Precision Control of an Autonomous Surface Vessel

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Agenda

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

Introduction

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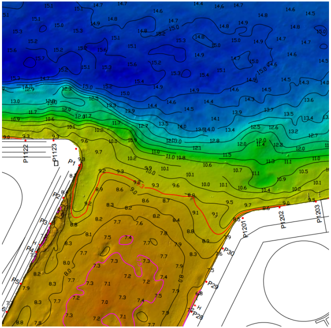
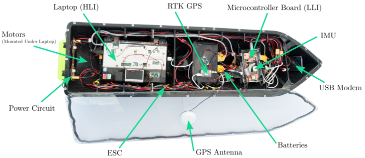
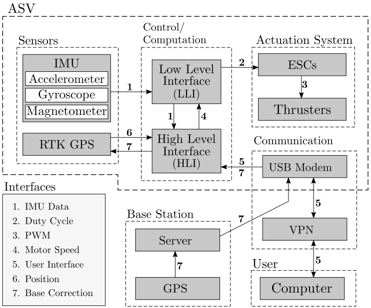
Introduction
Use Case

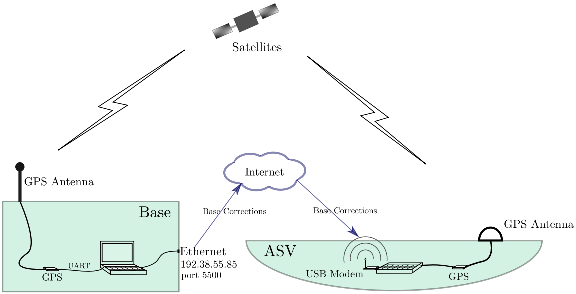


System Description

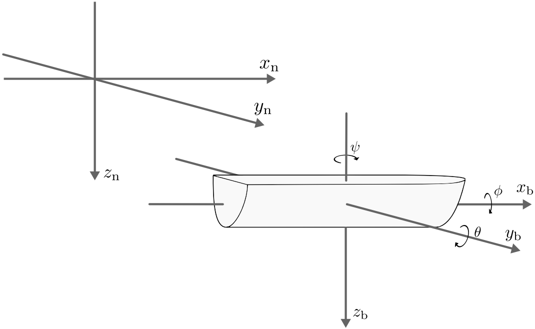


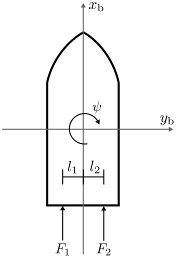


System Description
RTK GPS



Model
Reference Frames



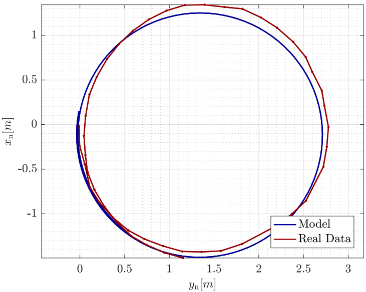


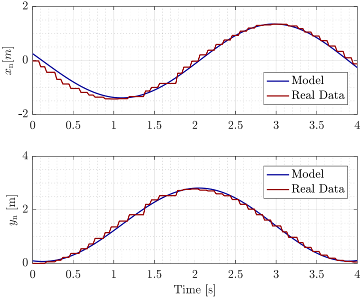
Model
Model Equations

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

Model

Model Verification





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- **Control Approach**
- **Sensor Fusion**
  - **Attitude Kalman Filter**
  - **Position Kalman Filter**
- Inner Controller
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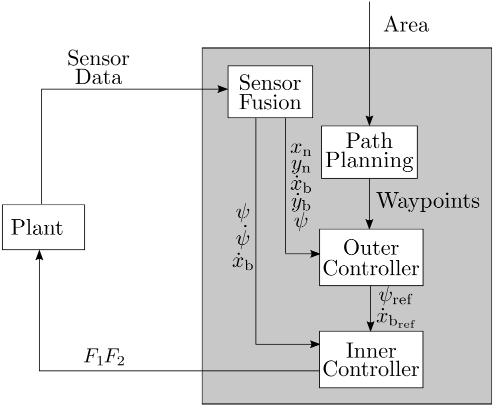
Control Approach



