Precision Control of an Autonomous Surface Vessel

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

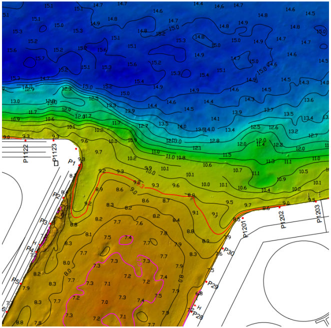
Agenda

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

Introduction

- What is an Autonomous Surface Vessel (ASV)
- Bathymetric Measurements
- Control of an ASV

Introduction
Use Case



- Used by Port of Aalborg
- Problem: No recent knowledge of depths of the port
- Solution: Automate smaller unmanned vessel

Introduction

Functional Requirements

A: It shall be possible to select the area in which the bathymetric measurements are to be performed.

B: The ASV shall be able to plan a route, such that the entire survey area is mapped.

C: The ASV shall be able to follow the planned route.

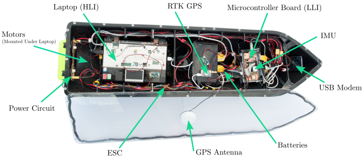
D: The controller shall be robust to external disturbances.

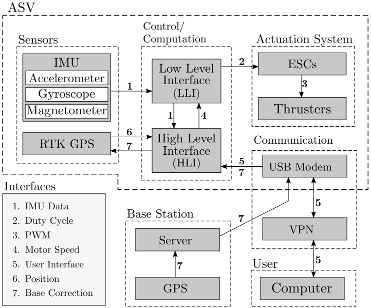
E: The THU shall not exceed 30 cm with a 95% confidence interval.

F: The ASV shall record and store data locally for extraction at the end of the survey.

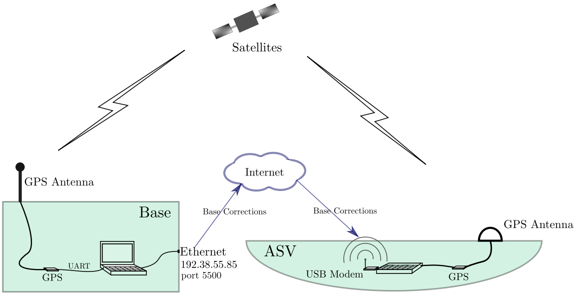
G: It shall be possible to give the ASV a command to stop and steer it back to land.

