Brief Intro to Libera Università di Bolzano

ISME Annual Meeting

Karl von Ellenrieder

12 February 2025

unibz
Freie Universität Bozen
Libera Università di Bolzano
Università Liedia de Bulsan

Libera Università di Bolzano

- 5 faculties
- 8 competence centres
- 4.600 students
- trilingual (german – italian - english)
- 3 campuses
  Bozen-Bolzano
  Brixen-Bressanone
  Bruneck-Brunico
- NOI-Techpark
  Bozen-Bolzano
  Bruneck-Brunico

Faculty of Engineering

855

Students

39

Professors

54

Researchers

3 Computer Science and Artificial Intelligence, Information Engineering, Mechanical & Industrial Engineering

Institutes

Bachelors

- Computer Science
- Electronics and Cyber-Physical Systems Engineering
- Industrial and Mechanical Engineering
- Informatics and Management of Digital Business
- Wood Technology

Masters

- Computing for Data Science
- Data Analytics for Economics and Management
- Energy Engineering
- Industrial Mechanical Engineering
- Software Engineering

PhDs

- Advanced-Systems Engineering
- Computer Science
- Sustainable Energy and Technologies

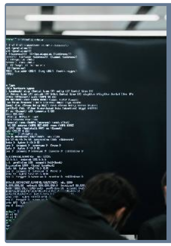
Lifelong Learning

- Controllo di gestione e reporting di sostenibilità: principi, standard e strumenti operativi
- Fire Safety Engineering
- Sustainable Management of Geo-hydrological Risk in Mountain Areas

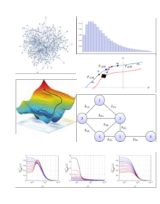
Research Macro Areas

Computer Science and Artificial Intelligence

Knowledge and Data



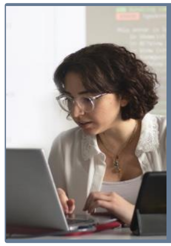
Data-driven Artificial Intelligence



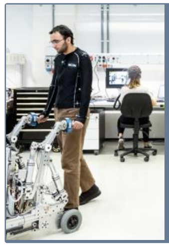
Mathematical Foundations

Information Engineering

Materials and Devices for Smart Systems



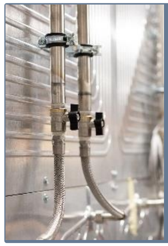
Software Engineering and Autonomous Systems



Human-centered Intelligent Systems

Industrial and Energy Engineering

Industrial Engineering and Automation



Energy Resources and Energy Efficiency

Sustainability and Safety for the Natural and Built Environment

UnBZ ISME Reference Faculty

Prof. Massimiliano Renzi

Hydropower Machines
Energy Conversion/Storage

Prof. Karl von Ellenrieder

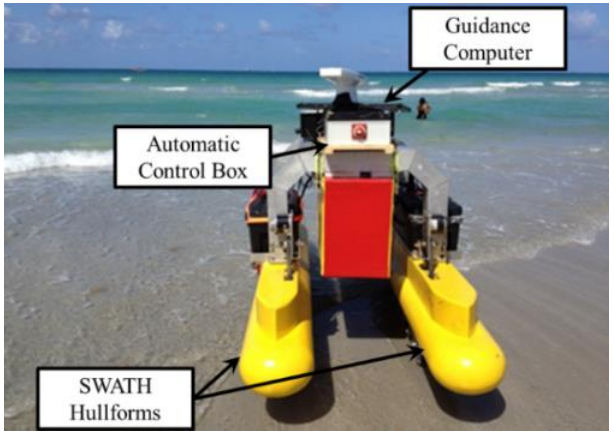
Robotics & Nonlinear Control

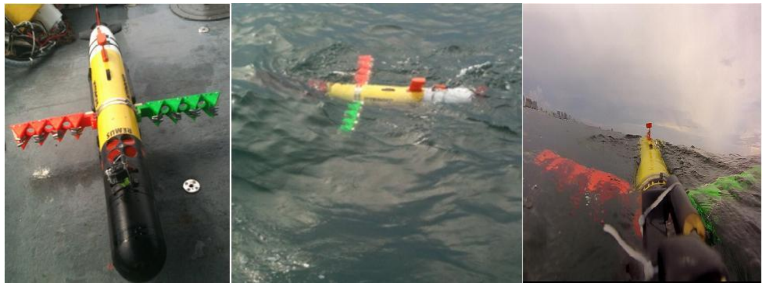
Dr. Federica Morandi

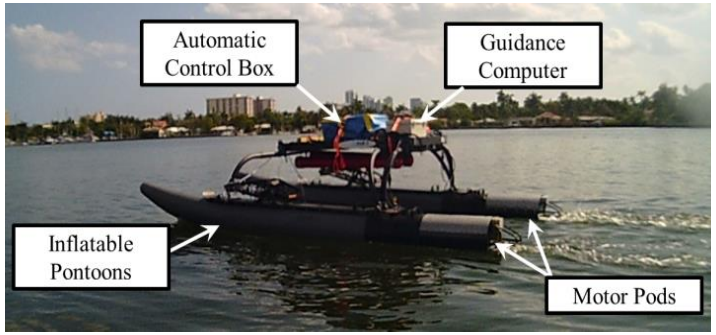
Acoustics

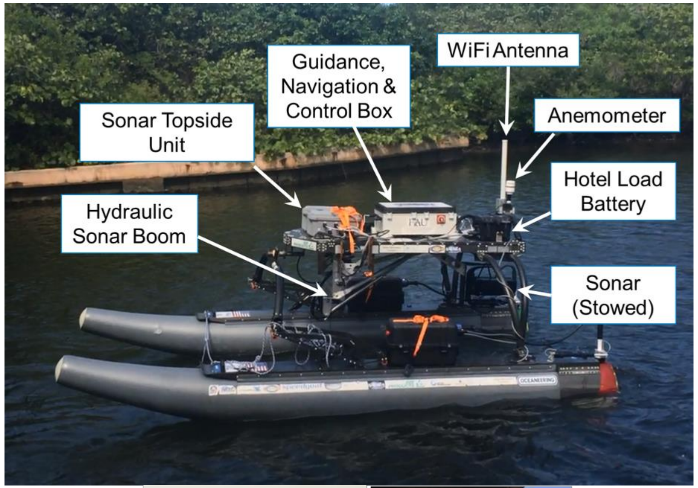
Karl von Ellenrieder

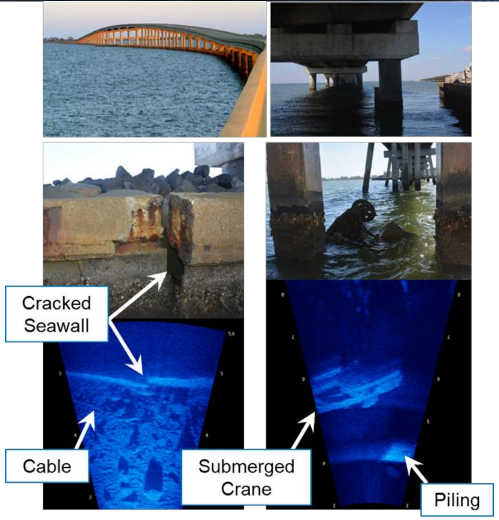
- Current Position:
  - Professor IINF-04/A (Automatica)
  - EiC IEEE Journal of Oceanic Engineering
  - Field Robots:
    - Study and development of robots for unstructured and dynamic environments.
    - Autonomous and semi-autonomous platforms for monitoring applications (e.g. mountains, streams, lakes, slopes).
- Prior Work:
  - Professor of Ocean Engineering (2003-2016)
  - Associate Director, SeaTech Institute for Ocean Systems Engineering
  - Florida Atlantic University (near Miami)
  - Program Manager Link Foundation Ocean & Instrumentation PhD Fellowship Program
  - UMVs:
    - Study and development of systems for ocean/marine environments.
    - Development of autonomous and semi-autonomous marine vehicles.


