

Precision Control of an Autonomous Surface Vessel



Alejandro Alonso García, Anders Egelund Kjeldal, Himal Kooverjee,
Niels Skov Vestergaard, Noelia Villamarzo Arruñada

Agenda



- ▶ **Introduction**
 - Use Case
- ▶ **System Description**
- ▶ **Model**
 - Reference Frames
 - Model Equations
 - Model Verification
- ▶ Control Approach
- ▶ Sensor Fusion
- ▶ Inner Controller
- ▶ Outer Controller
- ▶ Results
- ▶ Conclusion

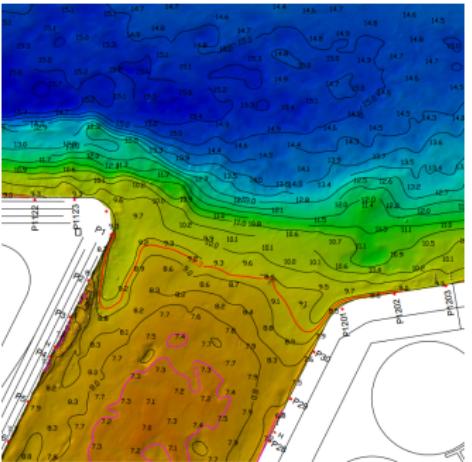
Introduction



- ▶ Environmental monitoring
- ▶ Marine biological research
- ▶ Bathymetric measurements
- ▶ Control theory for an ASV

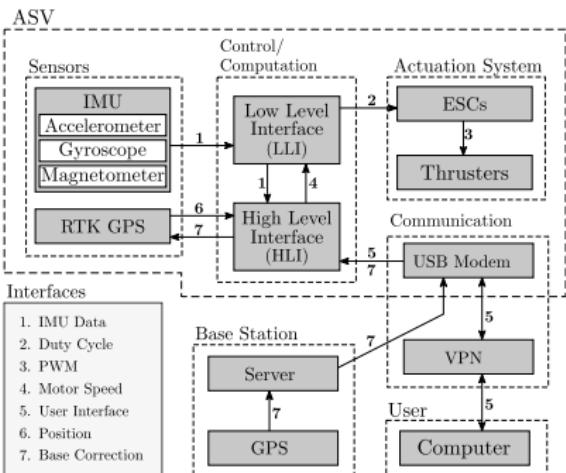
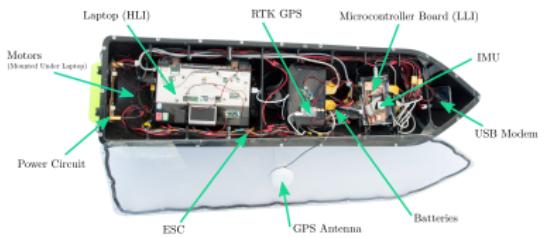
Introduction

Use Case



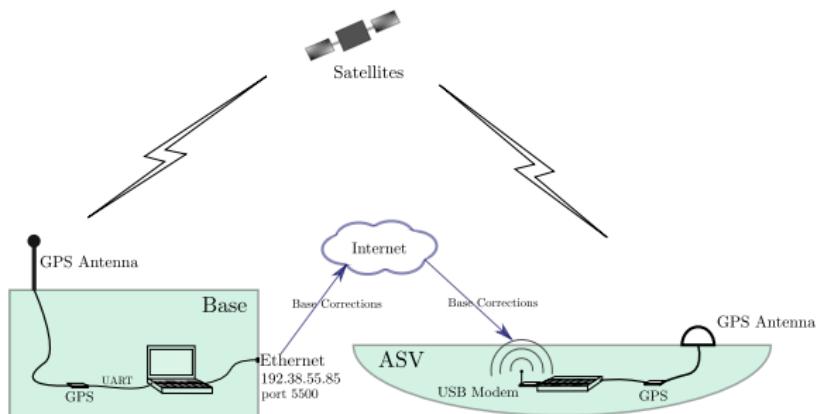
- ▶ Depth map used by Port of Aalborg
 - ▶ Problem: No recent knowledge of depths of the port
 - ▶ Solution: Automate smaller unmanned vessel

System Description



System Description

RTK GPS

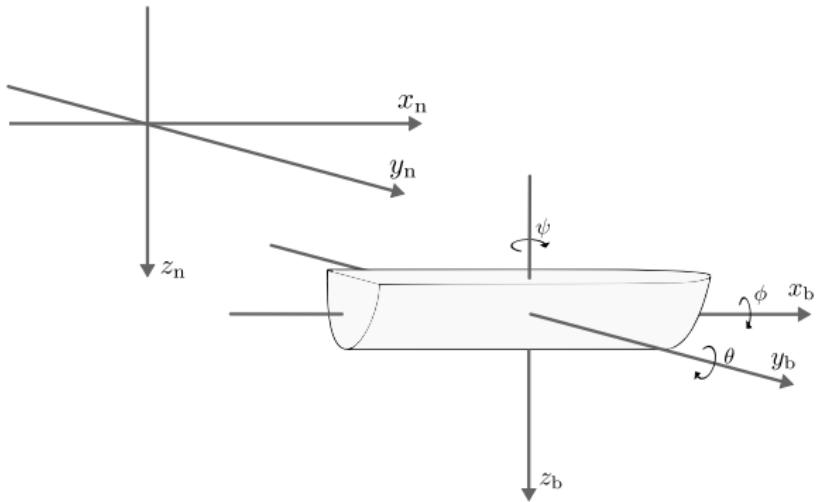


Model

Reference Frames



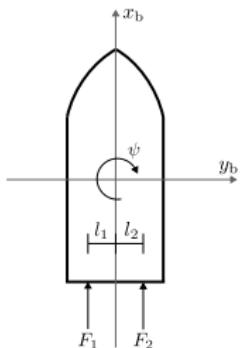
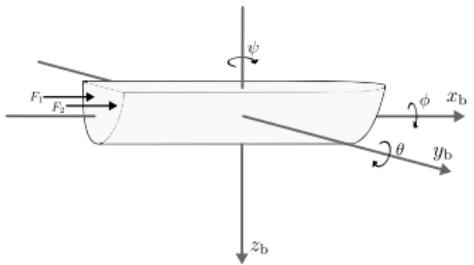
7



- ▶ Inertial Frame (NED)
- ▶ Body Frame

Model

Model Dynamics



► Rigid Body Dynamics

$$\sum F = m\ddot{x}$$

$$\sum \tau = I\ddot{\theta}$$

► Hydrostatics

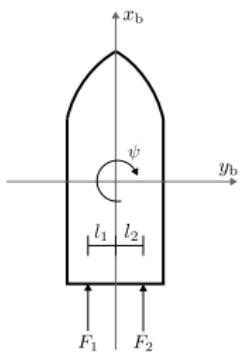
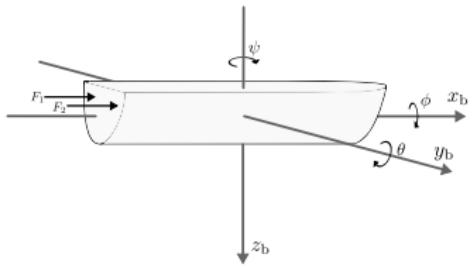
- Buoyancy Force