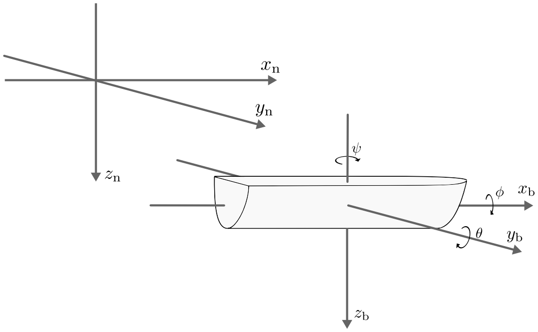
System Description

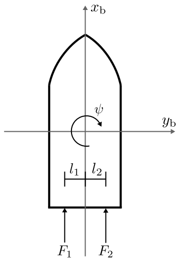




System Description
RTK GPS




x_n
y_n
z_n
ψ
ϕ
x_b
θ
y_b
z_b

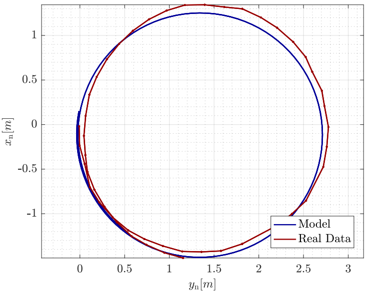

x_b
ψ
y_b
l_1
l_2
F_1
F_2

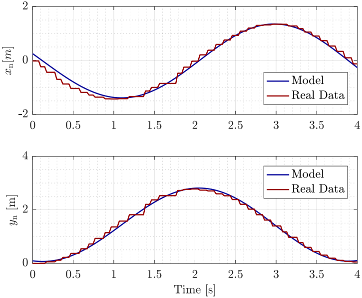
Model
Model Equations

$$
\begin{aligned}
m\ddot{x}_{\mathrm{b}} &= F_1 + F_2 - d_{\dot{x}_{\mathrm{b}}}\dot{x}_{\mathrm{b}} + F_{x_{\mathrm{b}}} \\
m\ddot{y}_{\mathrm{b}} &= -d_{\dot{y}_{\mathrm{b}}}\dot{y}_{\mathrm{b}} + F_{y_{\mathrm{b}}} \\
m\ddot{z}_{\mathrm{b}} &= -d_{\dot{z}_{\mathrm{b}}}\dot{z}_{\mathrm{b}} + F_{z_{\mathrm{b}}} \\
I_{\mathrm{x}}\ddot{\phi} &= -d_{\dot{\phi}}\dot{\phi} + T_{\phi} \\
I_{\mathrm{y}}\ddot{\theta} &= -d_{\dot{\theta}}\dot{\theta} + T_{\theta} \\
I_{\mathrm{z}}\ddot{\psi} &= F_1 l_1 - F_2 l_2 - d_{\dot{\psi}}\dot{\psi}
\end{aligned}
$$

Model

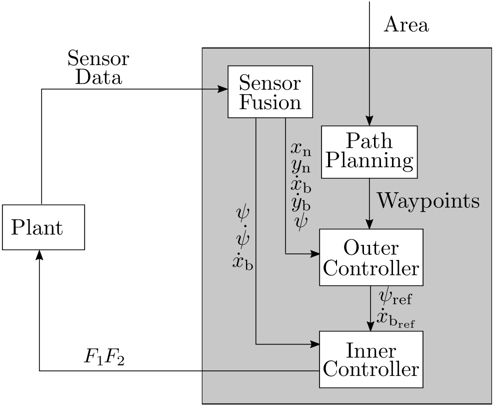
Model Verification





Agenda

Control Approach



Sensor Fusion
Kalman Filter Structure

Sensor Fusion
Attitude Kalman Filter

$$\hat{\mathbf{x}}_{\mathrm{att}}(k+1) = \mathbf{A}_{\mathrm{att}}\hat{\mathbf{x}}_{\mathrm{att}}(k) + \mathbf{B}_{\mathrm{att}}\mathbf{u}(k) + \mathbf{w}_{\mathrm{att}}(k)$$
$$\mathbf{y}_{\mathrm{att}}(k) = \mathbf{C}_{\mathrm{att}}\hat{\mathbf{x}}_{\mathrm{att}}(k) + \mathbf{v}_{\mathrm{att}}(k)$$

$$\mathbf{Q}_{\mathrm{att}} = diag\left(\sigma^2_{\phi}, \sigma^2_{\theta}, \sigma^2_{\psi}, \sigma^2_{\dot{\phi}}, \sigma^2_{\dot{\theta}}, \sigma^2_{\dot{\psi}}, \sigma^2_{\ddot{\phi}}, \sigma^2_{\ddot{\theta}}, \sigma^2_{\ddot{\psi}}\right)$$
$$\mathbf{R}_{\mathrm{att}} = diag\left(\sigma^2_{\phi,\mathrm{acc}}, \sigma^2_{\theta,\mathrm{acc}}, \sigma^2_{\psi,\mathrm{mag}}, \sigma^2_{\dot{\phi},\mathrm{gyro}}, \sigma^2_{\dot{\theta},\mathrm{gyro}}, \sigma^2_{\dot{\psi},\mathrm{gyro}}\right)$$

$$\hat{\mathbf{x}}_{\mathrm{att}} = \begin{bmatrix}\phi & \theta & \psi & \dot{\phi} & \dot{\theta} & \dot{\psi} & \ddot{\phi} & \ddot{\theta} & \ddot{\psi}\end{bmatrix}^{\mathrm{T}}$$

