Precision Control of an Autonomous Surface Vessel

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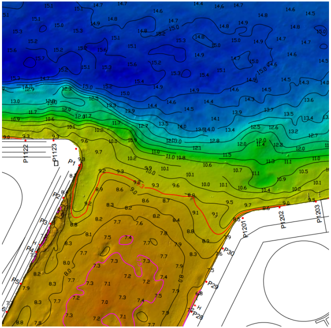
Agenda

Introduction

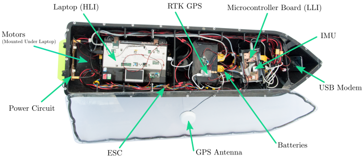
- What is an Autonomous Surface Vessel (ASV)
- Bathymetric Measurements
- Control of an ASV

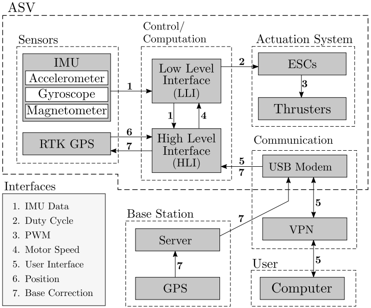
Introduction
Use Case



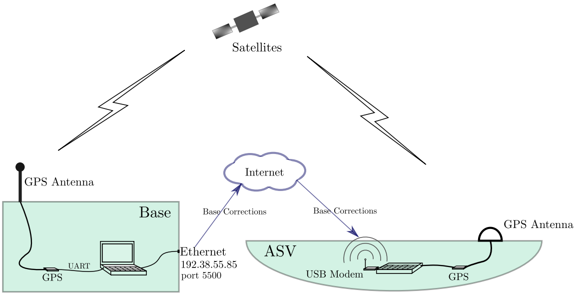
- Depth map used by Port of Aalborg
- Problem: No recent knowledge of depths of the port
- Solution: Automate smaller unmanned vessel

