Trajectory Planning and Control of Bathy-drone: A Drone Towing a Boat equipped with Sonar for Bathymetry Mapping

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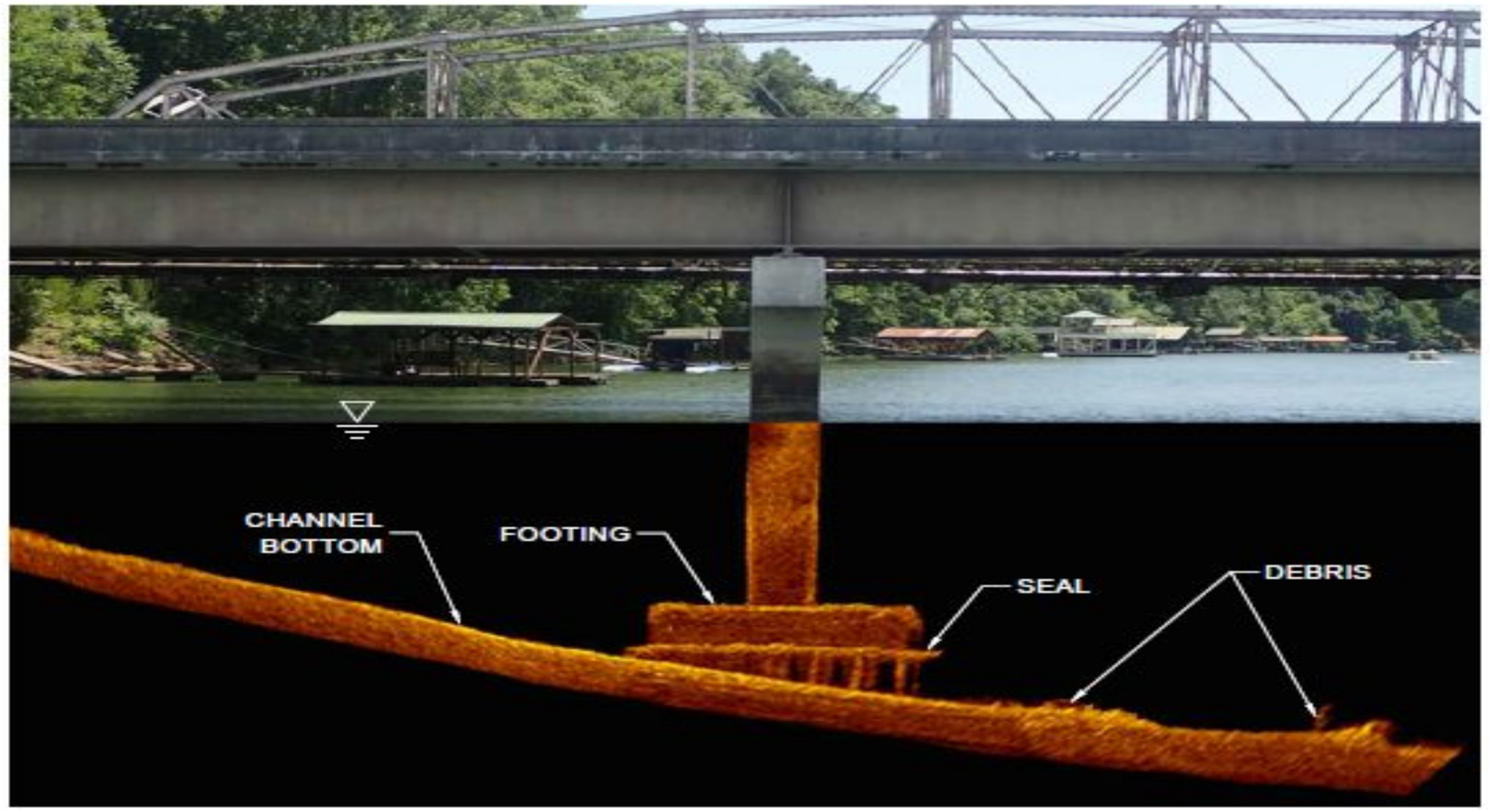
Bathymetry: Potential Applications

Artificial object inspection (pipes, bridges)



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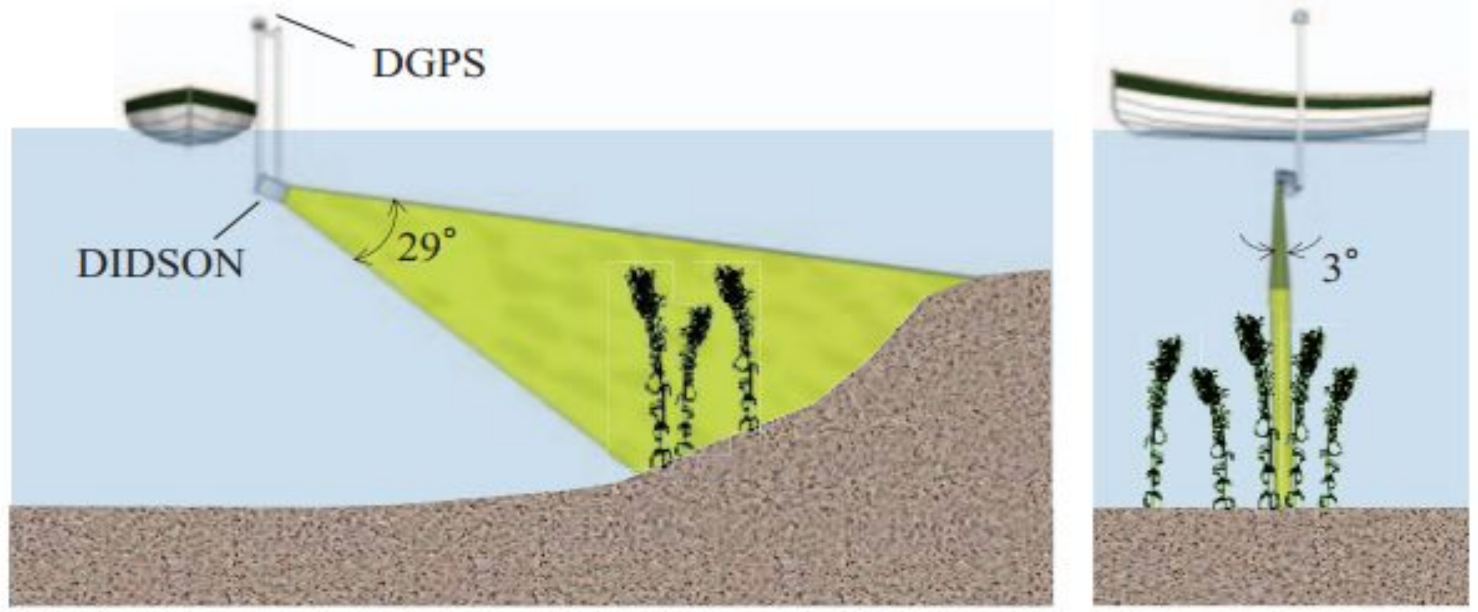

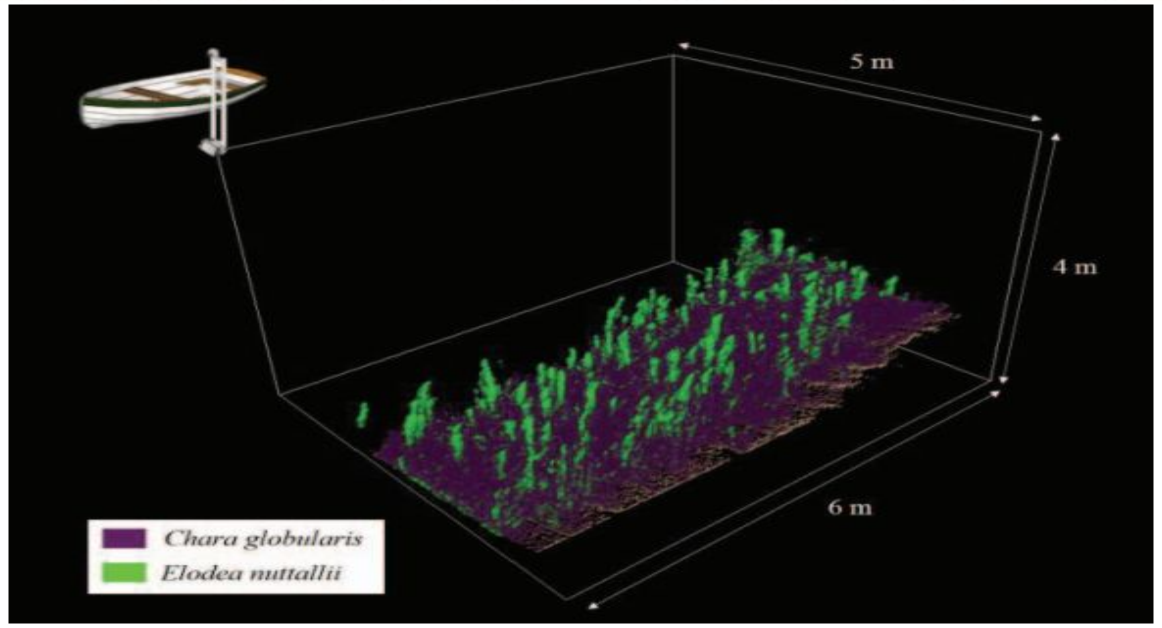

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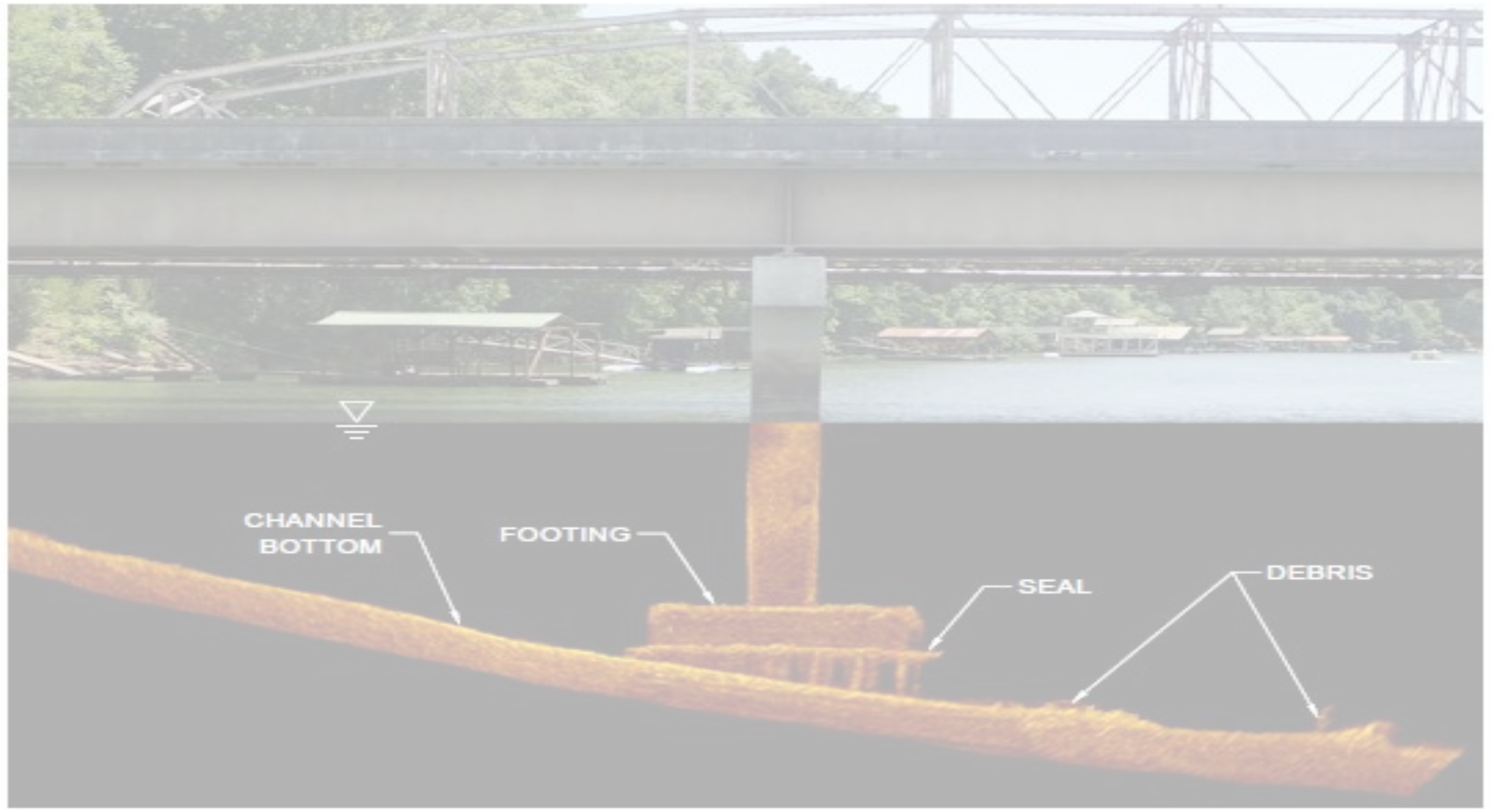

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Survey of aquatic plants

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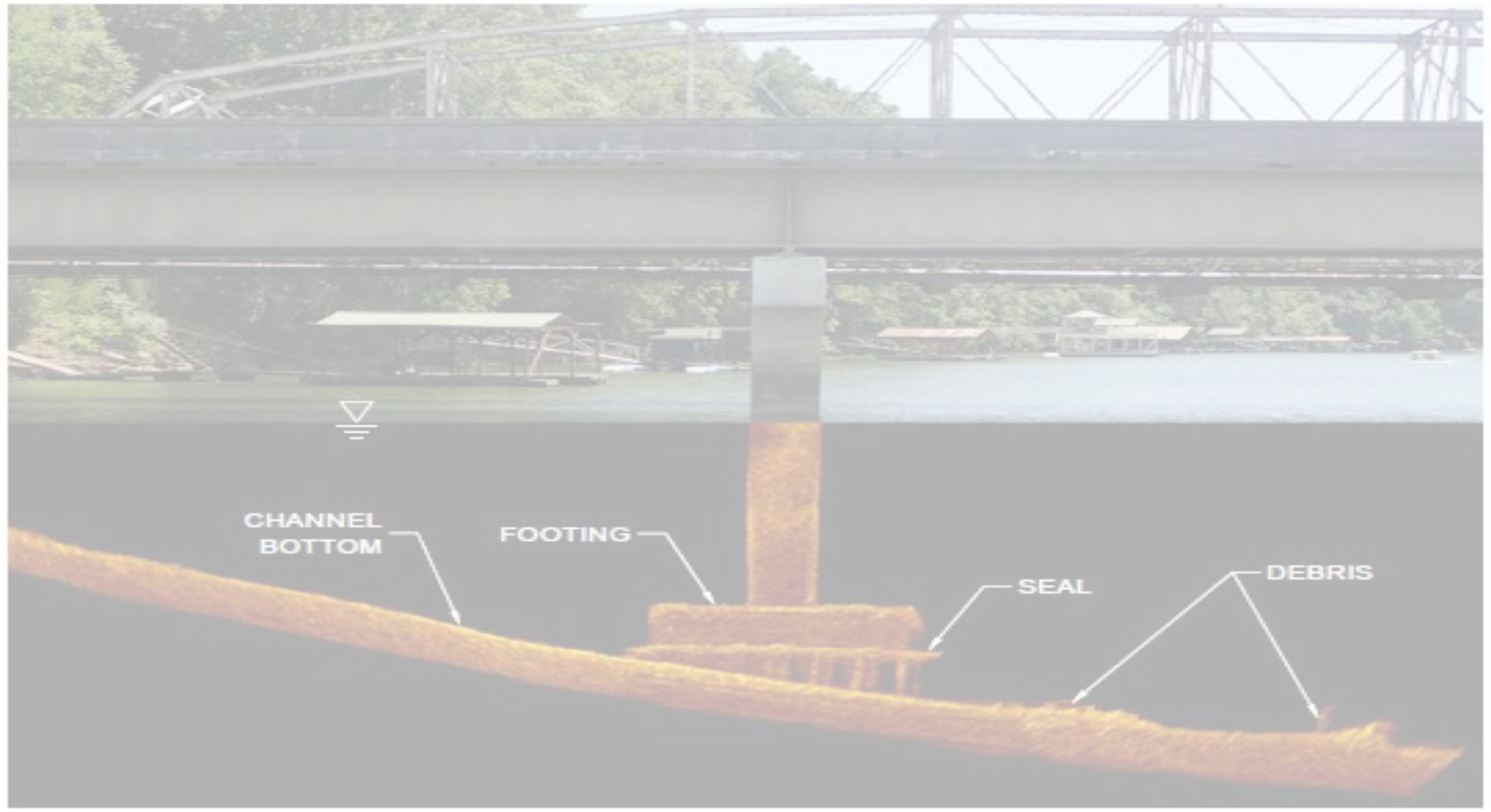

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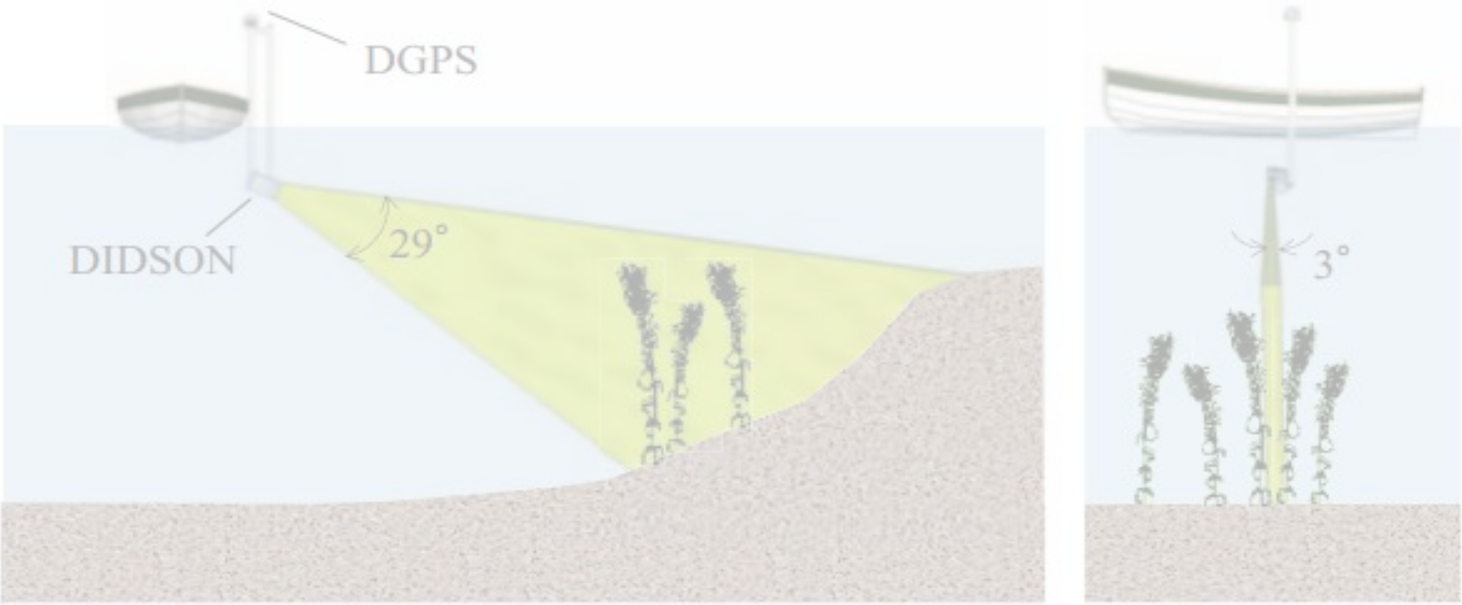