$$\mathbf{y}_{\mathrm{att}} = \begin{bmatrix}\phi_{\mathrm{acc}} & \theta_{\mathrm{acc}} & \psi_{\mathrm{mag}} & \dot{\phi}_{\mathrm{gyro}} & \dot{\theta}_{\mathrm{gyro}} & \dot{\psi}_{\mathrm{gyro}}\end{bmatrix}^{\mathrm{T}}$$

$$\mathbf{u} = \begin{bmatrix}F_1 & F_2\end{bmatrix}^{\mathrm{T}}$$

$$\mathbf{A}_{\text{att}} = \begin{bmatrix} 1 & 0 & 0 & T_{\text{s}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & T_{\text{s}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & T_{\text{s}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & T_{\text{s}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & T_{\text{s}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & T_{\text{s}} \\ 0 & 0 & 0 & -\frac{d_\phi}{I_{\text{x}}} & 0 & 0 & -T_{\text{s}}\frac{d_\phi}{I_{\text{x}}} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{d_\theta}{I_{\text{y}}} & 0 & 0 & -T_{\text{s}}\frac{d_\theta}{I_{\text{y}}} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{d_\psi}{I_{\text{z}}} & 0 & 0 & -T_{\text{s}}\frac{d_\psi}{I_{\text{z}}} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

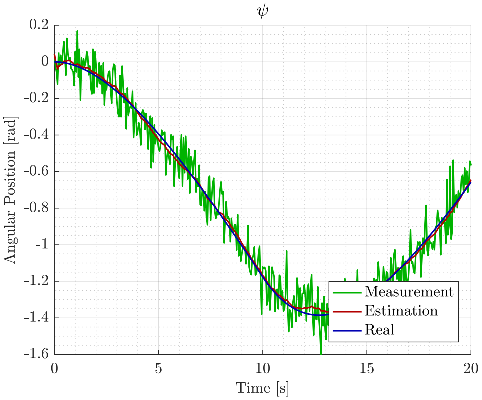
$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\hat{\mathbf{x}}_{\mathrm{att}}(k+1|k) = \mathbf{A}_{\mathrm{att}}\hat{\mathbf{x}}_{\mathrm{att}}(k|k) + \mathbf{B}_{\mathrm{att}}\mathbf{u}(k)$$
$$\mathbf{P}_{\mathrm{att}}(k+1|k) = \mathbf{A}_{\mathrm{att}}\mathbf{P}_{\mathrm{att}}(k|k)\mathbf{A}_{\mathrm{att}}^{\mathrm{T}} + \mathbf{Q}_{\mathrm{att}}$$

$$\hat{\mathbf{x}}_{\mathrm{att}}(k+1|k+1) = \hat{\mathbf{x}}_{\mathrm{att}}(k+1|k) + \mathbf{K}(k+1)\left[\mathbf{y}_{\mathrm{att}}(k+1) - \mathbf{C}_{\mathrm{att}}\hat{\mathbf{x}}_{\mathrm{att}}(k+1|k)\right.$$
$$\mathbf{P}_{\mathrm{att}}(k+1|k+1) = \left[\mathbf{I} - \mathbf{K}(k+1)\mathbf{C}_{\mathrm{att}}^{\mathrm{T}}\right]\mathbf{P}_{\mathrm{att}}(k+1|k)$$

Sensor Fusion

Attitude Kalman Filter



Sensor Fusion

Position Kalman Filter

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

$$
\begin{aligned}
\mathbf{Q}_{\mathrm{pos}} &= \mathrm{diag}\left(\sigma^2_{\mathrm{x_n}}, \sigma^2_{\mathrm{y_n}}, \sigma^2_{\underline{\mathrm{x}}_\mathrm{b}}, \sigma^2_{\underline{\mathrm{y}}_\mathrm{b}}, \sigma^2_{\cancel{\mathrm{x}}_\mathrm{b}}, \sigma^2_{\cancel{\mathrm{y}}_\mathrm{b}}\right) \\
\mathbf{R}_{\mathrm{pos}} &= \mathrm{diag}\left(\sigma^2_{x_{\mathrm{n,GPS}}}, \sigma^2_{y_{\mathrm{n,GPS}}}, \sigma^2_{\ddot{x}_{\mathrm{b}},\mathrm{acc}}, \sigma^2_{\ddot{y}_{\mathrm{b}},\mathrm{acc}}\right)
\end{aligned}
$$

