An Underwater Docking System for Sustained Presence at Sea

2nd Cycle Integrated Project in Electrical and Computer Engineering
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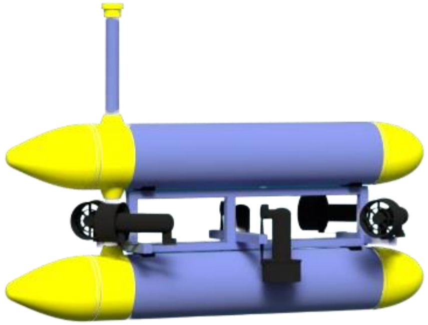
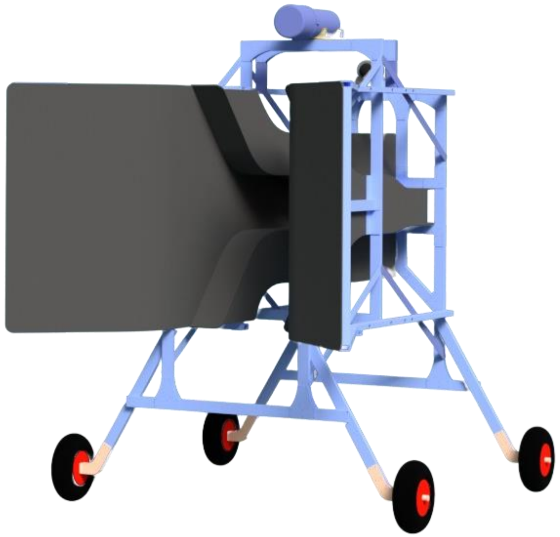




Motivation

- Oceans are **vital** due to **environmental** and **economic** factors
- **80%** of the oceans remain **unexplored**

- **Growing popularity** of Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs)
- **Unable to operate** for long periods at a time.

Solution: Docking Stations

Allow for **battery recharging** and **communication** with **base station**

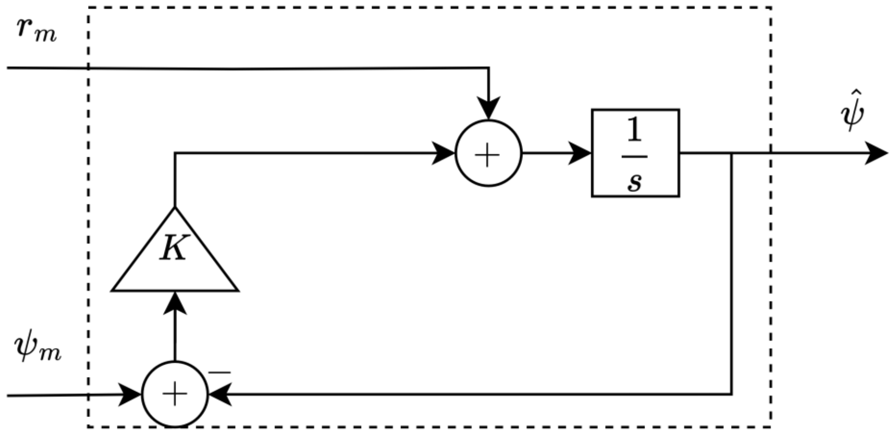
Development of an Autonomous Underwater Docking System

Navigation Contributions

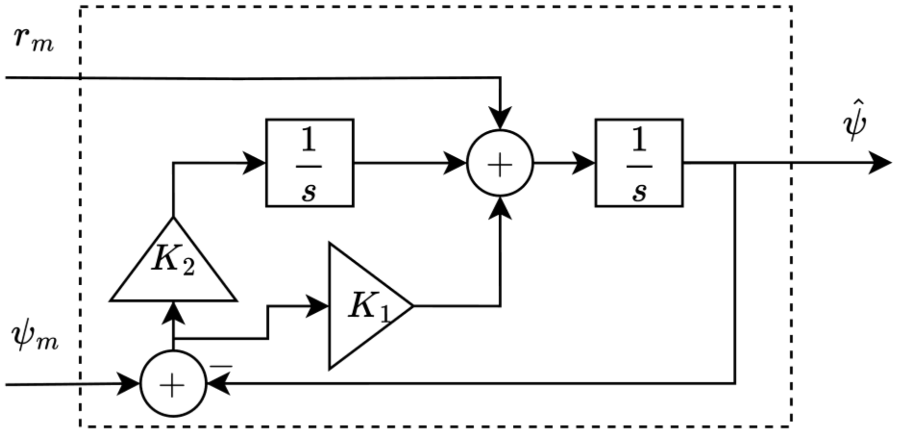
- Complementary Filter

	High Frequency	Low Frequency
Compass	✗	✓
Gyro	✓	✗

Low + High Pass Filter



Complementary filter block diagram.



Complementary filter with bias rejection block diagram.

Navigation Contributions

• Kalman Filter

- Linear State Model:

$$\begin{cases} \boldsymbol{x}(k+1) = A_k \boldsymbol{x}(k) + B_k \boldsymbol{u}(k) + G_k \boldsymbol{w}(k) \\ \boldsymbol{y}(k) = C_k \boldsymbol{x}(k) + \boldsymbol{v}(k) \end{cases}$$

- Gaussian White Noise:

Process noise Covariance

$$E\left(\begin{bmatrix} w_k \\ v_k \end{bmatrix} \begin{bmatrix} w_k^T & v_k^T \end{bmatrix} \right) = \begin{bmatrix} Q_k & 0 \\ 0 & R_k \end{bmatrix}$$

Measurement noise Covariance

- Initial state is a gaussian random vector

- Kalman Cycle:

$$p\left(x_k | Y_1^k, U_0^{k-1}\right) \xrightarrow[\uparrow u_k]{\textbf{Predict}} p\left(x_{k+1} | Y_1^k, U_0^k\right) \xrightarrow[\uparrow y_{k+1}]{\textbf{Update}} p\left(x_{k+1} | Y_1^{k+1}, U_0^k\right)$$

Navigation Contributions

- Extended Kalman Filter

$$F(k) = \nabla f\big|_{\hat{x}(k|k)} \qquad H(k) = \nabla h\big|_{\hat{x}(k+1|k)}$$

Kalman Filter **Extended Kalman Filter**

$$A_k \longrightarrow F(k)$$

$$C_k \longrightarrow H(k)$$

$\longrightarrow$

Not optimal estimate !

Not the real PDF !

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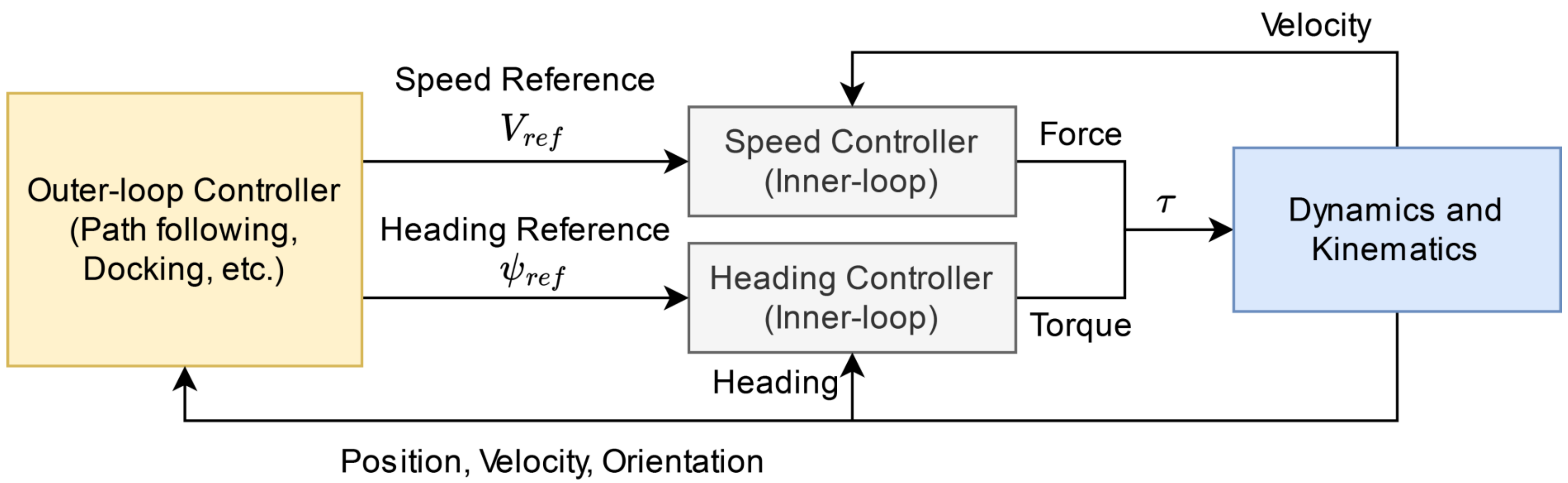
Motion Control