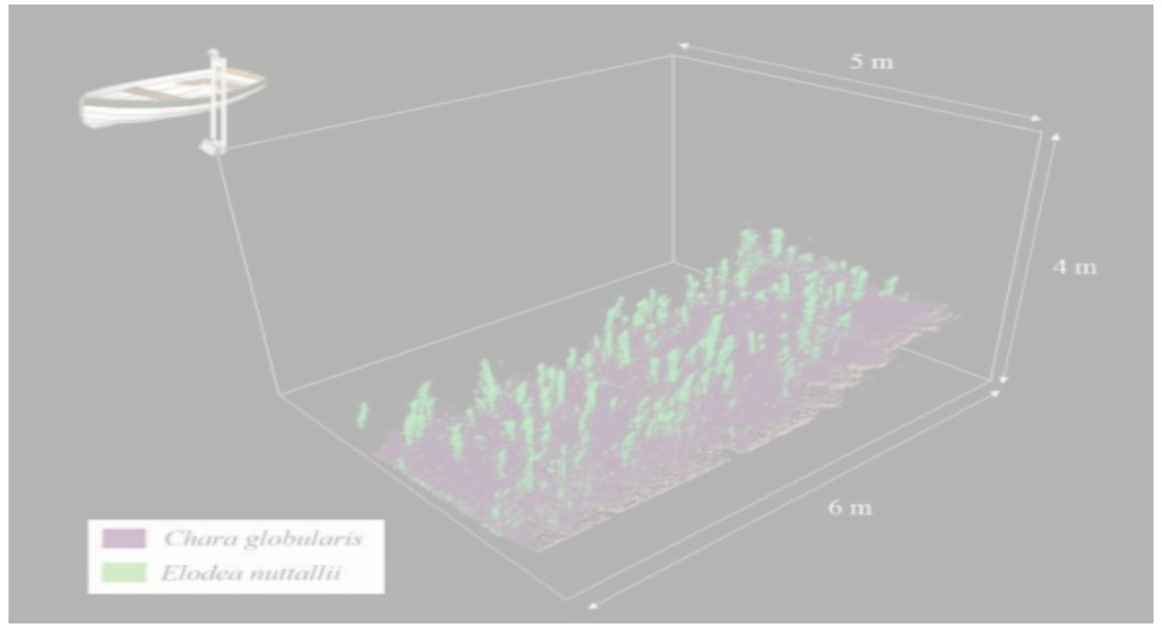

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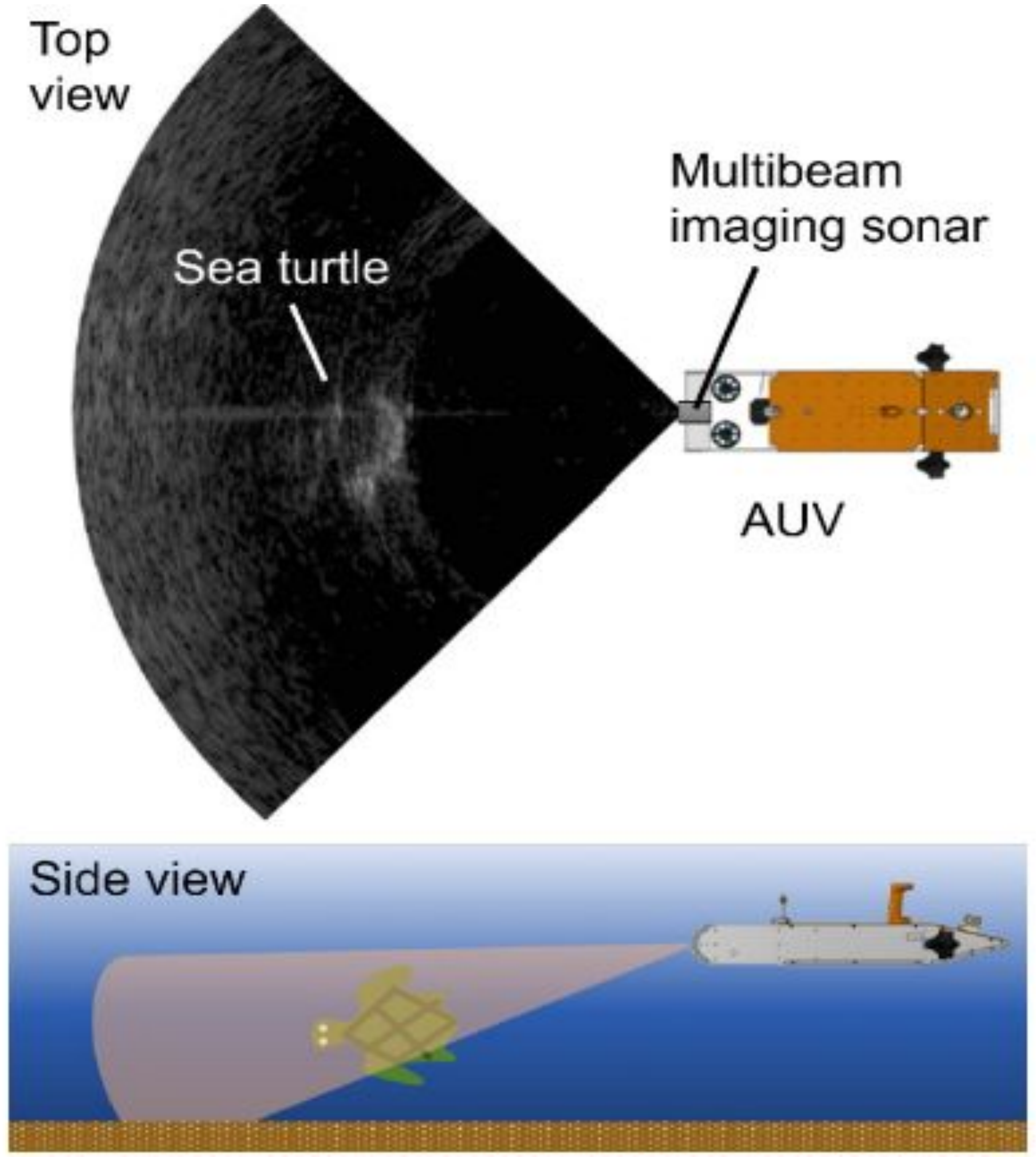
- Survey of aquatic plants

Survey of marine life



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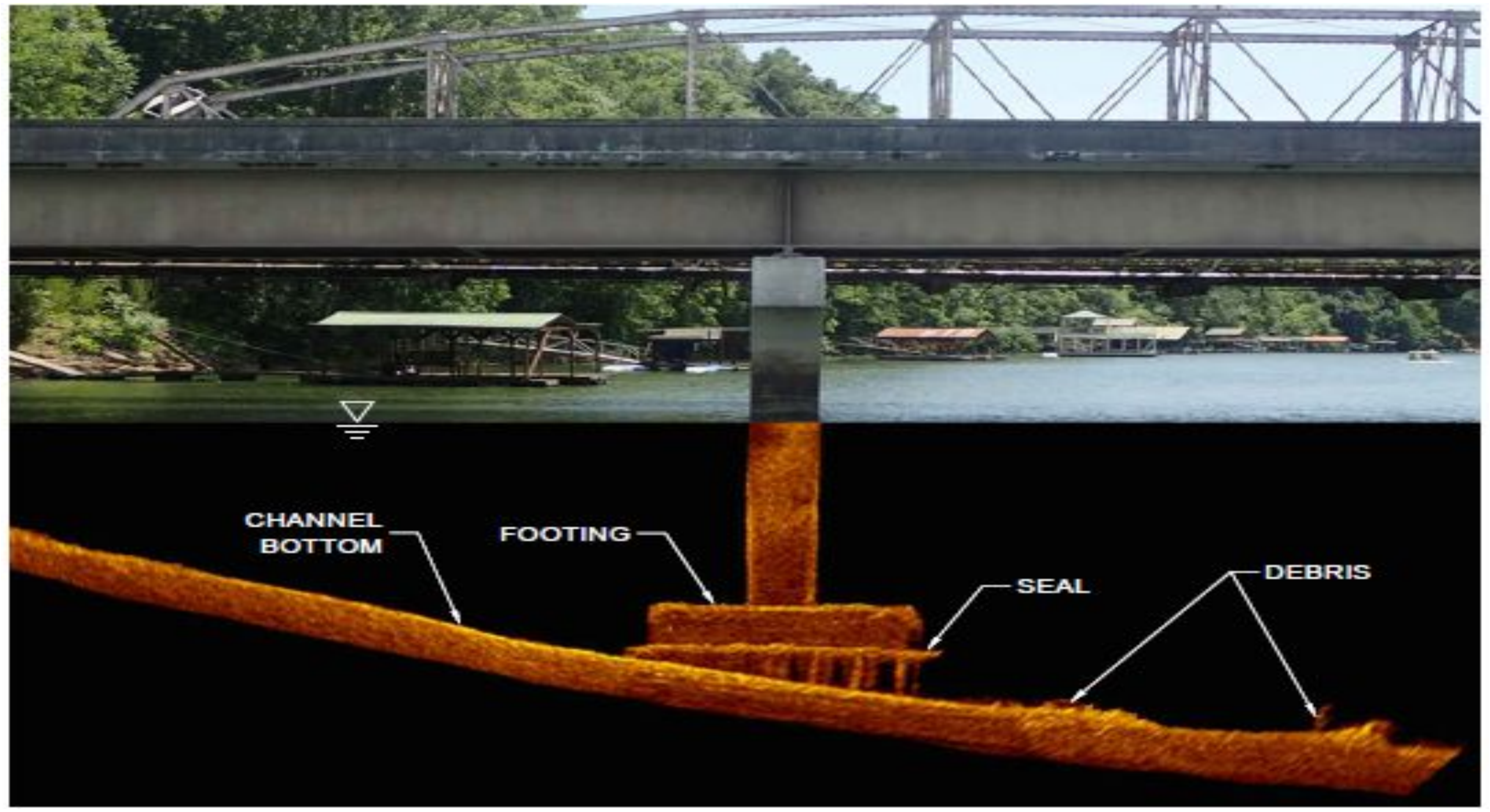

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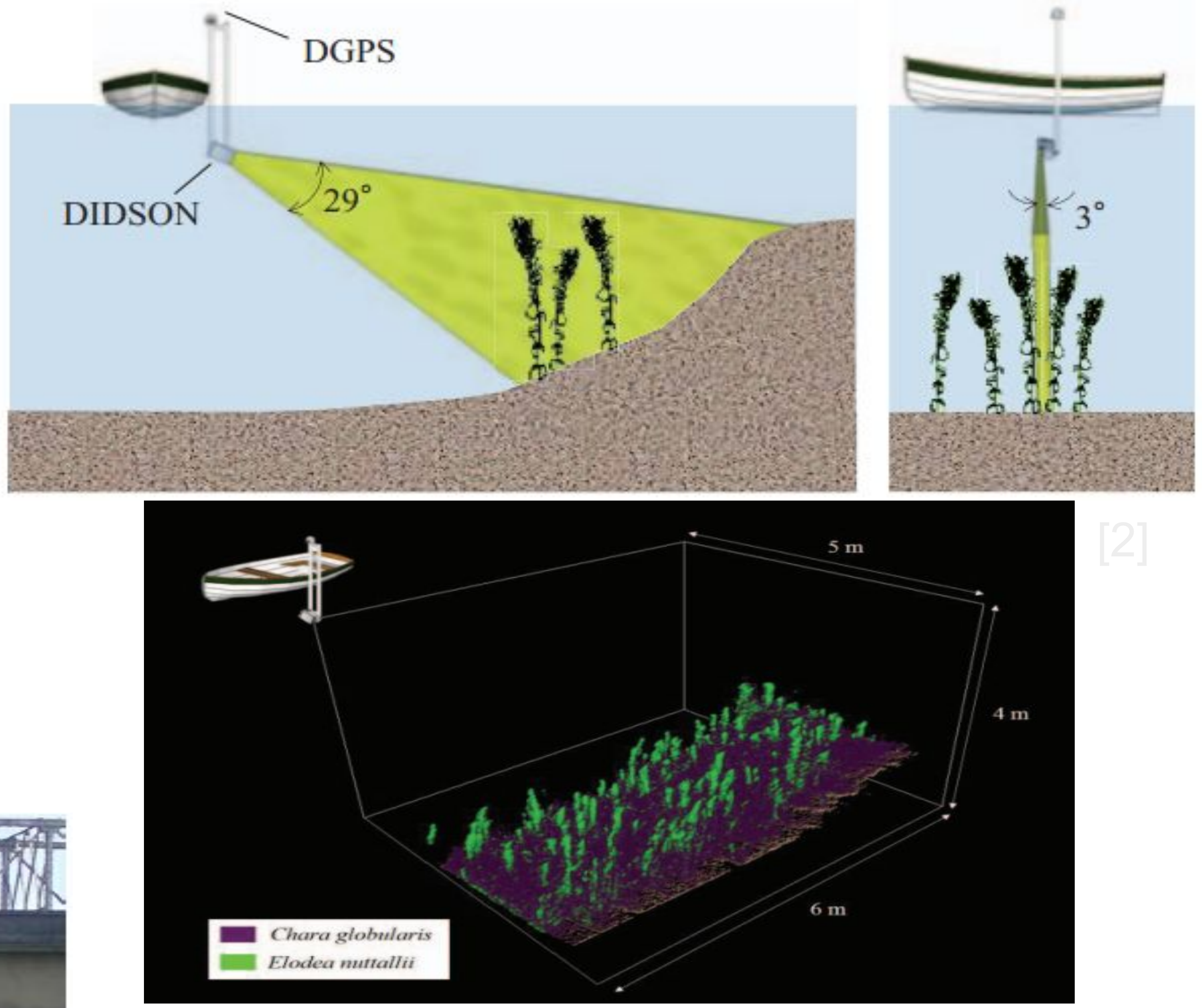