Sensor Fusion
Kalman Filter Structure

Sensor Fusion

Attitude Kalman Filter

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

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

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

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

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

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

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

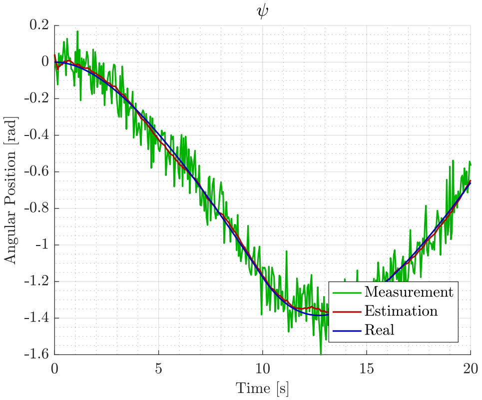
$$
\mathbf{C} = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

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

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

Sensor Fusion

Attitude Kalman Filter



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

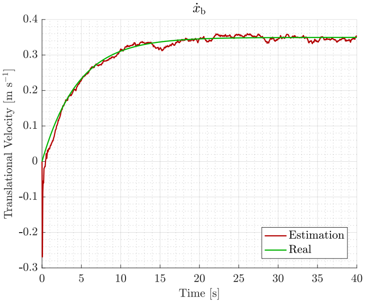
$$
\begin{aligned}
\mathbf{Q}_{\mathrm{pos}} &= \mathrm{diag}\left(\sigma^2_{x_n}, \sigma^2_{y_n}, \sigma^2_{\dot{x}_b}, \sigma^2_{\dot{y}_b}, \sigma^2_{\ddot{x}_b}, \sigma^2_{\ddot{y}_b}\right) \\
\mathbf{R}_{\mathrm{pos}} &= \mathrm{diag}\left(\sigma^2_{x_{n,\mathrm{GPS}}}, \sigma^2_{y_{n,\mathrm{GPS}}},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

$$
\hat{\mathbf{x}}_{\mathrm{pos}} = \begin{bmatrix} x_n & y_n & \dot{x}_b & \dot{y}_b & \ddot{x}_b & \ddot{y}_b \end{bmatrix}^{\mathrm{T}}
$$

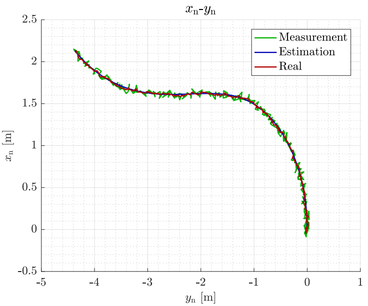
$$
\mathbf{y}_{\mathrm{pos}} = \begin{bmatrix} x_{n,\mathrm{GPS}} & y_{n,\mathrm{GPS}} & \ddot{x}_{b,\mathrm{acc}} & \ddot{y}_{b,\mathrm{acc}} \end{bmatrix}^{\mathrm{T}}
$$

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

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



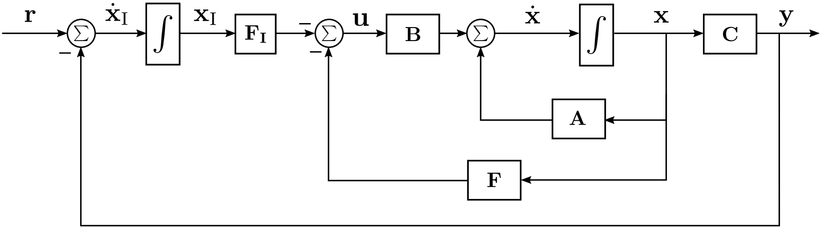
$\dot{x}_b$
Translational Velocity [m s^{-1}]
Time [s]
Estimation
Real