- Inner-outer-loop structure



Inner-outer-loop control structure block diagram.

Motion Control

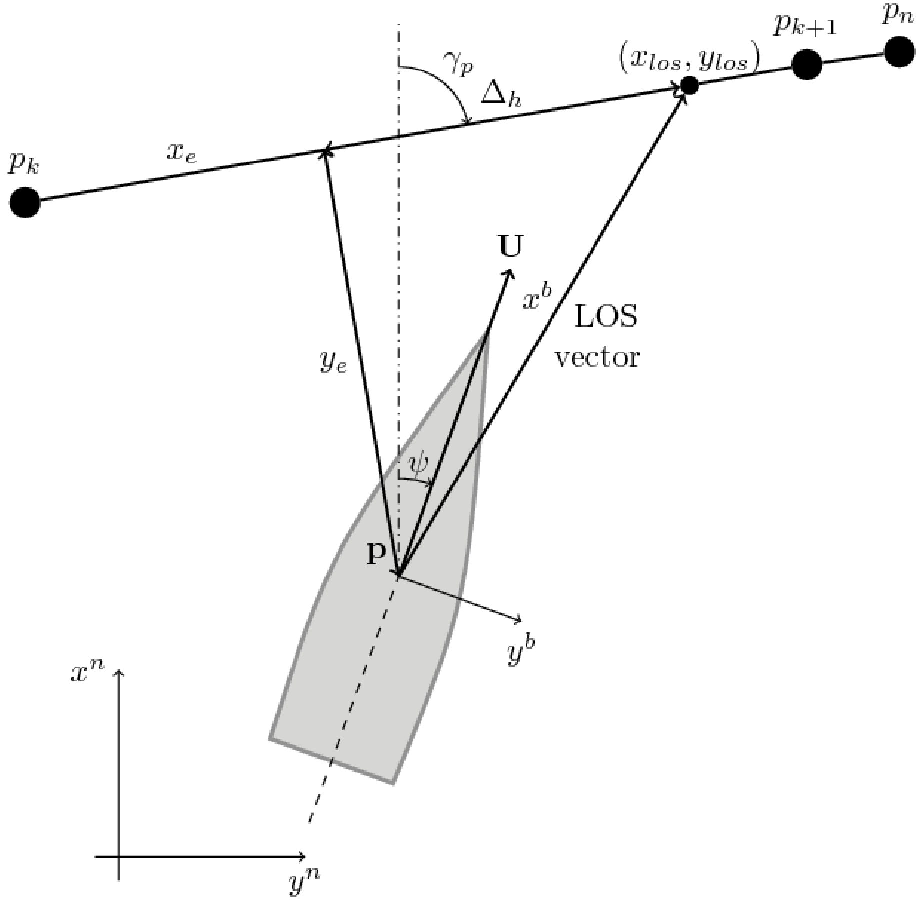
- **Line-of-Sight (LOS) Path Following (PF)**

Guidance Law:

$$\psi_d = arctan\left(-\frac{y_e}{\Delta h}\right)$$

✓ Simple, yield asymptotic convergence to path in the absence of disturbances (i.e. ocean currents)

✗ Steady-state error in the presence of currents.



LOS algorithm scheme, from A. Lekkas and T. Fossen “Line-of-sight guidance for path following of marine Vehicles”

Motion Control

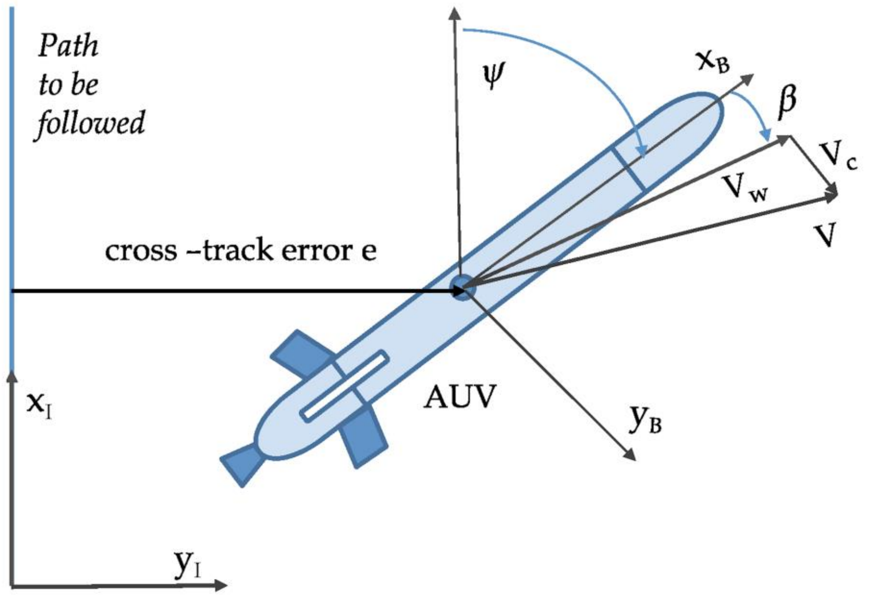
- **Simplified LOS (P. Maurya)**

Guidance Law:

$$\psi_d = sin^{-1}\left(\sigma\left(-\frac{1}{u}(K_1 e + K_2 \varsigma)\right)\right)$$