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Survey of aquatic plants

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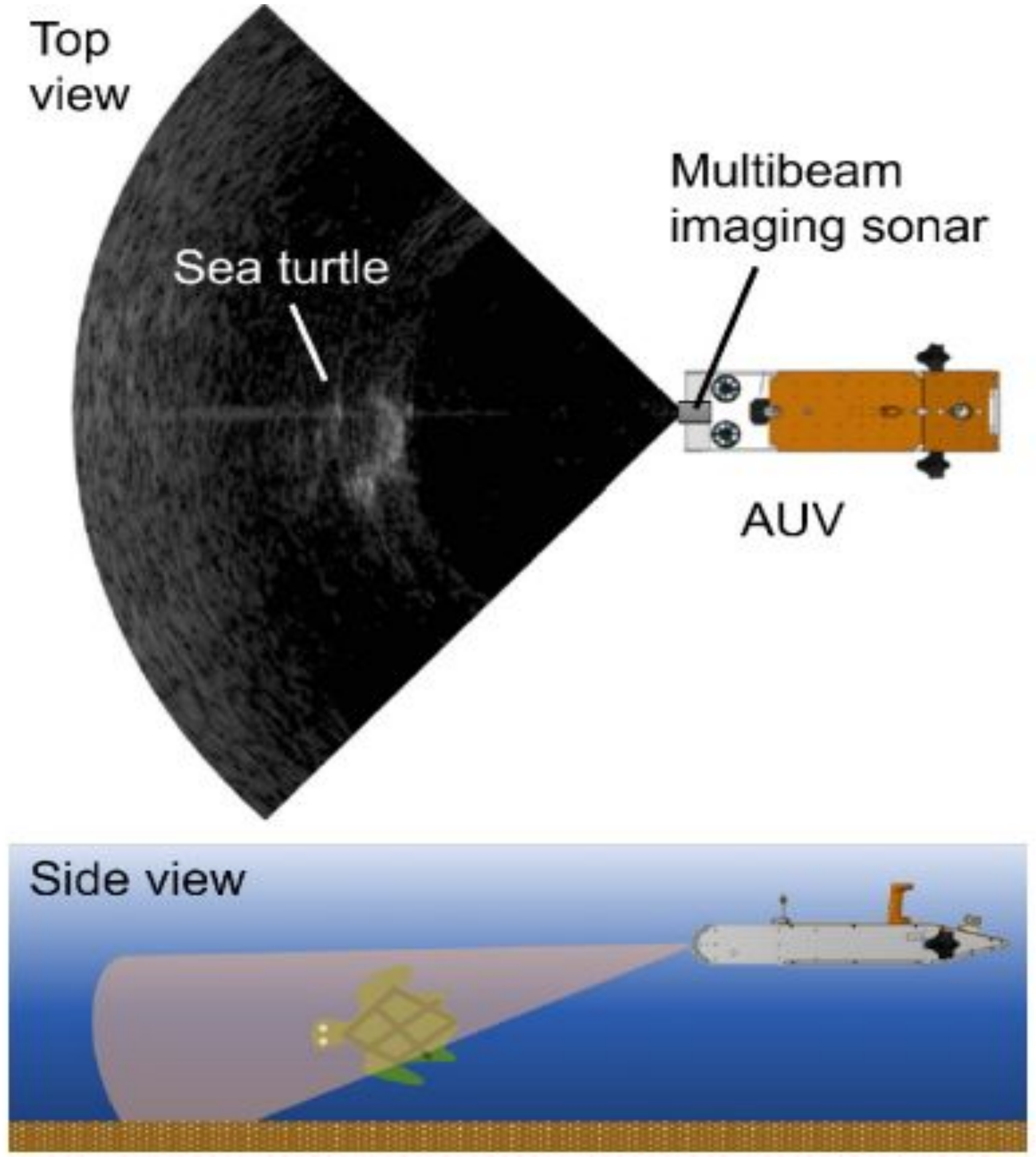
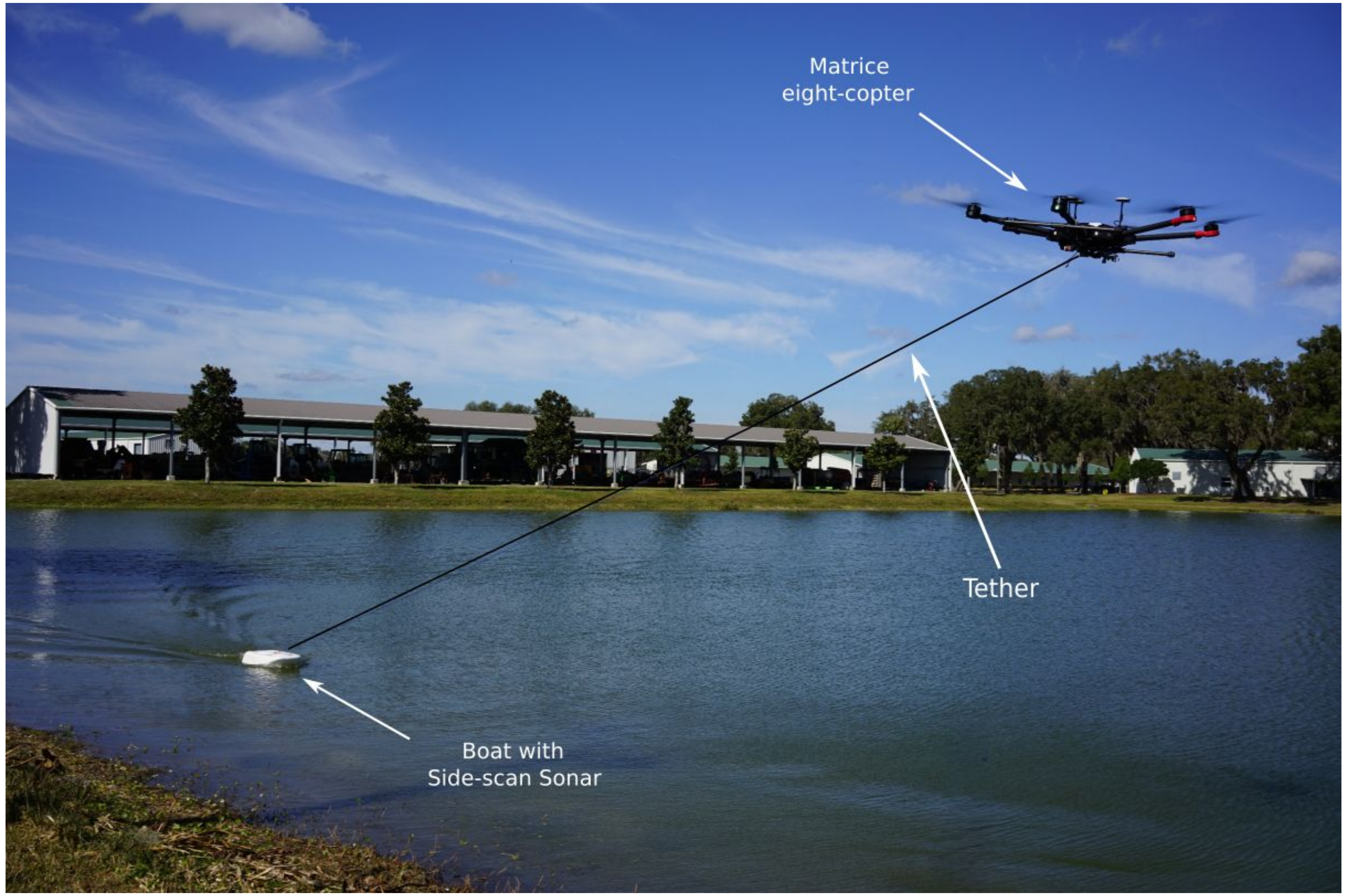


[3]

The Bathy-drone

- Autonomous **drone towing a tethered boat** equipped with a sonar
- Can be flown to the survey location
- No propulsion system on boat
- Can traveling at speeds of 0-15 mph
- The boat houses a low-cost commercial off-the-shelf recreational fish-finder and a downscan sonar



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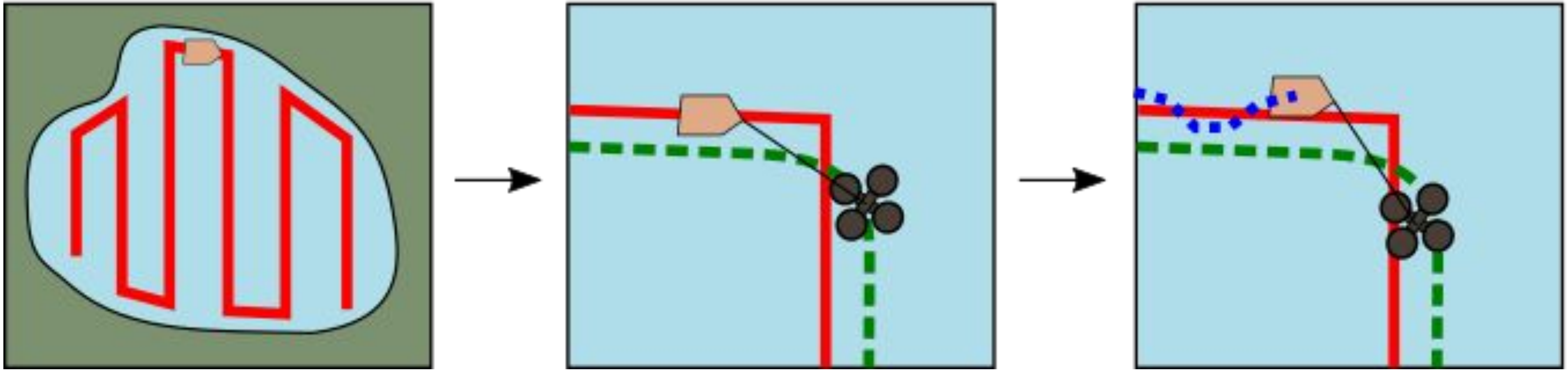
The Bathy-drone

Objective

- develop a G&C system that can handle the tethered dynamics such that the onboard sensor's field-of-view fully **covers the region of interest**

- Need to solve the following three components:

Boat Path Planning | Boat Trajectory Planning | Trajectory Tracking Control



SPARSE POINT CLOUD GENERATION AND AUTOMATIC OBJECT DETECTION USING BATHY-DRONE

The algorithm consists of two stages:

(1) Dynamic model
(2) Tracking Control
(3) Trajectory Planning
(4) Path Planning

Dynamic Model

Dynamics Model of Bathydrone

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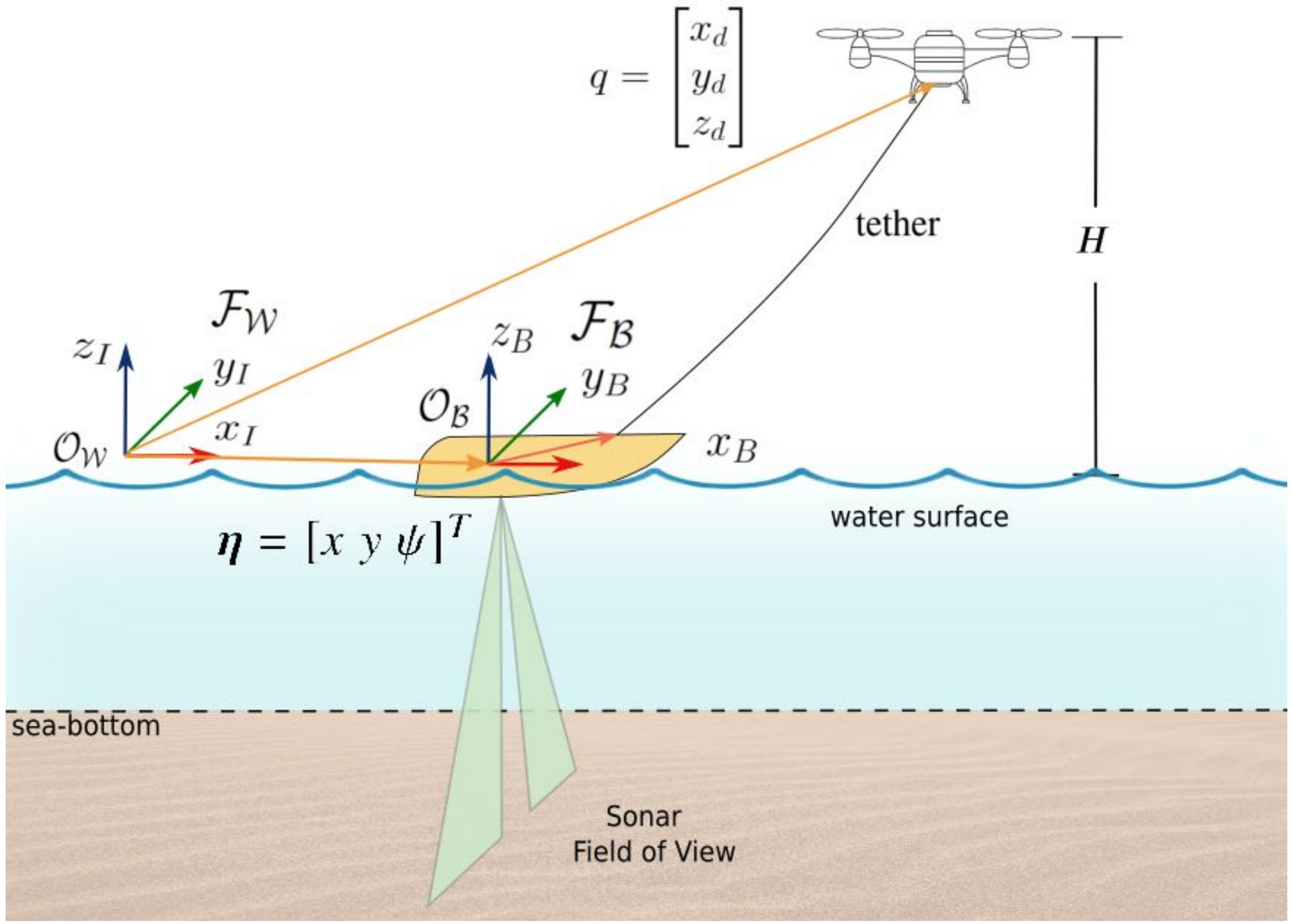
- The hydrodynamics model of the boat getting pulled by the tether can be derived by with a FBD
- Tension force is calculated by the pose difference between boat and drone



Mass matrices — Coriolis matrices — Drag matrix — Tension Force of tether

$$\underbrace{\boldsymbol{M}_{RB}\dot{\boldsymbol{\nu}} + \boldsymbol{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu}}_{\text{rigid-body forces}} + \underbrace{\boldsymbol{M}_{A}\dot{\boldsymbol{\nu}}_r + \boldsymbol{C}_{A}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \boldsymbol{D}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r}_{\text{hydrodynamic forces}} = \boldsymbol{\tau}$$

Dynamics Model of Bathydrone

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Adding the rigid-body and hydrodynamic forces matrices:

$$M = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_g - Y_{\dot{r}} \\ 0 & mx_g - Y_{\dot{r}} & I_z - N_{\dot{r}} \end{bmatrix}$$

$$C(v) = \begin{bmatrix} 0 & 0 & -mx_g r - mv + Y_{\dot{v}} v + Y_{\dot{r}} r \\ 0 & 0 & mu - X_{\dot{u}} u \\ mx_g r + mv - Y_{\dot{v}} v - Y_{\dot{r}} r & -mu + X_{\dot{u}} u & 0 \end{bmatrix}$$

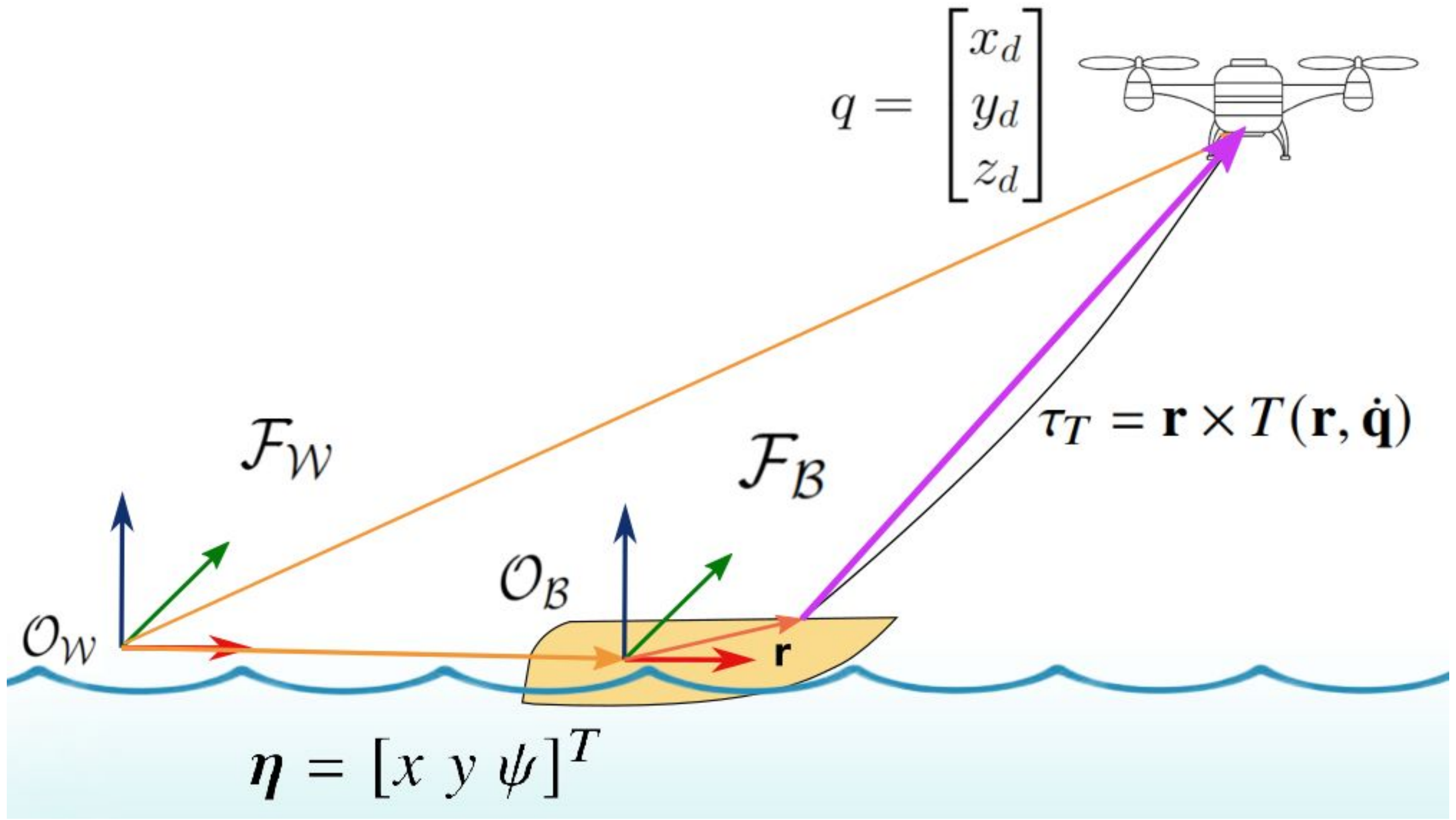
$$D(v) = \begin{bmatrix} -X_{|u|u}|u| & 0 & 0 \\ 0 & -Y_{|v|v}|v| - Y_{|r|v}|r_\psi| & -Y_{|v|r}|v| - Y_{|r|r}|r_\psi| \\ 0 & -N_{|v|v}|v| - N_{|r|v}|r_\psi| & -N_{|v|r}|v| - N_{|r|r}|r_\psi| \end{bmatrix}$$