► Hydrodynamics

- Viscous Damping

Model

Model Equations



$$m\ddot{x}_b = F_1 + F_2 - d_{\dot{x}_b} \dot{x}_b + F_{x_b}$$

$$m\ddot{y}_b = -d_{\dot{y}_b} \dot{y}_b + F_{y_b}$$

$$m\ddot{z}_b = -d_{\dot{z}_b} \dot{z}_b + F_{z_b}$$

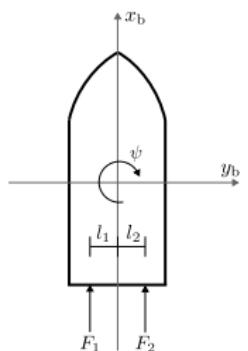
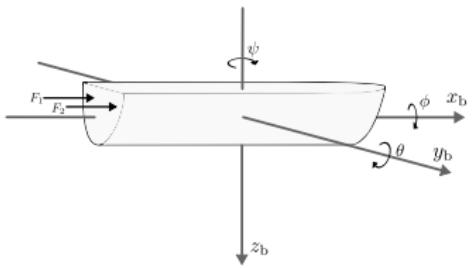
$$I_x \ddot{\phi} = -d_{\dot{\phi}} \dot{\phi} + T_\phi$$

$$I_y \ddot{\theta} = -d_{\dot{\theta}} \dot{\theta} + T_\theta$$

$$I_z \ddot{\psi} = F_1 l_1 - F_2 l_2 - d_{\dot{\psi}} \dot{\psi}$$

Model

Linearized Model Equations



$$m\ddot{x}_b = F_1 + F_2 - d_{\dot{x}_b} \dot{x}_b$$

$$m\ddot{y}_b = -d_{\dot{y}_b} \dot{y}_b$$

$$m\ddot{z}_b = -d_{\dot{z}_b} \dot{z}_b - \rho g A_w p \tilde{z}_n$$

$$I_x \ddot{\phi} = -d_{\dot{\phi}} \dot{\phi} - \rho g V \overline{GM_T} \cdot \phi$$

$$I_y \ddot{\theta} = -d_{\dot{\theta}} \dot{\theta} - \rho g V \overline{GM_L} \cdot \theta$$

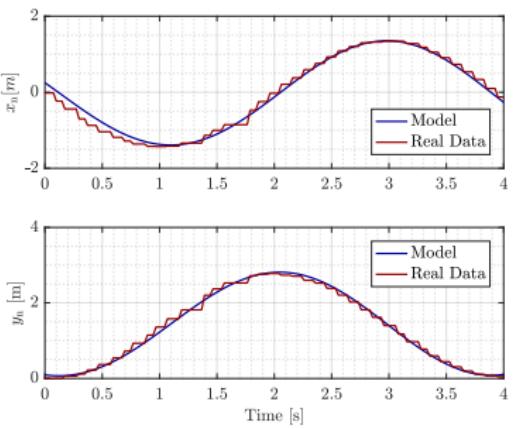
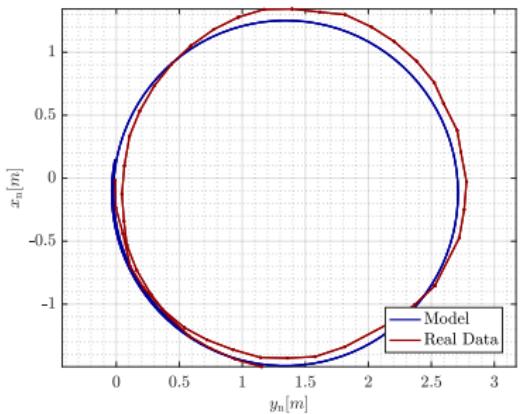
$$I_z \ddot{\psi} = F_1 l_1 - F_2 l_2 - d_{\dot{\psi}} \dot{\psi}$$

Model

Model Verification



► Verified model

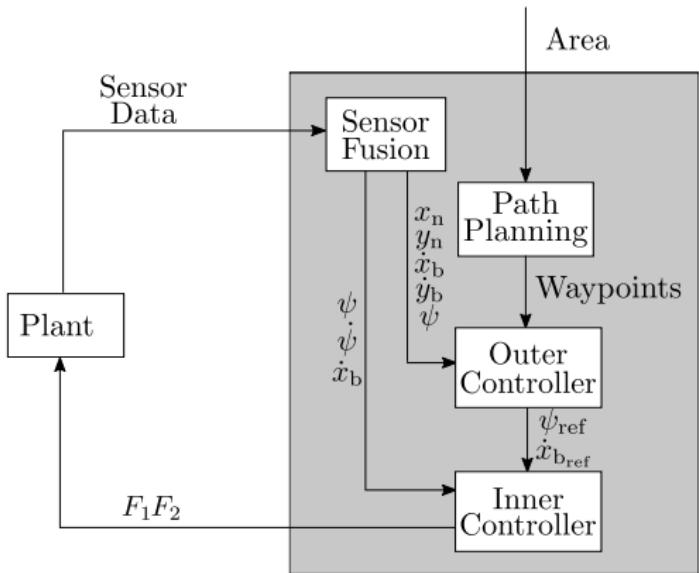


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 - Attitude Kalman Filter
 - Position Kalman Filter
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- ▶ Outer Controller
- ▶ Results
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Control Approach



Sensor Fusion

Structure



- ▶ Fuses GPS and IMU data
- ▶ Achieved using a Kalman filter
- ▶ Sensor fusion contains
 - ▶ Attitude
 - ▶ Position

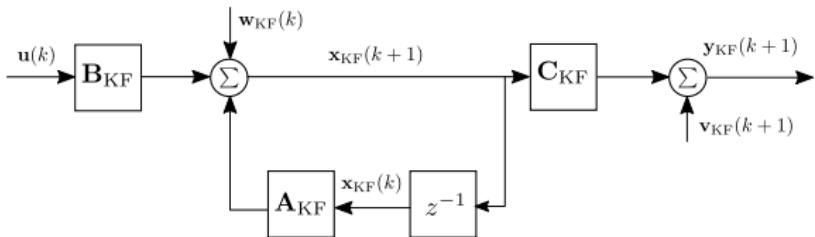
Sensor Fusion

Signal Model



15

$$\begin{aligned}\mathbf{x}_{\text{KF}}(k+1) &= \mathbf{A}_{\text{KF}}\mathbf{x}_{\text{KF}}(k) + \mathbf{B}_{\text{KF}}\mathbf{u}(k) + \mathbf{w}_{\text{KF}}(k) \\ \mathbf{y}_{\text{KF}}(k+1) &= \mathbf{C}_{\text{KF}}\mathbf{x}_{\text{KF}}(k+1) + \mathbf{v}_{\text{KF}}(k+1)\end{aligned}$$



- ▶ $w(k)$ and $v(k)$ are assumed white Gaussian
- ▶ Matrices \mathbf{Q}_{KF} and \mathbf{R}_{KF} are the respective covariance matrices

Sensor Fusion

Signal Model - State and Measurement Vectors



16

$$\mathbf{u} = [F_1 \quad F_2]^T$$

► Attitude

$$\mathbf{x}_{\text{att}} = [\phi \quad \theta \quad \psi \quad \dot{\phi} \quad \dot{\theta} \quad \dot{\psi} \quad \ddot{\phi} \quad \ddot{\theta} \quad \ddot{\psi}]^T$$

$$\mathbf{y}_{\text{att}} = [\phi_{\text{acc}} \quad \theta_{\text{acc}} \quad \psi_{\text{mag}} \quad \dot{\phi}_{\text{gyro}} \quad \dot{\theta}_{\text{gyro}} \quad \dot{\psi}_{\text{gyro}}]^T$$

► Position

$$\mathbf{x}_{\text{pos}} = [x_n \quad y_n \quad \dot{x}_b \quad \dot{y}_b \quad \ddot{x}_b \quad \ddot{y}_b]^T$$

$$\mathbf{y}_{\text{pos}} = [x_{n,\text{GPS}} \quad y_{n,\text{GPS}} \quad \ddot{x}_{b,\text{acc}} \quad \ddot{y}_{b,\text{acc}}]^T$$

Sensor Fusion

Kalman Filter



- ▶ Step 0: Initialization

$$\hat{\mathbf{x}}_{\text{KF}}(0|0) = \mathbf{0}$$

$$\mathbf{P}_{\text{KF}}(0|0) = \mathbf{Q}_{\text{KF}}$$

- ▶ Step 1: Prediction
- ▶ Step 2: Update

Sensor Fusion

Kalman Filter



18

- ▶ Step 0: Initialization
- ▶ Step 1: Prediction

$$\hat{\mathbf{x}}_{\text{KF}}(k+1|k) = \mathbf{A}_{\text{KF}} \hat{\mathbf{x}}_{\text{KF}}(k|k) + \mathbf{B}_{\text{KF}} \mathbf{u}(k)$$

$$\mathbf{P}(k+1|k) = \mathbf{A}_{\text{KF}} \mathbf{P}(k|k) \mathbf{A}_{\text{KF}}^T + \mathbf{Q}_{\text{KF}}$$