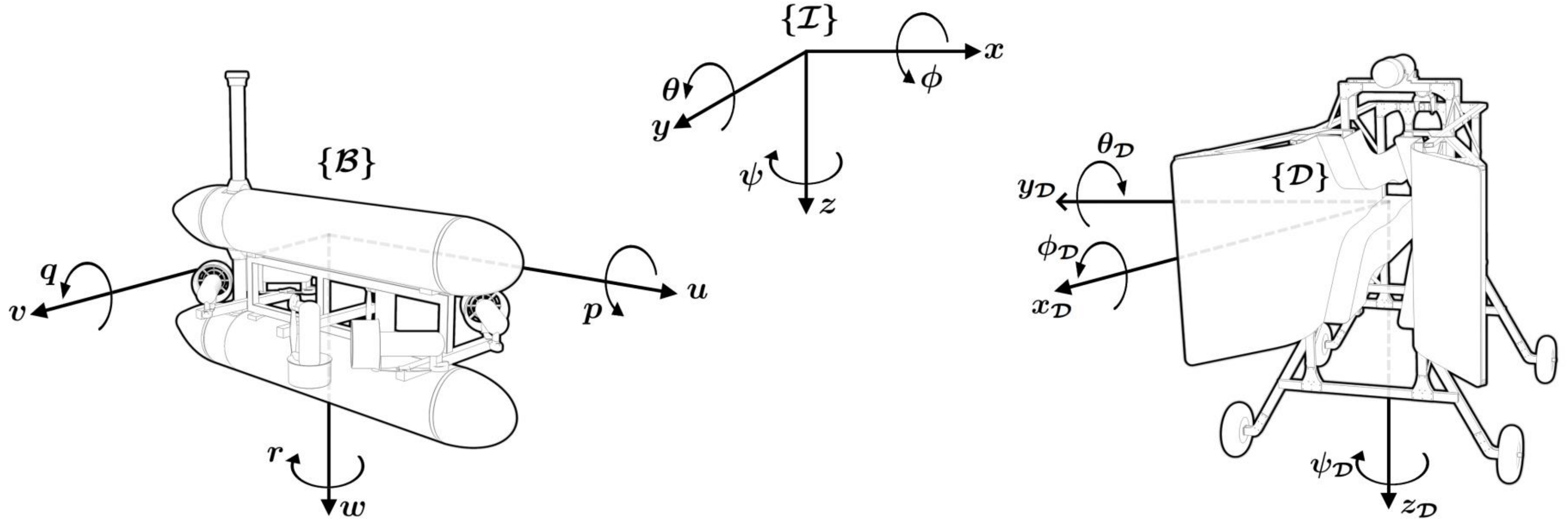
$$\dot{\varsigma} = y + K_a\left[-\frac{1}{u}(K_1 e + K_2 \varsigma) - \sigma\left(-\frac{1}{u}(K_1 e + K_2 \varsigma)\right)\right]$$

✔ Yields asymptotic convergence to path even in the presence of constant currents



Simplified LOS algorithm scheme, from P. Maurya, A. Aguiar and A. Pascoal "Marine vehicle path following using inner-outer loop control".

Reference Frames and General Notation



$$\boldsymbol{\eta}_1 = [x \; y \; z]^T \qquad \boldsymbol{\eta}_2 = [\phi \; \theta \; \psi]^T \qquad \boldsymbol{\nu}_1 = [u \; v \; w]^T \qquad \boldsymbol{\nu}_2 = [p \; q \; r]^T$$

Simplified Equations of Motion

Kinematics:

$$\begin{cases} \dot{x} = u\cos\psi - v\sin\psi \\ \dot{y} = u\sin\psi + v\cos\psi \\ \dot{\psi} = r \\ \dot{z} = w \end{cases}$$

Dynamics:

$$\begin{cases} m_u\dot{u} - m_v vr + d_u u = \tau_u \\ m_v\dot{v} + m_u ur + d_v v = \tau_v \\ m_r\dot{r} - m_{uv} uv + d_r r = \tau_r \\ m_w\dot{w} + d_w w + g_w = \tau_w \end{cases}$$

Assumptions:

- $\phi = 0, \quad \theta = 0$
- Decoupling horizontal and vertical motion
- Only actuated by forces along xyz-axes and torque around z-axis
- No environment disturbances

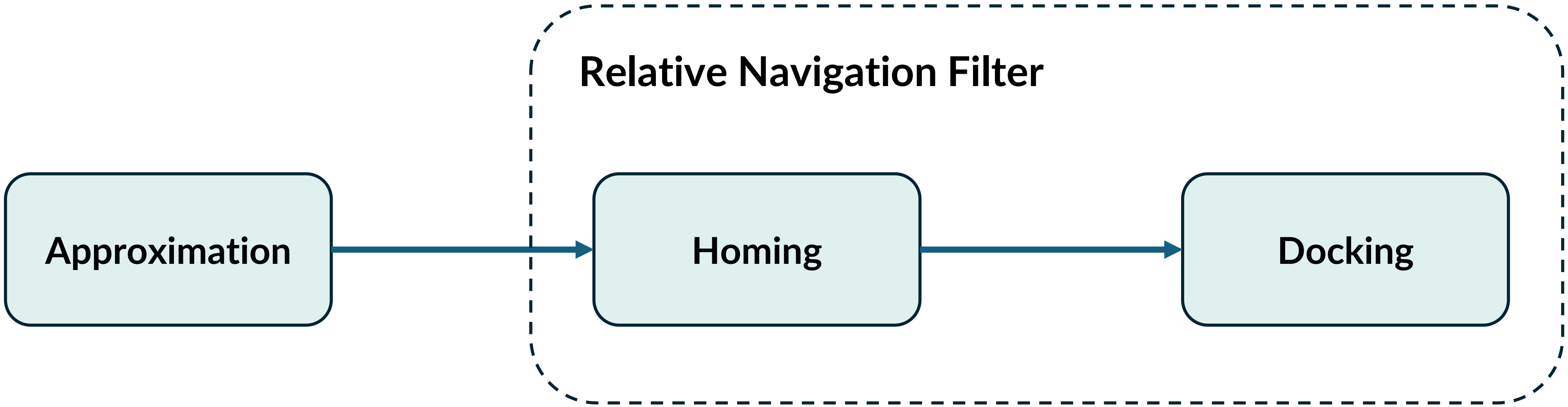
Sensor Suite

Doppler Velocity Logger (DVL)

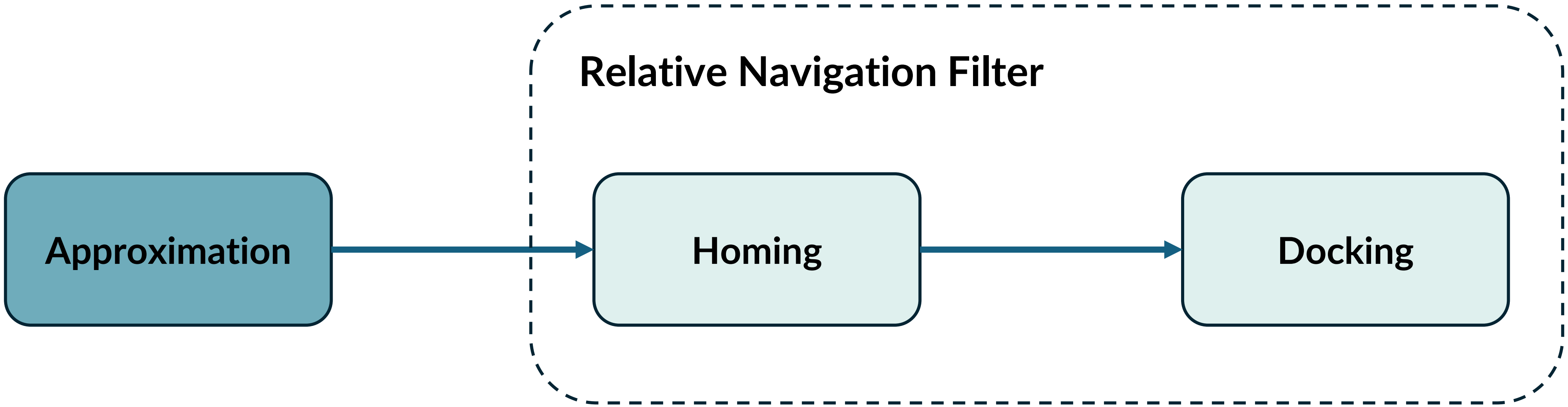
Ultrashort-Baseline (USBL)

Attitude and Heading Reference System (AHRS)