$$
\hat{\mathbf{x}}_{\mathrm{pos}} = \begin{bmatrix} x_{\mathrm{n}} & y_{\mathrm{n}} & \dot{x}_{\mathrm{b}} & \dot{y}_{\mathrm{b}} & \ddot{x}_{\mathrm{b}} & \ddot{y}_{\mathrm{b}} \end{bmatrix}^{\mathrm{T}}
$$

$$
\mathbf{y}_{\mathrm{pos}} = \begin{bmatrix} x_{\mathrm{n,GPS}} & y_{\mathrm{n,GPS}} & \ddot{x}_{\mathrm{b,acc}} & \ddot{y}_{\mathrm{b,acc}} \end{bmatrix}^{\mathrm{T}}
$$

$$
\mathbf{u} = \begin{bmatrix} F_1 & F_2 \end{bmatrix}^{\mathrm{T}}
$$

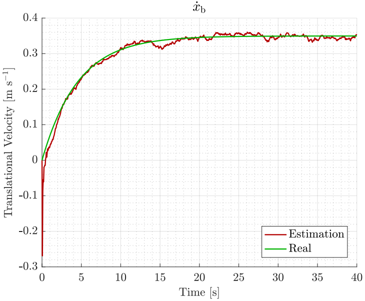
Sensor Fusion

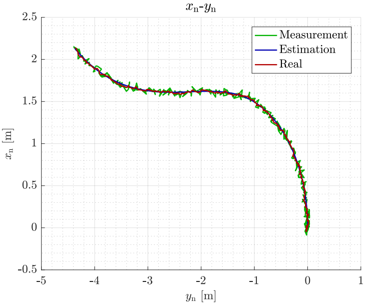
Position Kalman Filter

$$\mathbf{A}_{\mathrm{pos}}(\phi(k), \theta(k), \psi(k)) = \begin{bmatrix} 1 & 0 & T_{\mathrm{s}}\ \mathbf{R}_{\mathrm{b}}^{\mathrm{n}}(1,1) & T_{\mathrm{s}}\ \mathbf{R}_{\mathrm{b}}^{\mathrm{n}}(1,2) & 0 & 0 \\ 0 & 1 & T_{\mathrm{s}}\ \mathbf{R}_{\mathrm{b}}^{\mathrm{n}}(2,1) & T_{\mathrm{s}}\ \mathbf{R}_{\mathrm{b}}^{\mathrm{n}}(2,2) & 0 & 0 \\ 0 & 0 & 1 & 0 & T_{\mathrm{s}} & 0 \\ 0 & 0 & 0 & 1 & 0 & T_{\mathrm{s}} \\ 0 & 0 & -\frac{d_{\mathrm{x}}}{m} & 0 & -T_{\mathrm{s}}\frac{d_{\mathrm{x}}}{m} & 0 \\ 0 & 0 & 0 & -\frac{d_{\mathrm{y}}}{m} & 0 & -T_{\mathrm{s}}\frac{d_{\mathrm{y}}}{m} \end{bmatrix}$$