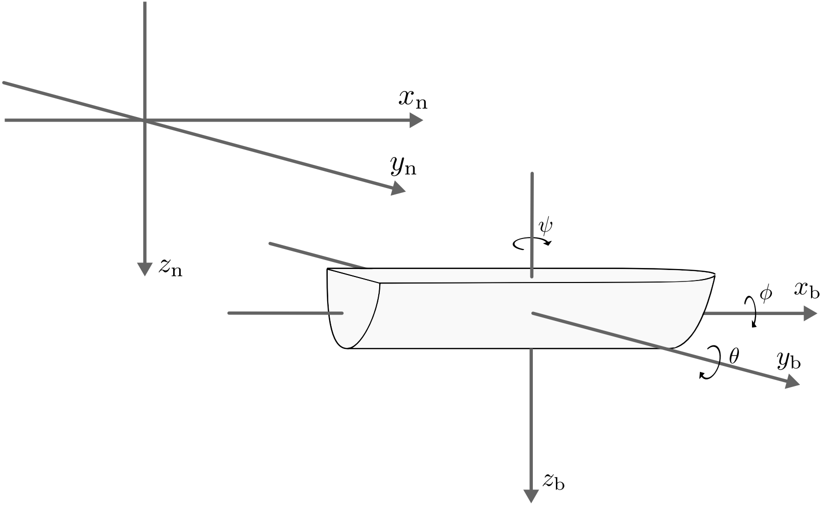
System Description





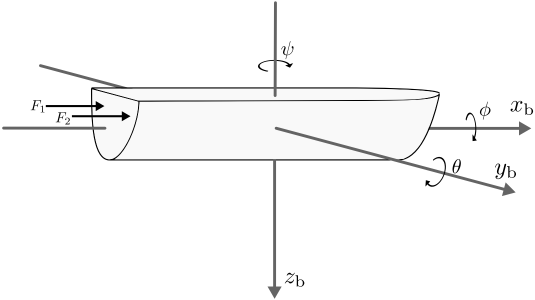
System Description
RTK GPS

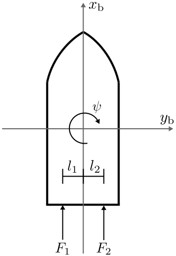




x_n
y_n
z_n
ψ
ϕ
x_b
θ
y_b
z_b

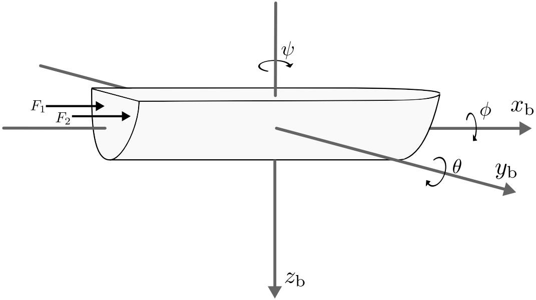
Model
Model Dynamics

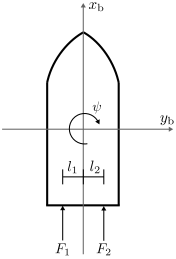




- Rigid Body Dynamics
- Hydrostatics
- Hydrodynamics

Model
Rigid Body Dynamics

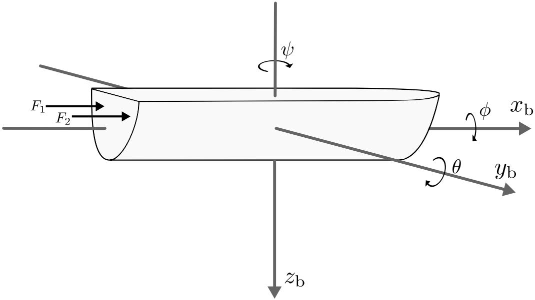


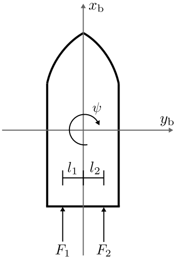


$$\sum F = m\ddot{x}$$

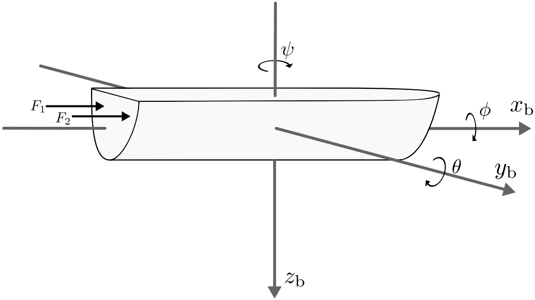
$$\sum \tau = I\ddot{\theta}$$

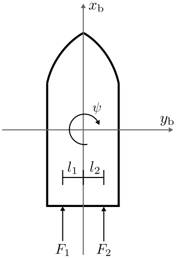
Model
Hydrostatics



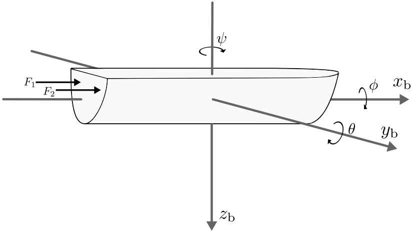


- Buoyancy Force

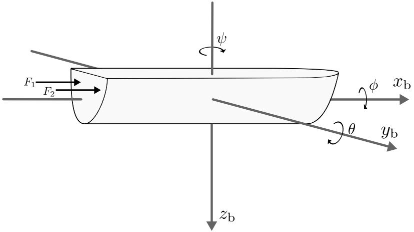




- Added mass
- Viscous Damping

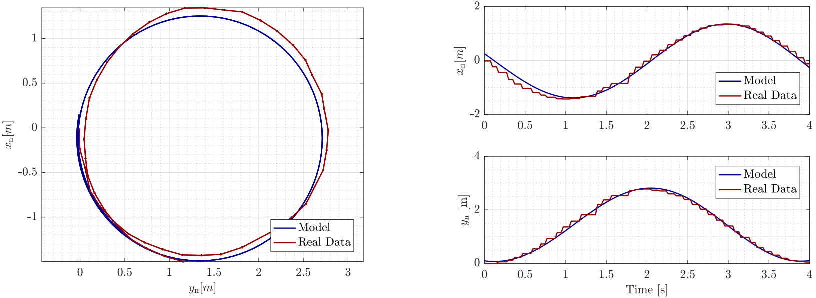


$$
\begin{aligned}
m\ddot{x}_{\mathrm{b}} &= F_1 + F_2 - d_{\dot{x}_{\mathrm{b}}}\dot{x}_{\mathrm{b}} + F_{x_{\mathrm{b}}} \\
m\ddot{y}_{\mathrm{b}} &= -d_{\dot{y}_{\mathrm{b}}}\dot{y}_{\mathrm{b}} + F_{y_{\mathrm{b}}} \\
m\ddot{z}_{\mathrm{b}} &= -d_{\dot{z}_{\mathrm{b}}}\dot{z}_{\mathrm{b}} + F_{z_{\mathrm{b}}}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