Tension Force applied to the Boat

- Applied in a determined application point r
- Tension direction is the position of the drone relative to the boat
- Magnitude measured experimentally

$$\frac{\boldsymbol{T}}{||\boldsymbol{T}||} = \frac{\boldsymbol{q} - \boldsymbol{\eta} + (J(\boldsymbol{\eta}) \cdot \mathbf{r})}{||\boldsymbol{q} - \boldsymbol{\eta} + (J(\boldsymbol{\eta}) \cdot \mathbf{r})||}$$

$$M = \mathbf{r} \times T(\mathbf{r}, \dot{\mathbf{q}})$$



Tension Force Measurement

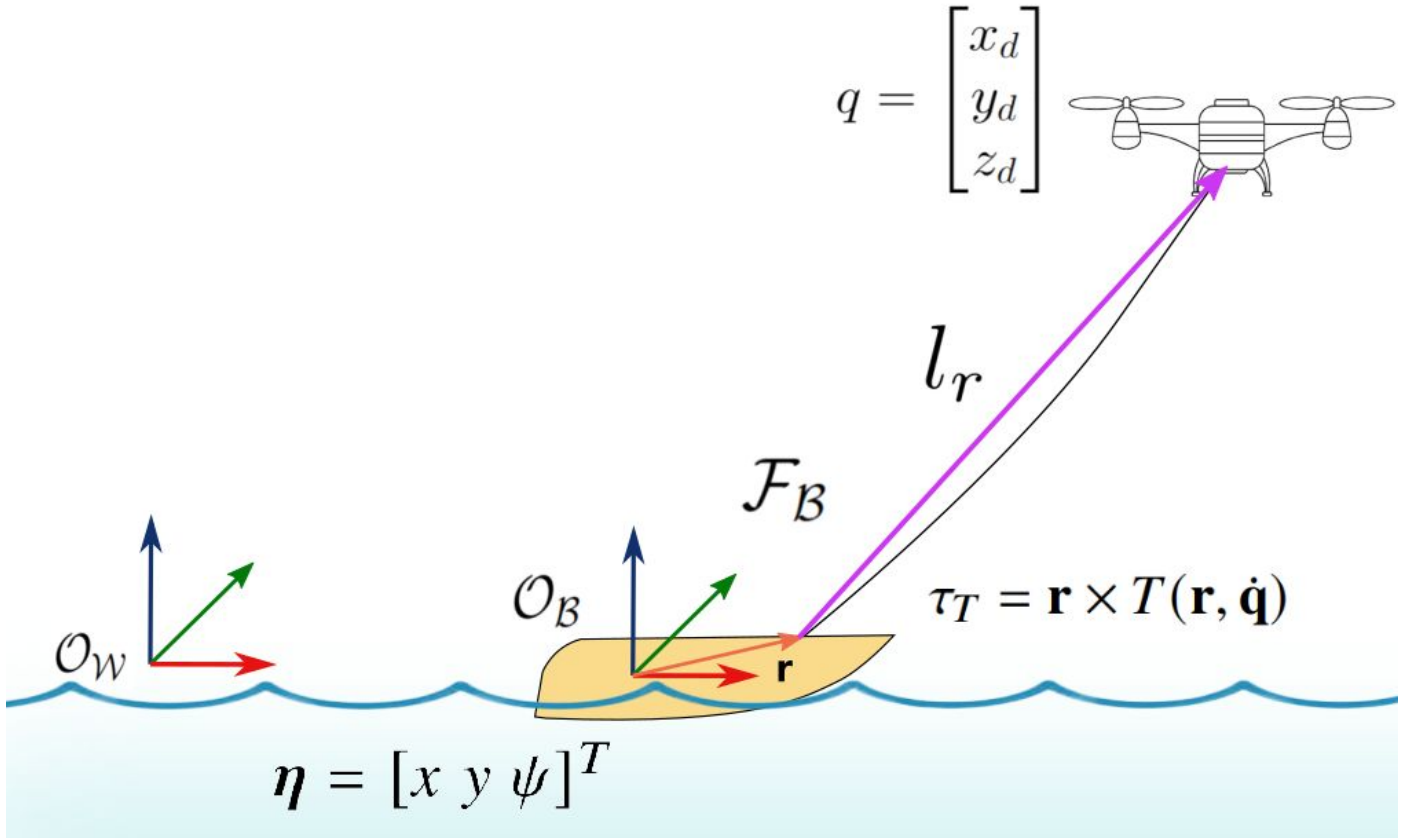
- **Force Gauge** in line with the rope of the boat and record the force as well as boat and drone inertial measurements to make model tension

NOTE: Force sensor not to scale

Tension Constraint

- We define an epsilon ϵ so that $l_r + \epsilon$ means drone is drone is going faster than vessel so we make drone velocity zero

- Additionally, $l_r - \epsilon$ means vessel is going faster than drone so we set the tension force to zero



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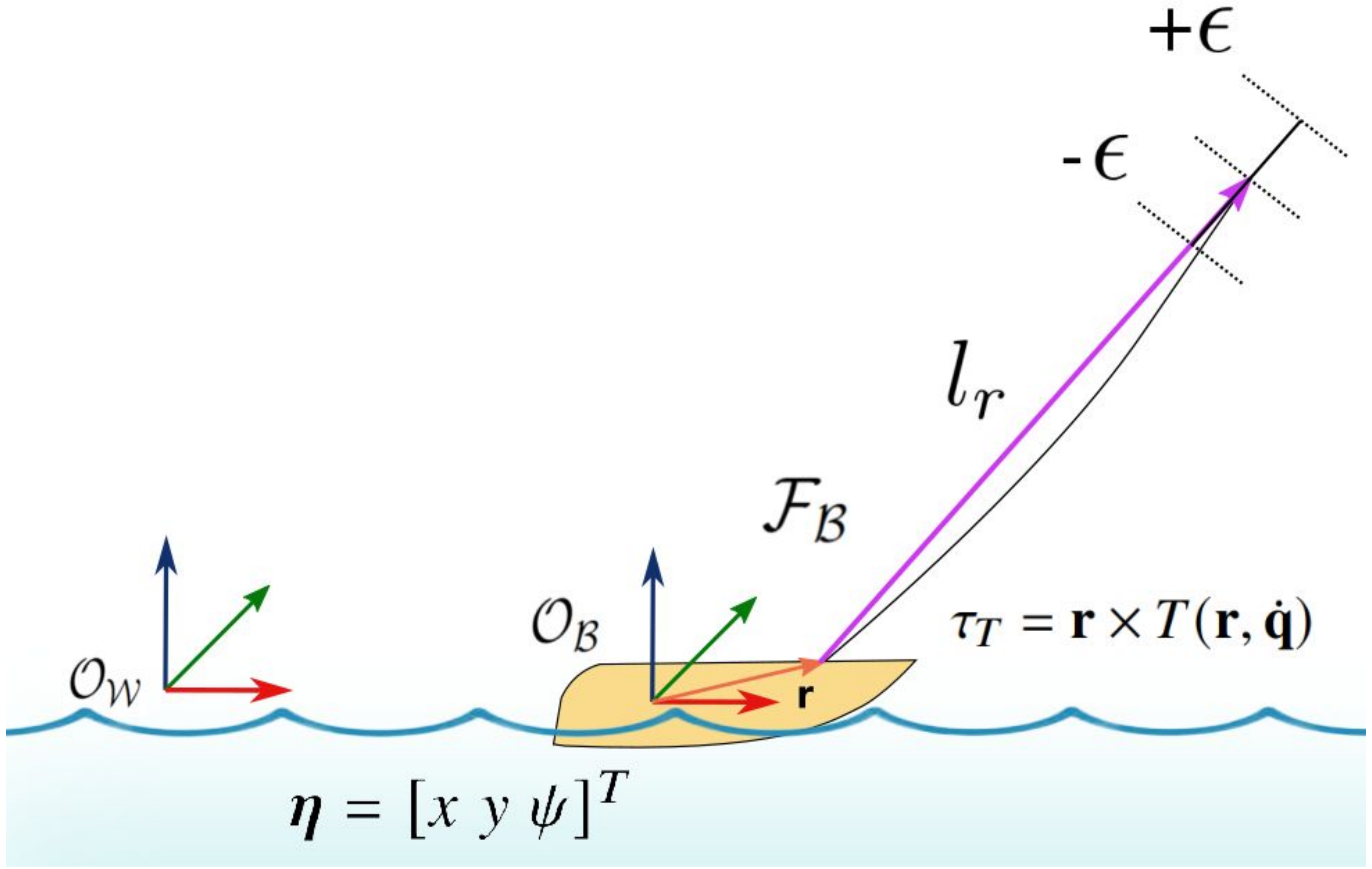
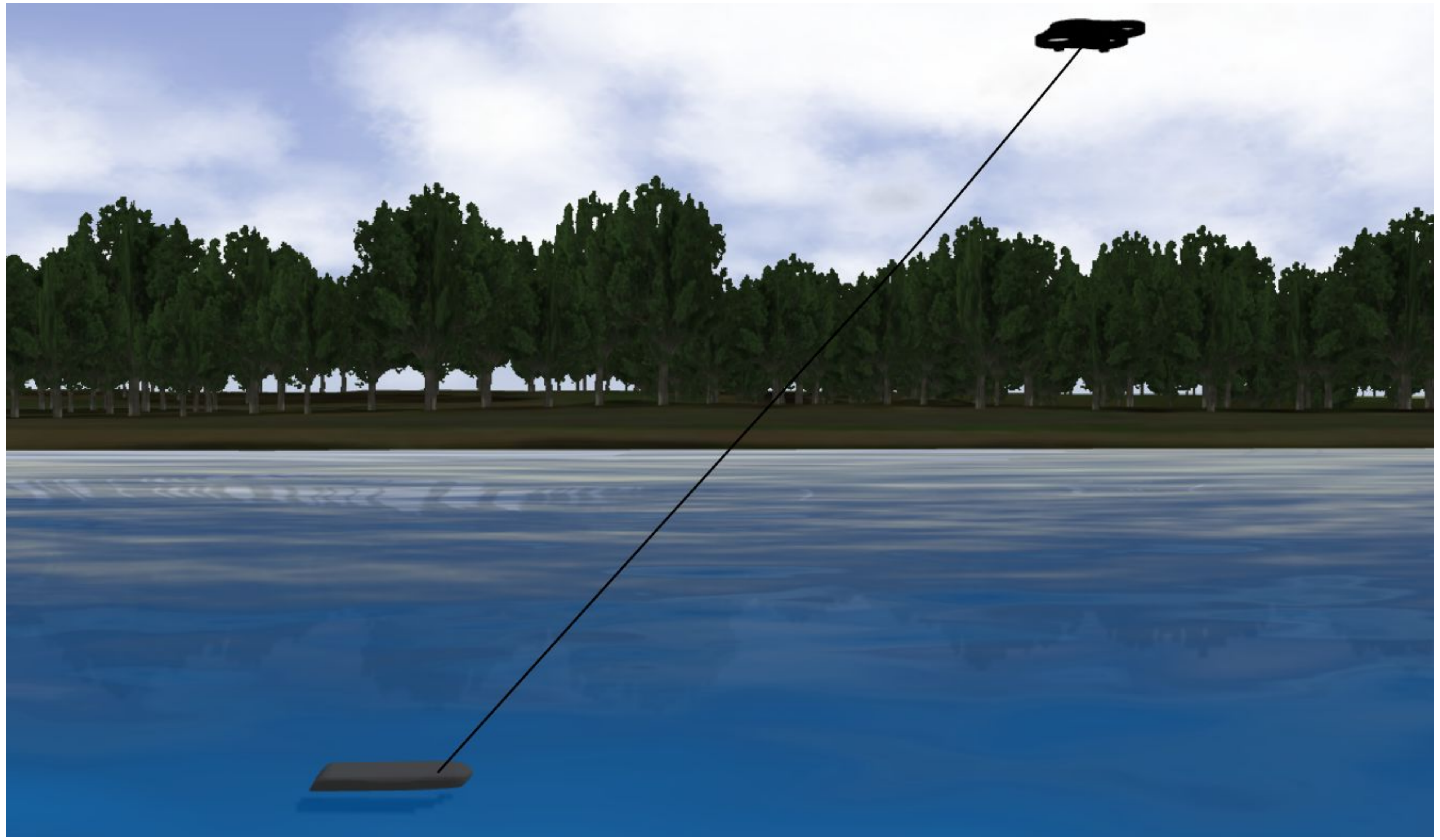
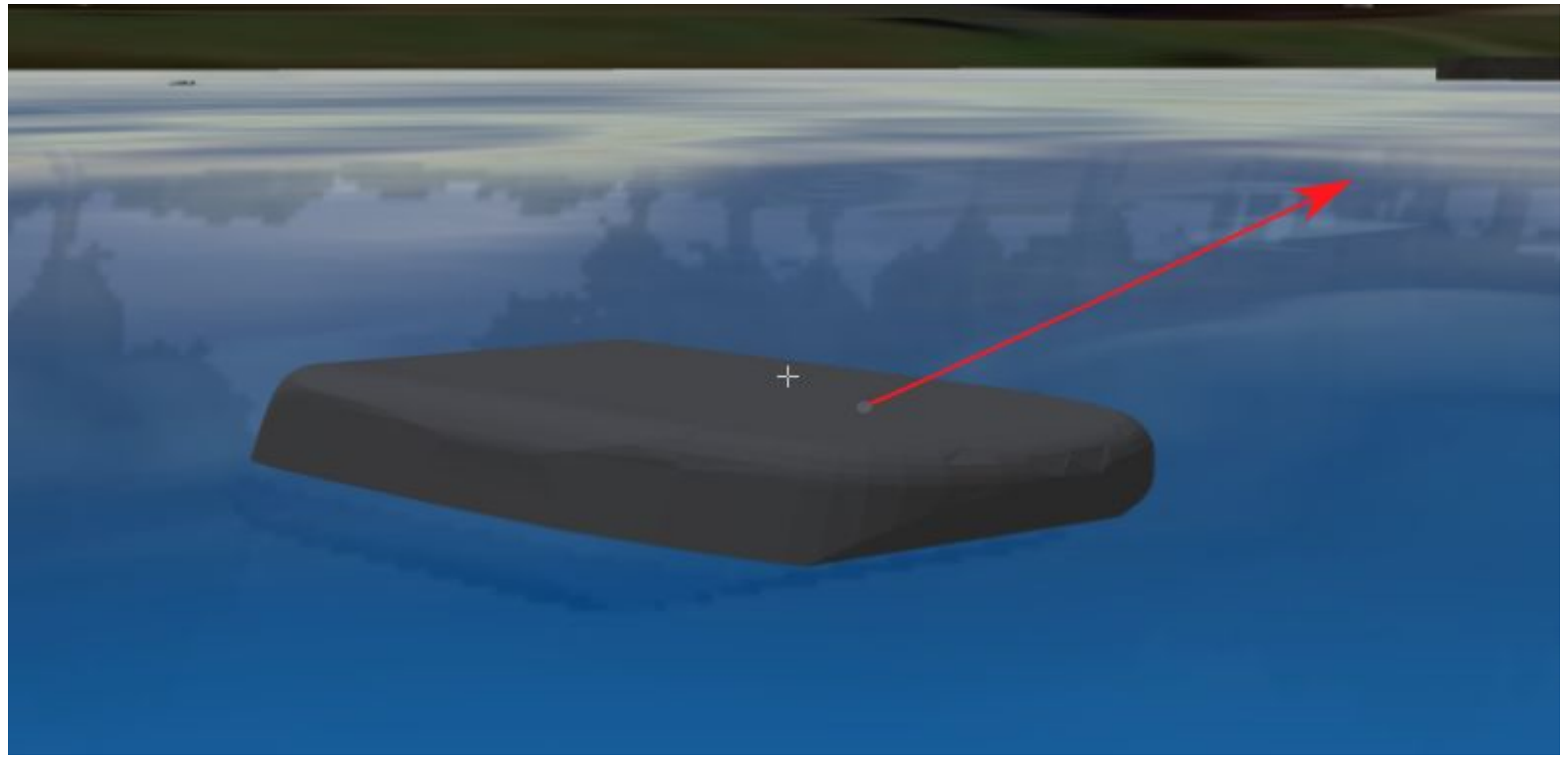


Gazebo Simulation

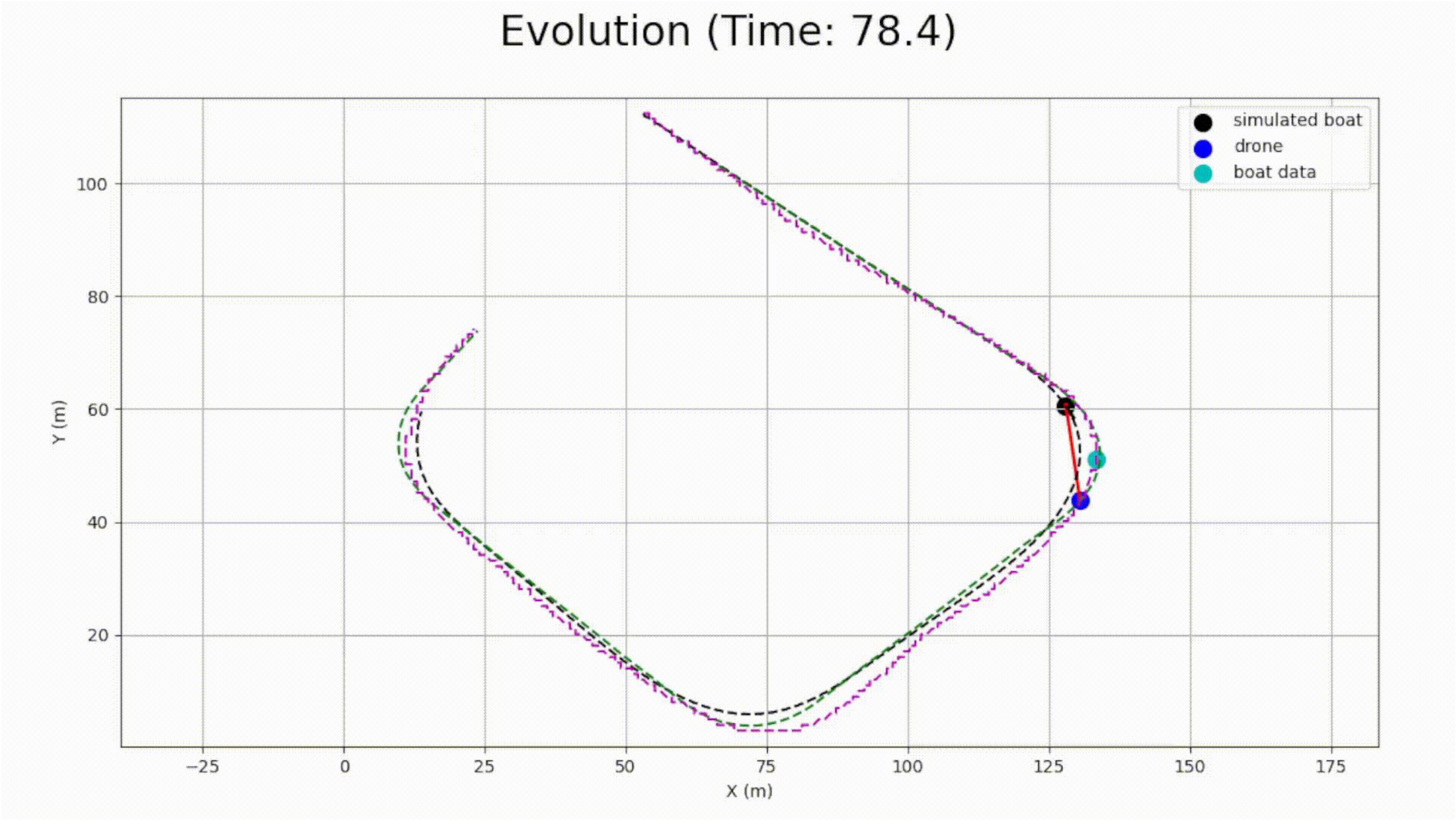
- ROS-based to implement communications in hardware
- Model (6DoF) hydrodynamics physics