Sensor Fusion

Position Kalman Filter

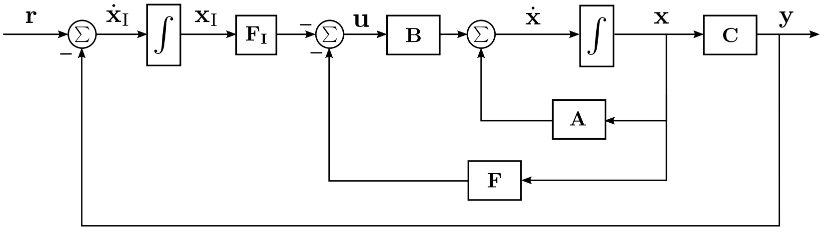




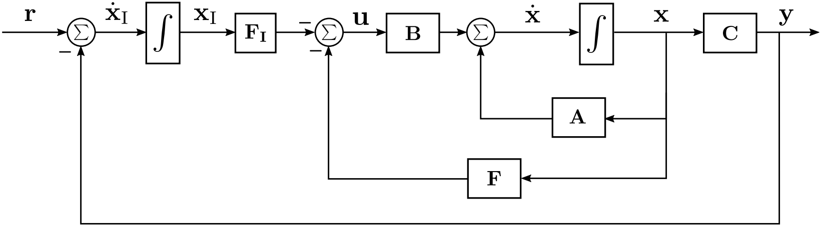
Agenda

- Introduction
- System Description
- Model
- Control Approach
- Sensor Fusion
- **Inner Controller**
  - **Robust Controller Design**
  - Linear Quadratic Regulator Design
  - Comparison of the Controllers
- Outer Controller
- Results
- Conclusion

Inner Controller

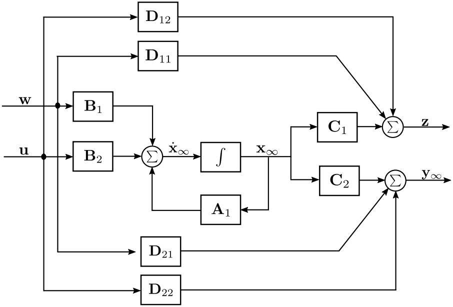


Inner Controller



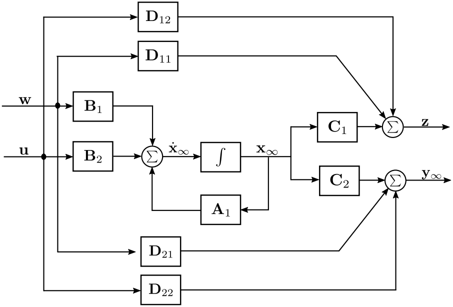
- Linear Quadratic Regulator
- $\mathcal{H}_\infty$ Controller

- System structure



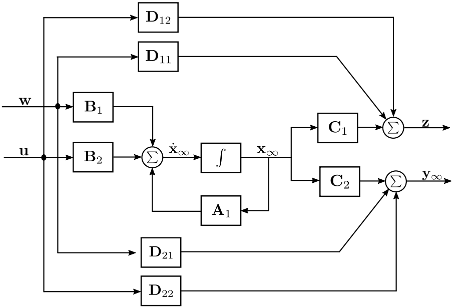
$$\begin{aligned}
\dot{\mathbf{x}}_\infty(t) &= \mathbf{A}_1\mathbf{x}_\infty(t) + \mathbf{B}_1\mathbf{w}(t) + \mathbf{B}_2\mathbf{u}(t) \\
\mathbf{z}(t) &= \mathbf{C}_1\mathbf{x}_\infty(t) + \mathbf{D}_{11}\mathbf{w}(t) + \mathbf{D}_{12}\mathbf{u}(t) \\
\mathbf{y}_\infty(t) &= \mathbf{C}_2\mathbf{x}_\infty(t) + \mathbf{D}_{21}\mathbf{w}(t) + \mathbf{D}_{22}\mathbf{u}(t)
\end{aligned}$$

- System structure



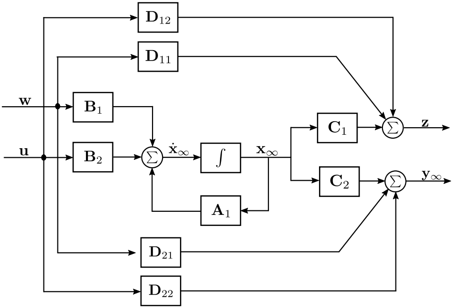
$$\mathbf{x}_\infty(t) = \begin{bmatrix} \psi & \dot{\psi} & \dot{x}_\mathrm{b} & x_{int_\psi} & x_{int_{\dot{x}_\mathrm{b}}} & x_{F_\mathrm{wc}} & x_{\tau_\mathrm{wc}} & x_{F_\mathrm{wave}} & x_{\tau_\mathrm{wave}} & x_{n_\psi} & x_{n_{\dot{x}_\mathrm{b}}} \end{bmatrix}^\mathrm{T}$$