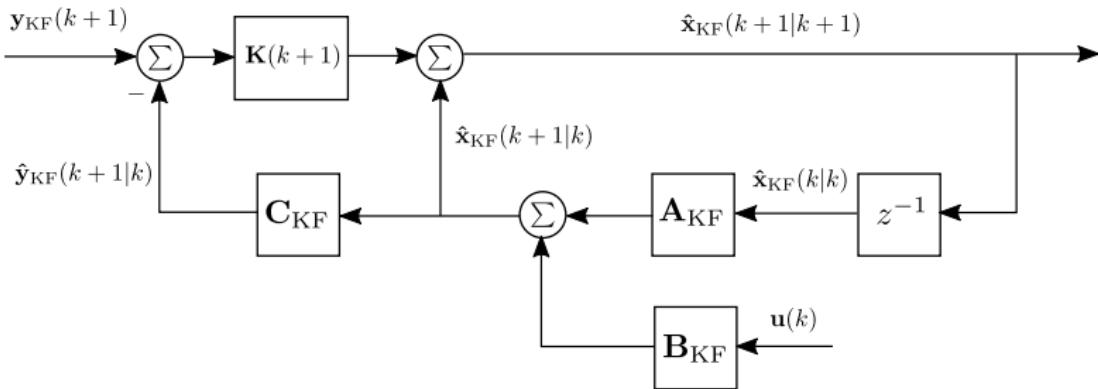
- ▶ Step 2: Update

$$\hat{\mathbf{x}}_{\text{KF}}(k+1|k+1) = \hat{\mathbf{x}}_{\text{KF}}(k+1|k) + \mathbf{K}(k+1) [\mathbf{y}_{\text{KF}}(k+1) - \mathbf{C}_{\text{KF}} \hat{\mathbf{x}}_{\text{KF}}(k+1|k)]$$

$$\mathbf{P}(k+1|k+1) = \left[\mathbf{I} - \mathbf{K}(k+1) \mathbf{C}_{\text{KF}}^T \right] \mathbf{P}(k+1|k)$$

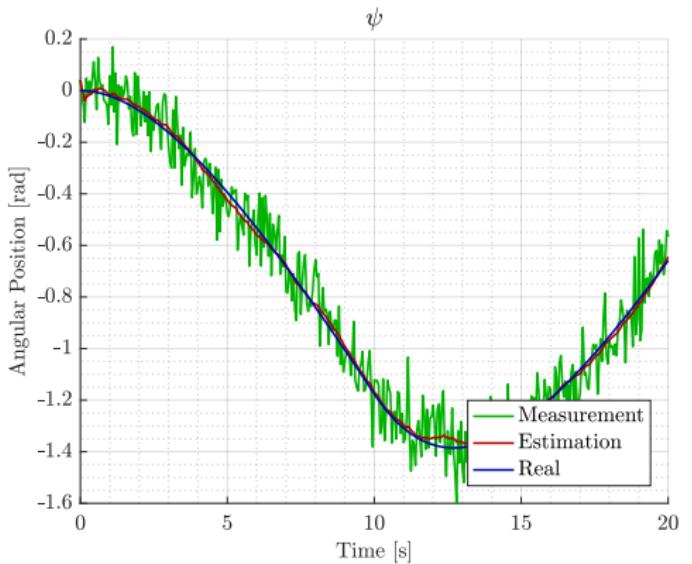
Sensor Fusion

Kalman Filter



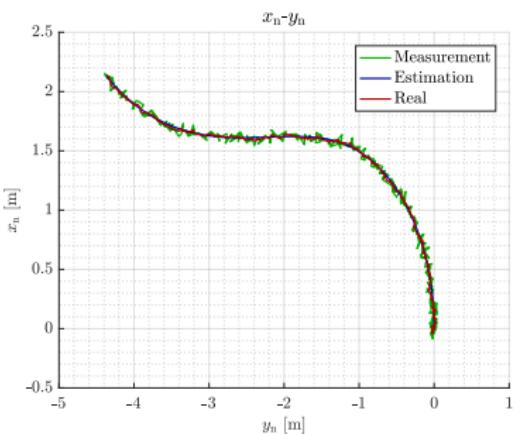
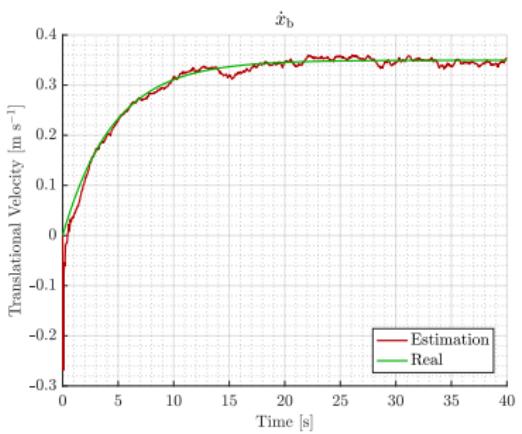
Sensor Fusion

Attitude Kalman Filter



Sensor Fusion

Position Kalman Filter

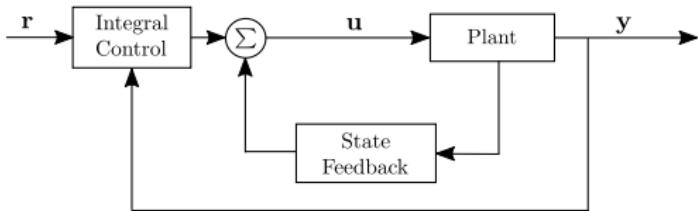


Agenda

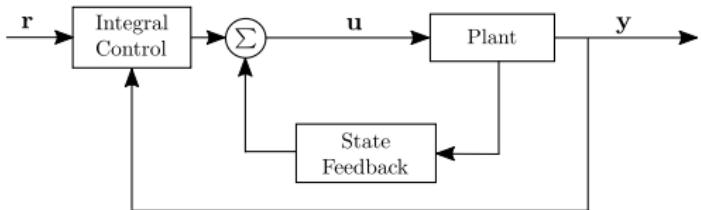


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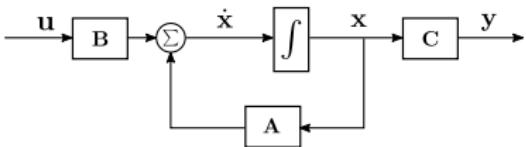
Inner Controller



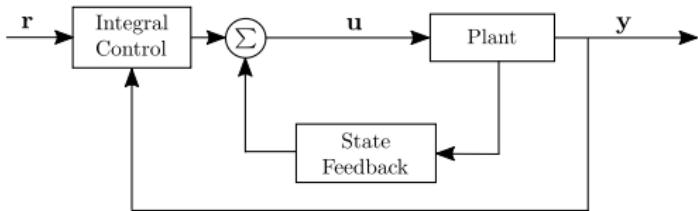
Inner Controller



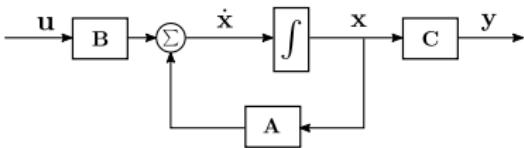
► Plant



Inner Controller



- ▶ Plant



- ▶ Approaches
 - ▶ \mathcal{H}_∞ Controller
 - ▶ Linear Quadratic Regulator

Inner Controller

\mathcal{H}_∞ Controller Design



- ▶ Suboptimal \mathcal{H}_∞ controller

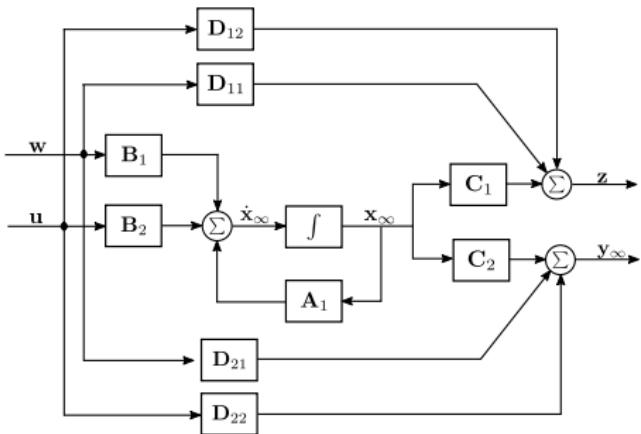
Find an internally stabilizing controller that provides a closed loop \mathcal{H}_∞ norm less than some bound γ