Task description



Task description

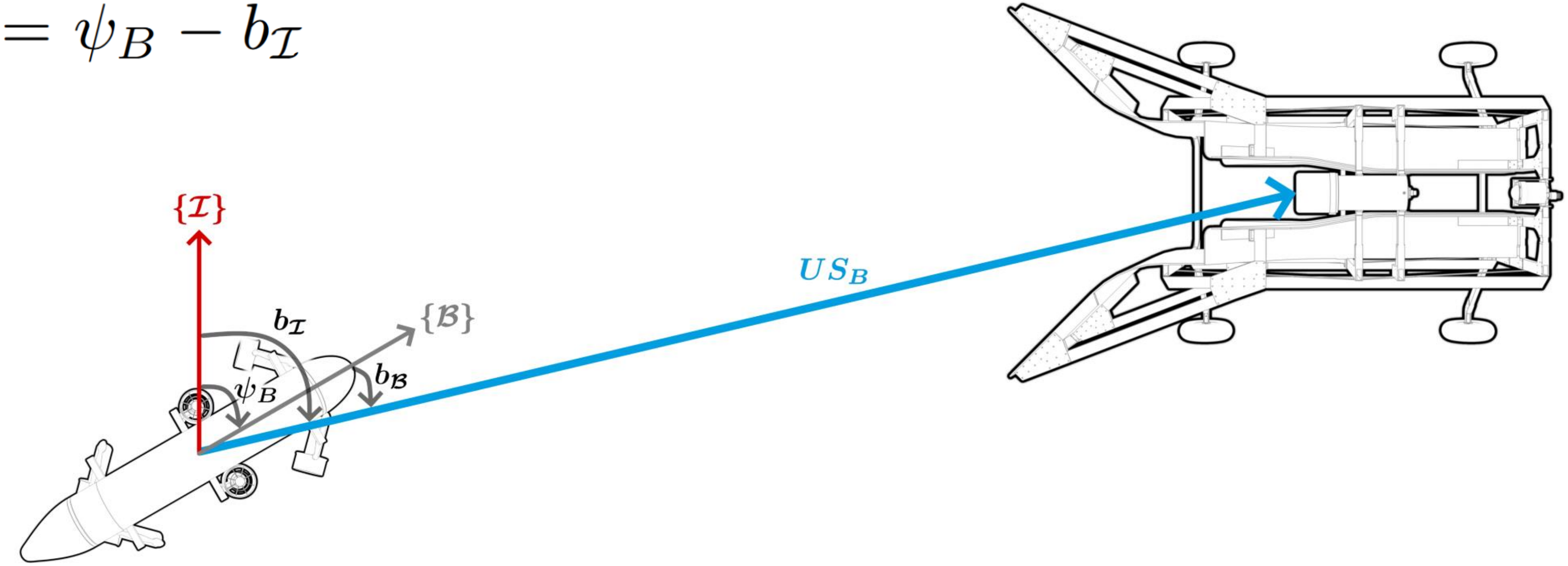


Approximation Stage

Control Law:

$$r = -K_b\delta$$

$$\delta = \psi_B - b_{\mathcal{I}}$$



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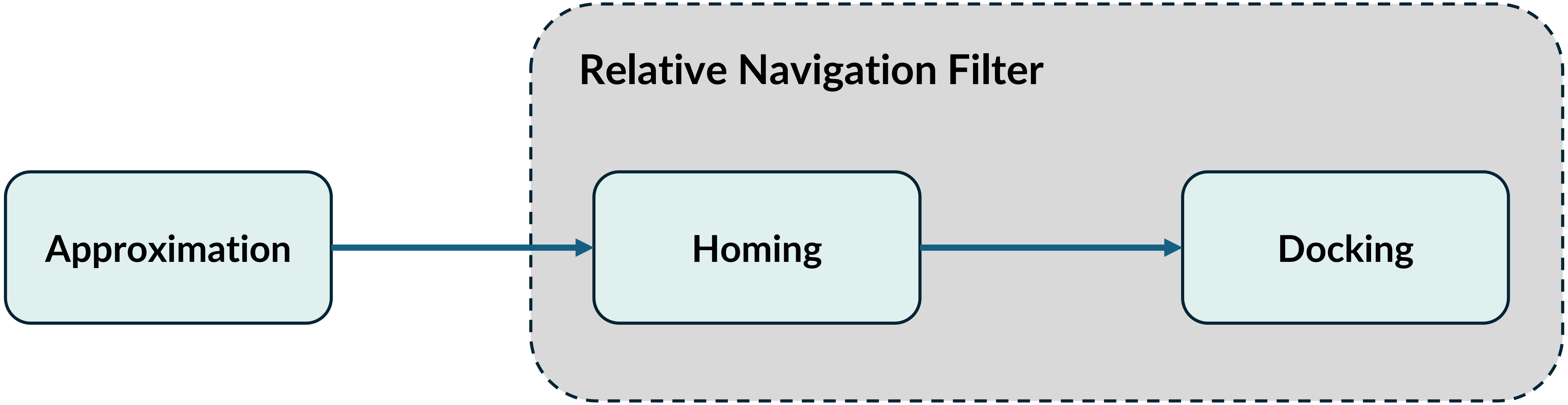


Relative Navigation Filter - Orientation

$${}^{\mathcal{B}}_{\mathcal{D}}R(\psi_{D\to B}) = \frac{1}{r^2}\begin{bmatrix} r_1 & -r_2 \\ r_2 & r_1 \end{bmatrix}$$

$$\boldsymbol{US_B} = {}^{\mathcal{B}}_{\mathcal{I}}R(\psi_B)\,{}^{\mathcal{I}}\boldsymbol{P_{D,B}}$$

$$\boldsymbol{US_D} = -{}^{\mathcal{D}}_{\mathcal{I}}R(\psi_D)\,{}^{\mathcal{I}}\boldsymbol{P_{D,B}}$$

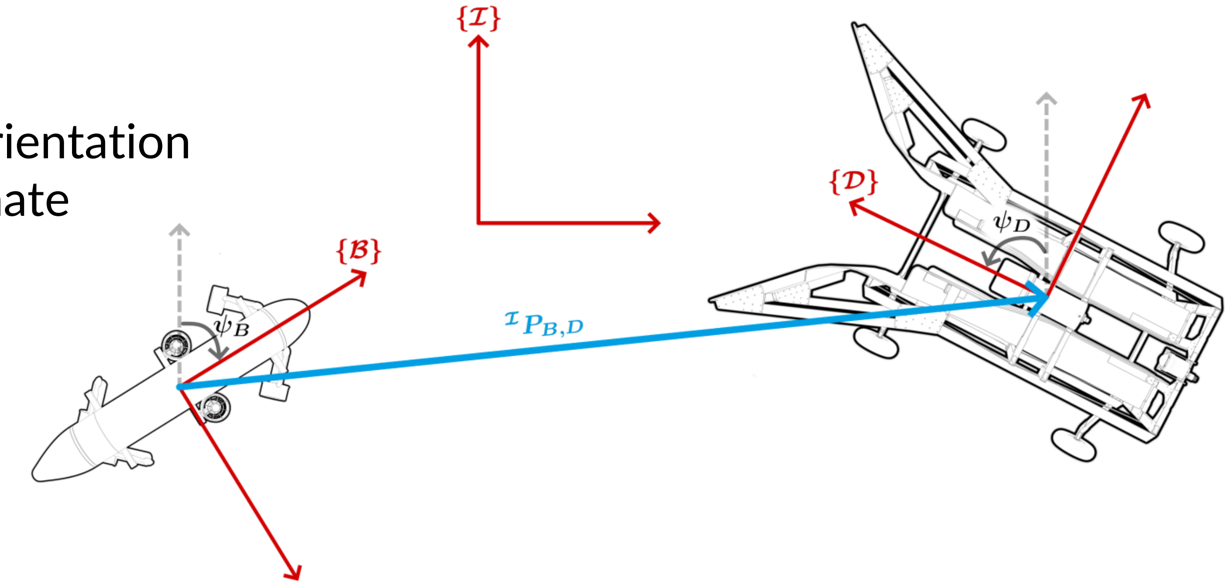
$$r = ||\boldsymbol{US_B}|| \qquad r_1 = -\langle \boldsymbol{US_D}, \boldsymbol{US_B} \rangle$$