Python Simulation

- Faster development and testing
- Model (3DoF) hydrodynamics physics



11x speed

Python Simulation

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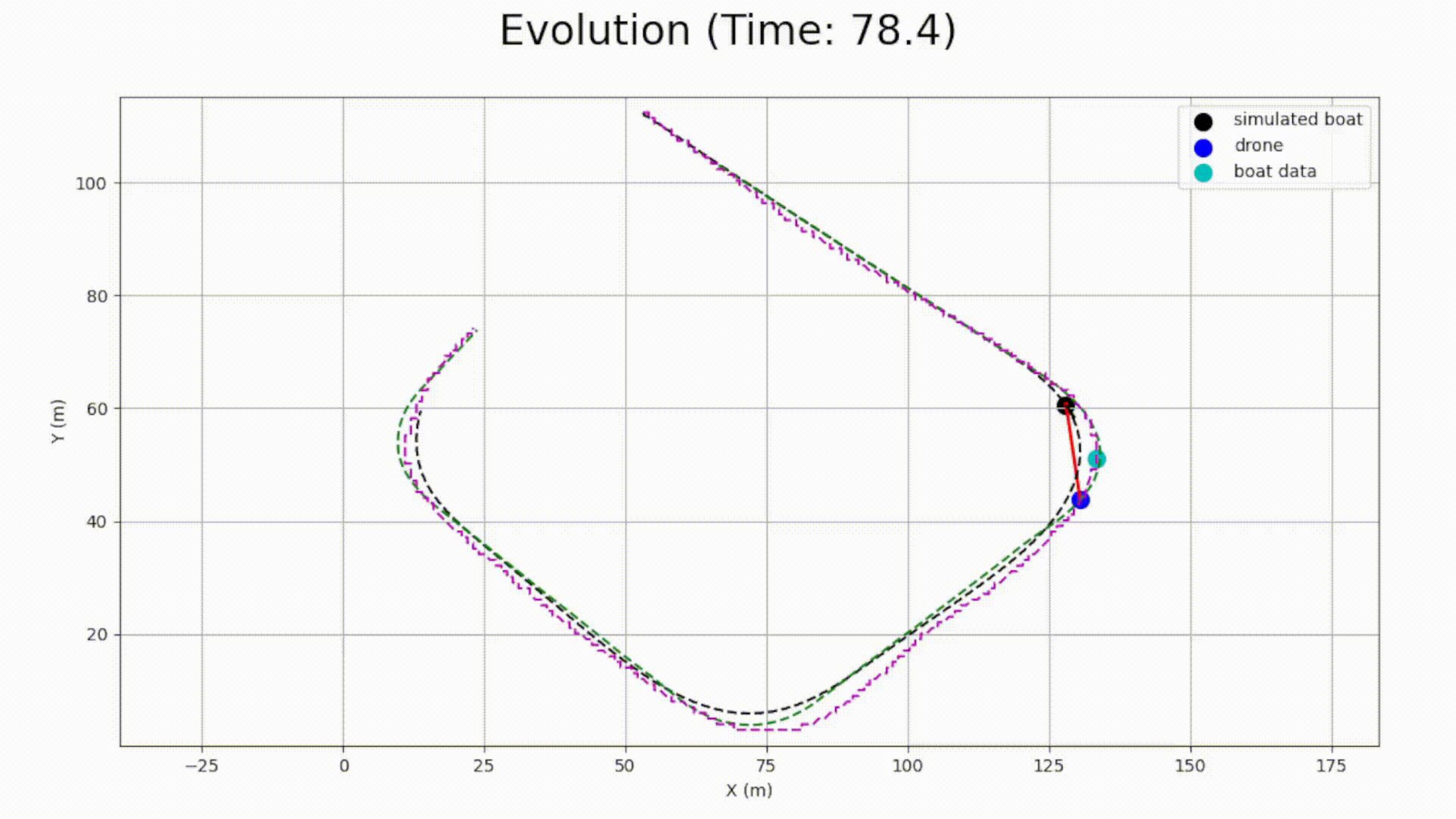
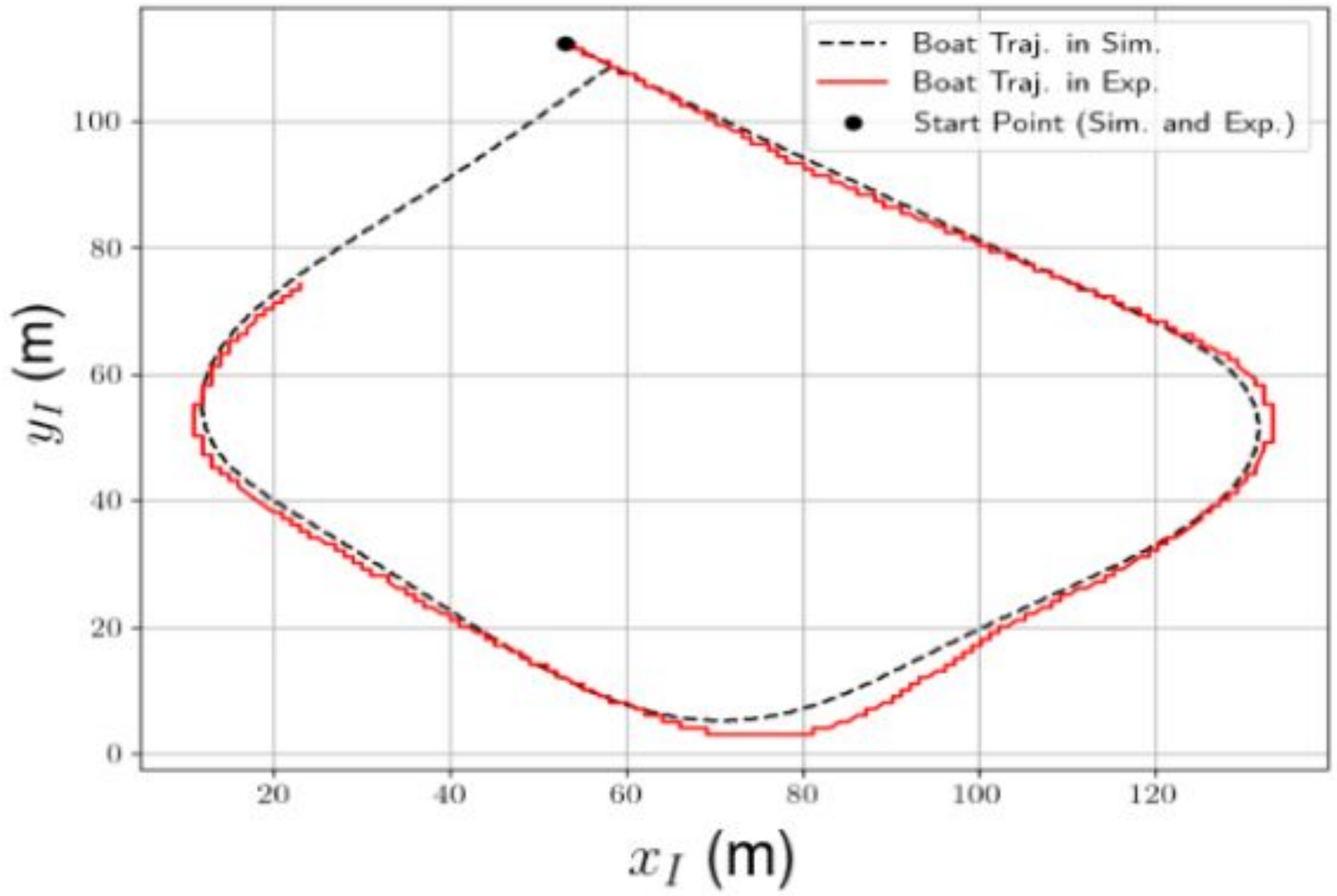
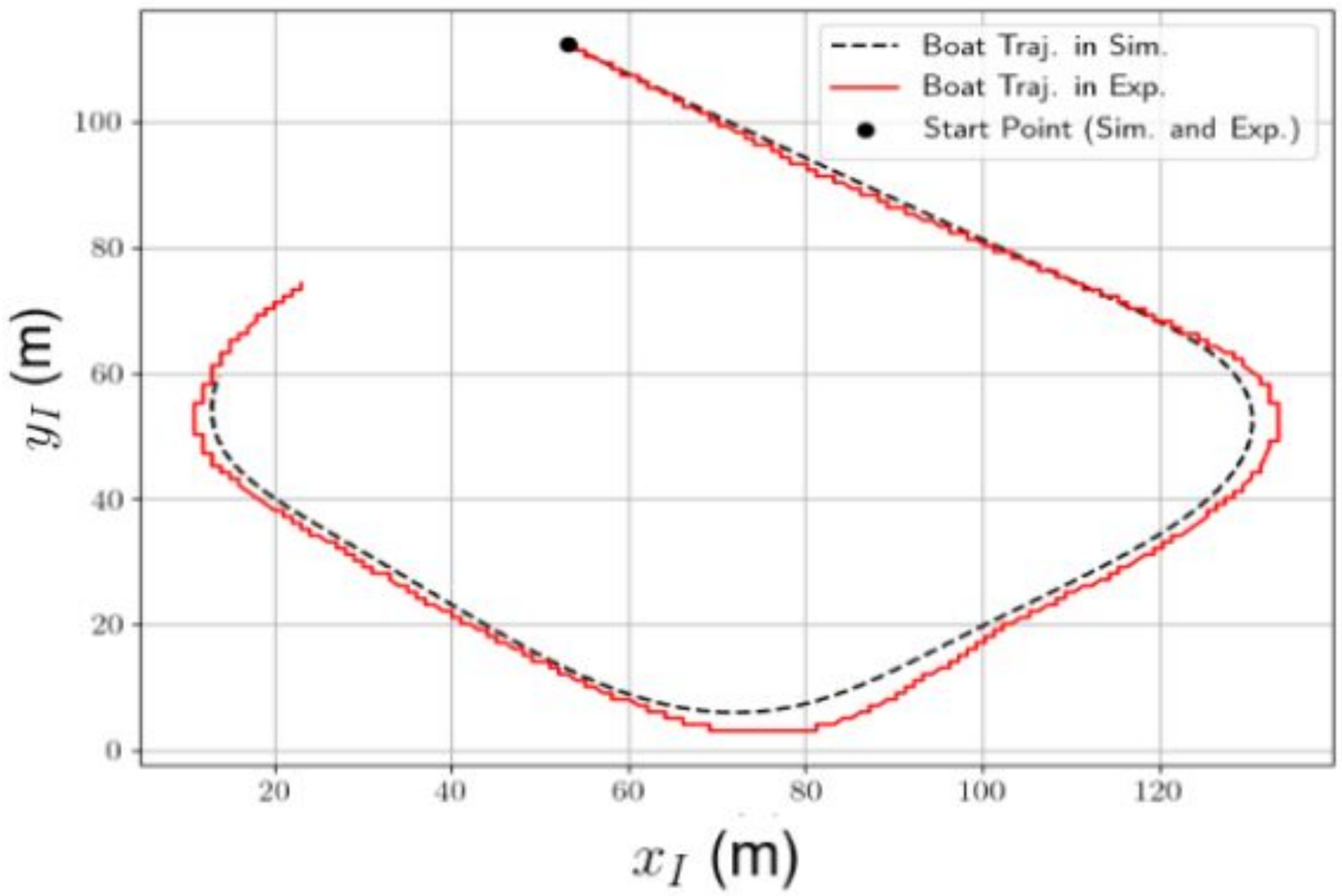


11x speed

Simulation Tuning

- Initial guess from Fossen Book [4]
- Tuned parameters to reduce error with data





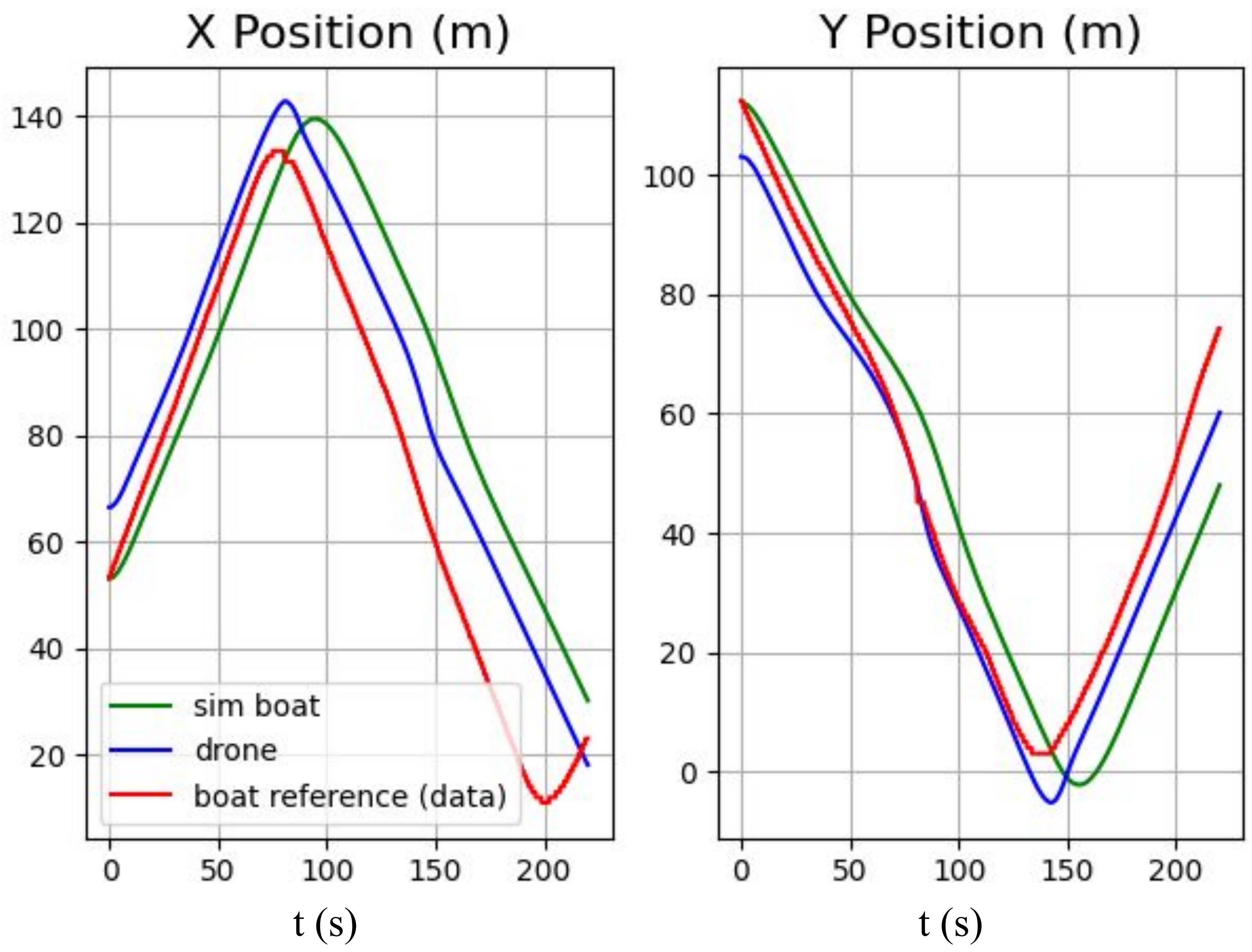
Trajectory Tracking Control

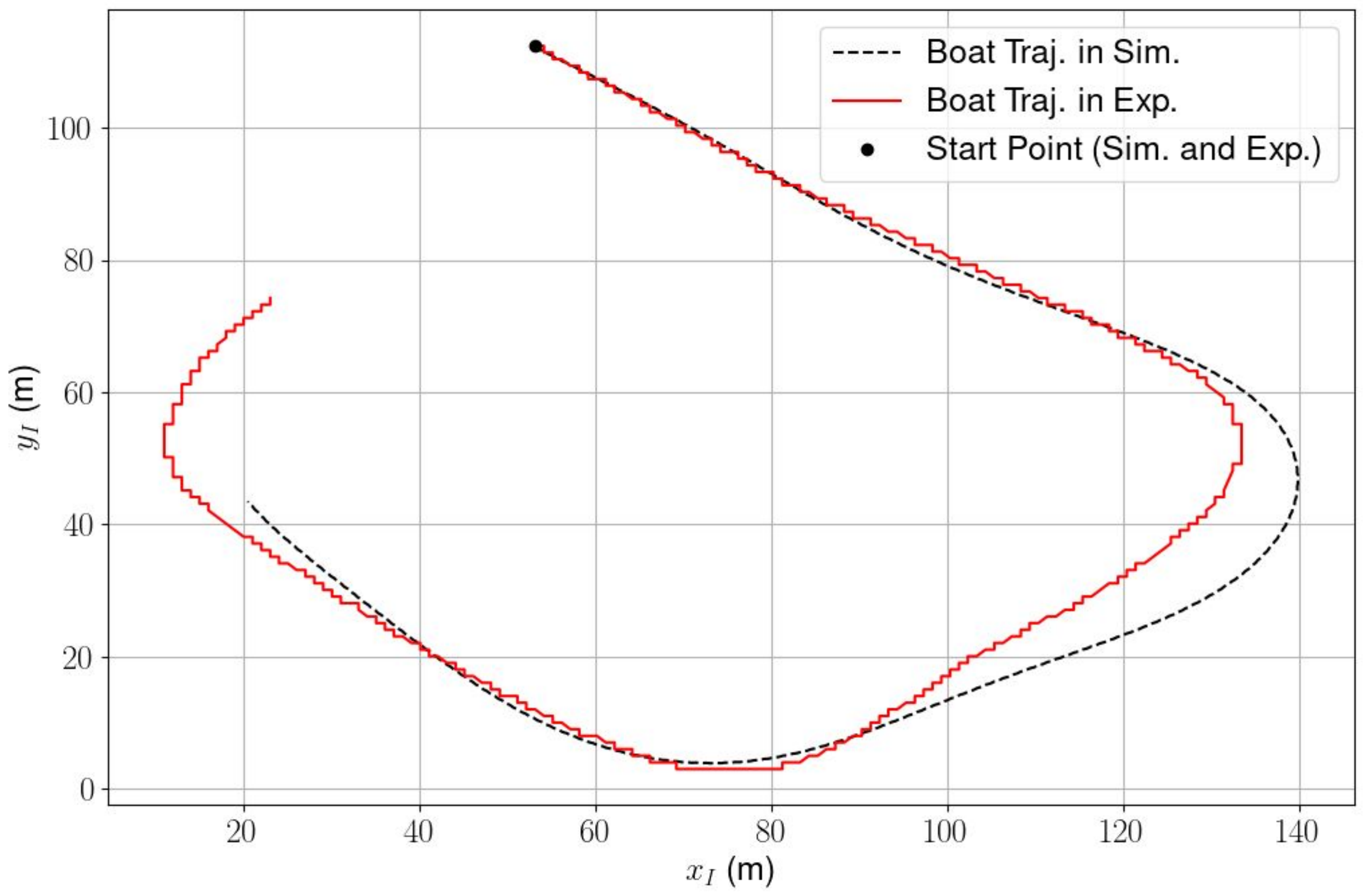
Tracking Controls

- Implemented PID control -> output is drone velocity

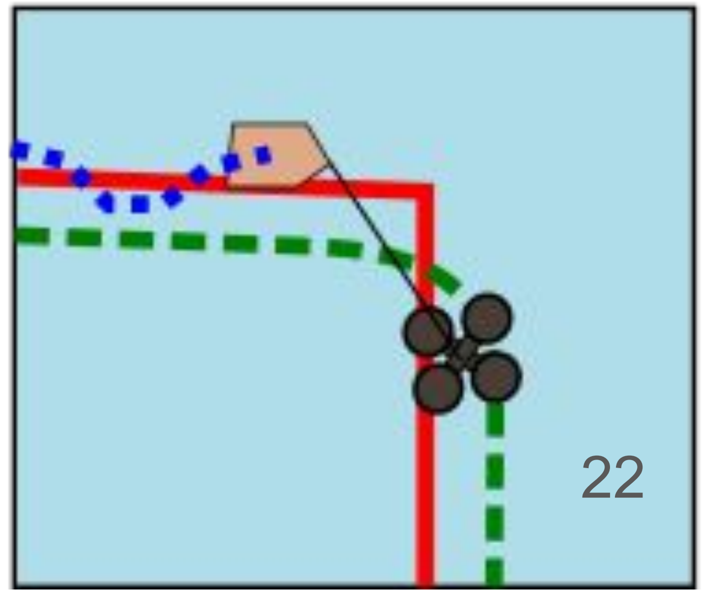
$$v_d = [v_x \; v_y \; 0]^T$$

$$\boldsymbol{v_d} = K_p \boldsymbol{e}(t) + K_i \int_0^t \boldsymbol{e}(t)dt + K_d \frac{\boldsymbol{de}(t)}{dt}$$