$$
\begin{aligned}
m\ddot{x}_\mathrm{b} &= F_1 + F_2 - d_{\dot{x}_\mathrm{b}}\dot{x}_\mathrm{b} \\
m\ddot{y}_\mathrm{b} &= -d_{\dot{y}_\mathrm{b}}\dot{y}_\mathrm{b} \\
m\ddot{z}_\mathrm{b} &= -d_{\dot{z}_\mathrm{b}}\dot{z}_\mathrm{b} - \rho g A_\mathrm{wp}\tilde{z}_\mathrm{n} \\
I_\mathrm{x}\ddot{\phi} &= -d_{\dot{\phi}}\dot{\phi} - \rho g V\overline{GM_T}\cdot\phi \\
I_\mathrm{y}\ddot{\theta} &= -d_{\dot{\theta}}\dot{\theta} - \rho g V\overline{GM_L}\cdot\theta \\
I_\mathrm{z}\ddot{\psi} &= F_1 l_1 - F_2 l_2 - d_{\dot{\psi}}\dot{\psi}
\end{aligned}
$$

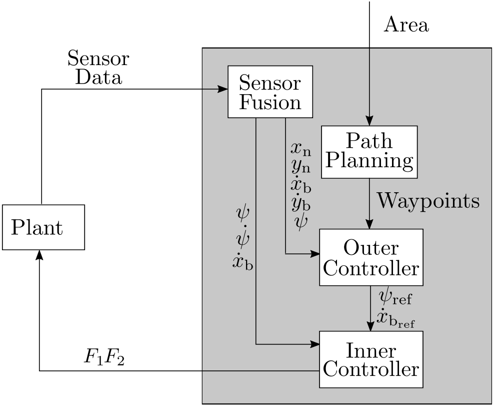
- Verified Nonlinear Model



Agenda

- Introduction
- System Description
- Model
- **Control Approach**
- **Sensor Fusion**
  - **Attitude Kalman Filter**
  - **Position Kalman Filter**
- Inner Controller
- Outer Controller
- Results
- Conclusion

Control Approach



Sensor Fusion
Structure

- Fuses GPS and IMU data
- Achieved using a Kalman Filter
- Sensor Fusion Contains
  - Attitude
  - Position

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

- w(k) and v(k) are assumed white Gaussian.
- Covariance matrices Q and R holds the respective variances.