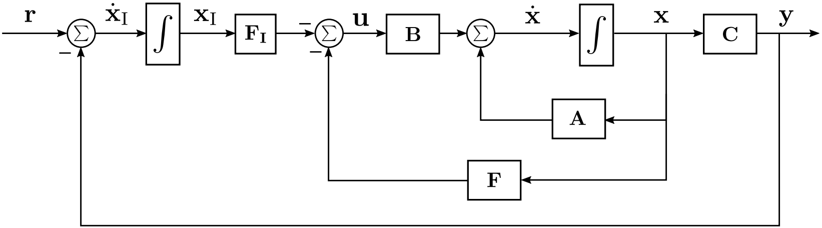
x_n-y_n
x_n [m]
y_n [m]
Measurement
Estimation
Real

Agenda

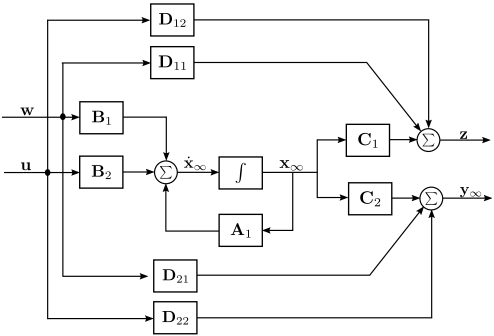
Inner Controller



Inner Controller



- Linear Quadratic Regulator
- Robust Controller



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

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  - Robust Controller Design
  - **Linear Quadratic Regulator Design**
  - **Controllers Comparison**
- Outer Controller
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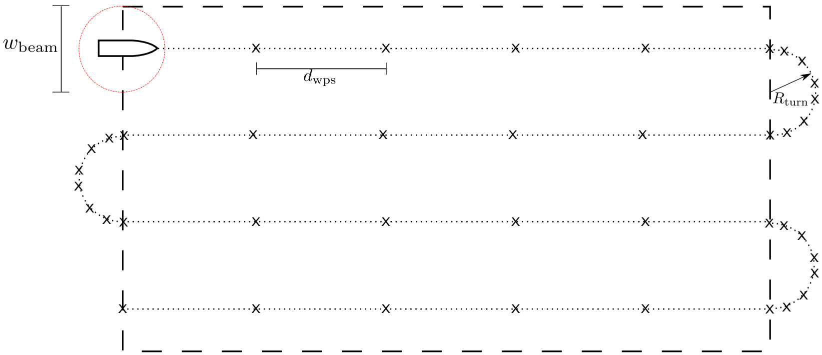
Inner Controller
Linear Quadratic Controller Design

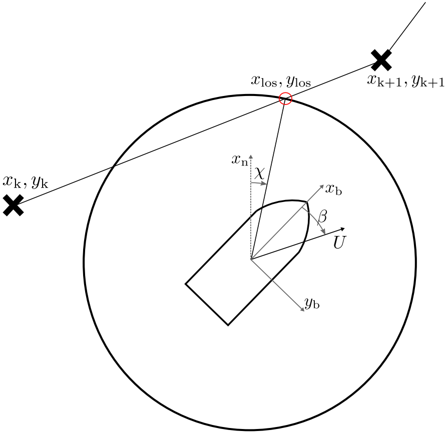
Inner Controller
Comparison of the Controllers

