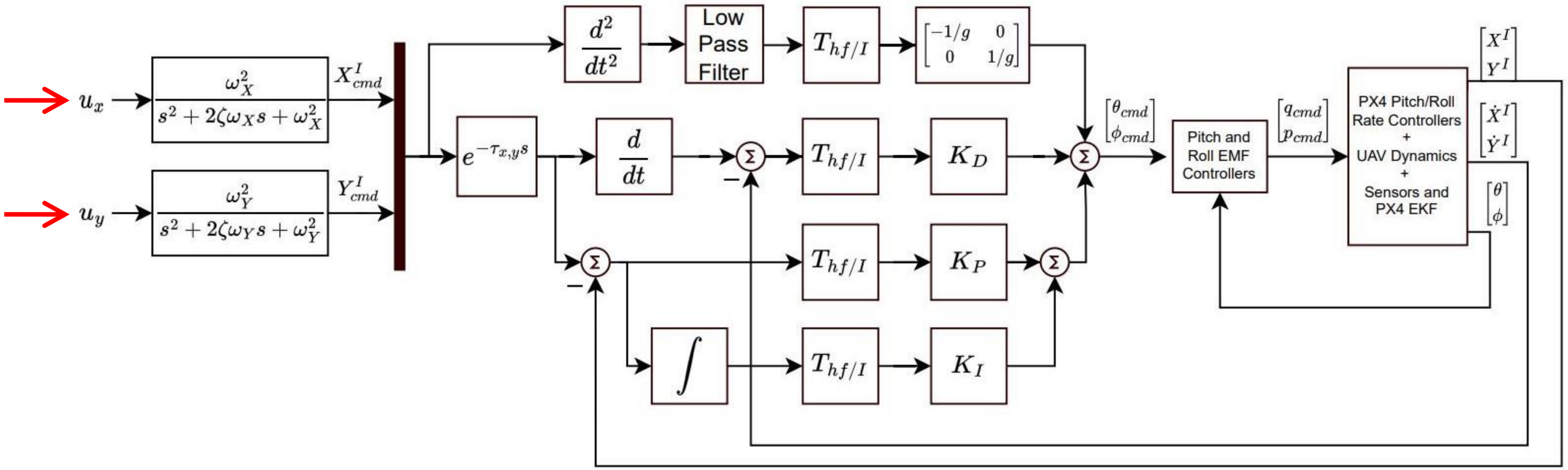
Appendix

Outer Loops and Froude Scaled Control

From Path Planner



- Tracking bandwidth: $\omega_{\theta,fs} \rightarrow \omega_{\theta,cf} = \omega_{\theta,fs}\sqrt{N_F} \rightarrow \omega_{X,cf} = \frac{\omega_{\theta,cf}}{5}$
- Outer loop delay: $\frac{\theta(s)}{\theta_{cmd}(s)} \approx \frac{\omega^2_{\theta,cf}}{s^2+2\zeta\omega_{\theta,cf}s+\omega^2_{\theta,cf}} e^{-\tau_\theta s} \rightarrow \tau_x = \frac{1.65}{\omega_{\theta,cf}} + \tau_\theta$
- PID gains set to meet DRB for scaled level 1 HQ

Quadratic Program Transcription

Cost Function

reference trajectory and control input — jerk

$$J = \overbrace{\sum_{k=0}^{N-1}\left[\left(\vec{y}_{ref,k}-\vec{y}_k\right)^T Q\left(\vec{y}_{ref,k}-\vec{y}_k\right)+u_k^T R u_k\right]}^{\text{reference trajectory and control input}} + \overbrace{\sum_{k=0}^{N-1}\left[j_k^T Q_\Delta j_k\right]}^{\text{jerk}}$$

$$+ \underbrace{u_N^T R u_N + N\left[\left(\vec{y}_{ref,N}-\vec{y}_N\right)^T S\left(\vec{y}_{ref,N}-\vec{y}_N\right)+j_N^T S_\Delta j_N\right]}_{\text{terminal cost}}$$

terminal cost

variable length horizon

Constraints

$$\vec{y}_{low,k} \le \vec{y}_k \le \vec{y}_{up,k}$$

Standard QP Form

$$J = \frac{1}{2}\bar{U}^T H \bar{U} + F^T \bar{U}$$

$$s.t.\quad A_c \bar{U} \le b_0$$

Output Constraints

Vel (m/s)	± 7
Accel (m/s^2)	± 3.5
jerk, low (m/s^3)	± 5.0
jerk, med (m/s^3)	± 7.0
jerk, high (m/s^3)	± 9.0

Discrete Model

$$\vec{x}_{k+1} = A\vec{x}_k + Bu_{k-\tau_d}$$

$$\vec{y}_{k+1} = A\vec{x}_k + Bu_{k-\tau_d}$$

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Discrete Model for QP Trajectory Generation