States are extended to:

- Attitude:

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

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

- Position:

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

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

- Step 0: Initialization

$$\hat{\mathbf{x}}_{\mathrm{att}}(0|0) = \mathbf{0}_{6\mathrm{x}1} \;, \tag{1}$$
$$\mathbf{P}_{\mathrm{att}}(0|0) = \mathbf{Q}_{\mathrm{att}} \;. \tag{2}$$

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

- Step 0: Initialization
- Step 1: Prediction:

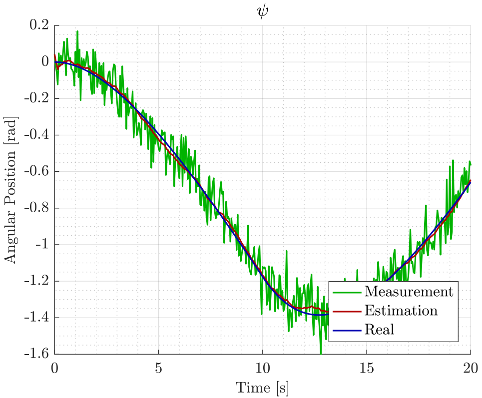
$$\hat{\mathbf{x}}(k+1|k) = \mathbf{A}\hat{\mathbf{x}}(k|k) + \mathbf{B}\mathbf{u}(k)$$
$$\mathbf{P}(k+1|k) = \mathbf{A}\mathbf{P}(k|k)\mathbf{A}^{\mathrm{T}} + \mathbf{Q}$$

- Step 2: Update:

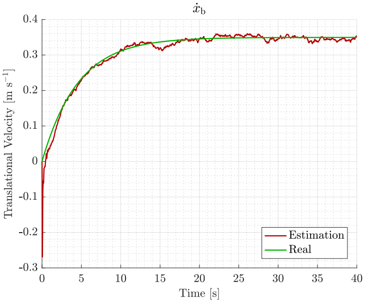
$$\hat{\mathbf{x}}(k+1|k+1) = \hat{\mathbf{x}}(k+1|k) + \mathbf{K}(k+1)\left[\mathbf{y}(k+1) - \mathbf{C}\hat{\mathbf{x}}(k+1|k)\right]$$
$$\mathbf{P}(k+1|k+1) = \left[\mathbf{I} - \mathbf{K}(k+1)\mathbf{C}^{\mathrm{T}}\right]\mathbf{P}(k+1|k)$$
$$\mathbf{K}(k+1) = \mathbf{P}(k+1|k)\mathbf{C}^{\mathrm{T}}\left[\mathbf{C}\mathbf{P}(k+1|k)\mathbf{C}^{\mathrm{T}}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