Guidance Computer
Automatic Control Box
SWATH Hullforms




Automatic Control Box
Guidance Computer
Inflatable Pontoons
Motor Pods


Sonar Topside Unit
Guidance, Navigation & Control Box
WiFi Antenna
Anemometer
Hotel Load Battery
Hydraulic Sonar Boom
Sonar (Stowed)


Cracked Seawall
Cable
Submerged Crane
Piling

Faculty of Engineering – Sept. 2024

https://firstlab.projects.unibz.it/

FiRST Lab Faculty, Researchers & Students

Prof. Karl von Ellenrieder
Full Professor
Automation and Automatic Control
Field Robotics and autonomous systems
Nonlinear control
Shared human-robot control
Unmanned vehicle dynamics

Prof. Santos Miguel Orozco Soto
RTD/A
Automation and Automatic Control
Field Robotics and autonomous systems
Nonlinear control
Unmanned aerial vehicles

Dr. Cheikh Melainine El Bou
Assegnista di Ricerca
Nonlinear control of ground vehicles
Shared human-robot control
Safety-critical control
Vehicle dynamics and modeling

Dr. Parvin Mahmoudabadi
Assegnista di Ricerca
Heavy-lift UAVs
Nonlinear control
Shared human-robot control

Dr. Alireza Naderi Akhormeh
Assegnista di Ricerca
Robotics & Mechatronics

dott. Ivan Enzo Gargano
PhD Student
Nonlinear control of ground vehicles
Trajectory planning
Vehicle dynamics and modeling

dott. Michael Chang Reynolds
PhD Student
(co-sup prof Marco Camurri UniTN)
Robotic imaging for agro-forestry

dott.ssa Sara Gomiero
PhD Student (DAuSy)
Nonlinear control of heavy-lift drones
Disturbance Rejection
Vehicle dynamics and modeling

FiRST Lab Faculty, Researchers & Students

dott. Sai Bhaskar Golapala
PhD Student
Opinion Dynamics for trajectory
Planning and control ground vehicles
Vehicle dynamics and modeling

dott. Enrico Severini
PhD Student
Nonlinear control of heavy-lift drones
Human-Robot Shared Control
Vehicle dynamics and modeling

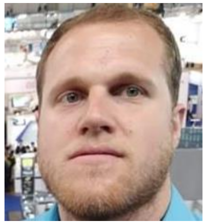
dott. Joel Enrique Esparza-Ramirez
PhD Student
(co-sup Dr. Abraham Mejia EURAC)
Nonlinear control of aerial drones
Mountain Search & Rescue

Affiliated Faculty, Researchers, & Alumni

dott. Giacomo Tomasi
Assistant researcher
Mechatronics and robotics
Mobile manipulators

Prof. Renato Vidoni
Founding Member FiRST Lab
UniUD
Multibody systems dynamics
Advanced mechatronic and (collaborative) robotic systems
Optimal motion planning

Prof. Marco Camurri
UniTN
Robotics
Quadrupeds
System localization and mapping



Dr. Stefan Leitner
Mechatronics
Electric/Hybrid solutions for agro-forestry

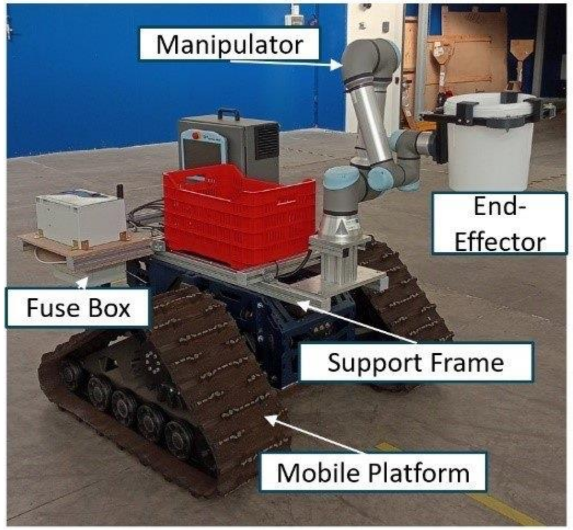
FiRST Lab Current Projects

Sestosenso (2022-2025) EU Horizon RIA – Physical Cognition for Intelligent Control and Safe Human-robot Interaction

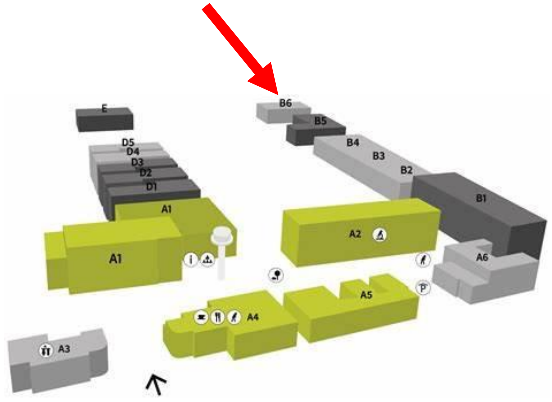
Amplif-AI (2024-2026) ERDF2021-2027 – Adaptive Mission Planning for LIve inFrAstructure Inspection (MavTech Srl & Fraunhofer Italia).

FORMA (2025-2027) ERDF2021-2027 – Forestry Mapping and Automation (FlyingBasket Srl & Eurac Research).

Piramide (2025-2026) Provincia Autonoma Bolzano - Program for Integrated Remote and Autonomous Mission Drive (Iveco Defense Vehicles, Astra, HiPert/UniMoRE, Este)



AnyMal by AnyBotics



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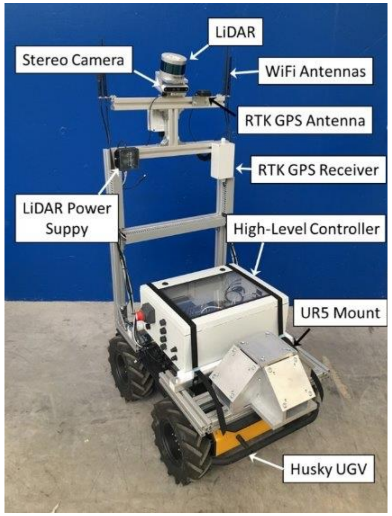

Politecnico di Bari

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Università Liedia de Bulsan

Localization of AUVs using a Higher Order Sliding Mode Observer and an Extended Kalman Filter

Sara Gomiero[1,2] & Karl D. von Ellenrieder[1]

Libera Università di Bolzano[1] & Politecnico di Bari[2]
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ISME

12th February 2025

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NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

Introduction

Motivation:

- Estimate pose/speed of underwater vehicles
- Challenge → GNSS unavailable underwater
- *Small-sized* AUVs use MEMS-based AHRS instead of sophisticated INS
- Magnetometer affected by thruster motors + environmental magnetic anomalies
- AUV navigation with MEMS AHRS requires accurate estimate of yaw angle navigation accuracy
- DVL measurements prone to error accumulation (from motion compensation)