- System structure



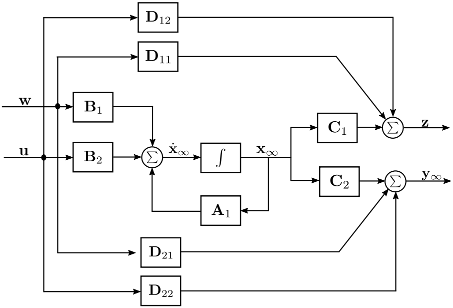
$$\mathbf{u}(t) = \begin{bmatrix} F_1 & F_2 \end{bmatrix}^{\mathrm{T}}$$

- System structure



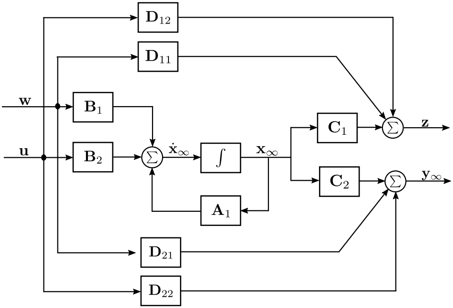
$$\mathbf{w}(t) = \begin{bmatrix} \psi_{\mathrm{ref}} & \dot{x}_{\mathrm{b,ref}} & F_{\mathrm{wc}} & \tau_{\mathrm{wc}} & F_{\mathrm{wave}} & \tau_{\mathrm{wave}} & n_\psi & n_{\dot{x}_\mathrm{b}} \end{bmatrix}^\mathrm{T}$$

- System structure



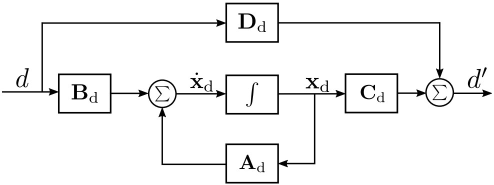
$$\mathbf{y}_\infty(t) = \begin{bmatrix} \psi & \dot{x}_\mathrm{b} & \mathbf{x}_\mathrm{I}^\mathrm{T} \end{bmatrix}^\mathrm{T}$$

- System structure



$$\mathbf{z}(t) = \begin{bmatrix} \mathbf{x}_\infty^{\mathrm{T}} & \mathbf{u}^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}}$$

- Disturbance model



$$\frac{d'}{d} = \frac{a}{s+a} \rightarrow \dot{d}' = -ad' + ad \rightarrow \begin{cases} \dot{x}_\mathrm{d} = -ax_\mathrm{d} + ad \\ d' = x_\mathrm{d} \end{cases}$$