Inner Controller

\mathcal{H}_∞ Controller Design



► System structure



$$\dot{\mathbf{x}}_\infty(t) = \mathbf{A}_1 \mathbf{x}_\infty(t) + \mathbf{B}_1 \mathbf{w}(t) + \mathbf{B}_2 \mathbf{u}(t)$$

$$\mathbf{z}(t) = \mathbf{C}_1 \mathbf{x}_\infty(t) + \mathbf{D}_{11} \mathbf{w}(t) + \mathbf{D}_{12} \mathbf{u}(t)$$

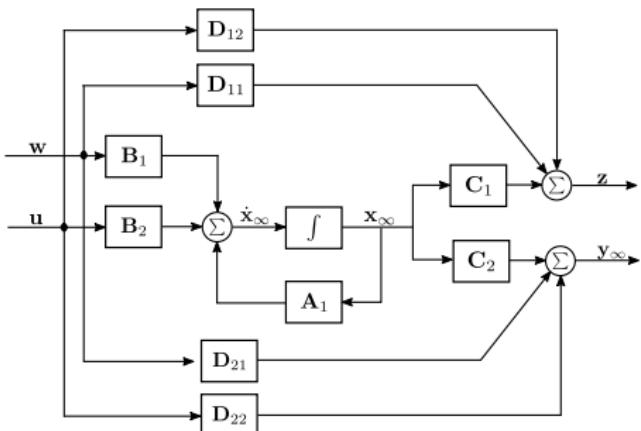
$$\mathbf{y}_\infty(t) = \mathbf{C}_2 \mathbf{x}_\infty(t) + \mathbf{D}_{21} \mathbf{w}(t) + \mathbf{D}_{22} \mathbf{u}(t)$$

Inner Controller

\mathcal{H}_∞ Controller Design



► System structure



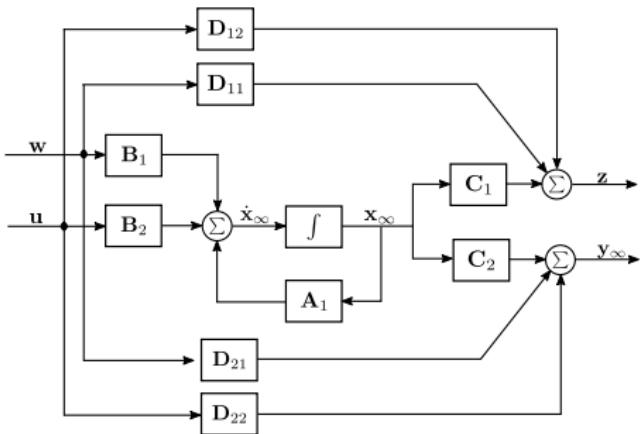
$$\mathbf{u}(t) = [F_1 \quad F_2]^T$$

Inner Controller

\mathcal{H}_∞ Controller Design



► System structure



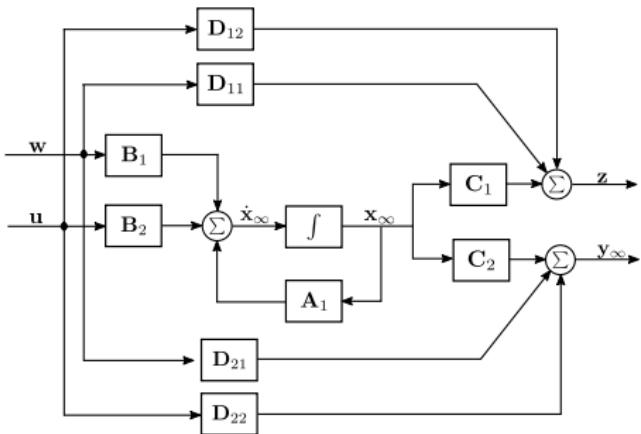
$$\mathbf{w}(t) = [\psi_{\text{ref}} \quad \dot{x}_{\text{b,ref}} \quad F_{\text{wc}} \quad \tau_{\text{wc}} \quad F_{\text{wave}} \quad \tau_{\text{wave}} \quad n_{\psi} \quad n_{\dot{x}_{\text{b}}}]^T$$

Inner Controller

\mathcal{H}_∞ Controller Design



► System structure



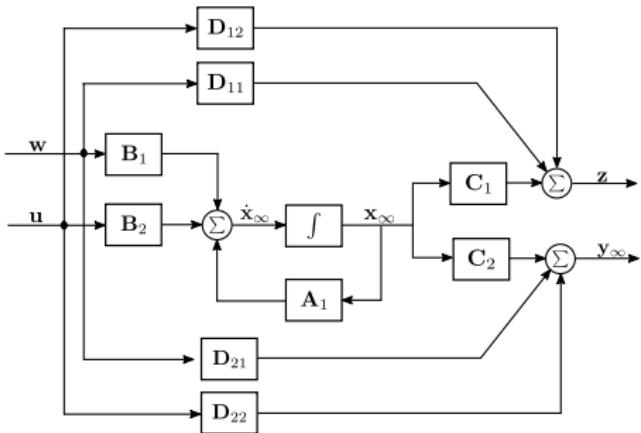
$$\mathbf{y}_\infty(t) = [\psi \quad \dot{x}_b \quad \mathbf{x}_I^T]^T$$

Inner Controller

\mathcal{H}_∞ Controller Design



► System structure



$$\mathbf{x}_\infty(t) = \begin{bmatrix} \psi & \dot{\psi} & \dot{x}_b & X_{I_\psi} & X_{I_{\dot{x}_b}} & X_{F_{wc}} & X_{T_{wc}} & X_{F_{wave}} & X_{T_{wave}} & X_{n_\psi} & X_{n_{\dot{x}_b}} \end{bmatrix}^T$$

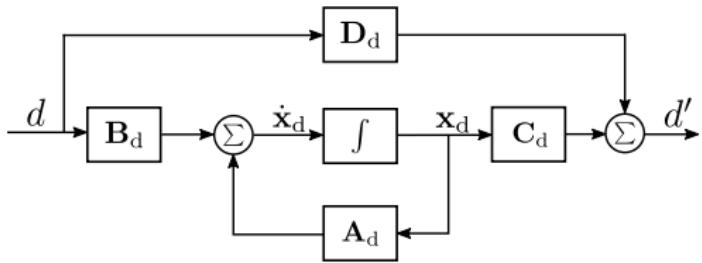
Inner Controller

\mathcal{H}_∞ Controller Design



26

- ▶ Disturbance model



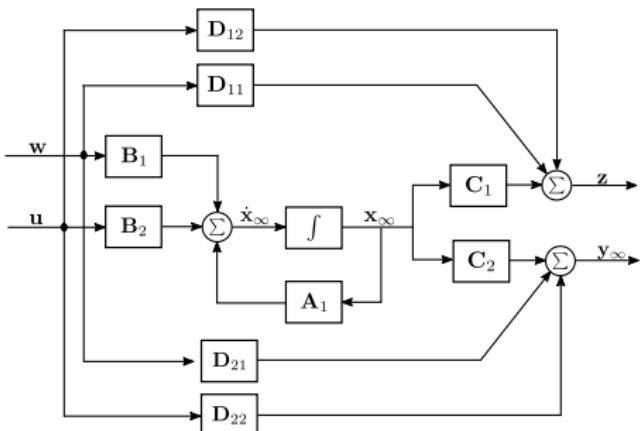
$$\frac{d'}{d} = \frac{a}{s+a} \rightarrow \dot{d}' = -ad' + ad \rightarrow \begin{cases} \dot{x}_d = -ax_d + ad \\ d' = x_d \end{cases}$$