Introduction

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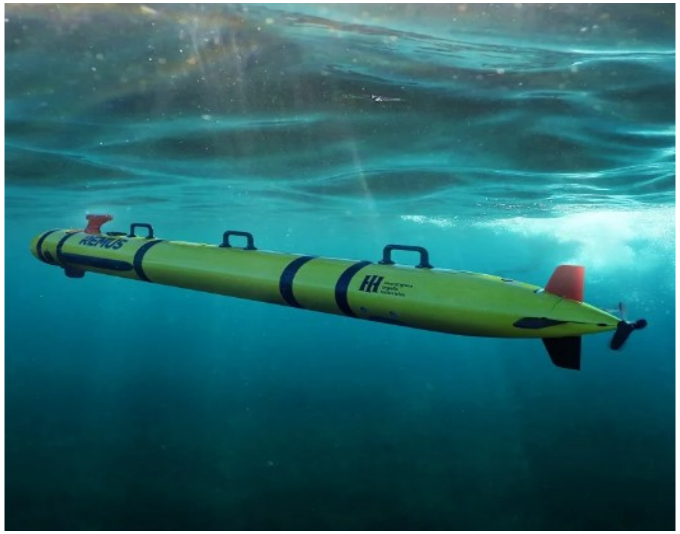
Common Approach:

- Use of recursive filters to estimate the AUV states of interest (Kalman and Particle Filters)
- Estimates are updated exploiting data from onboard sensors



Remus 300 AUV from Hydroid

Problem

Estimation problem

Given an autonomous underwater vehicle, an uncrewed surface vessel, and an acoustic communication system, design an observer to determine AUV position and heading

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Estimation problem

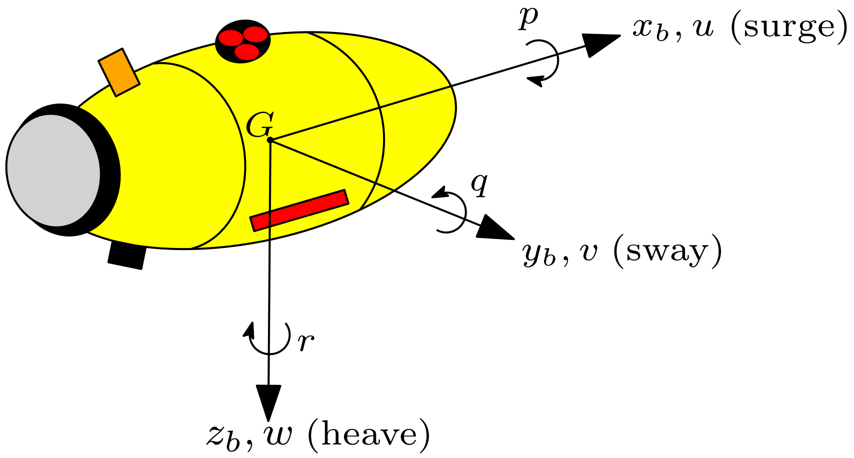
Given an autonomous underwater vehicle, an uncrewed surface vessel, and an acoustic communication system, design an observer to determine AUV position and heading

Idea: Compare Extended Kalman Filter and Higher Order Sliding Mode Observer

Data:

- Surface vessel broadcasts position via acoustic communication
- AUV computes position using bearing, elevation and depth difference (BEDD) from passive inverted super short baseline (piSSBL) acoustic positioning signal (Sekimori et al. [2024])
- Heading and velocity computations use onboard sensor data

System model

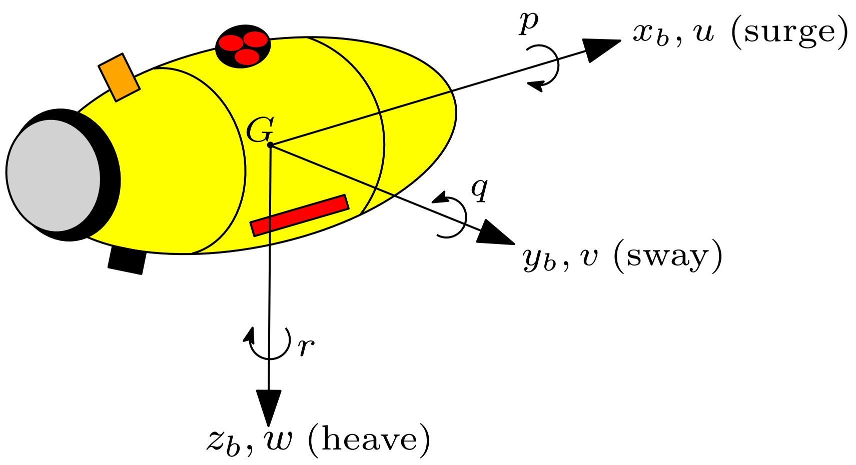


AUV with body-fixed frame

$\mathcal{N}$ = NED frame

$\mathcal{B}$ = body-fixed frame

System model



AUV with body-fixed frame

Generalized position:

$$\boldsymbol{\eta} = [\boldsymbol{p}^n_{b/n}, \, \boldsymbol{\Theta}_{bn}]^T$$

$$\boldsymbol{p}^n_{b/n} = [x_n, \; y_n, \; z_n]^T \rightarrow \text{position in } \mathcal{N}$$

$$\boldsymbol{\Theta}_{bn} = [\phi, \; \theta, \; \psi]^T \rightarrow \text{orientation in } \mathcal{N}$$

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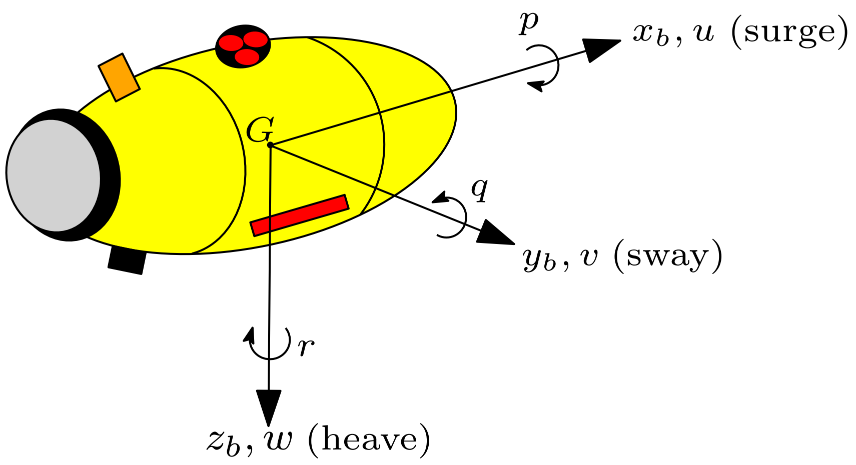
System model



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$\boldsymbol{\Theta}_{bn} = [\phi, \; \theta, \; \psi]^T$ → orientation in $\mathcal{N}$

Generalized velocity:

$$\boldsymbol{v} = [\boldsymbol{v}^b_{b/n}, \, \boldsymbol{\omega}^b_{b/n}]^T$$

$\boldsymbol{v}^b_{b/n} = [u, \; v, \; w]^T$ → linear vel. in $\mathcal{B}$

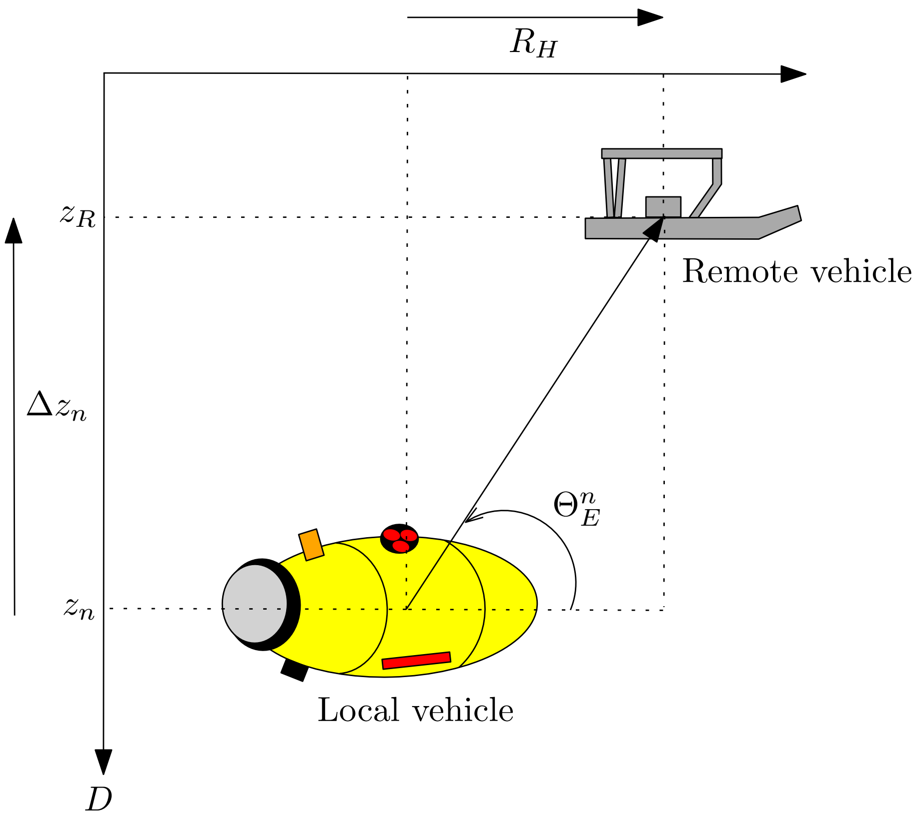
$\boldsymbol{\omega}^b_{b/n} = [p, \; q, \; r]^T$ → angular vel. in $\mathcal{B}$

Kinematic and kinetic equations

$$\begin{aligned}\dot{\boldsymbol{\eta}} &= \boldsymbol{J}_{\Theta}(\boldsymbol{\eta})\boldsymbol{v},\\ \boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{g}(\boldsymbol{\eta}) &= \boldsymbol{\tau}(t, \boldsymbol{\eta}, \boldsymbol{v}).\end{aligned} \tag{1}$$

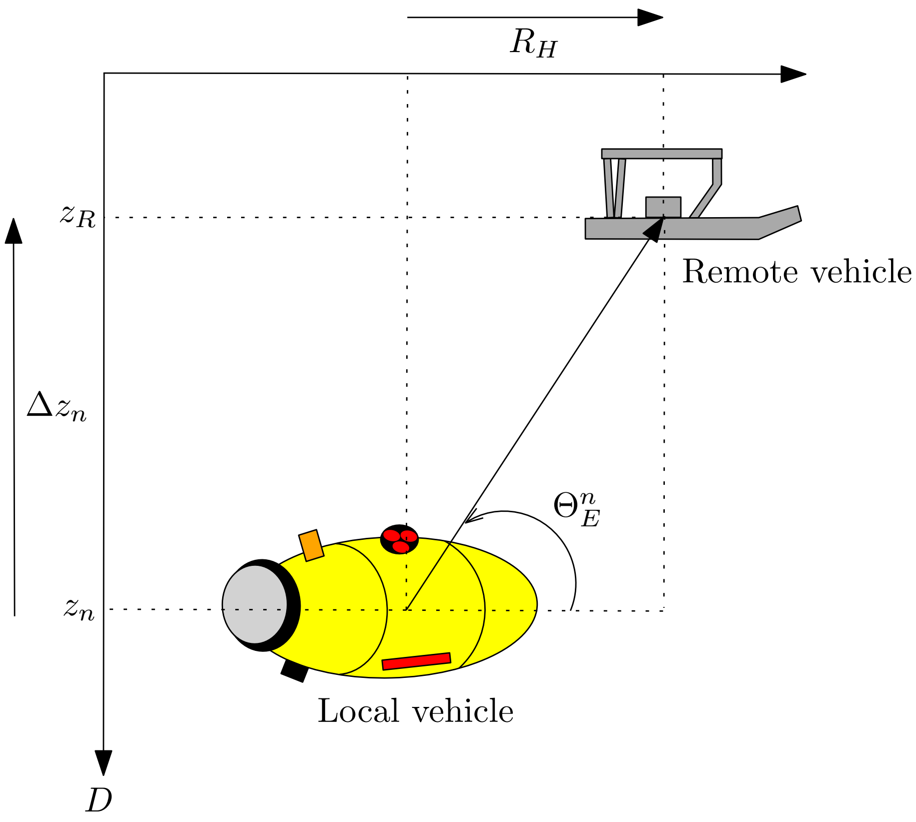
- $\boldsymbol{J}_{\Theta} \in \mathbb{R}^{6\times6}$ = Jacobian from $\mathcal{B}$ to $\mathcal{N}$
- $\boldsymbol{M} \in \mathbb{R}^{6\times6}$ = inertia tensor
- $\boldsymbol{C}(\boldsymbol{v}) \in \mathbb{R}^{6\times6}$ = Coriolis and centripetal matrix
- $\boldsymbol{D}(\boldsymbol{v}) \in \mathbb{R}^{6\times6}$ = hydrodynamic damping matrix
- $\boldsymbol{g}(\boldsymbol{\eta}) \in \mathbb{R}^{6}$ = hydrodynamic forces and moments
- $\boldsymbol{\tau}(t, \boldsymbol{\eta}, \boldsymbol{v}) \in \mathbb{R}^{6}$ = control inputs

Acoustic localization system



Elevation, depth difference and horizontal range between AUV and remote vehicle

Acoustic localization system

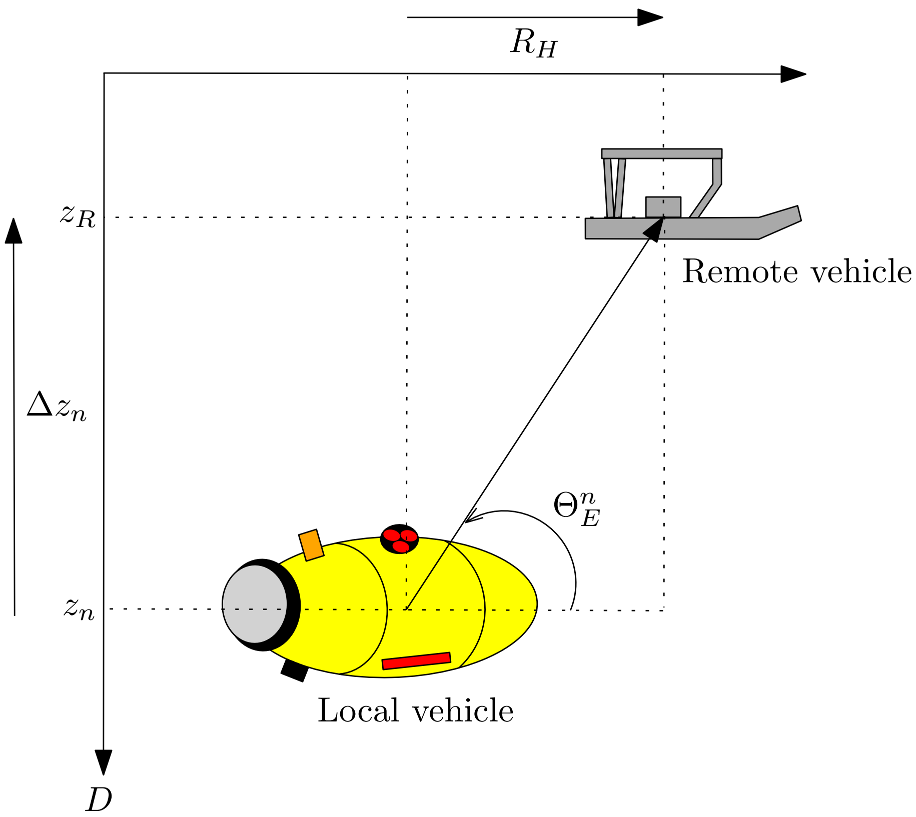


Elevation, depth difference and horizontal range between AUV and remote vehicle

Localization system:

1. Uncrewed surface vessel
    - Stationary
    - Able to use GNSS

Acoustic localization system

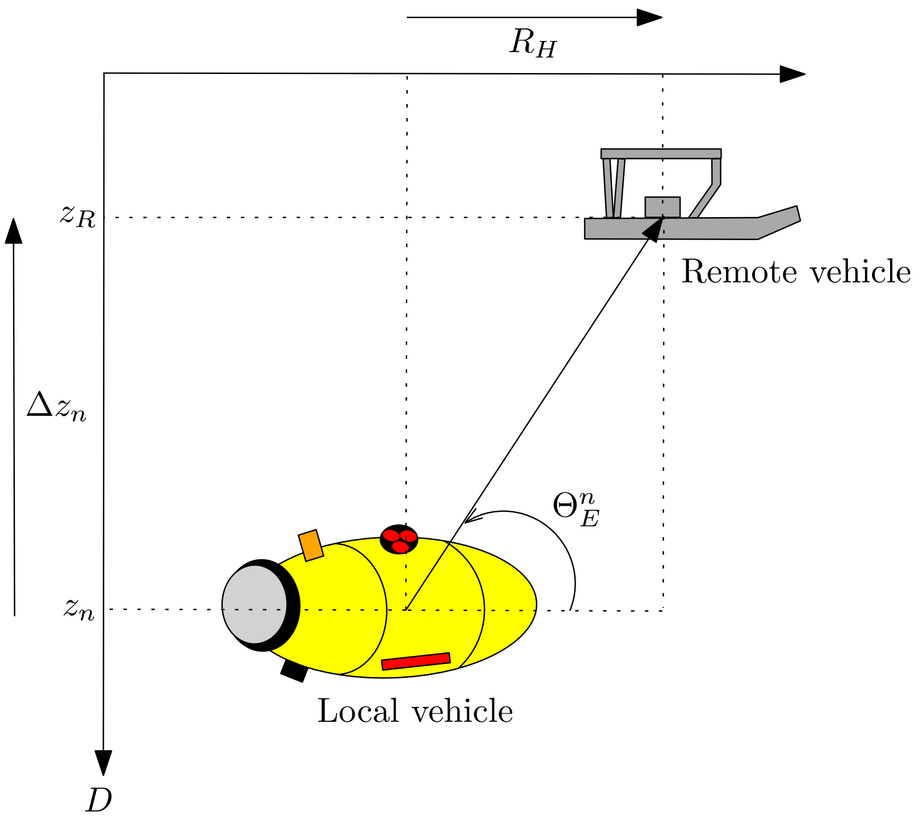


Elevation, depth difference and horizontal range between AUV and remote vehicle

Localization system:

1. Uncrewed surface vessel
    - Stationary
    - Able to use GNSS
2. Underwater vehicle
    - Evaluates bearing, elevation and depth difference (BEDD) relative to USV
    - Calculates its relative position with respect to the USV in the NED frame

Acoustic localization system



Elevation, depth difference and horizontal range between AUV and remote vehicle

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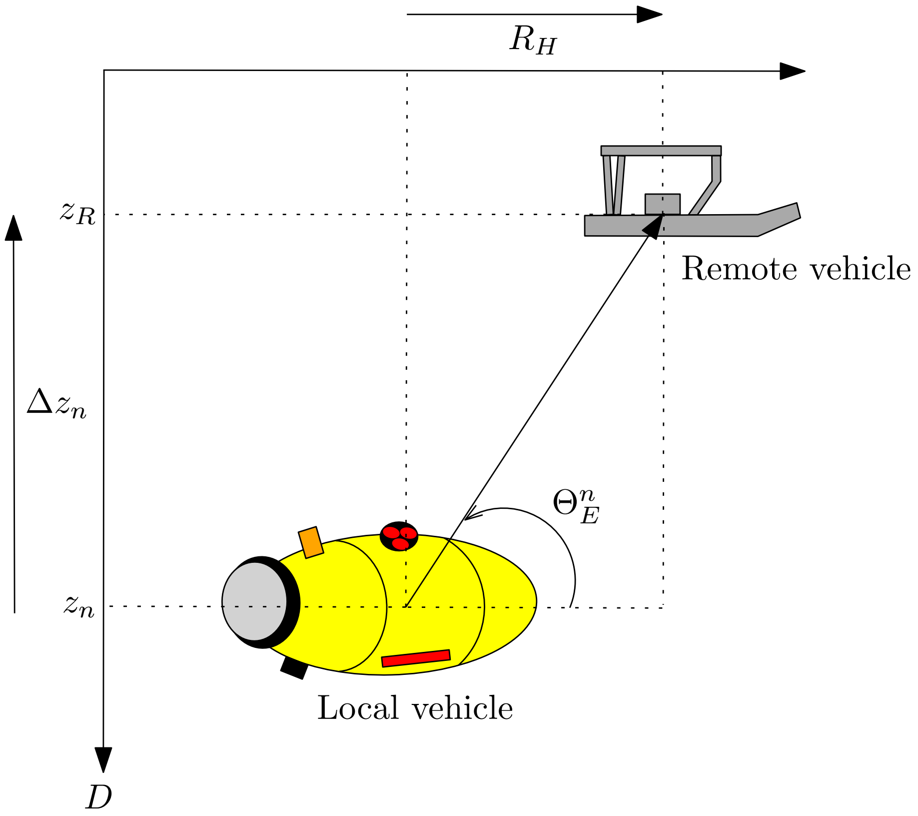
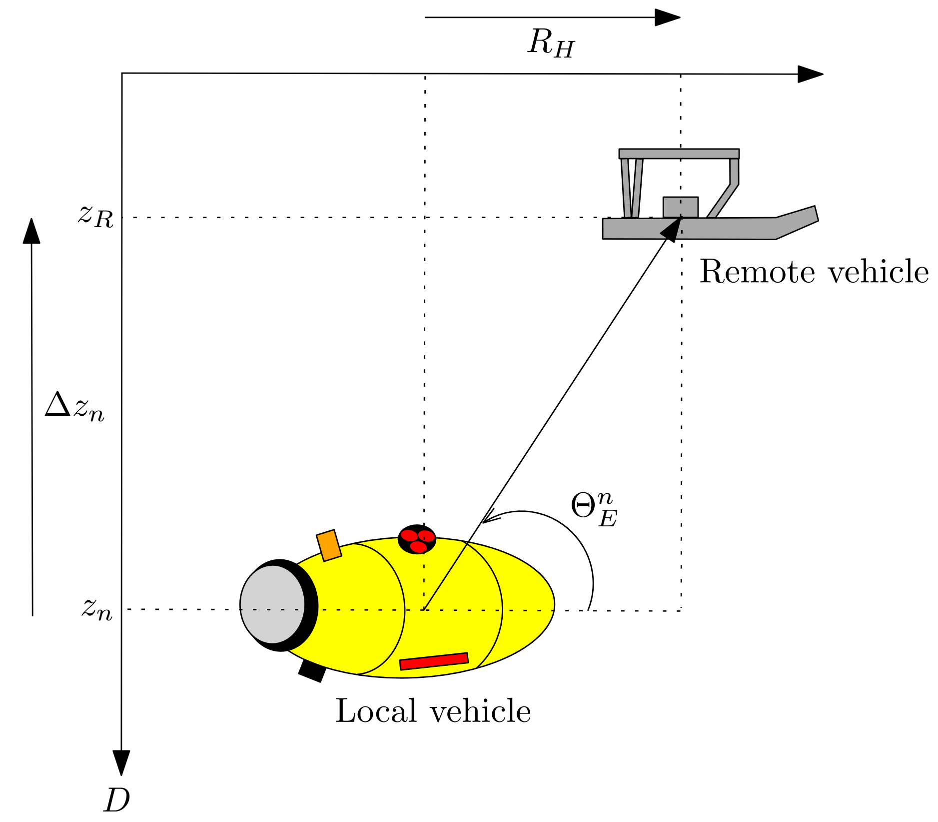