- **Mean Square Error X:** 422.3
- **Mean Square Error Y:** 230.4



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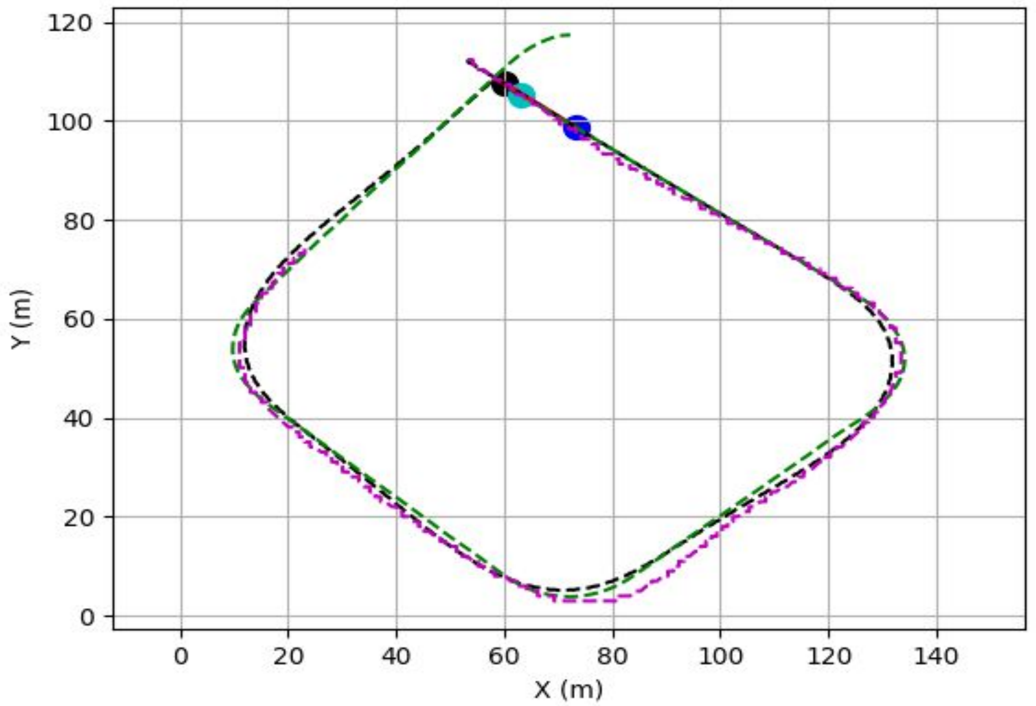

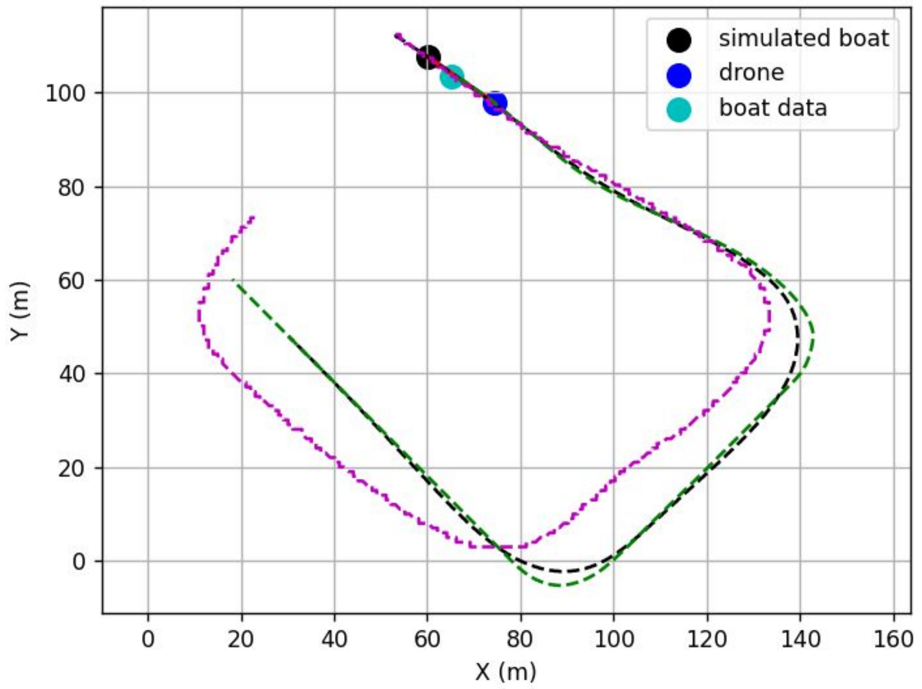

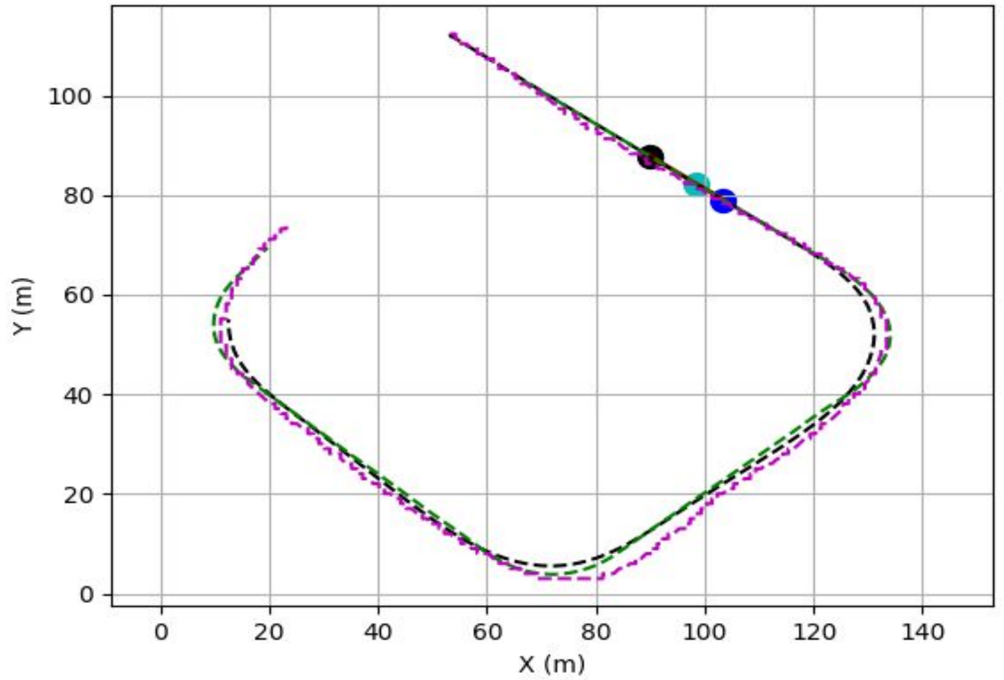

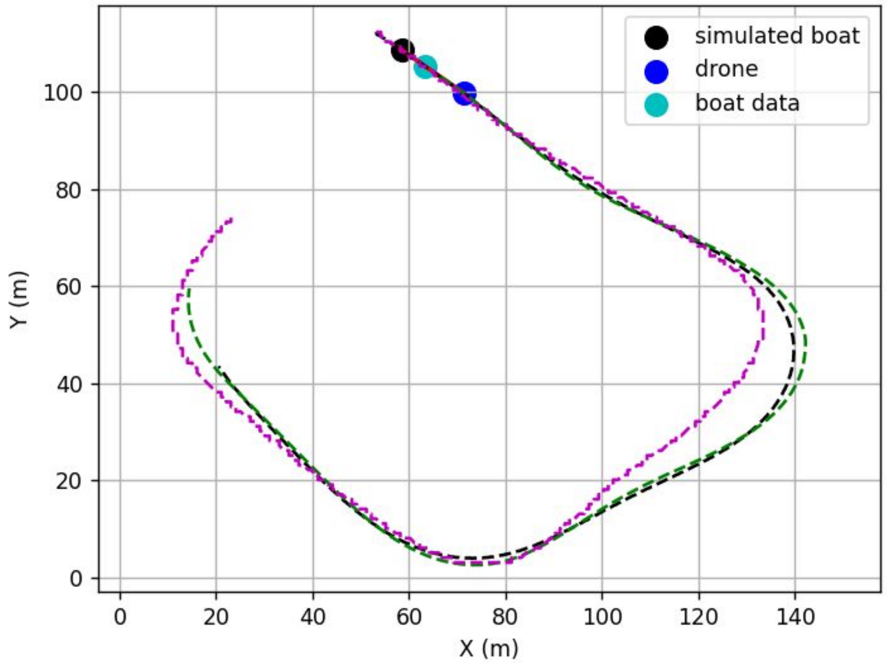

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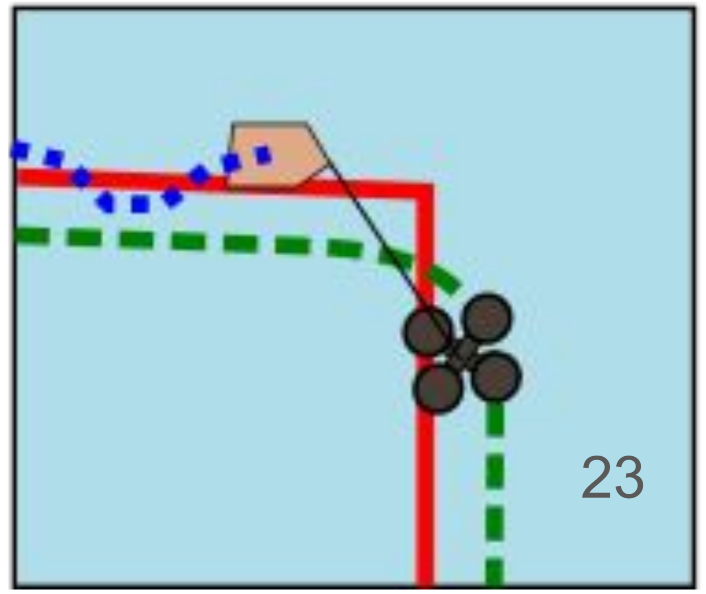
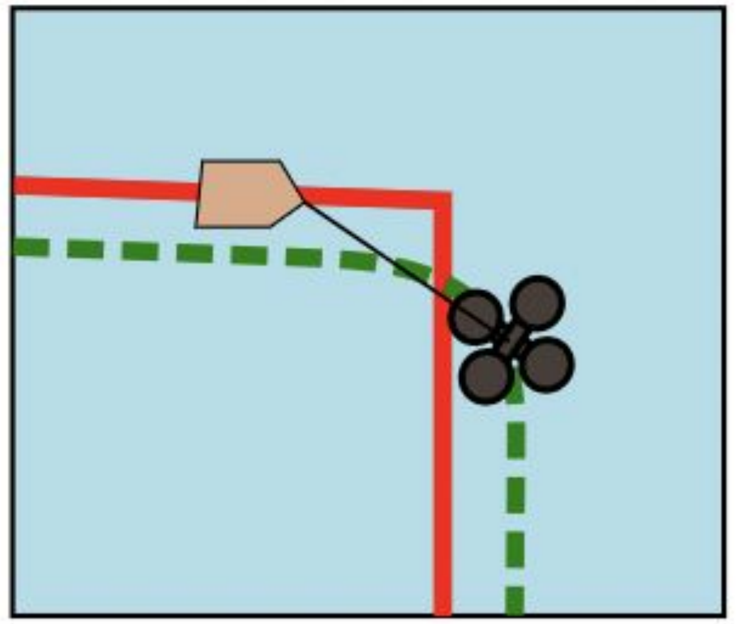


Drone Trajectory Planning

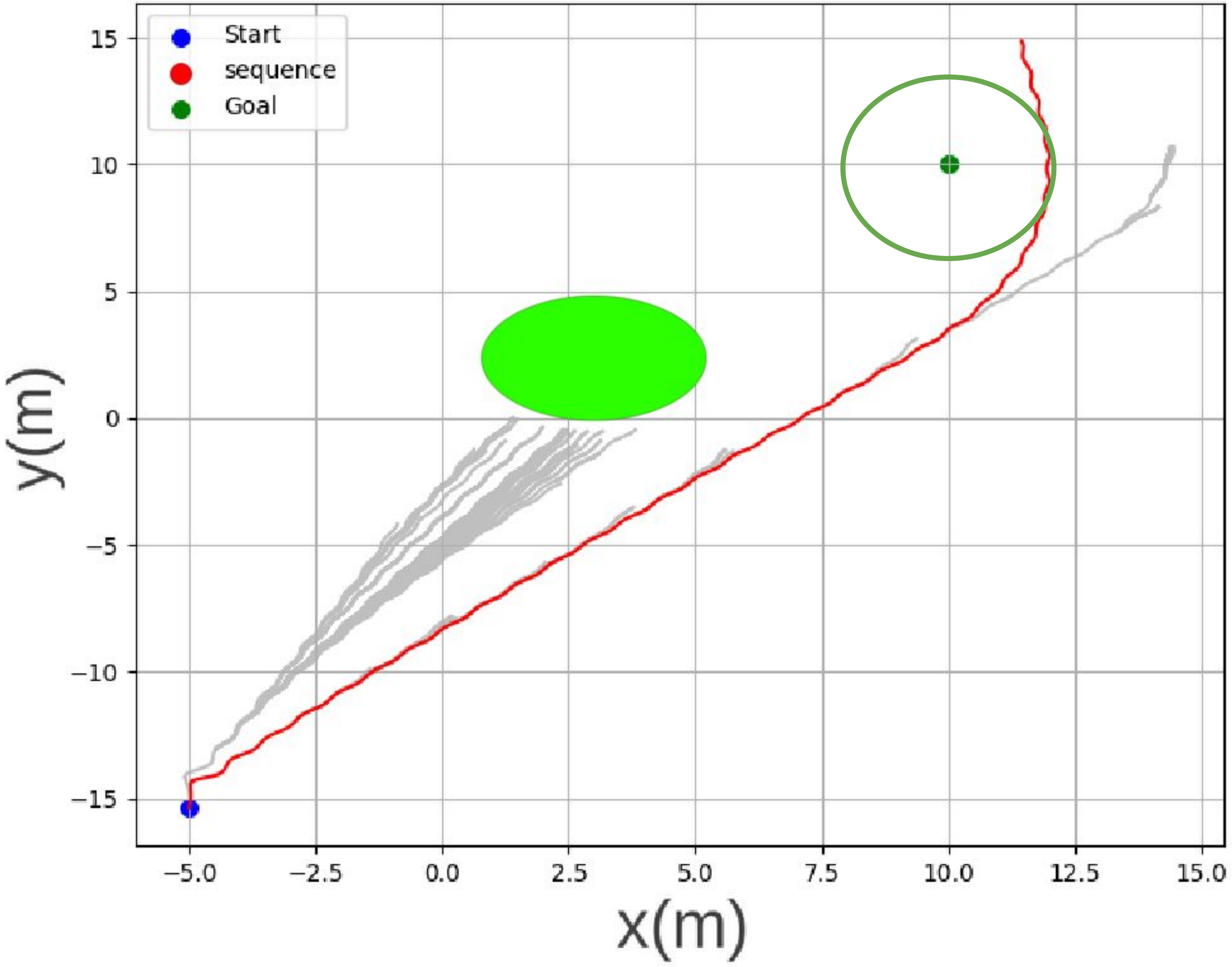
Trajectory Planning

Kinodynamic Rapidly-exploring Random Trees (RRT)

- Samples the state space of the robot and generates trajectories constrained by the dynamics to track the samples
- Chooses the trajectory with the least cost that achieves the goal