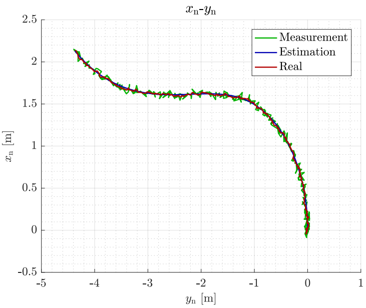
Sensor Fusion

Attitude Kalman Filter



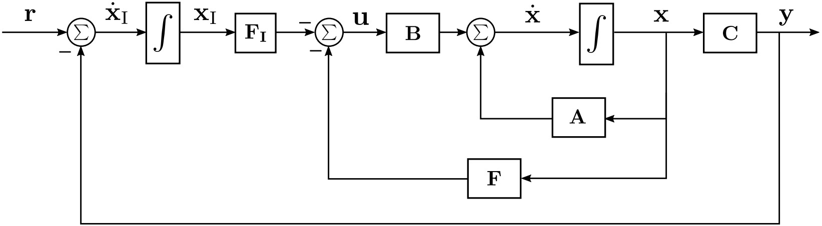
Sensor Fusion
Position Kalman Filter



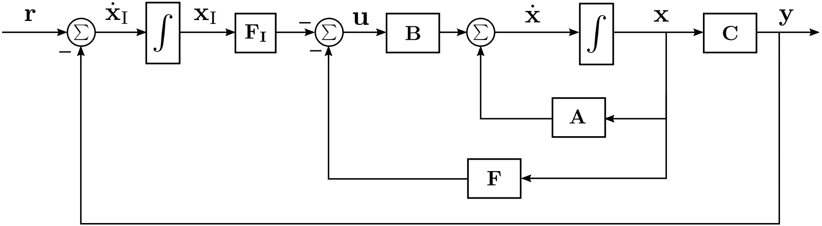


Agenda

Inner Controller



Inner Controller

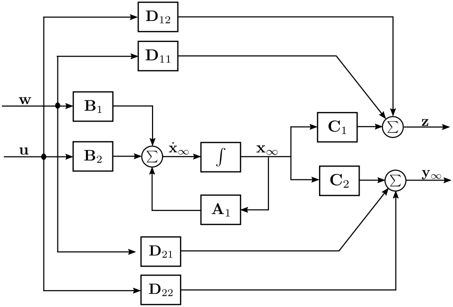


- Linear Quadratic Regulator
- $\mathcal{H}_\infty$ Controller

- Suboptimal $\mathcal{H}_\infty$ controller

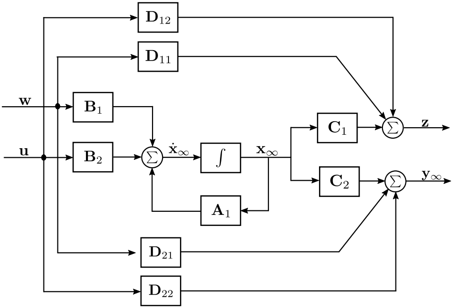
Find an internally stabilizing controller that provides a closed loop $\mathcal{H}_\infty$ norm less than some bound γ

- System structure



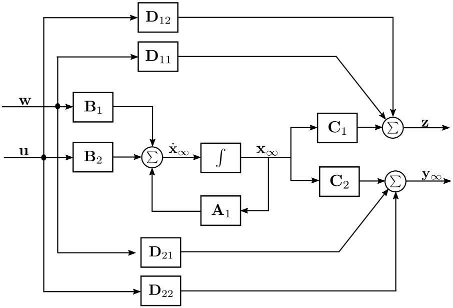
$$
\begin{aligned}
\dot{\mathbf{x}}_\infty(t) &= \mathbf{A}_1\mathbf{x}_\infty(t) + \mathbf{B}_1\mathbf{w}(t) + \mathbf{B}_2\mathbf{u}(t) \\
\mathbf{z}(t) &= \mathbf{C}_1\mathbf{x}_\infty(t) + \mathbf{D}_{11}\mathbf{w}(t) + \mathbf{D}_{12}\mathbf{u}(t) \\
\mathbf{y}_\infty(t) &= \mathbf{C}_2\mathbf{x}_\infty(t)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

- System structure



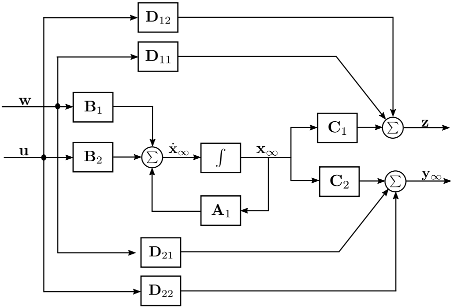
$$\mathbf{u}(t) = \begin{bmatrix} F_1 & F_2 \end{bmatrix}^{\mathrm{T}}$$

- System structure



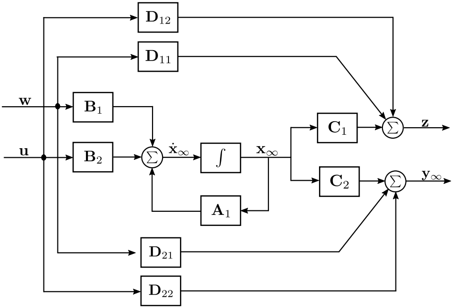
$$\mathbf{w}(t) = \begin{bmatrix} \psi_{\mathrm{ref}} & \dot{x}_{\mathrm{b,ref}} & F_{\mathrm{wc}} & \tau_{\mathrm{wc}} & F_{\mathrm{wave}} & \tau_{\mathrm{wave}} & n_\psi & n_{\dot{x}_{\mathrm{b}}} \end{bmatrix}^{\mathrm{T}}$$