$$r_2 = [0\;0\;1][\boldsymbol{US_D} \times \boldsymbol{US_B}]$$

$$\psi_{D\to B} = atan(r_2, r_1)$$

Observation → Complementary Kalman Filter → Relative Orientation Estimate

Yaw rate from AHRS → **Input** → Complementary Kalman Filter



Relative Navigation Filter - Position

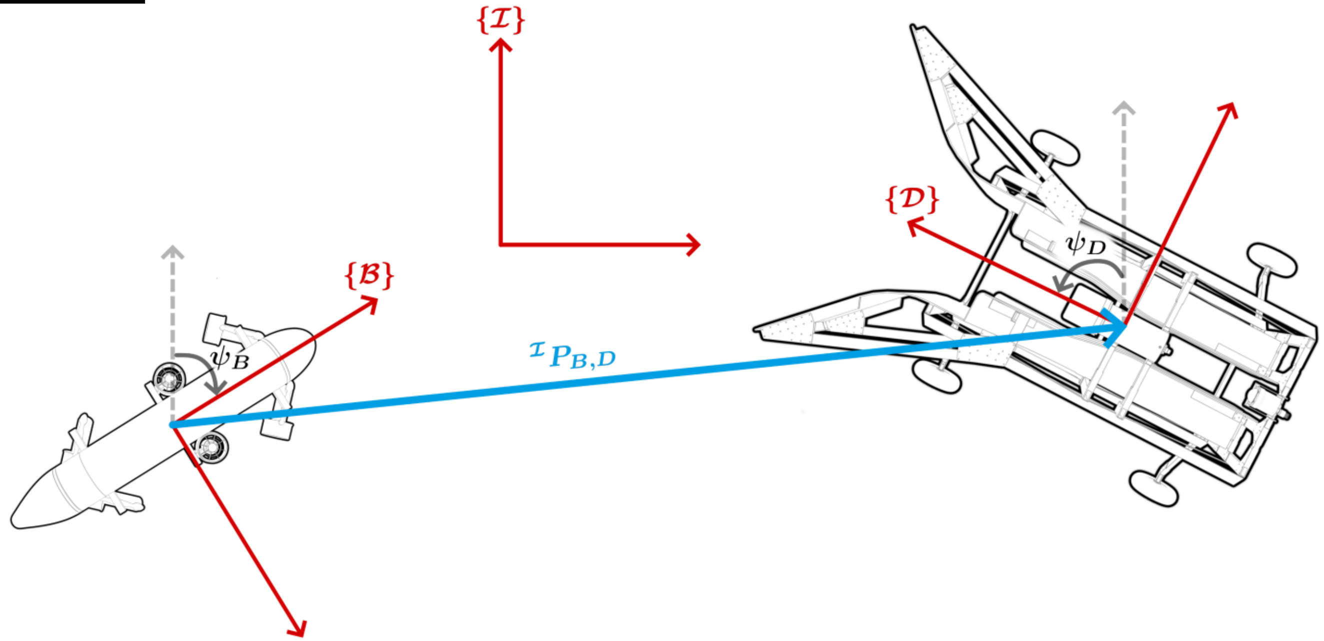
$$\boldsymbol{US_B} = {}^{\mathcal{B}}_{\mathcal{I}}R(\psi_B)\,{}^{\mathcal{I}}\boldsymbol{P_{D,B}}$$

$$\boldsymbol{US_D} = -{}^{\mathcal{D}}_{\mathcal{I}}R(\psi_D)\,{}^{\mathcal{I}}\boldsymbol{P_{D,B}}$$

$$V_m = {}^{\mathcal{D}}_{\mathcal{B}}R(\psi)V_{DVL} \qquad P_m = \boldsymbol{US_D} \quad \vee \quad P_m = {}^{\mathcal{D}}_{\mathcal{B}}R(\psi)\boldsymbol{US_B}$$

Input → Complementary Kalman Filter ← Observation

Complementary Kalman Filter → Relative Position Estimate



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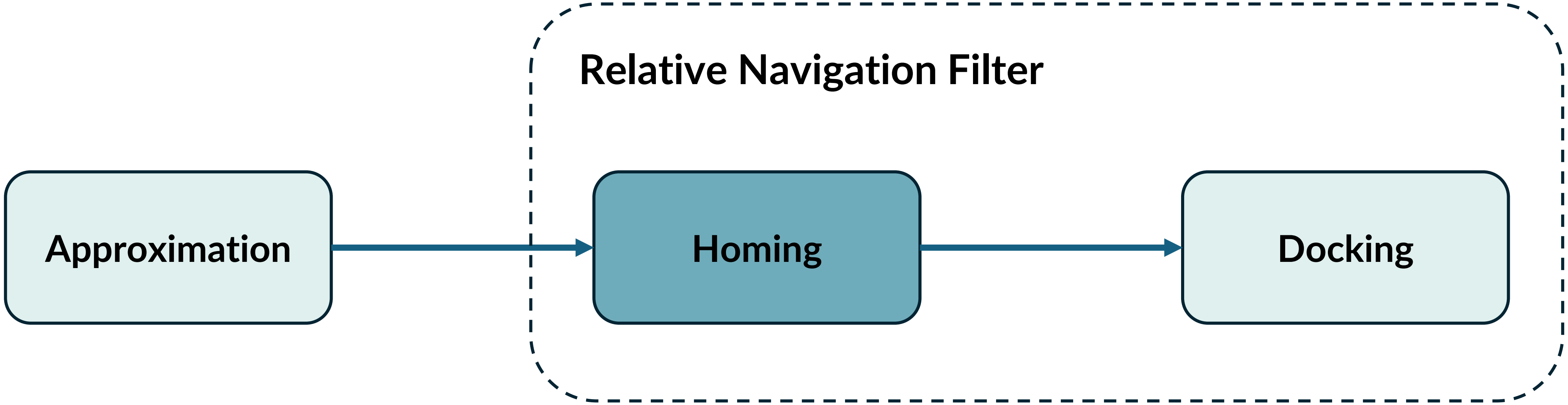


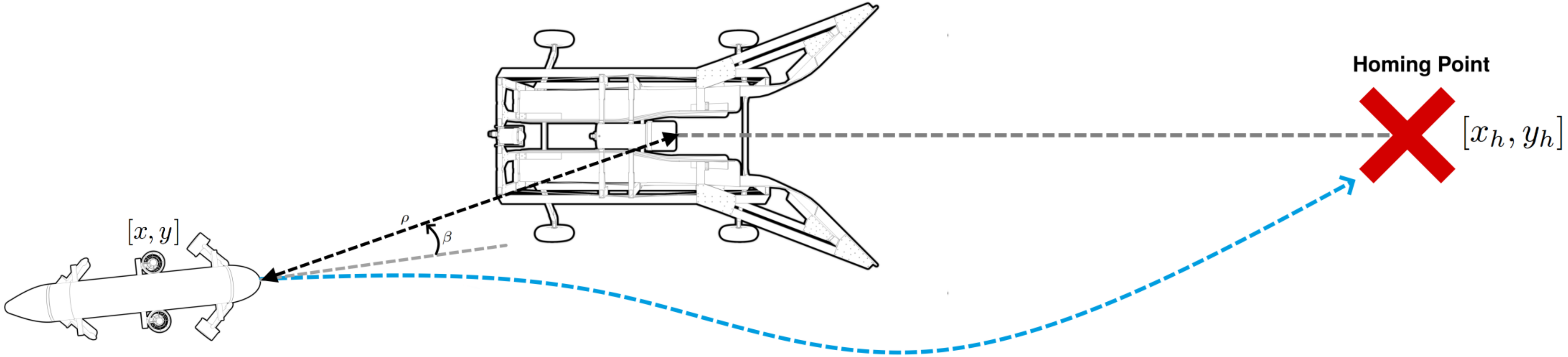
Homing Stage

Guidance Law:

$$\psi_d = atan\left(\frac{y_h - y}{x_h - x}\right) + \psi_c,$$

Obstacle avoidance term:

$$\dot{\psi}_c = \begin{cases} \frac{\alpha-\beta}{\rho} K_\gamma, & \text{if } 0 < \beta < \alpha \\ \frac{\alpha+\beta}{\rho} K_\gamma, & \text{if } -\alpha < \beta < 0 \end{cases}$$