- Allows for real time collision avoidance



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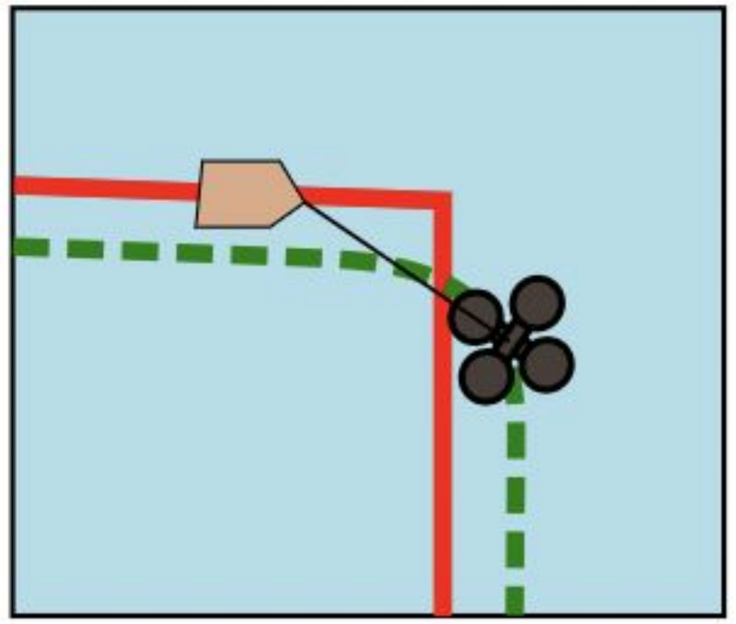

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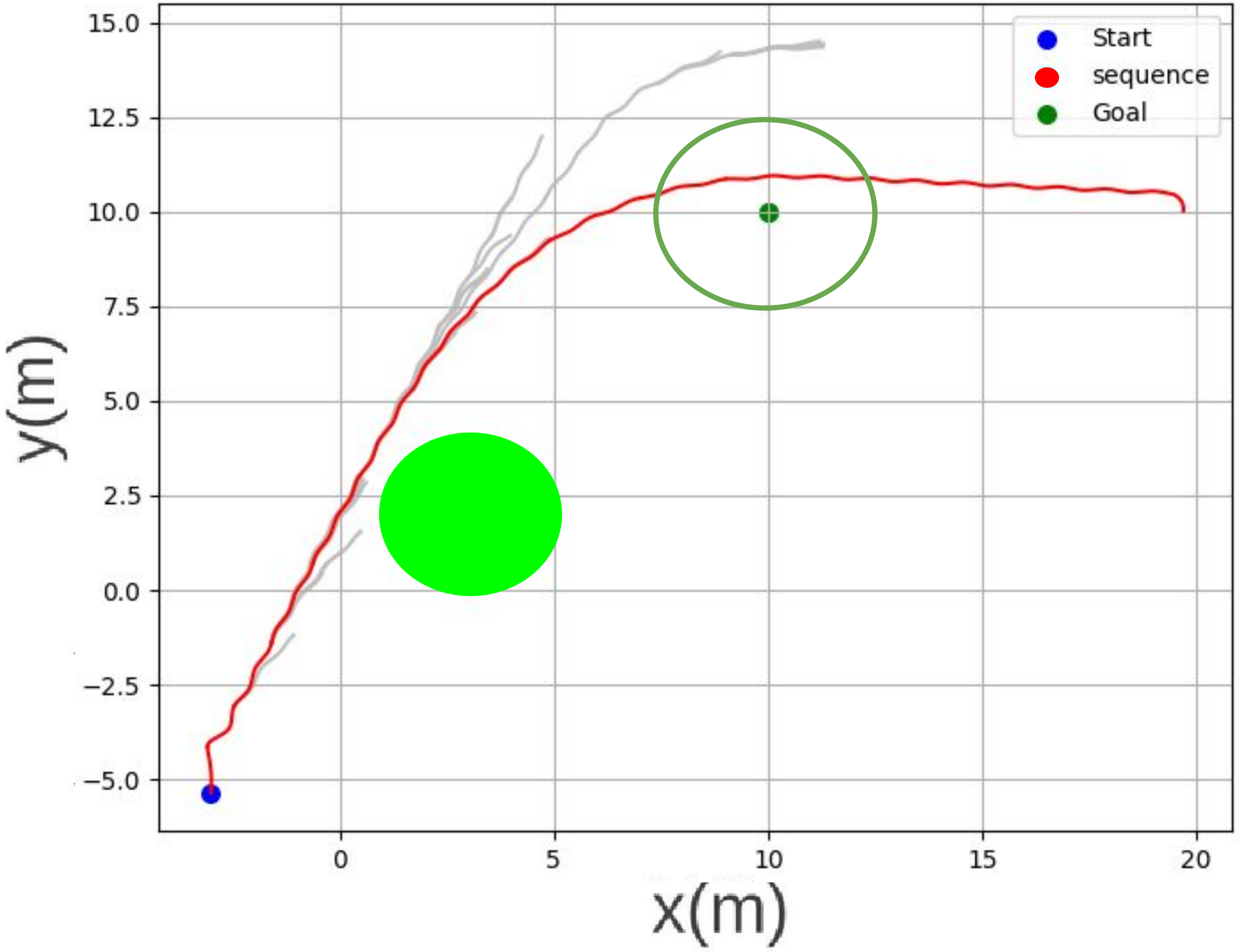
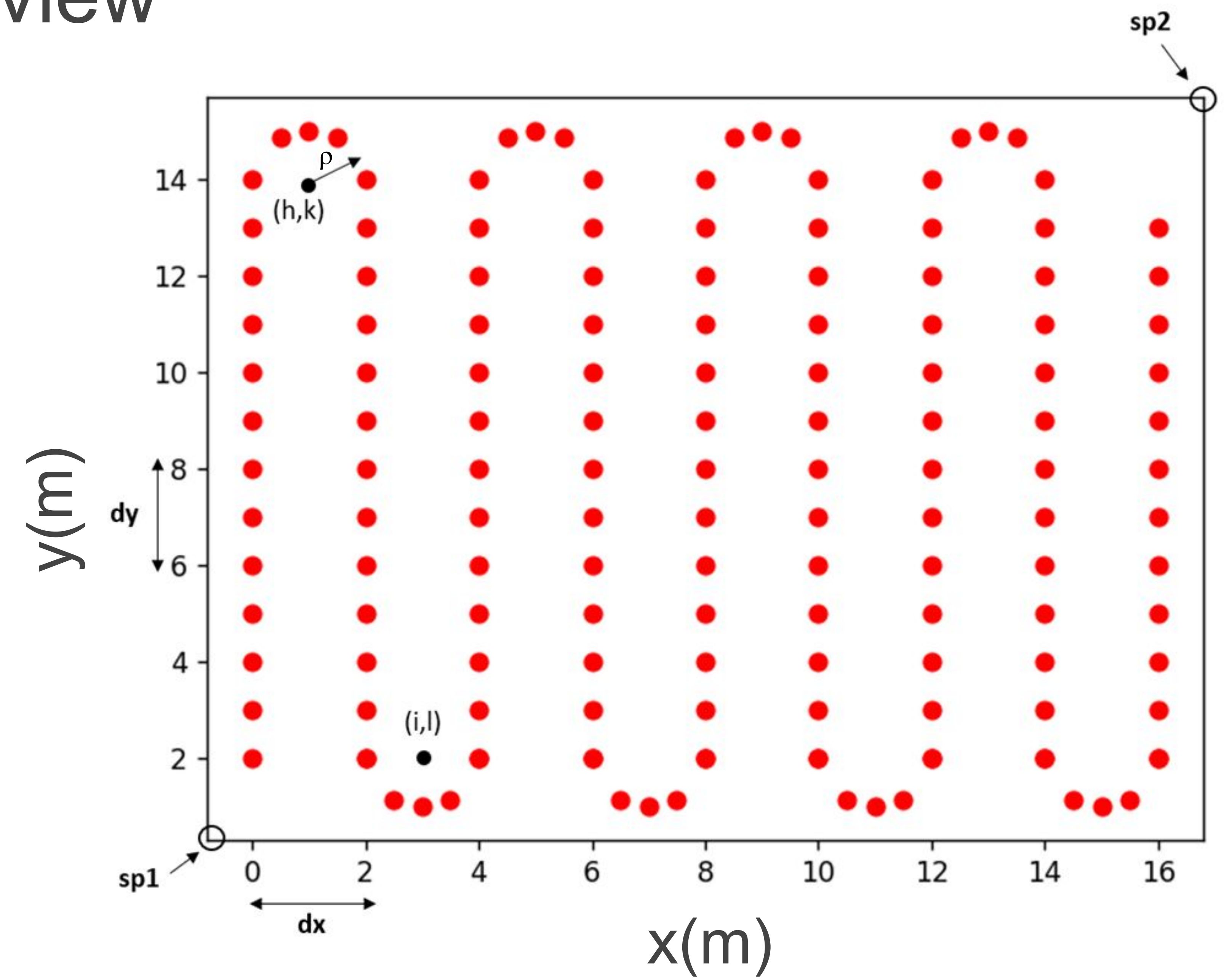


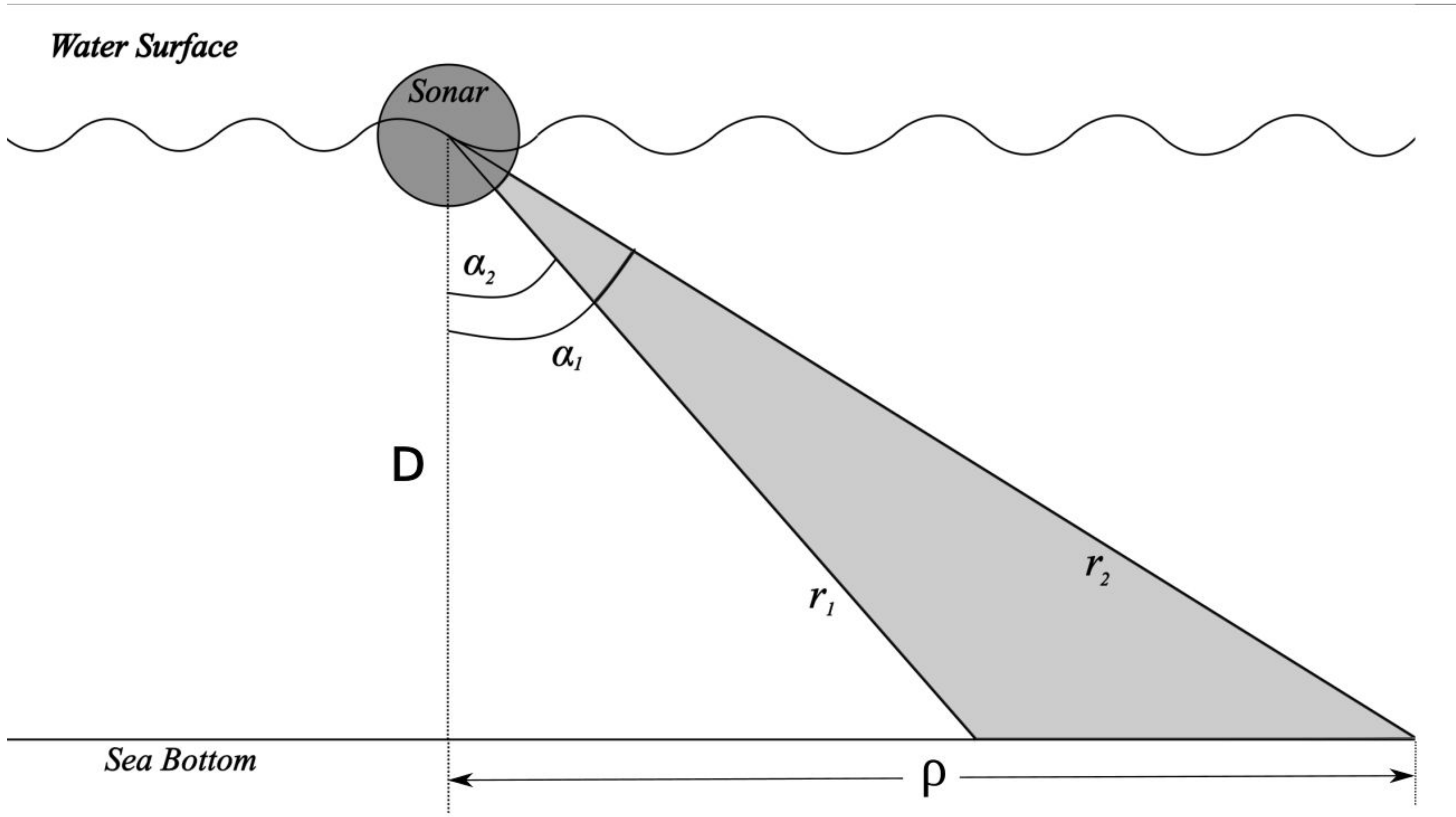
Boat Path Planning

Path Planning Algorithm

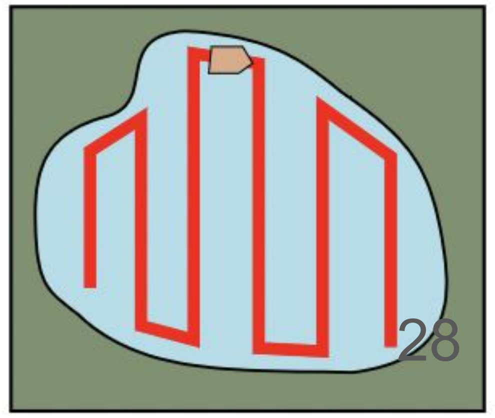
- Generates Boustrophedonic path that covers the maximum area rectangle that is inscribed in a convex polygon
- Parameters are based on sensor field of view



Depth and horizontal distance



$$\rho = D \tan(\alpha_2)$$



Future Work

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- Implement controller that can better reduce tracking error. Candidates are adaptive, MPC, neural, RL
- Coverage path planning for non-convex polygons and polygons with islands
- Implement in hardware

References

[1] Melo, José and Aníbal Matos. “Survey on advances on terrain based navigation for autonomous underwater vehicles.” Ocean Engineering 139 (2017): 250-264.

[2] K. Mizuno and A. Asada, “Three dimensional mapping of aquatic plants at shallow lakes using 1.8 MHz high-resolution acoustic imaging sonar and image processing technology,” in 2014 IEEE International Ultrasonics Sym-posium, pp. 1384–1387, ISSN: 1051-0117.

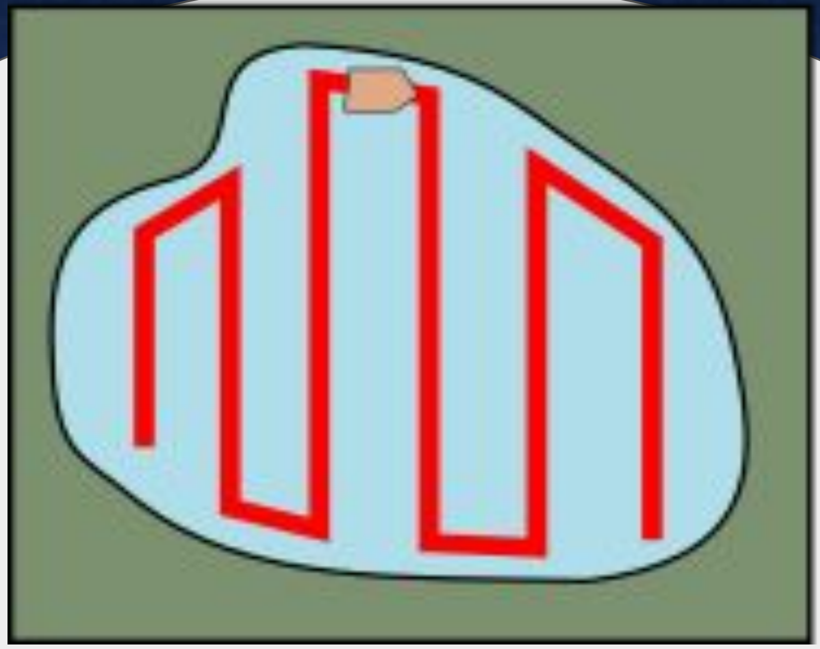
[3] T. Maki, H. Horimoto, T. Ishihara, and K. Kofuji, “Tracking a sea turtle by an AUV with a multibeam imaging sonar: Toward robotic observation of marine life,” vol. 18, no. 3, pp. 597–604.

[4] Fossen, T. I., Handbook of Marine Craft Hydrodynamics and Motion Control, Wiley, 2011.

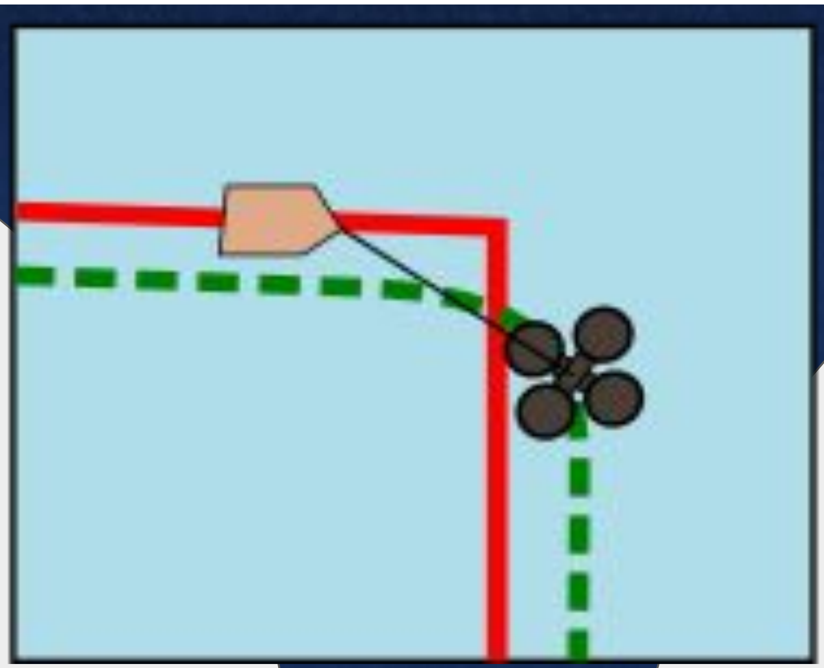
Thank you! Questions?