- Feedback gain

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

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

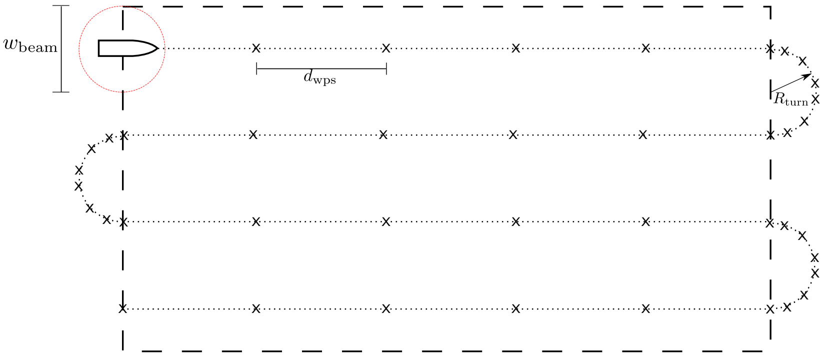
Agenda

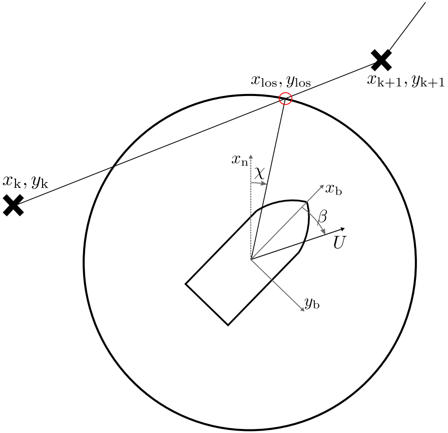
Inner Controller
Linear Quadratic Controller Design

Inner Controller
Comparison of the Controllers

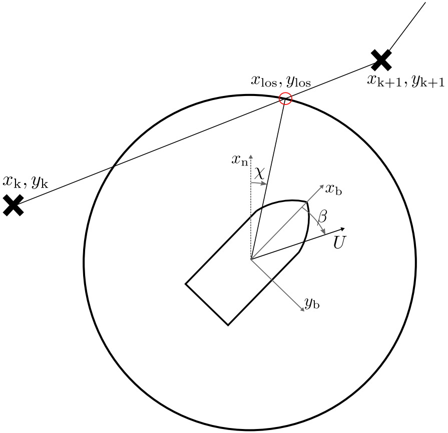
Agenda

Outer Controller
Path Generation Algorithm



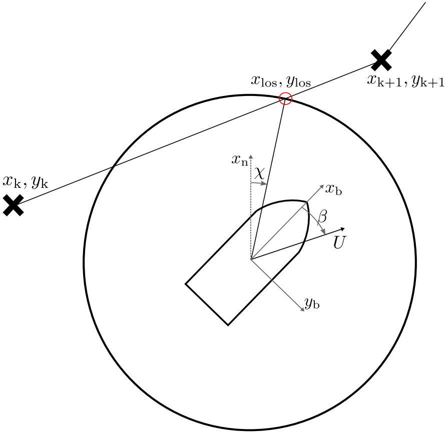


$x_{\text{los}}, y_{\text{los}}$
$x_{\text{k+1}}, y_{\text{k+1}}$
$x_{\text{k}}, y_{\text{k}}$
x_{n}
χ
x_{b}
β
U
y_{b}



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

Outer Controller
Path Following Algorithm

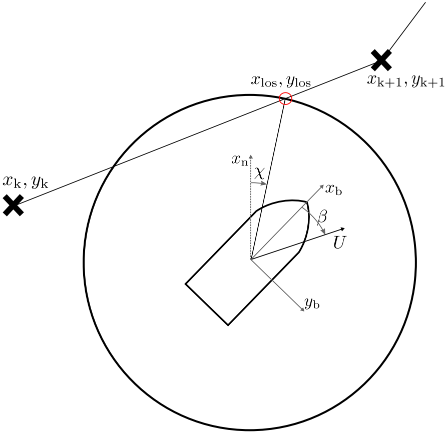


$$\chi = \arctan\left(\frac{y_{\rm LOS} - y_{\rm n}}{x_{\rm LOS} - x_{\rm n}}\right)$$

$$\beta = \arctan\left(\frac{\dot{y}_{\rm b}}{\dot{x}_{\rm b}}\right)$$

Outer Controller

Path Following Algorithm

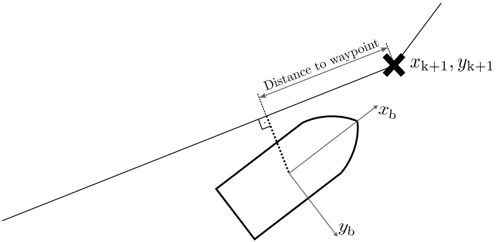


$$\chi = \arctan\left(\frac{y_{\mathrm{LOS}} - y_{\mathrm{n}}}{x_{\mathrm{LOS}} - x_{\mathrm{n}}}\right)$$