Agenda

Outer Controller

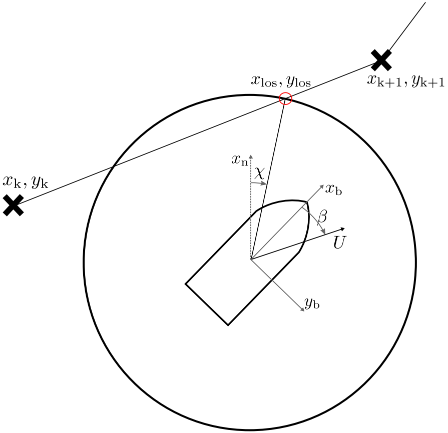
Outer Controller
Path Generation Algorithm





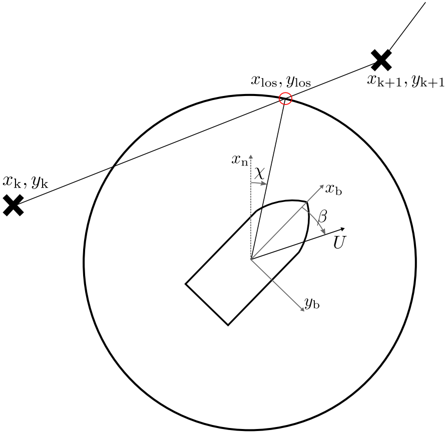
$x_{\mathrm{los}}, y_{\mathrm{los}}$
$x_{\mathrm{k+1}}, y_{\mathrm{k+1}}$
$x_{\mathrm{k}}, y_{\mathrm{k}}$
x_{n}
χ
x_{b}
β
U
y_{b}

Outer Controller
Path Following Algorithm



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

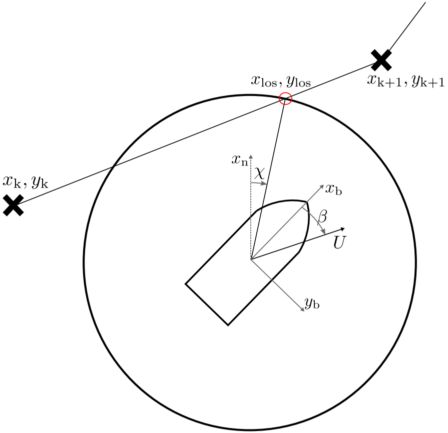
Outer Controller
Path Following Algorithm



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

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

Outer Controller
Path Following Algorithm

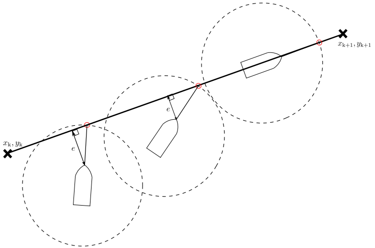


$$\chi = \text{arctan}\left(\frac{y_{\mathrm{LOS}} - y_{\mathrm{n}}}{x_{\mathrm{LOS}} - x_{\mathrm{n}}}\right)$$

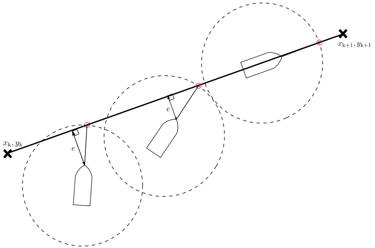
$$\beta = \text{arctan}\left(\frac{\dot{y}_{\mathrm{b}}}{\dot{x}_{\mathrm{b}}}\right)$$