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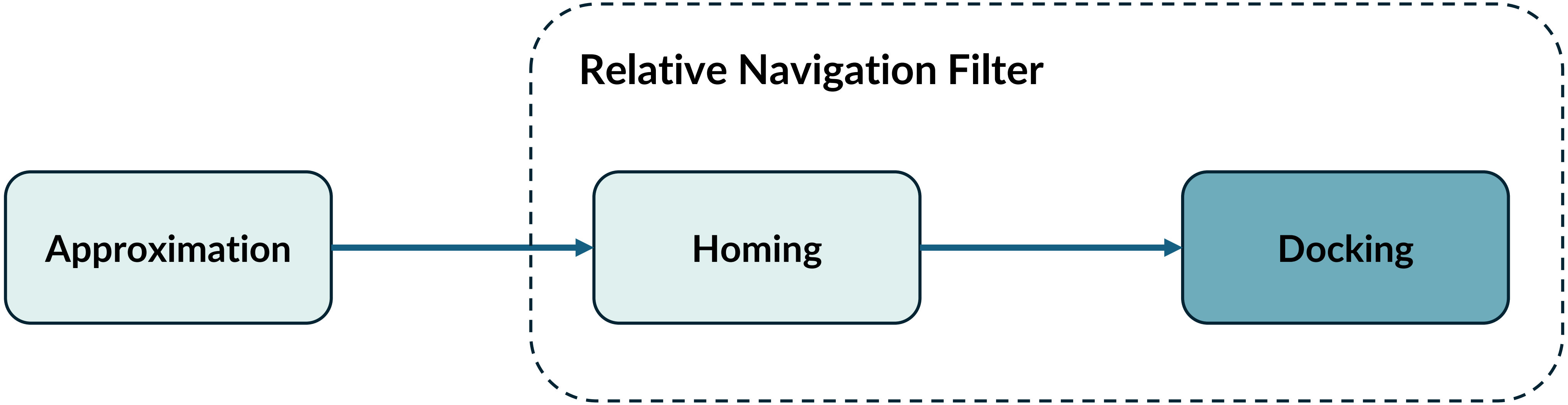


Docking Stage

Guidance Law:

$$\varphi = \psi_{path} + sin^{-1}\left(\sigma\left(-\frac{1}{u}\left(K_1 y + K_2 \varsigma\right)\right)\right)$$

$$\dot{\varsigma} = y + K_a\left[-\frac{1}{u}\left(K_1 y + K_2 \varsigma\right) - \sigma\left(-\frac{1}{u}\left(K_1 y + K_2 \varsigma\right)\right)\right]$$

$$V = T_t + \frac{V_c}{2} + \frac{V_c}{2} tanh\left(\frac{1}{2}(x-8)\right)$$

Fully Actuated Vehicles

$$[u_d, v_d] =^{\mathcal{B}}_{\mathcal{D}} R(\psi) \cdot [V cos(\varphi),\ V sin(\varphi)]^T$$