Inner Controller

\mathcal{H}_∞ Controller Design



► System structure



$$\mathbf{z}(t) = [\mathbf{x}_\infty^T \quad \mathbf{u}^T]^T$$

Inner Controller

\mathcal{H}_∞ Controller Design



- Controller design parameters (γ , \mathbf{C}_1 , \mathbf{D}_{12})

$$\mathbf{C}_1 = \begin{bmatrix} \mathbf{W}_x & \mathbf{0}_{3 \times 2} & \mathbf{0}_{3 \times 2} & \mathbf{0}_{3 \times 2} & \mathbf{0}_{3 \times 2} \\ \mathbf{0}_{2 \times 3} & \mathbf{W}_I & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} \\ \mathbf{0}_{2 \times 3} & \mathbf{0}_{2 \times 2} & \mathbf{W}_{w_c} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} \\ \mathbf{0}_{2 \times 3} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} & \mathbf{W}_{wave} & \mathbf{0}_{2 \times 2} \\ \mathbf{0}_{2 \times 3} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} & \mathbf{W}_{noise} \\ \mathbf{0}_{2 \times 3} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} \\ \mathbf{0}_{2 \times 3} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 2} \end{bmatrix} \quad \mathbf{D}_{12} = \begin{bmatrix} \mathbf{0}_{2 \times 3} \\ \mathbf{0}_{2 \times 2} \\ \mathbf{0}_{2 \times 2} \\ \mathbf{0}_{2 \times 2} \\ \mathbf{0}_{2 \times 2} \\ \mathbf{W}_u \end{bmatrix}$$

Inner Controller

\mathcal{H}_∞ Controller Design



- ▶ Feedback gain

$$\mathbf{X}_\infty = Ric \begin{bmatrix} \mathbf{A}_1 & \gamma^{-2} \mathbf{B}_1 \mathbf{B}_1^T - \mathbf{B}_2 \mathbf{B}_2^T \\ -\mathbf{C}_1^T \mathbf{C}_1 & -\mathbf{A}_1^T \end{bmatrix}$$

$$\mathbf{F}_\infty = -\mathbf{B}_2^T \mathbf{X}_\infty$$

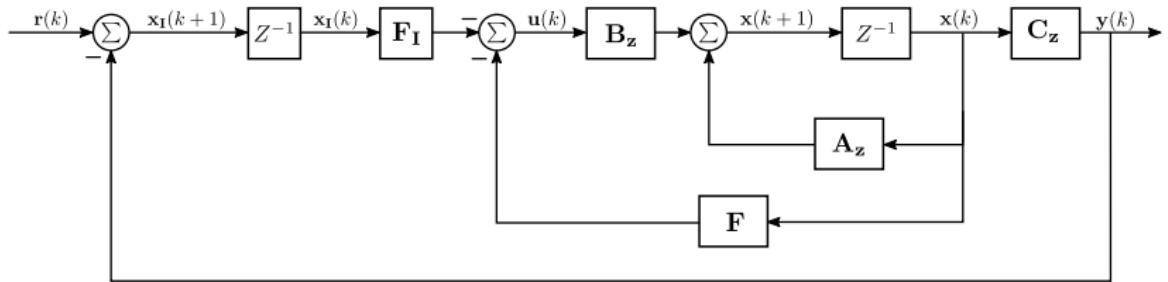
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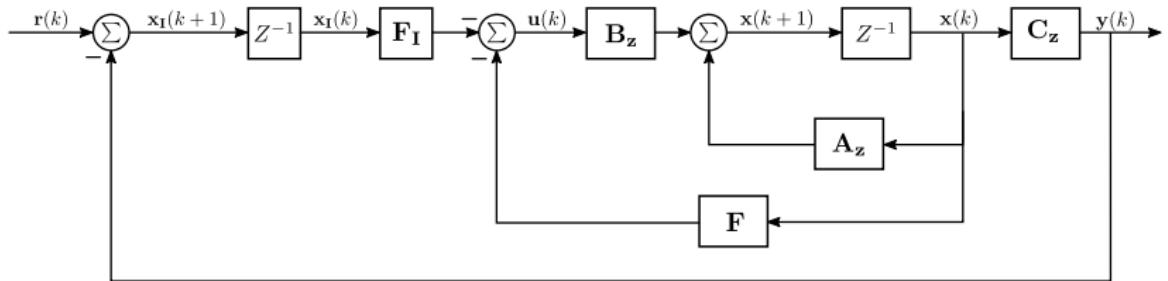
Inner Controller

Linear Quadratic Controller Design



Inner Controller

Linear Quadratic Controller Design



$$\begin{bmatrix} \mathbf{x}(k+1) \\ \mathbf{x}_I(k+1) \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{z,3x3} & \mathbf{0}_{3x2} \\ -\mathbf{C}_{z,2x3} & \mathbf{I}_{2x2} \end{bmatrix} \begin{bmatrix} \mathbf{x}(k) \\ \mathbf{x}_I(k) \end{bmatrix} + \begin{bmatrix} \mathbf{B}_{z,3x2} \\ \mathbf{0}_{2x2} \end{bmatrix} \mathbf{u}(k) + \begin{bmatrix} \mathbf{0}_{3x2} \\ \mathbf{I}_{2x2} \end{bmatrix} \mathbf{r}(k)$$

$$\mathbf{y}(k) = [\mathbf{C}_{z,2x3} \quad \mathbf{0}_{2x2}] \begin{bmatrix} \mathbf{x}(k) \\ \mathbf{x}_I(k) \end{bmatrix}$$

Inner Controller

Linear Quadratic Controller Design



- Discrete cost function

$$\mathcal{J}_z = \sum_{k=0}^{\infty} \mathbf{x}^T(k) \mathbf{Q}_z \mathbf{x}(k) + \mathbf{u}^T(k) \mathbf{R}_z \mathbf{u}(k)$$

Inner Controller

Linear Quadratic Controller Design



- Continuous cost function

$$\mathcal{J} = \int_0^{\infty} \mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t) + \mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t) \, dt$$

Inner Controller

Linear Quadratic Controller Design



- Continuous cost function

$$\mathcal{J} = \int_0^{\infty} \mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t) + \mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t) dt$$

$$Q = diag \left(\frac{1}{\psi_{\max}^2}, \frac{1}{\dot{\psi}_{\max}^2}, \frac{1}{\dot{x}_{b,\max}^2}, \frac{1}{x_{I,\psi,\max}^2}, \frac{1}{x_{I,\dot{x}_b,\max}^2} \right)$$

$$R = diag \left(\frac{1}{F_{1\max}^2}, \frac{1}{F_{2\max}^2} \right)$$

Inner Controller

Linear Quadratic Controller Design



- ▶ Discretize the cost function to get \mathbf{Q}_z and \mathbf{R}_z
- ▶ Solve the discrete-time algebraic Riccati equation
- ▶ Get the feedback gains

$$\mathbf{u}(k) = - [\mathbf{F} \quad \mathbf{F}_I] \begin{bmatrix} \mathbf{x}(k) \\ \mathbf{x}_I(k) \end{bmatrix}$$

Inner Controller

Comparison of the Controllers



Simulation of LQR and \mathcal{H}_∞ design

- ▶ Wind and current disturbances
 - ▶ ± 1.5 N along \dot{x}_b
 - ▶ ± 1.5 N·m around z_b
- ▶ Wave disturbance
 - ▶ Sinusoidal
 - ▶ frequency between 0-10 Hz

Inner Controller

Comparison of the Controllers



Simulation of LQR and \mathcal{H}_∞ design

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 - ▶ frequency between 0-10 Hz
- ▶ The parameters are varied $\pm 20\%$
 - ▶ Mass, m
 - ▶ Moment of inertia, I_z , around z_b
 - ▶ The damping coefficients d_x and d_y
 - ▶ The lengths l_1 and l_2