Elevation, depth difference and horizontal range between AUV and remote vehicle

Relative position:

$$\Delta \mathbf{p}_{b/n}^{n} = \begin{bmatrix} R_H \cos(\Theta_B^n) \\ R_H \sin(\Theta_B^n) \\ z_R - z_n \end{bmatrix}. \qquad (2)$$

Acoustic localization system



Elevation, depth difference and horizontal range between AUV and remote vehicle

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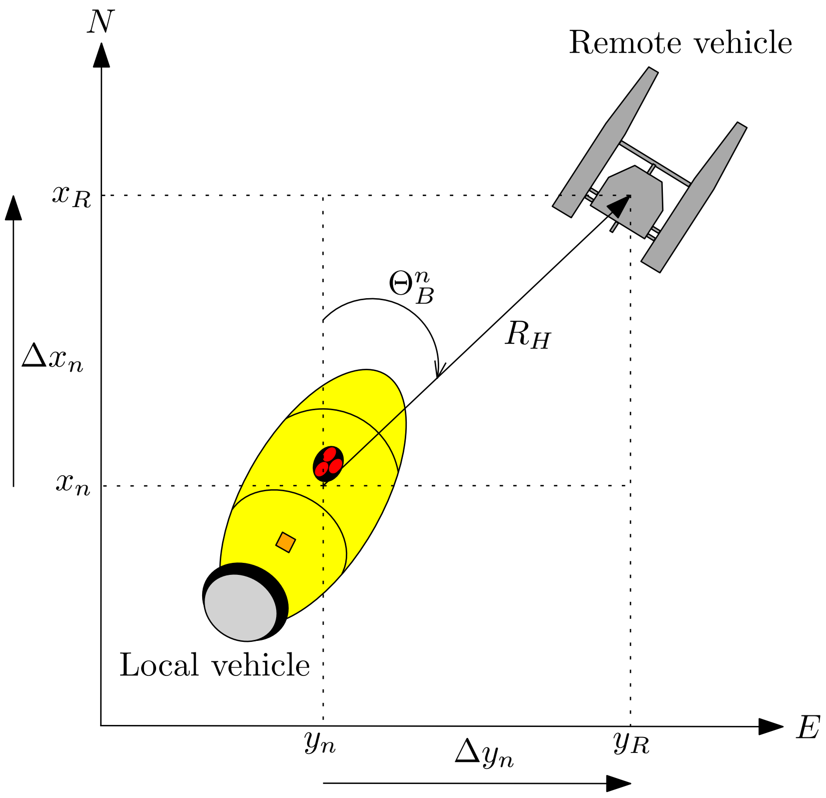
$$\Delta \mathbf{p}_{b/n}^{n} = \begin{bmatrix} R_H \cos(\Theta_B^n) \\ R_H \sin(\Theta_B^n) \\ z_R - z_n \end{bmatrix}. \quad (2)$$

Horizontal range:

$$R_H = \frac{-\Delta z_n}{\tan(\Theta_E^n)}. \quad (3)$$

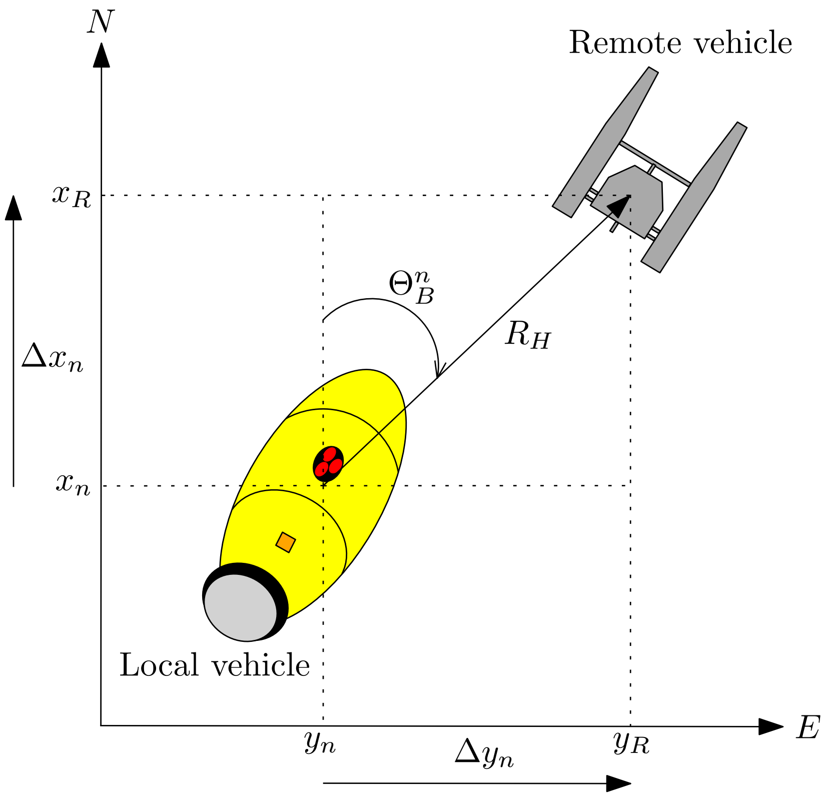
- Θ_B^n = bearing
- z_R = depth of the surface vessel
- Θ_E^n = elevation

Acoustic localization system



Bearing and horizontal range

Acoustic localization system

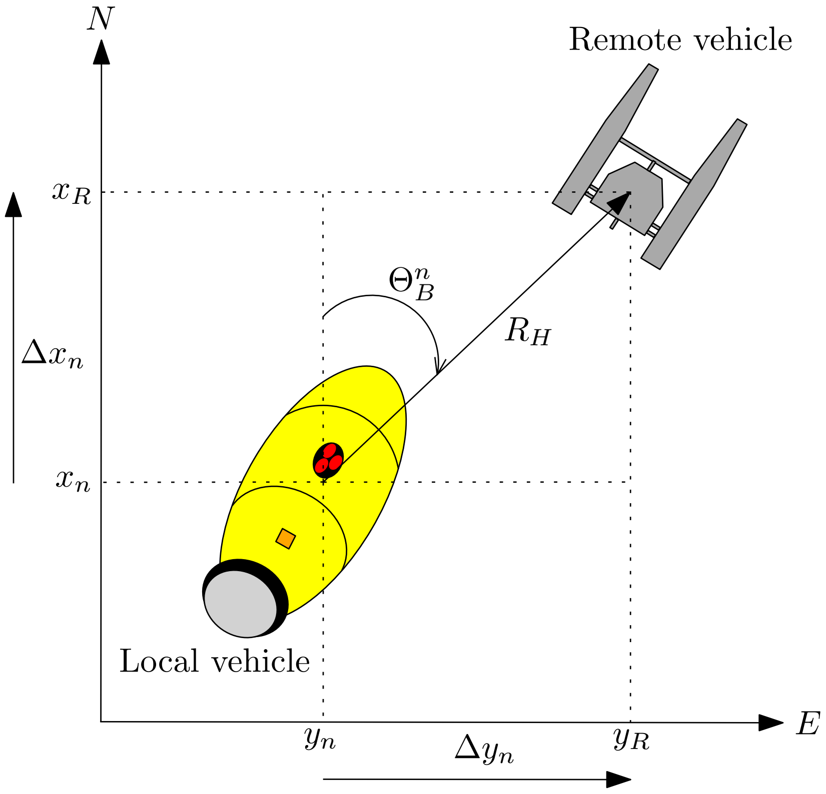


Bearing and horizontal range

Bearing:

$$\Theta_B^n = \operatorname{atan2}(\Delta y_n, \Delta x_n). \tag{4}$$

Acoustic localization system



Bearing and horizontal range

Bearing:

$$\Theta_B^n = \operatorname{atan2}(\Delta y_n, \Delta x_n). \tag{4}$$

Elevation:

$$\Theta_E^n = \operatorname{atan2}\left(-\Delta z_n, \sqrt{{\Delta x_n}^2 + {\Delta y_n}^2}\right). \tag{5}$$