- System structure



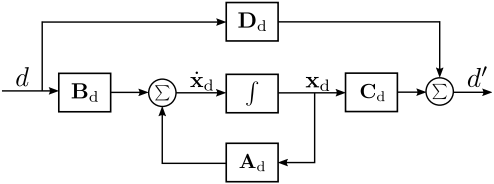
$$\mathbf{y}_\infty(t) = \begin{bmatrix} \psi & \dot{x}_\mathrm{b} & \mathbf{x}_\mathrm{I}^\mathrm{T} \end{bmatrix}^\mathrm{T}$$

- System structure



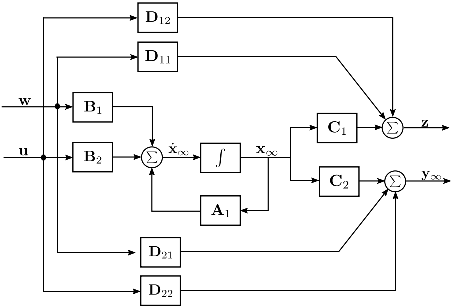
$$\mathbf{x}_\infty(t) = \begin{bmatrix} \psi & \dot{\psi} & \dot{x}_\mathrm{b} & x_{int_\psi} & x_{int_{\dot{x}_\mathrm{b}}} & x_{F_\mathrm{wc}} & x_{\tau_\mathrm{wc}} & x_{F_\mathrm{wave}} & x_{\tau_\mathrm{wave}} & x_{n_\psi} & x_{n_{\dot{x}_\mathrm{b}}} \end{bmatrix}^\mathrm{T}$$

- Disturbance model



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

- System structure



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

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

$$\mathbf{C}_1 = \begin{bmatrix} \mathbf{W}_\mathrm{x} & \mathbf{0}_{3x2} & \mathbf{0}_{3x2} & \mathbf{0}_{3x2} & \mathbf{0}_{3x2} \\ \mathbf{0}_{2x3} & \mathbf{W}_\mathrm{I} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} \\ \mathbf{0}_{2x3} & \mathbf{0}_{2x2} & \mathbf{W}_\mathrm{wc} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} \\ \mathbf{0}_{2x3} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} & \mathbf{W}_\mathrm{wave} & \mathbf{0}_{2x2} \\ \mathbf{0}_{2x3} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} & \mathbf{W}_\mathrm{noise} \\ \mathbf{0}_{2x3} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} \\ \mathbf{0}_{2x3} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} & \mathbf{0}_{2x2} \end{bmatrix} \qquad \mathbf{D}_{12} = \begin{bmatrix} \mathbf{0}_{2x3} \\ \mathbf{0}_{2x2} \\ \mathbf{0}_{2x2} \\ \mathbf{0}_{2x2} \\ \mathbf{0}_{2x2} \\ \mathbf{W}_\mathrm{u} \end{bmatrix}$$