Trajectory Planning and Control of Bathy-drone

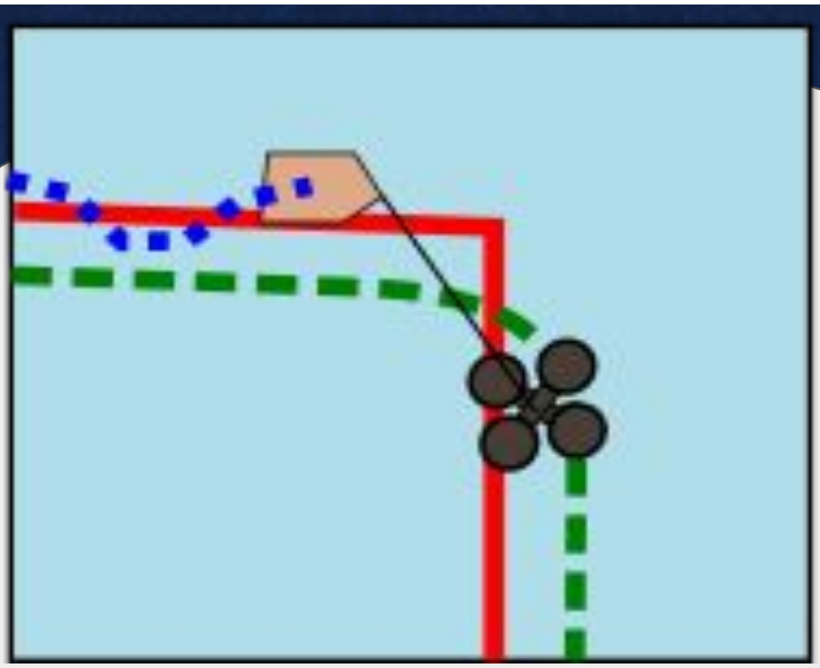
Boat Path Planning

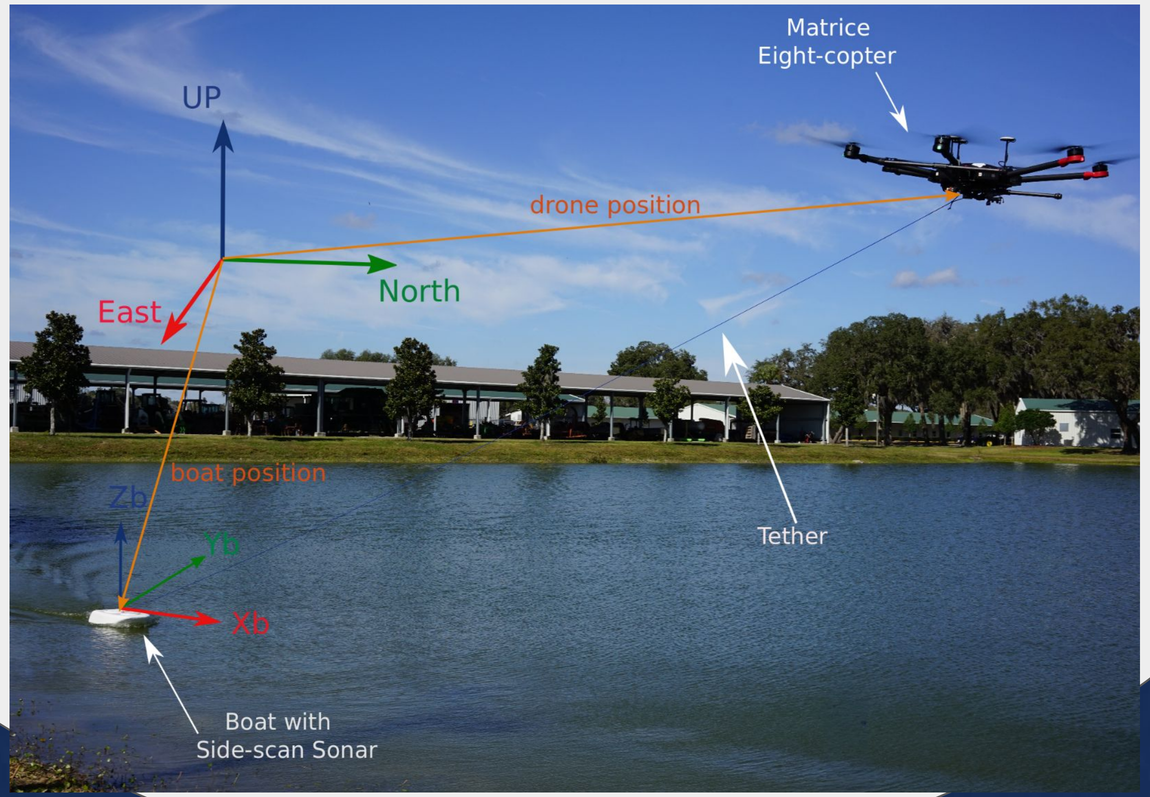


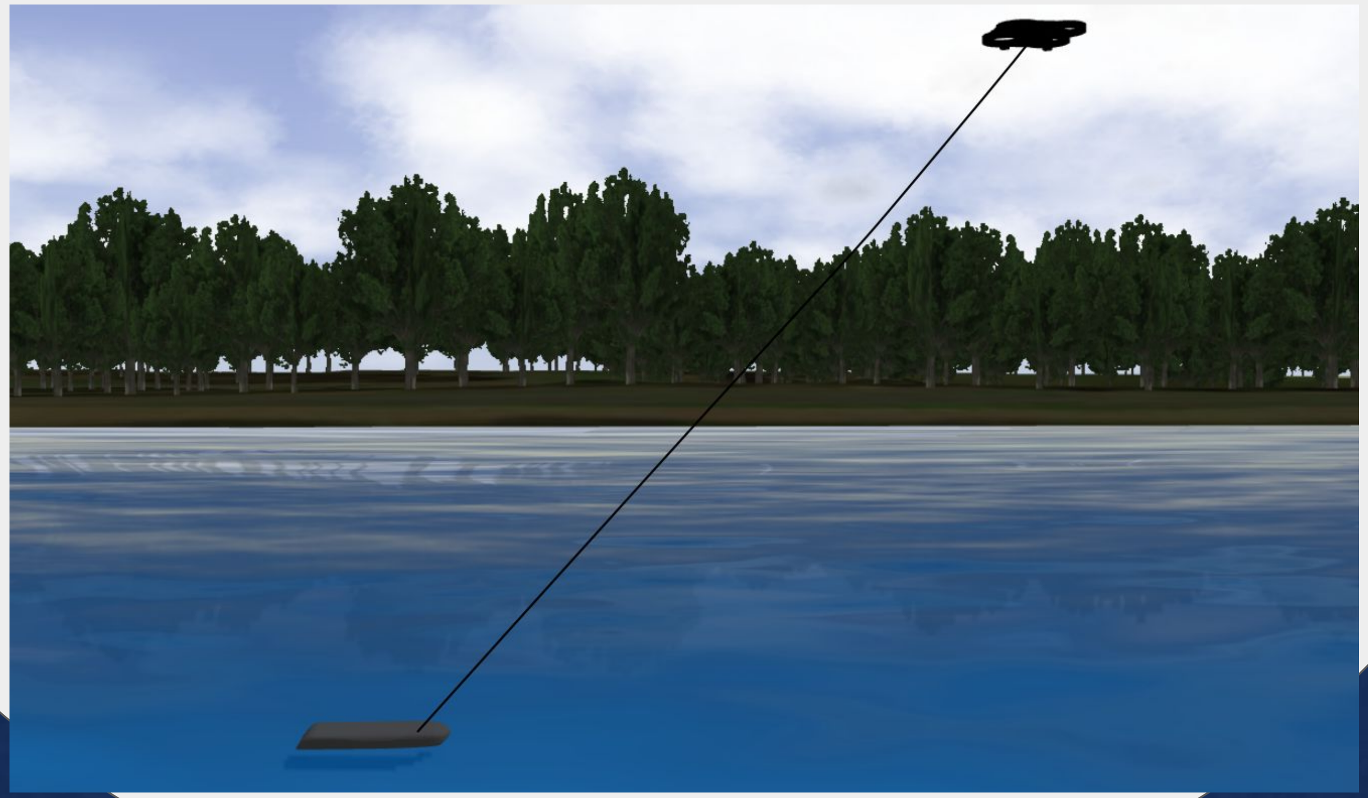
Drone Trajectory Planning



Trajectory Tracking Control







Thank you!
Question?

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Static Experiment: Steady State

At steady state, the equation **no longer contains the acceleration**, so the unknowns are the linear and quadratic drag coefficients

$$m_\xi \dot{\xi} + d_\xi \xi + g_\xi = \tau_\xi$$

One can solve it inverting the H matrix

$$\lambda = H\Lambda$$

$$\lambda = \begin{bmatrix} \tau_{\xi,1} - g_\xi \\ \tau_{\xi,2} - g_\xi \\ \vdots \\ \tau_{\xi,n} - g_\xi \end{bmatrix} \quad H = \begin{bmatrix} \xi_1 & \xi_1 |\xi_1| \\ \xi_2 & \xi_2 |\xi_2| \\ \vdots & \vdots \\ \xi_n & \xi_n |\xi_n| \end{bmatrix} \quad \Lambda = \begin{bmatrix} d_\xi \\ d_{\xi|\xi|} \end{bmatrix}$$

Static Experiment: Steady State

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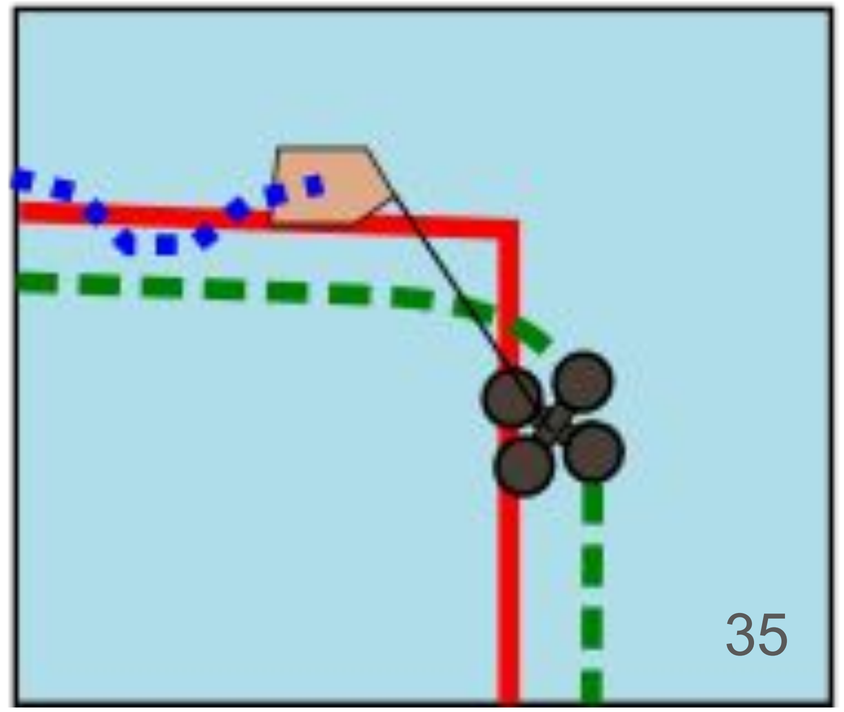
$$\begin{bmatrix} \tau_{x,1} \\ \tau_{x,2} \\ \vdots \\ \tau_{x,n} \end{bmatrix} = \begin{bmatrix} u_1 & u_1|u_1| \\ u_2 & u_2|u_2| \\ \vdots & \vdots \\ u_n & u_n|u_n| \end{bmatrix} \begin{bmatrix} d_x \\ d_{x|x|} \end{bmatrix} \qquad \begin{bmatrix} \tau_{\omega_z,1} \\ \tau_{\omega_z,2} \\ \vdots \\ \tau_{\omega_z,n} \end{bmatrix} = \begin{bmatrix} \omega_{z,1} & \omega_{z,1}|\omega_{z,1}| \\ \omega_{z,2} & \omega_{z,2}|\omega_{z,2}| \\ \vdots & \vdots \\ \omega_{z,=n} & \omega_{z,n}|\omega_{z,n}| \end{bmatrix} \begin{bmatrix} d_{\omega_z} \\ d_{\omega_z|\omega_z|} \end{bmatrix}$$

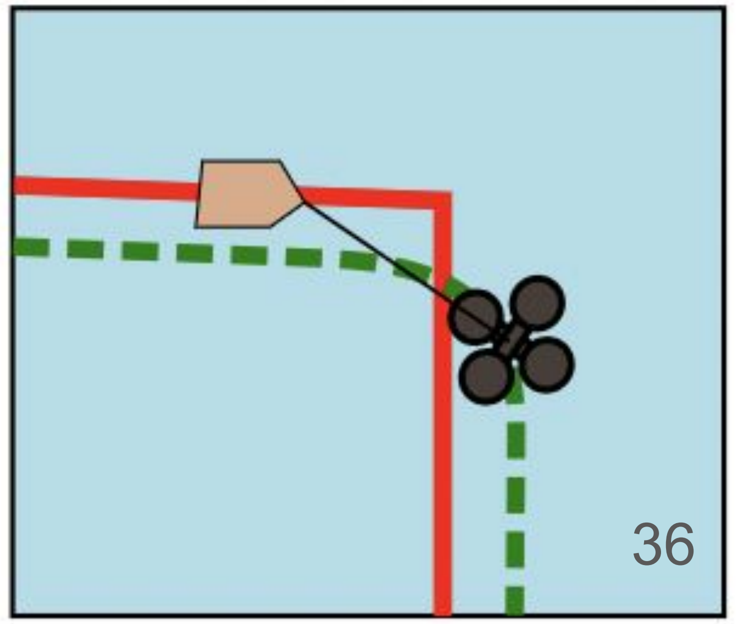
Tracking Controls

- **Goal:** Compute the control input to the system based on the reference signal
- **Inputs:**
  - Trajectory the drone needs to follow
  - State of the system (positions and velocities of the boat)
- **Outputs:**
  - Drone’s velocity at the current time step
- **Approach:**
  - PID control with saturation



Trajectory Planning

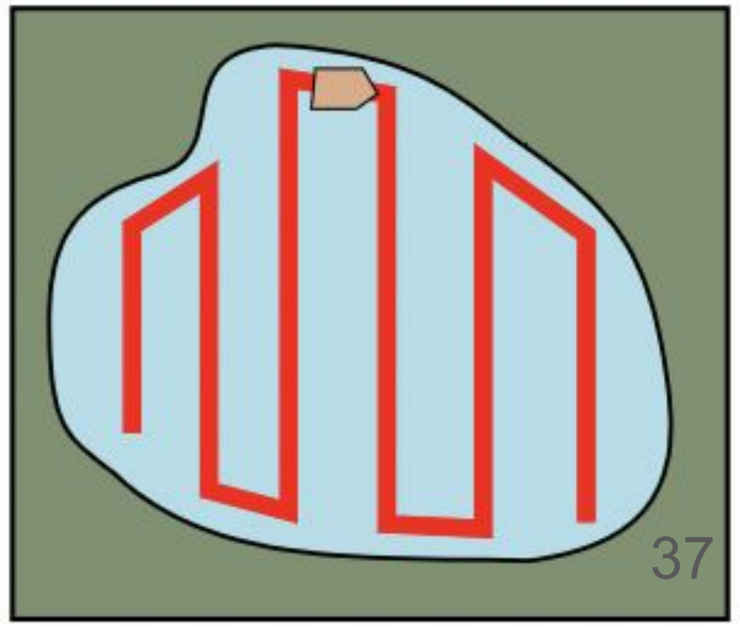
- **Goal:** To compute the drone's trajectory such that the boat can follow the planned path
- **Inputs:**
    - Path planned for the boat
    - Dynamics model of Bathydrone
    - Control law for the drone (PID)
- **Outputs:**
    - Drone's trajectory (or control inputs to the drone)
- **Approach:**
    - Plan the drone's trajectory similar to the boat's path first, and revise the trajectory using the Gazebo simulation by iterations.



Path Planning Algorithm

- **Goal:** To cover the region of interest with sensor field-of-view
- **Inputs:**
  - The geometry of the area of interest (2D polygon), representing the water surface
  - Sensor field-of-view geometry, with respect to the boat configuration
- **Outputs:**
  - A sequence of waypoints for the boat

- **Approach:**
  - Complete coverage path planning algorithms modified to incorporate the given sensor field-of-view geometry and sensor characteristics



Kinematics

Challenge: Weird tethered dynamics

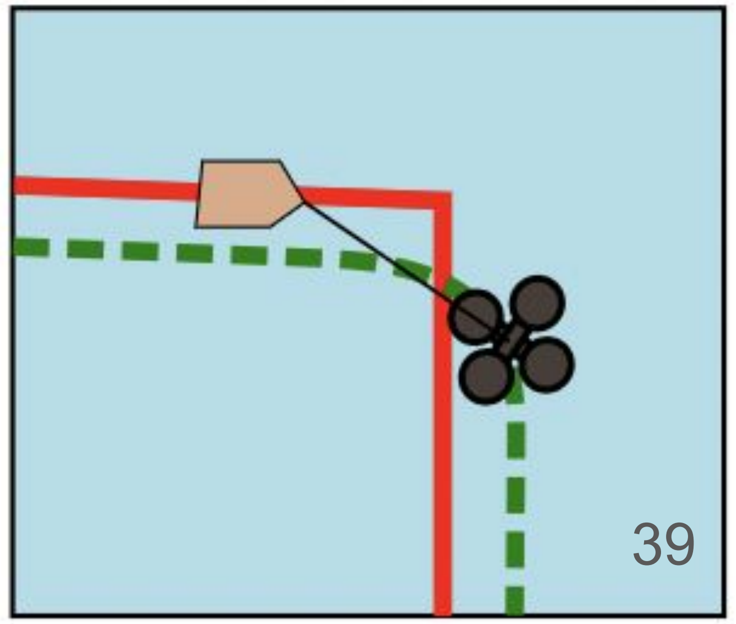
Solution:

- The drone position x, y and orientation θ will be **constrained** to move in a straight line or a **minimum turning radius** ρ, and will not be able to move backwards, which results in the formulation of a Dubins Path,

$$\begin{bmatrix} \dot{x}_d \\ \dot{y}_d \\ \dot{\theta}_d \end{bmatrix} = \begin{bmatrix} \cos\theta \\ \sin\theta \\ K/\rho \end{bmatrix}$$

Trajectory Planning

- **Goal:** To compute the drone's trajectory such that the boat can follow the planned path
- **Inputs:**
  - Path planned for the boat
  - Dynamics model of Bathydrone
  - Control law for the drone (PID)
- **Outputs:**
  - Drone's trajectory (or control inputs to the drone)
- **Approach:**
  - Plan the drone's trajectory similar to the boat's path first, and revise the trajectory using the Gazebo simulation by iterations.



References

[4]
[5]