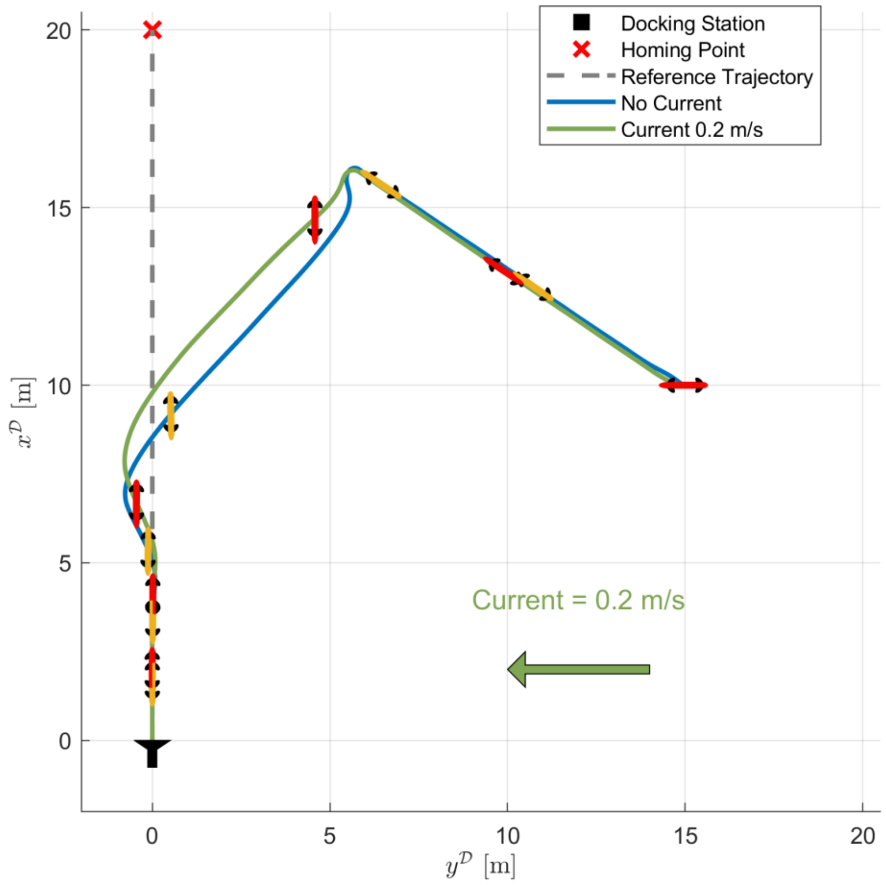
$$\psi_d = 180°$$

Under Actuated Vehicles

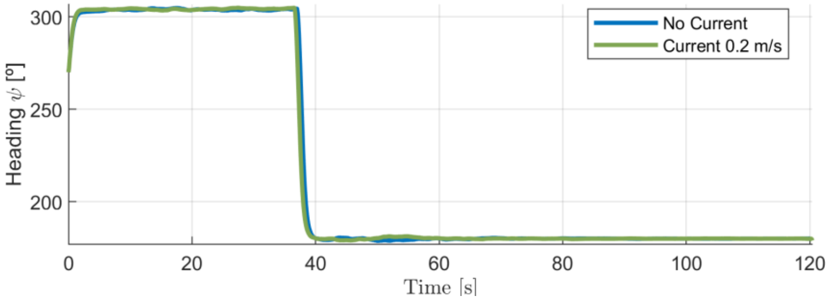
$$u_d = V$$

$$\psi_d = \varphi$$

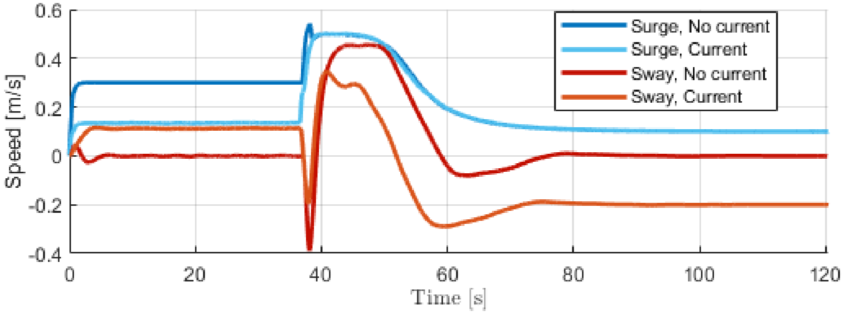
Simulations – Fully Actuated



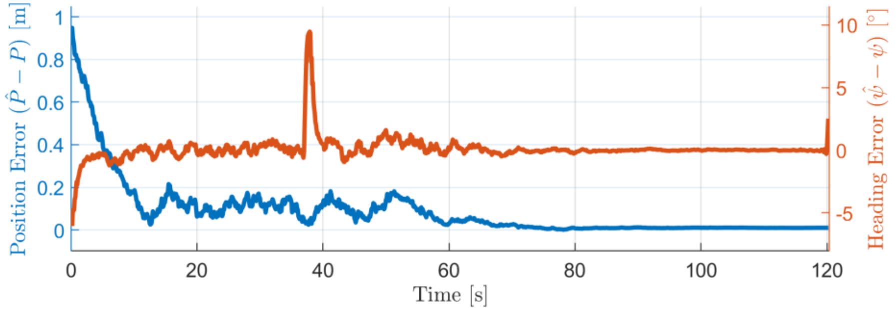
AUV Trajectory in the $\mathcal{D}$-frame.



AUV relative heading ψ.

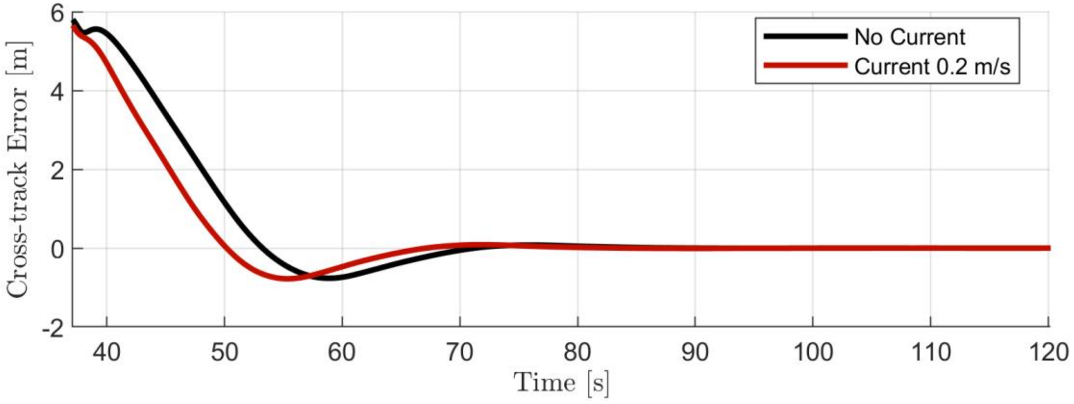


Body velocities with respect to the water.

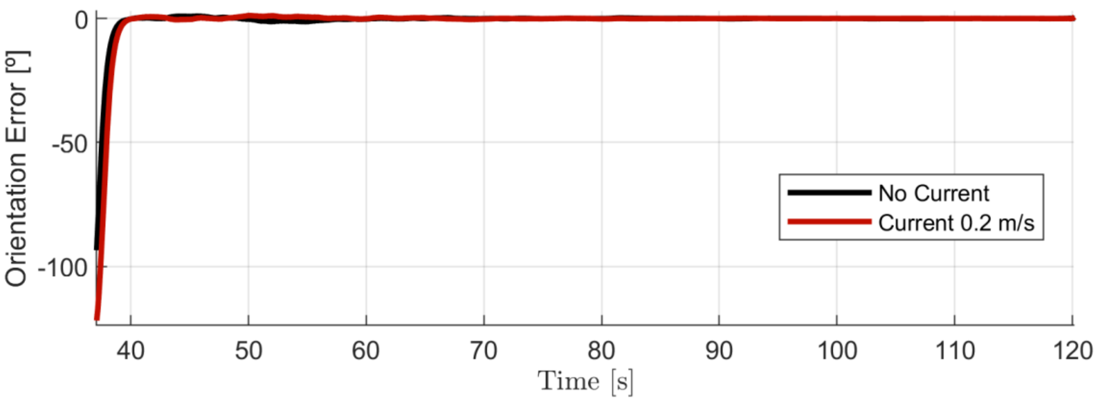


Estimation errors.

Simulations – Fully Actuated

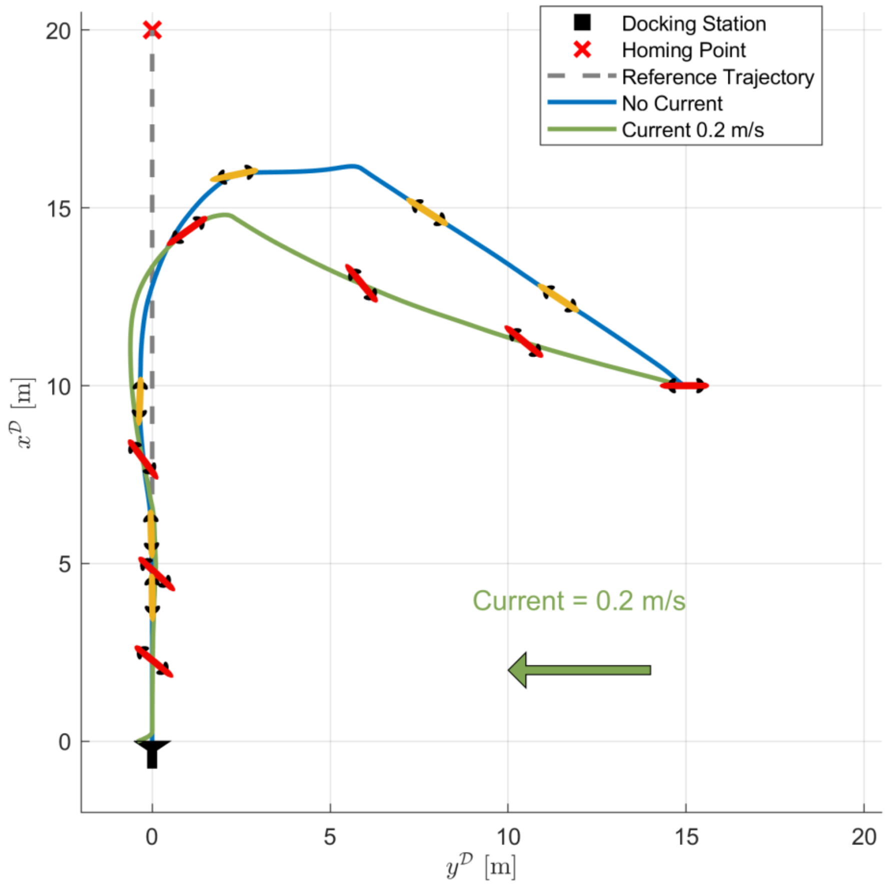


Cross-track error.



Alignment error.