- 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

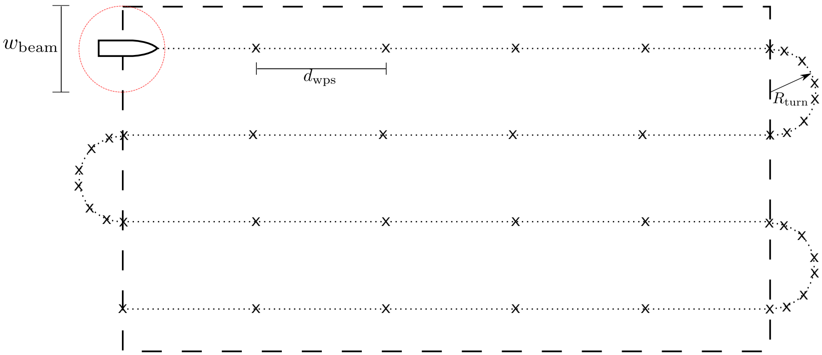
Inner Controller

Linear Quadratic Controller Design

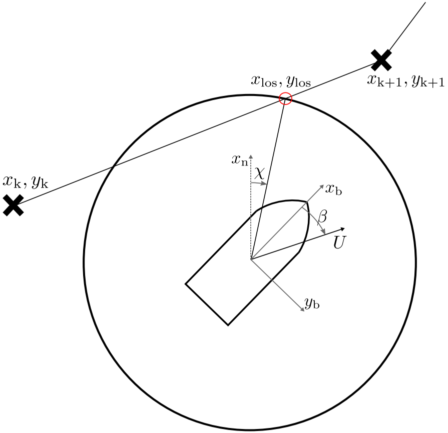
Inner Controller
Comparison of the Controllers

Agenda

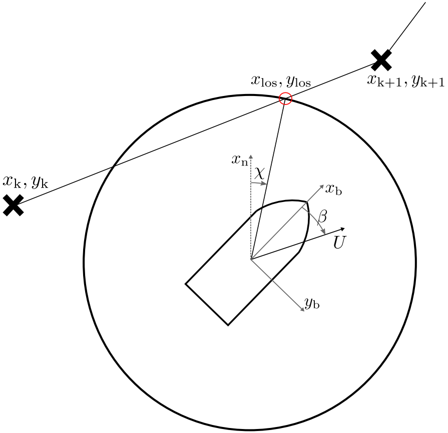
Outer Controller
Path Generation Algorithm



Outer Controller
Path Following Algorithm



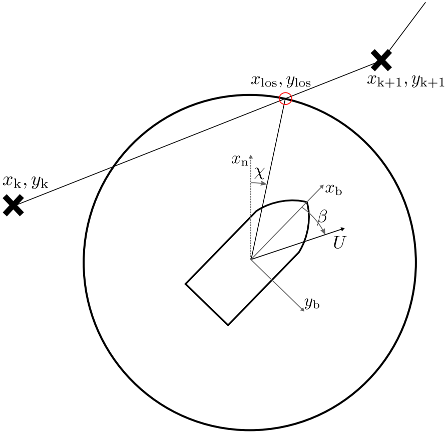
Outer Controller
Path Following Algorithm



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

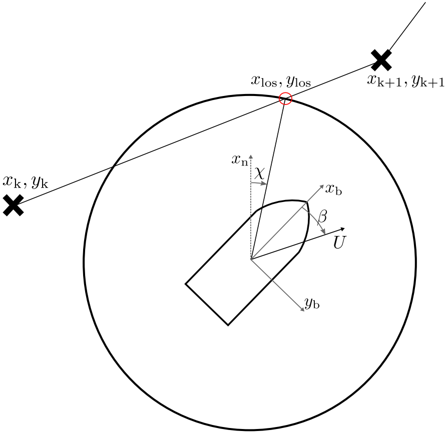
Outer Controller

Path Following Algorithm



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

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

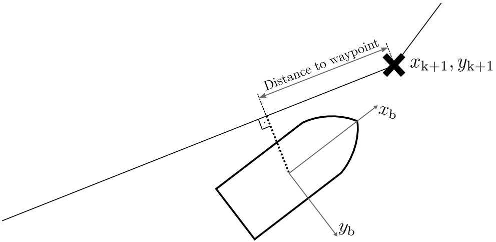


$$\chi = \arctan\left(\frac{y_{\mathrm{LOS}} - y_{\mathrm{n}}}{x_{\mathrm{LOS}} - x_{\mathrm{n}}}\right)$$