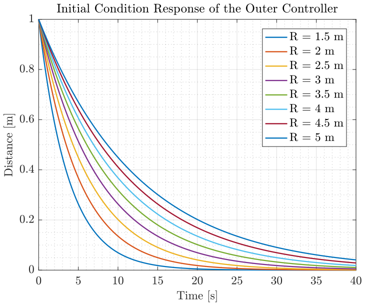
$$\psi_{\mathrm{ref}} = \chi - \beta$$

Outer Controller
Path Following Algorithm

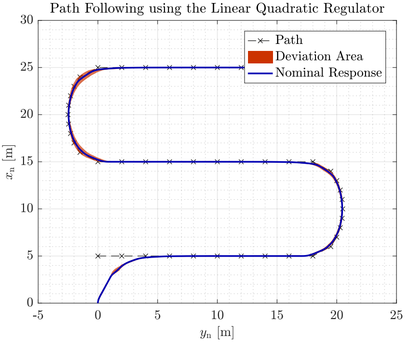


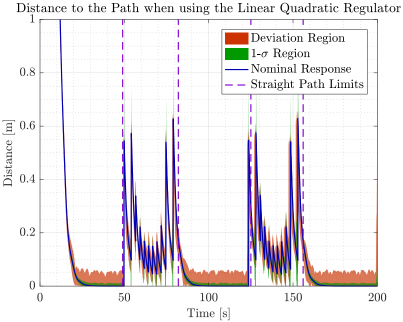
Outer Controller
Path Following Algorithm



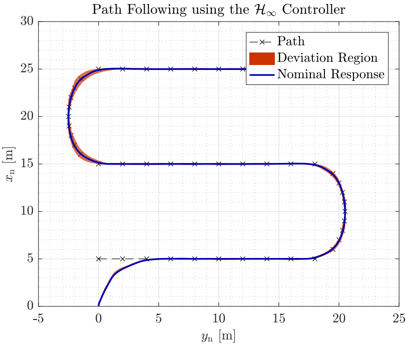


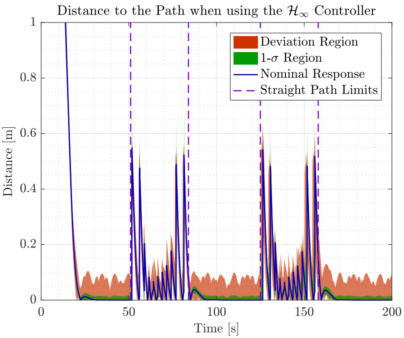
- LQR as inner controller



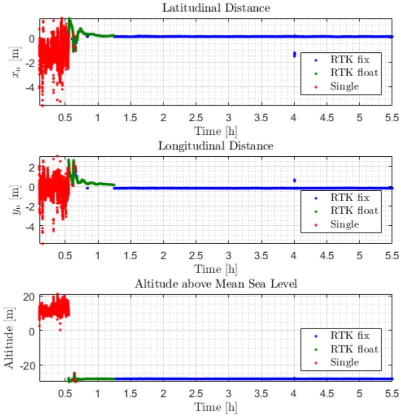


- Robust controller as inner controller

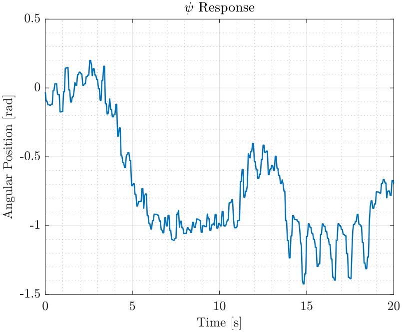


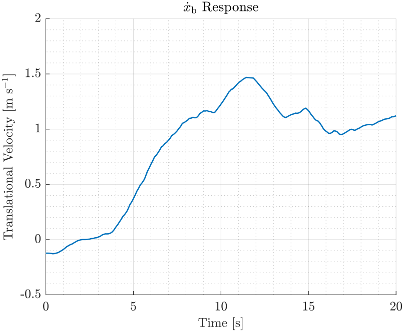


- RTK GPS test


Latitudinal Distance
x_n [m]
Time [h]
RTK fix
RTK float
Single
Longitudinal Distance
y_n [m]
Time [h]
RTK fix
RTK float
Single
Altitude above Mean Sea Level
Altitude [m]
Time [h]
RTK fix
RTK float
Single

- Inner controller test





Conclusion

- The estimator has been tuned and tested through simulation to check its performance.
- The outer controller performance when using both inner controllers 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, they show a promising behavior of the control system.

Precision Control of an Autonomous Surface Vessel

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