Extended Kalman Filter

Assumptions about sensors:

- Pressure sensor → Constant depth
- Attitude and Heading Reference System → ϕ and θ, angular velocities
- Doppler Velocity Logger → Linear velocities along x_b and y_b

Extended Kalman Filter

Assumptions about sensors:

- Pressure sensor → Constant depth
- Attitude and Heading Reference System → ϕ and θ, angular velocities
- Doppler Velocity Logger → Linear velocities along x_b and y_b

Reduced kinematic equations:

$$\begin{aligned} x_{n_t} &= x_{n_{t-1}} + (u_t^m \cos(\psi_t) - v_t^m \sin(\psi_t))\Delta t, \\ y_{n_t} &= y_{n_{t-1}} + (u_t^m \sin(\psi_t) + v_t^m \cos(\psi_t))\Delta t, \\ \psi_t &= \psi_{t-1} + r_t^m \Delta t. \end{aligned} \tag{6}$$

Extended Kalman Filter equations

State and measurement equations:

$$\begin{aligned} \boldsymbol{X}_t &= \boldsymbol{f}(\boldsymbol{X}_{t-1}, \boldsymbol{U}_{t-1}) + \boldsymbol{W}_{t-1}, \\ \boldsymbol{Y}_t &= \boldsymbol{h}(\boldsymbol{X}_t) + \boldsymbol{V}_t. \end{aligned} \tag{7}$$

- $\boldsymbol{X}_t = [x_{n_t},\, y_{n_t},\, \psi_t]^T$
- $\boldsymbol{U}_t = [u_t^m,\, v_t^m,\, r_t^m]^T$
- $\boldsymbol{Y}_t = [\Delta z_{n_t},\, \Theta^n_{E_t},\, \Theta^n_{B_t},\, R_{H_t}]^T$

Extended Kalman Filter equations

State and measurement equations:

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- $\boldsymbol{Y}_t = [\Delta z_{n_t},\, \Theta^n_{E_t},\, \Theta^n_{B_t},\, R_{H_t}]^T$

$\hat{\boldsymbol{X}}^-_{t\|t-1} = \boldsymbol{f}(\hat{\boldsymbol{X}}^+_{t-1}, \boldsymbol{U}_{t-1})$	Prediction
$\boldsymbol{P}^-_{t\|t-1} = \boldsymbol{F}\boldsymbol{P}^+_{t\|t-1}\boldsymbol{F}^T + \boldsymbol{B}\boldsymbol{\Omega}_{t-1}\boldsymbol{B}^T + \boldsymbol{Q}_{t-1}$	Prediction
$\boldsymbol{K}_t = \boldsymbol{P}^-_{t\|t-1}\boldsymbol{H}^T\left(\boldsymbol{H}\boldsymbol{P}^-_{t\|t-1}\boldsymbol{H}^T + \boldsymbol{R}_t\right)^{-1}$	Kalman gain
$\hat{\boldsymbol{X}}^+_t = \hat{\boldsymbol{X}}^-_{t\|t-1} + \boldsymbol{K}_t\left(\boldsymbol{Y}_t - \boldsymbol{h}(\hat{\boldsymbol{X}}^-_{t\|t-1})\right)$	Update
$\boldsymbol{P}^+_t = (\boldsymbol{I} - \boldsymbol{K}_t\boldsymbol{H})\,\boldsymbol{P}^-_{t\|t-1}$	Update

Higher Order Sliding Mode Observer

Rewrite equations of motion as

$$\begin{aligned} \dot{\boldsymbol{\eta}} &= \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{v}, \\ \dot{\boldsymbol{v}} &= \boldsymbol{N}(t, \boldsymbol{\eta}, \boldsymbol{v}, \boldsymbol{\tau}) + \boldsymbol{\xi}(t, \boldsymbol{\eta}, \boldsymbol{v}, \boldsymbol{\tau}). \end{aligned} \tag{8}$$

Higher Order Sliding Mode Observer

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Assume that the measured states are

$$\boldsymbol{y} = [x_n \;\; y_n \;\; z_n \;\; \phi \;\; \theta]^T. \tag{9}$$

Higher Order Sliding Mode Observer

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$$\begin{aligned} \dot{\boldsymbol{\eta}} &= \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{v}, \\ \dot{\boldsymbol{v}} &= \boldsymbol{N}(t, \boldsymbol{\eta}, \boldsymbol{v}, \boldsymbol{\tau}) + \boldsymbol{\xi}(t, \boldsymbol{\eta}, \boldsymbol{v}, \boldsymbol{\tau}). \end{aligned} \tag{8}$$

Assume that the measured states are

$$\boldsymbol{y} = [x_n \;\; y_n \;\; z_n \;\; \phi \;\; \theta]^T. \tag{9}$$

Propose a Higher Order Sliding Mode observer of the form

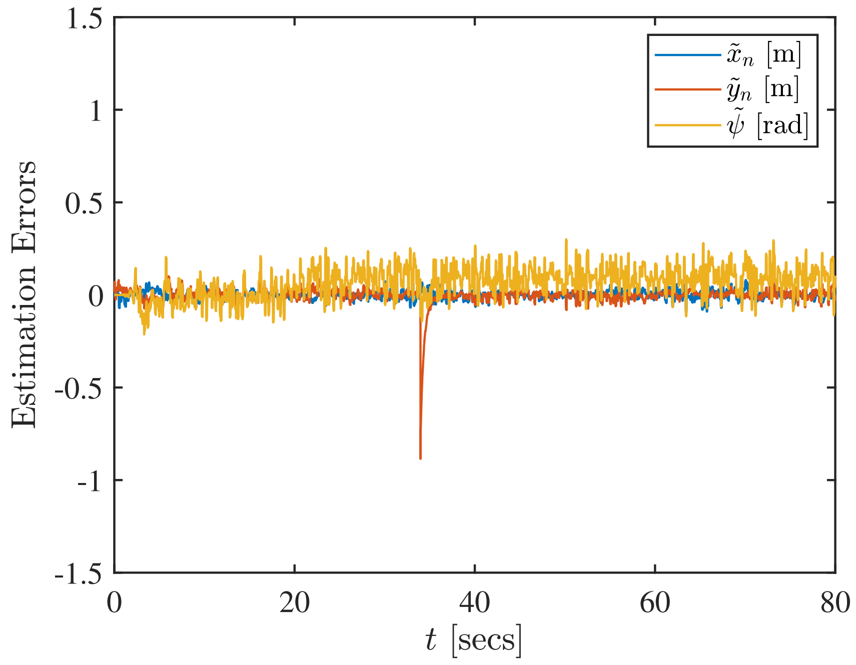
$$\begin{aligned} \dot{\hat{\boldsymbol{\eta}}} &= \boldsymbol{J}(\hat{\boldsymbol{\eta}})\hat{\boldsymbol{v}} + \boldsymbol{\alpha}_2\boldsymbol{\lambda}(\tilde{\boldsymbol{y}})\mathrm{sgn}(\tilde{\boldsymbol{y}}), \\ \dot{\hat{\boldsymbol{v}}} &= \boldsymbol{N}(t, \hat{\boldsymbol{\eta}}, \boldsymbol{v}, \boldsymbol{\tau}) + \boldsymbol{\alpha}_1\mathrm{sgn}(\tilde{\boldsymbol{y}}), \end{aligned} \tag{10}$$