Inner Controller

Comparison of the Controllers

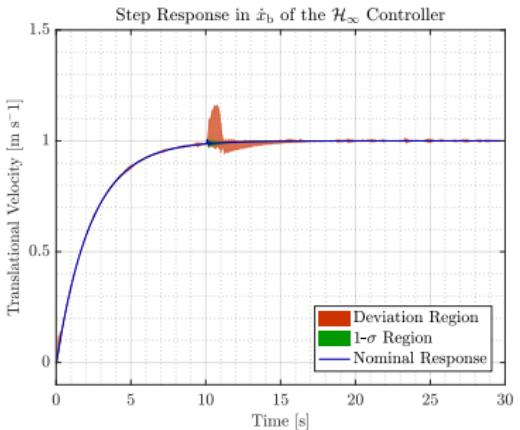
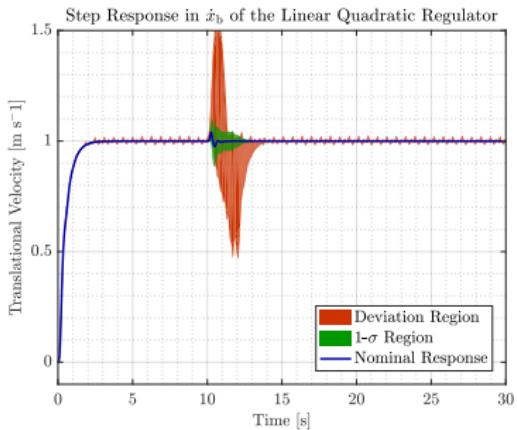


Simulation of LQR and \mathcal{H}_∞ design

- ▶ Wind and current disturbances
 - ▶ ± 1.5 N along \dot{x}_b
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- ▶ The parameters are varied $\pm 20\%$
 - ▶ Mass, m
 - ▶ Moment of inertia, I_z , around z_b
 - ▶ The damping coefficients d_x and d_y
 - ▶ The lengths l_1 and l_2
- ▶ Monte Carlo simulations with 1000 realizations

Inner Controller

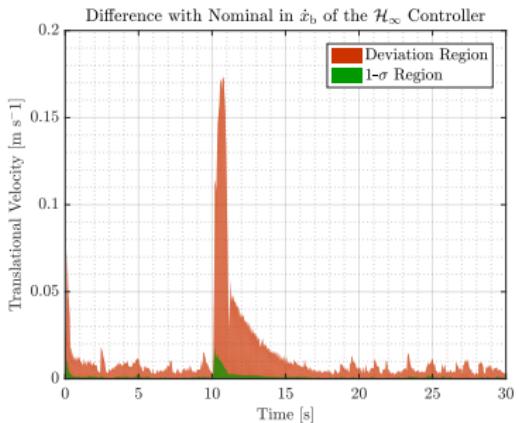
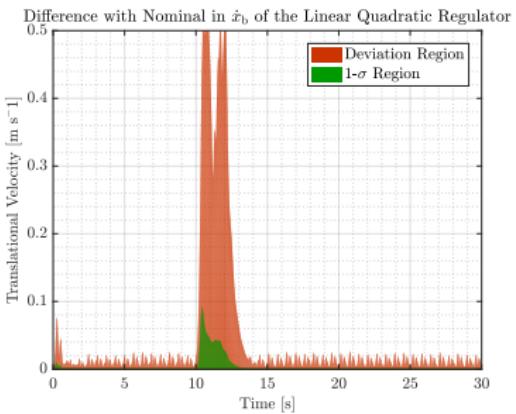
Comparison of the Controllers



- ▶ Influence from change in reference in ψ
- ▶ LQR gives a faster response
- ▶ \mathcal{H}_{∞} controller is more robust to disturbances

Inner Controller

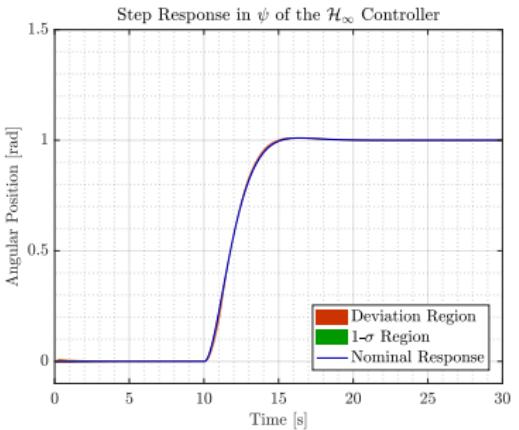
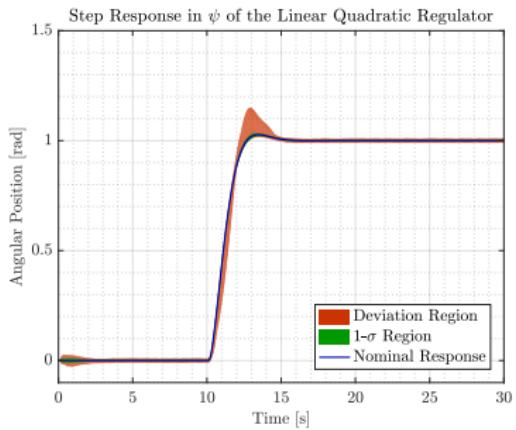
Comparison of the Controllers



- ▶ Influence from change in reference in ψ
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Inner Controller

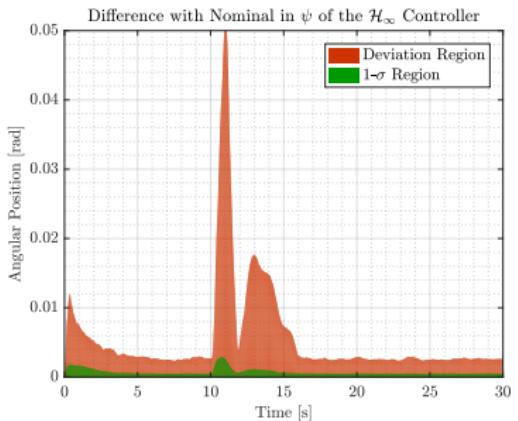
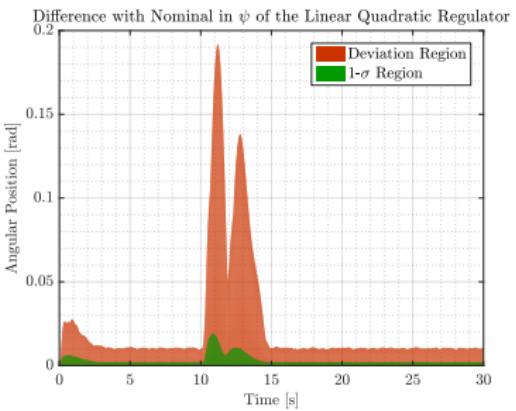
Comparison of the Controllers



- ▶ LQR gives a faster response
- ▶ \mathcal{H}_∞ controller is more robust to disturbances
- ▶ \mathcal{H}_∞ controller tracks ψ fast but \dot{x}_b slow