Simulations – Under Actuated



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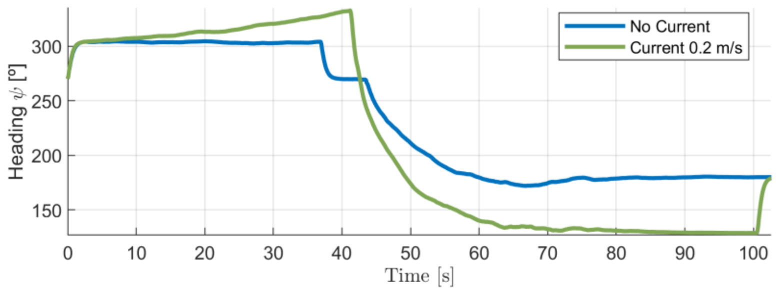

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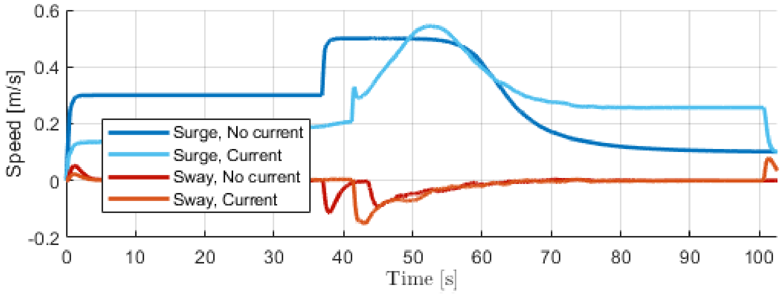

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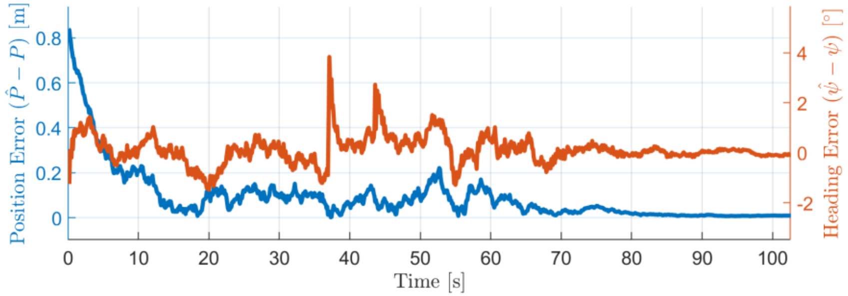

Estimation errors.

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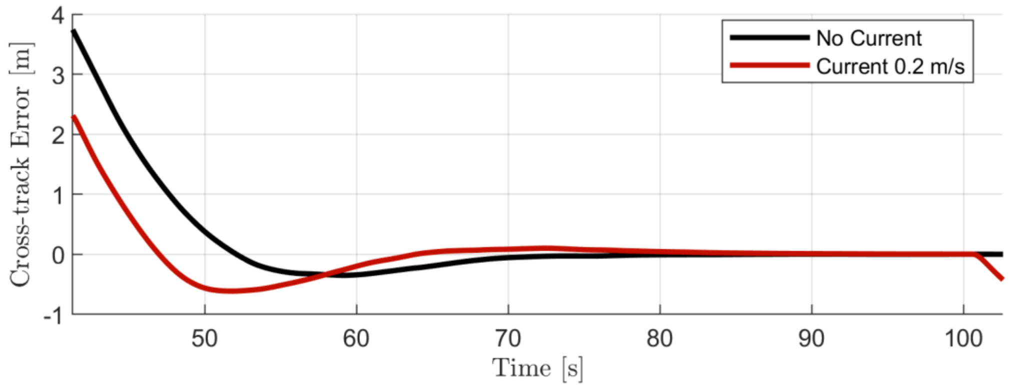

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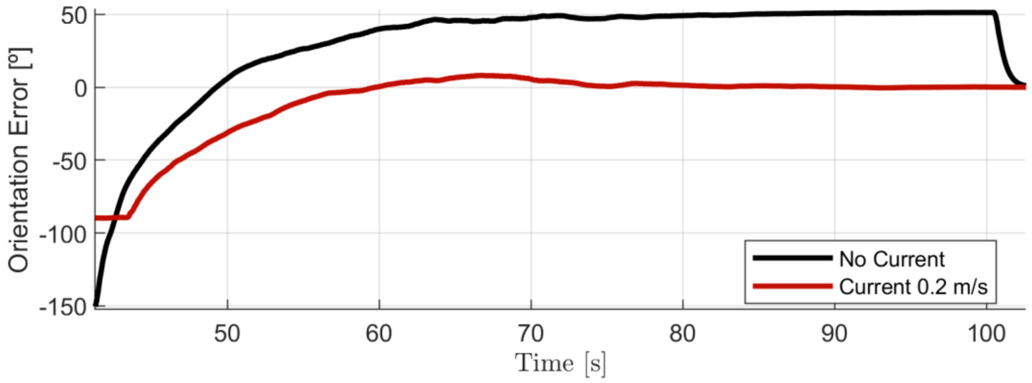


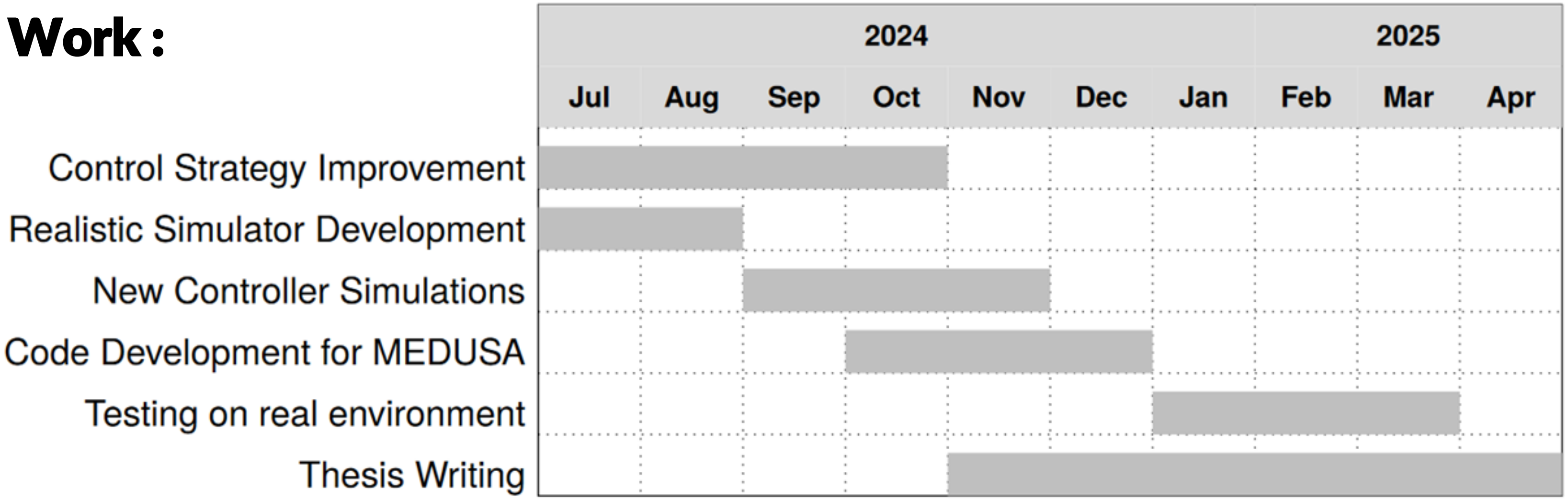
Alignment error.

Conclusion & Planning

Achieved thus far:

- **Introduced** and analysed the docking task
- Formulated **mathematical models** for underwater motion
- Proposed a **navigation system** w.r.t. the **docking station**
- Provided a **basic solution** for the docking manoeuvre

Future Work :



Questions ?