- $\tilde{\boldsymbol{y}} = \boldsymbol{y} - \hat{\boldsymbol{y}}$
- $\hat{\boldsymbol{\eta}}$, $\hat{\boldsymbol{v}}$, $\hat{\boldsymbol{y}}$ = estimates of $\boldsymbol{\eta}$, $\boldsymbol{v}$, $\boldsymbol{y}$
- $\boldsymbol{\alpha}_1 = \boldsymbol{\alpha}_1^T > 0$, $\boldsymbol{\alpha}_2 = \boldsymbol{\alpha}_2^T > 0$
- $\boldsymbol{\lambda}(\tilde{\boldsymbol{y}}) = \mathrm{diag}\left[\tilde{x},\; \tilde{y},\; \tilde{z},\; \tilde{\phi},\; \tilde{\theta}\right]$ and $\mathrm{sgn}(\tilde{\boldsymbol{y}}) = \left[|\tilde{x}|^{\frac{1}{2}},\; |\tilde{y}|^{\frac{1}{2}},\; |\tilde{z}|^{\frac{1}{2}},\; |\tilde{\phi}|^{\frac{1}{2}},\; |\tilde{\theta}|^{\frac{1}{2}}\right]^T$

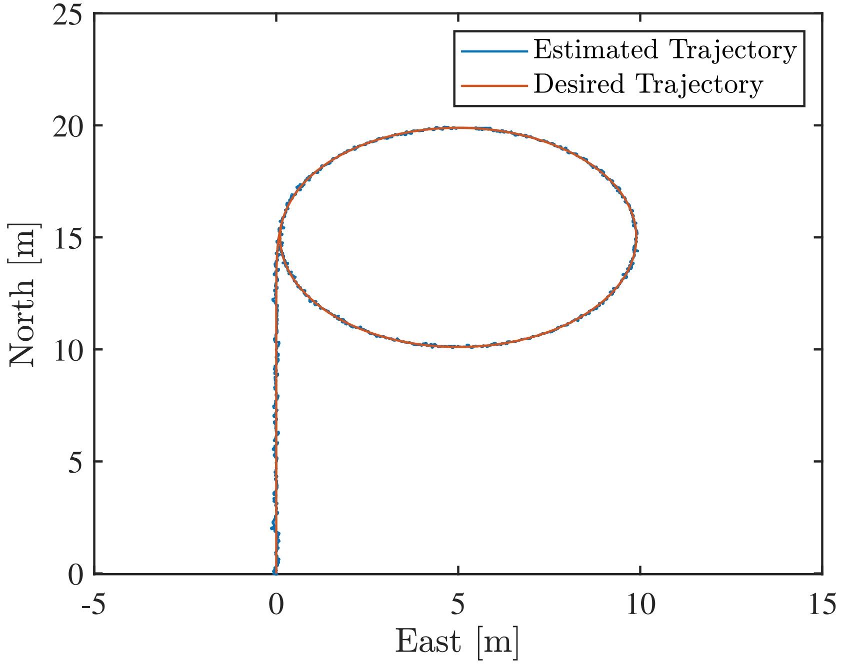
Simulations: EKF

Assumptions:

- Circle maneuver, depth of 10 meters, USV in the center of the trajectory
- Sensors are corrupted by white noise, amplitude depends on the accuracy



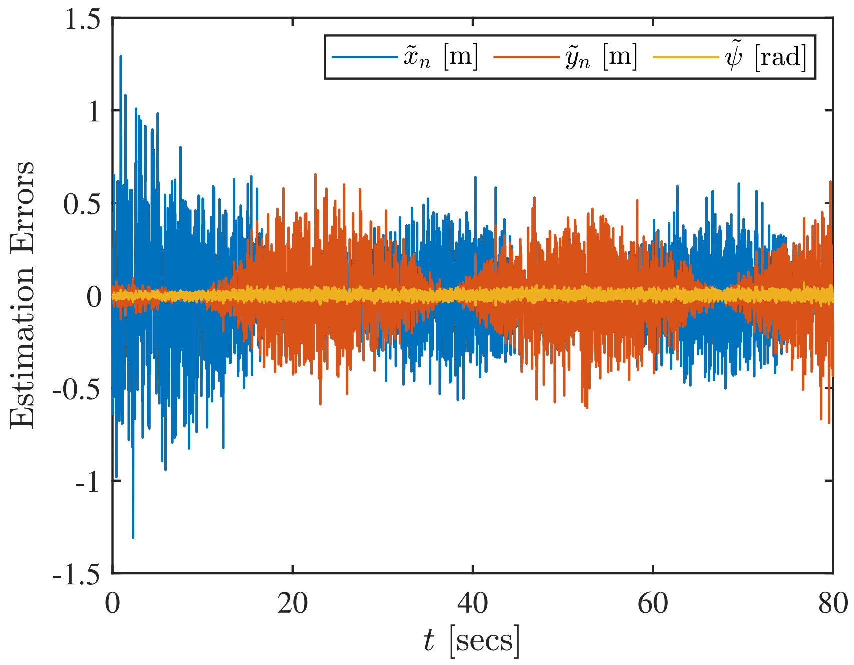
Estimation errors with EKF



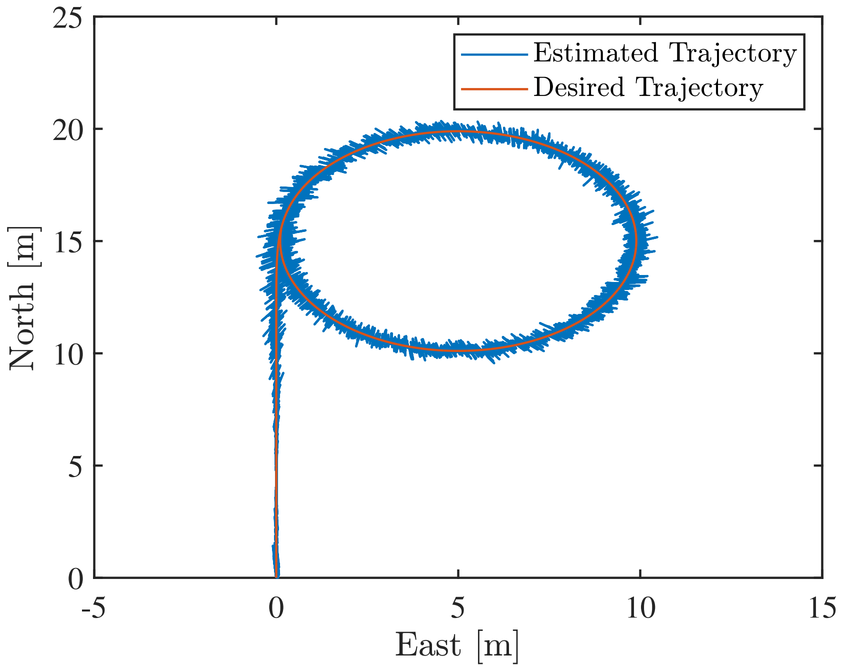
Desired and estimated trajectory with EKF

Results: Heading estimate is less precise, but good tracking of desired trajectory

Simulations: HOSMO



Estimation errors with HOSMO



Desired and estimated trajectory with HOSMO

Results: Better tracking of heading angle with respect to EKF

Note: Pose estimates generated by both observers are very sensitive to IMU noise → performance degrades as noises in the measurements of ϕ, θ and angular rate increase

Conclusions

- **Problem**: localization of an AUV with respect to a fixed USV, using BEDD measurements
- **Solution**: estimation of positions along North and East and of heading with EKF and HOSMO
- **Results**: considering a circle maneuver, EKF performs better in position tracking, HOSMO tracks heading angle better
- **Future directions**: modify HOSMO to improve its tracking capabilities

Thank you for your attention!

Any comments or questions?

Bibliography I

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