Inner Controller

Comparison of the Controllers



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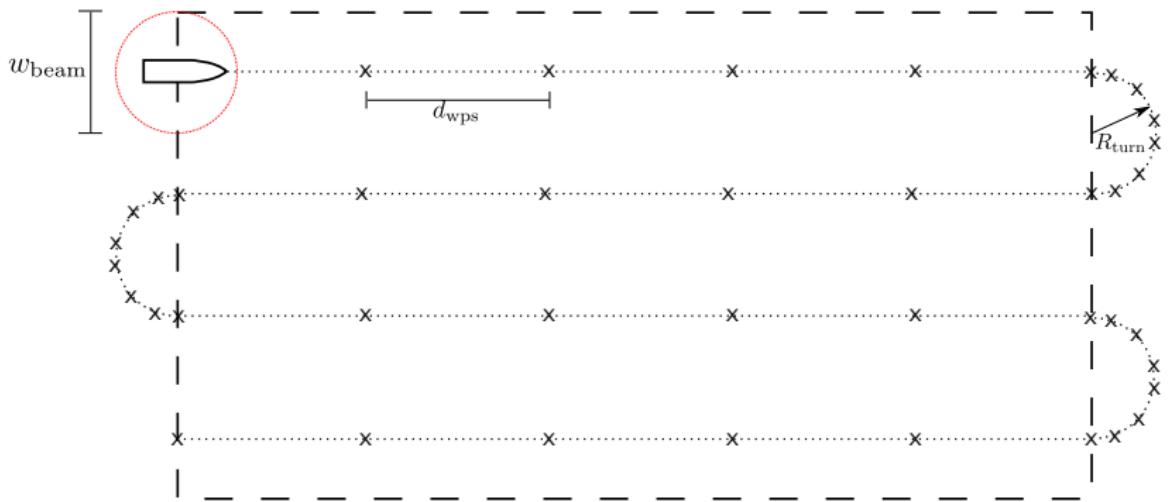
Agenda



- ▶ Introduction
- ▶ System Description
- ▶ Model
- ▶ Control Approach
- ▶ Sensor Fusion
- ▶ Inner Controller
- ▶ **Outer Controller**
 - Path Generation Algorithm
 - Path Following Algorithm
- ▶ **Results**
 - Controller Results
 - Implementation Results
- ▶ **Conclusion**

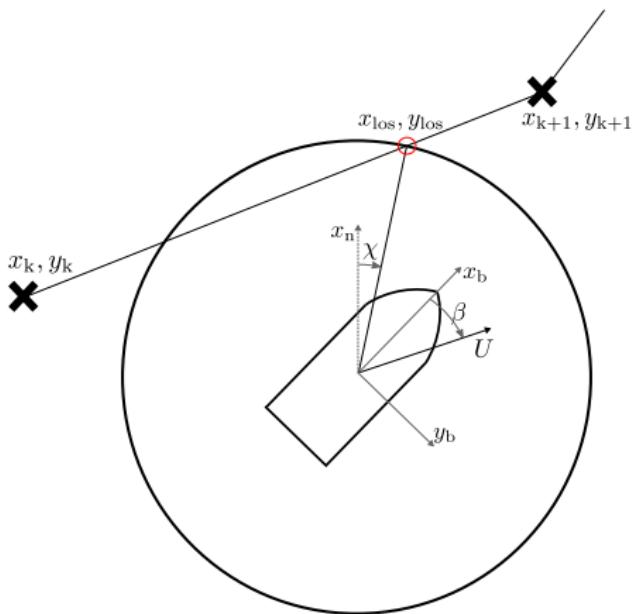
Outer Controller

Path Generation Algorithm



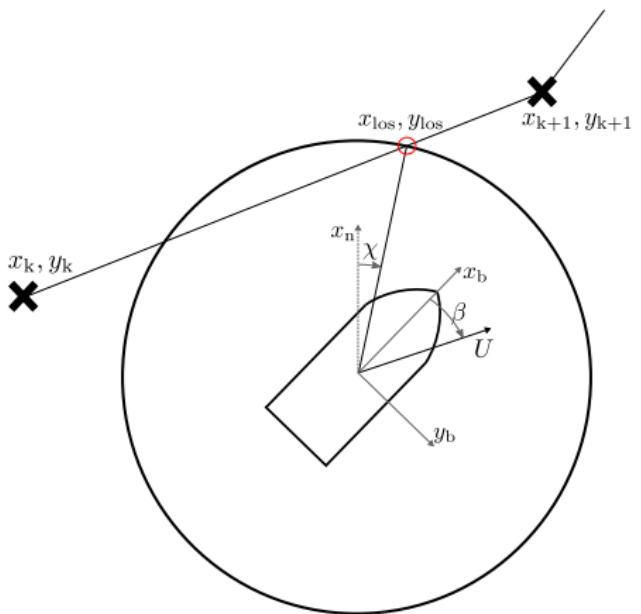
Outer Controller

Path Following Algorithm



Outer Controller

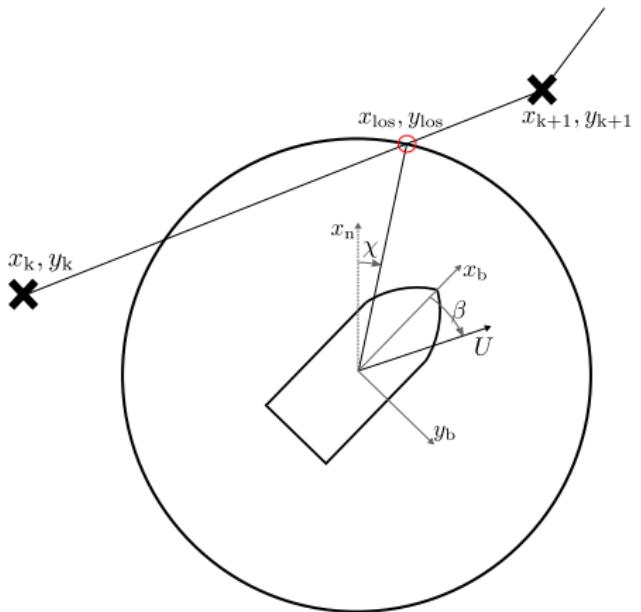
Path Following Algorithm



$$\chi = \arctan \left(\frac{y_{\text{LOS}} - y_n}{x_{\text{LOS}} - x_n} \right)$$

Outer Controller

Path Following Algorithm

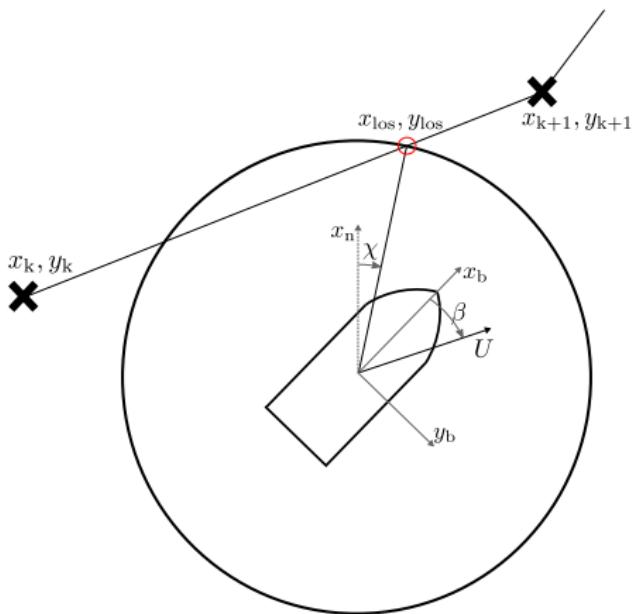


$$\chi = \arctan \left(\frac{y_{\text{LOS}} - y_n}{x_{\text{LOS}} - x_n} \right)$$

$$\beta = \arctan \left(\frac{\dot{y}_b}{\dot{x}_b} \right)$$

Outer Controller

Path Following Algorithm



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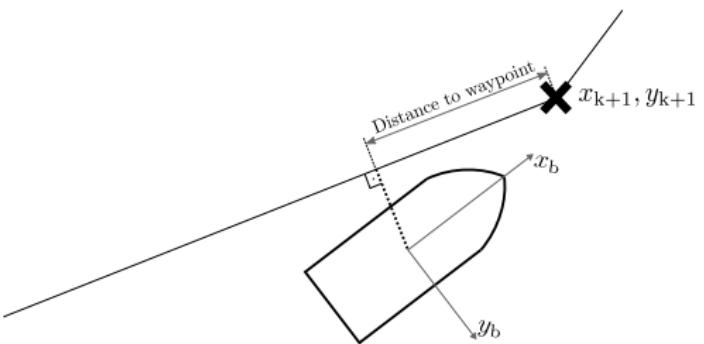
$$\psi_{\text{ref}} = \chi - \beta$$