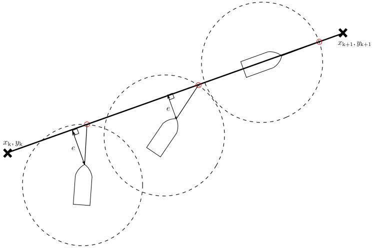
$$\beta = \arctan\left(\frac{\dot{y}_{\mathrm{b}}}{\dot{x}_{\mathrm{b}}}\right)$$

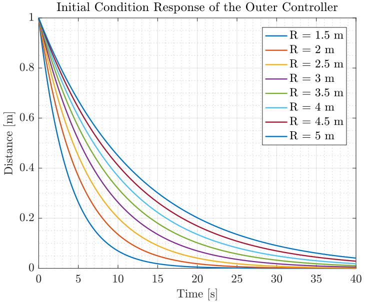
$$\psi_{\mathrm{ref}} = \chi - \beta$$

- Change active waypoints

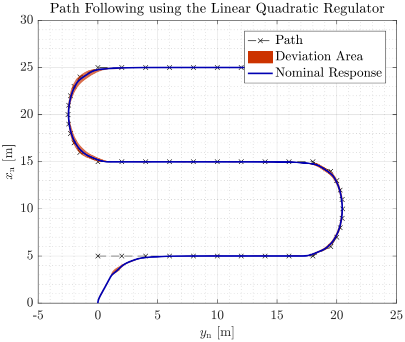


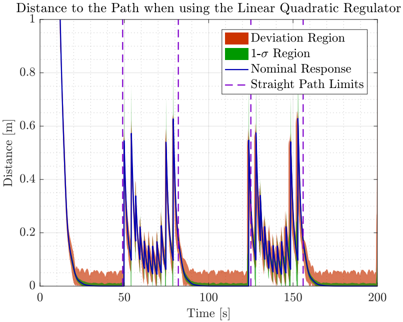
- Convergence to the path



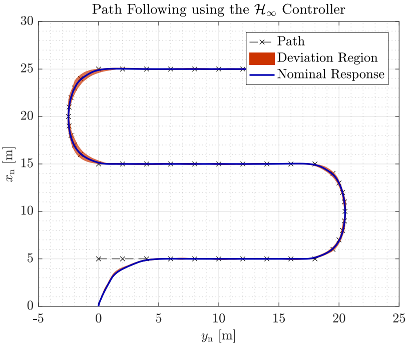


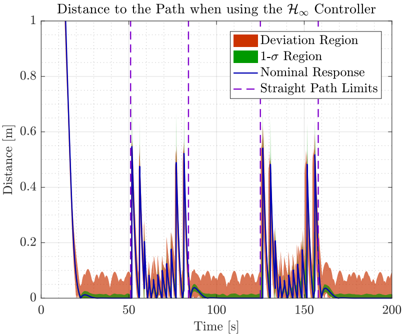
- LQR as inner controller



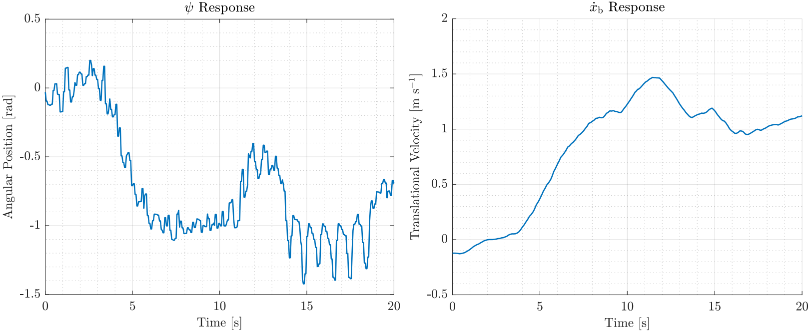


- Robust controller as inner controller





- Inner controller test



Conclusion

- The estimator has been tuned and tested through simulation.
- The controller has also been analyzed though 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