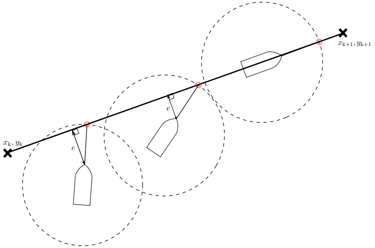
$$\beta = \arctan\left(\frac{\dot{y}_{\mathrm{b}}}{\dot{x}_{\mathrm{b}}}\right)$$

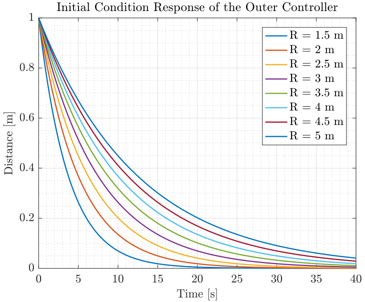
$$\psi_{\mathrm{ref}} = \chi - \beta$$

- Change active waypoints

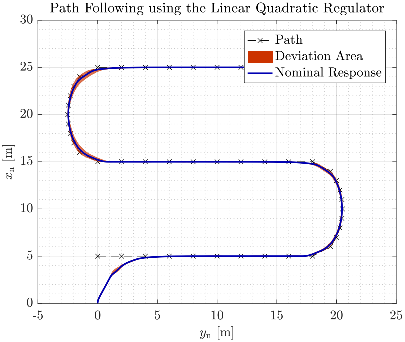


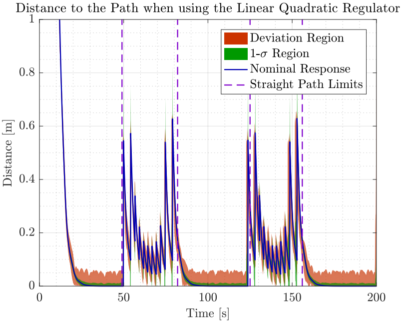
- Convergence to the path



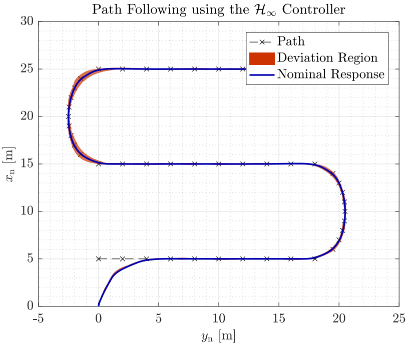


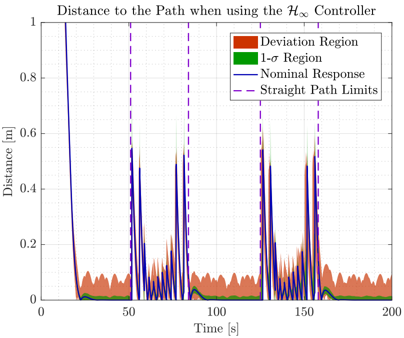
- LQR as inner controller





- Robust controller as inner controller

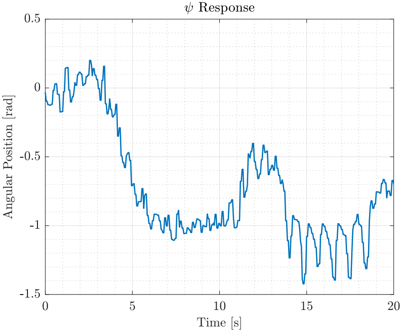


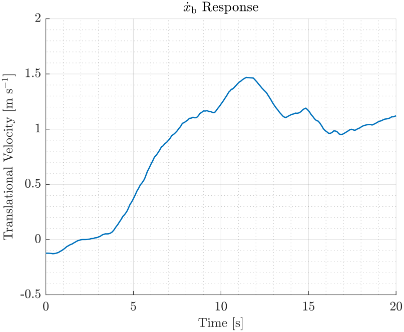


Results

Implementation Results

- 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.

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