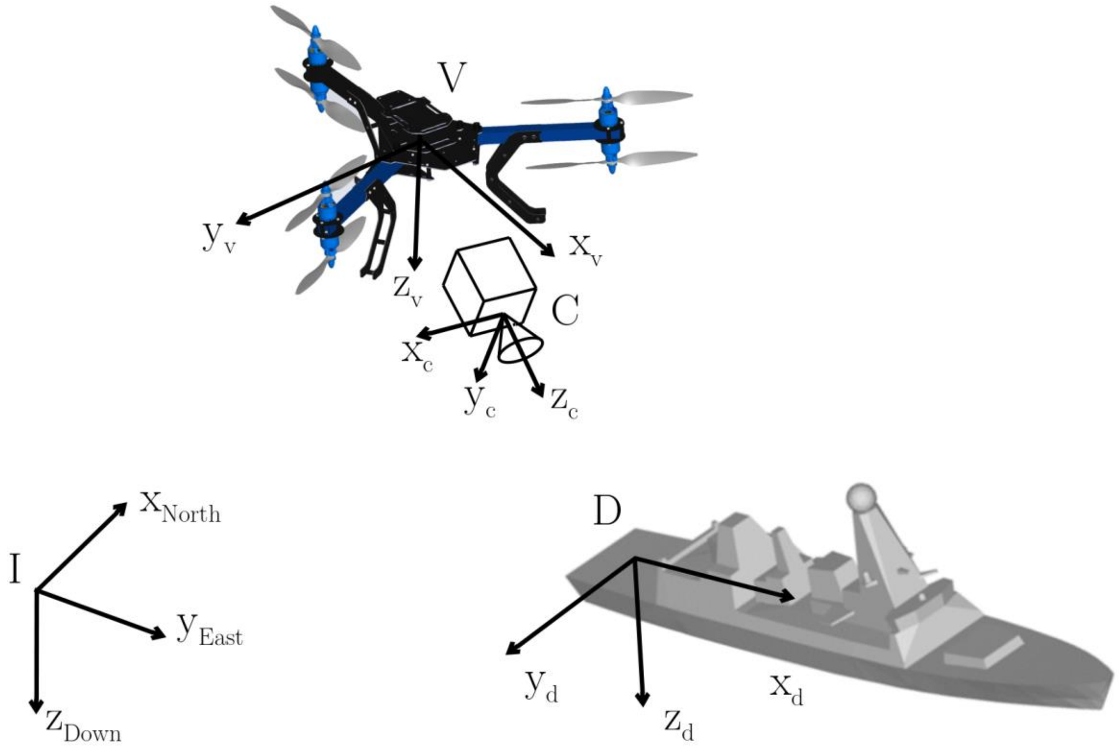
- Separate QP solvers for inertial X, Y, and Z commands
- Dynamics modeled as theoretical ideal result for EMF position controllers:

$$G_X(s) = \frac{\omega_{X,cf}^2}{s^2 + 2\zeta\omega_{X,cf}s + \omega_{X,cf}^2} e^{-\tau_X s} \quad \rightarrow \quad \begin{array}{c} \vec{x}_{X,k+1} = A_X \vec{x}_{X,k} + B_X u_{X,k-\tau_d} \\ \vec{y}_{X,k} = C_X \vec{x}_{X,k} + D_X u_{X,k-\tau_d} \end{array}$$

- Outputs are pos, vel, and accel
- Approximate jerk with a back difference:

$$j_k = \frac{a_k - a_{k-1}}{\Delta t}$$

Vision Based Unscented Kalman Filter



$$\hat{\mathbf{x}} = \begin{bmatrix} \mathbf{r}_d^v \\ \Phi_{d/v} \\ \mathbf{v}_d^v \\ \boldsymbol{\omega}_{d/i} \end{bmatrix}$$

- Relative deck **position**
- Relative deck **attitude**
- Relative deck **velocity**
- Deck **angular velocity**

Process Model

$$\ddot{\mathbf{r}}^{\mathbf{h}}_{\mathbf{d/h}} = \underbrace{\ddot{\mathbf{r}}^{\mathbf{I}}_{\mathbf{d/h}}} - \dot{\omega} \times \mathbf{r}_{\mathbf{d/h}} - \mathbf{2}\omega \times \dot{\mathbf{r}}_{\mathbf{d/h}} - \omega \times \left(\omega \times \mathbf{r}^{\mathbf{h}}_{\mathbf{d/h}}\right)$$

Assume $\ddot{\mathbf{r}}^{\mathbf{I}}_{\mathbf{d}} = \mathbf{0}$ and capture with process noise

Pose Estimation During Landing