Outer Controller

Path Following Algorithm



- ▶ Change active waypoints



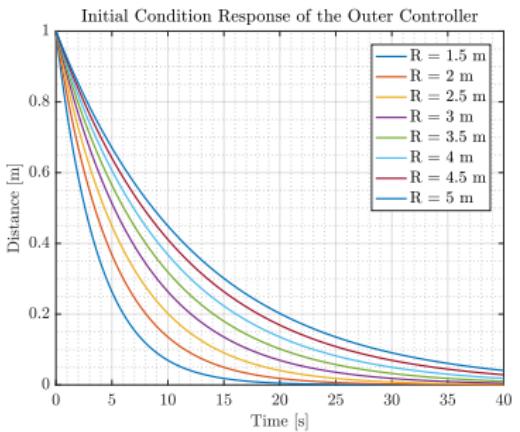
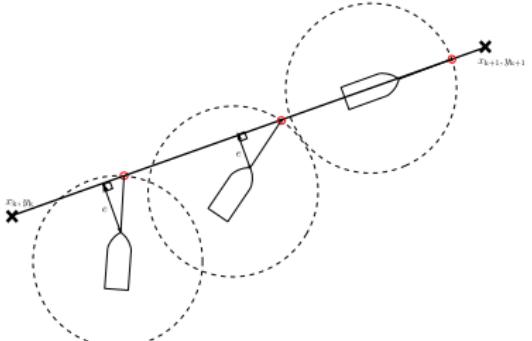
Outer Controller

Path Following Algorithm



43

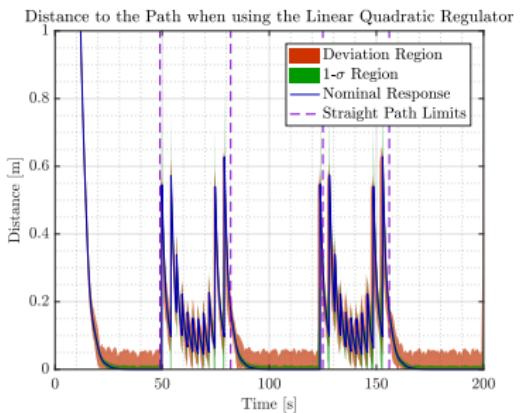
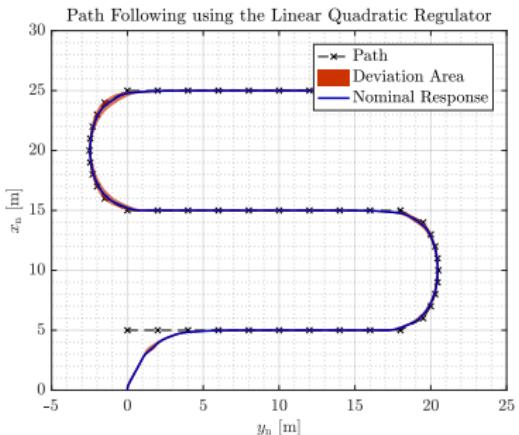
- ▶ Convergence to the path



Results

Controller Results

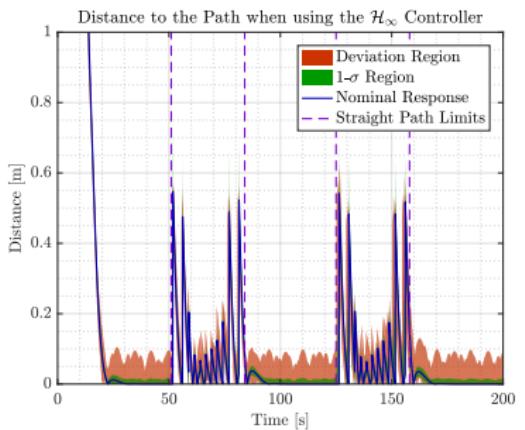
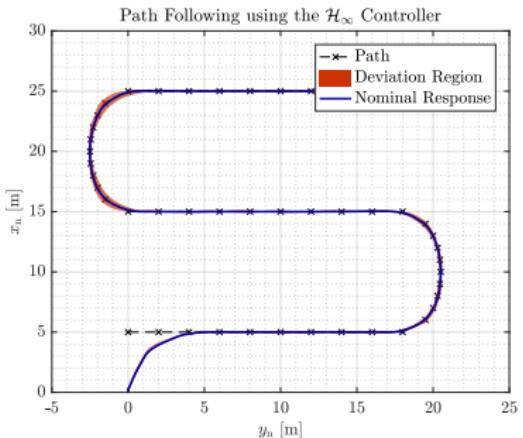
► LQR as inner controller



Results

Controller Results

► Robust controller as inner controller

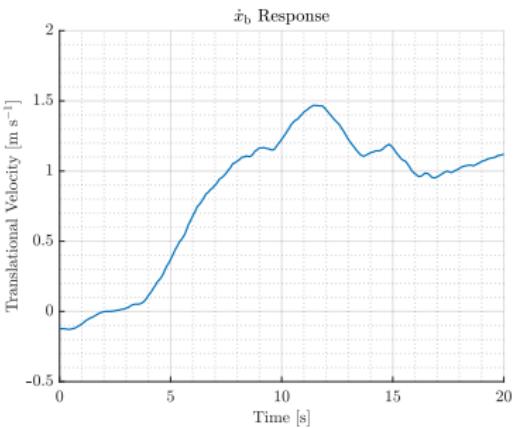
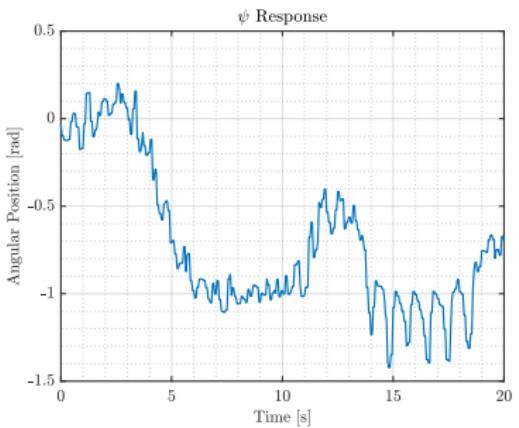


Results

Implementation Results



► Inner controller test

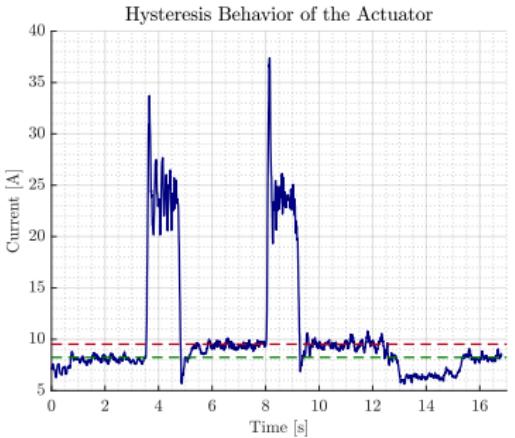
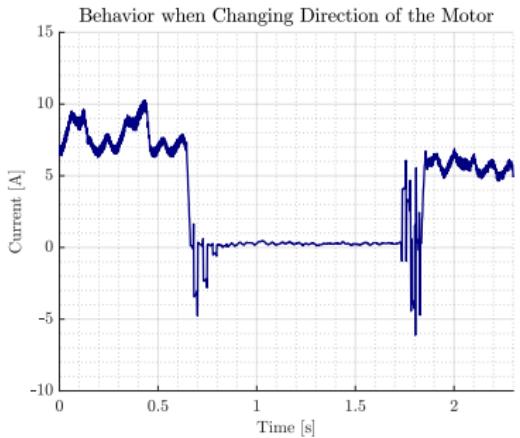


Results

Implementation Results



► Actuator tests



Conclusion



- ▶ A dynamic model of the system has been derived
- ▶ The estimator has been designed and tested through simulation
- ▶ The control system has also been analyzed through simulations that include disturbances, noise and varying parameters
- ▶ The simulated results have not been fully replicated in the real vessel, but they show a promising behavior of the control system

Precision Control of an Autonomous Surface Vessel



AALBORG UNIVERSITY
DENMARK