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### Motivation

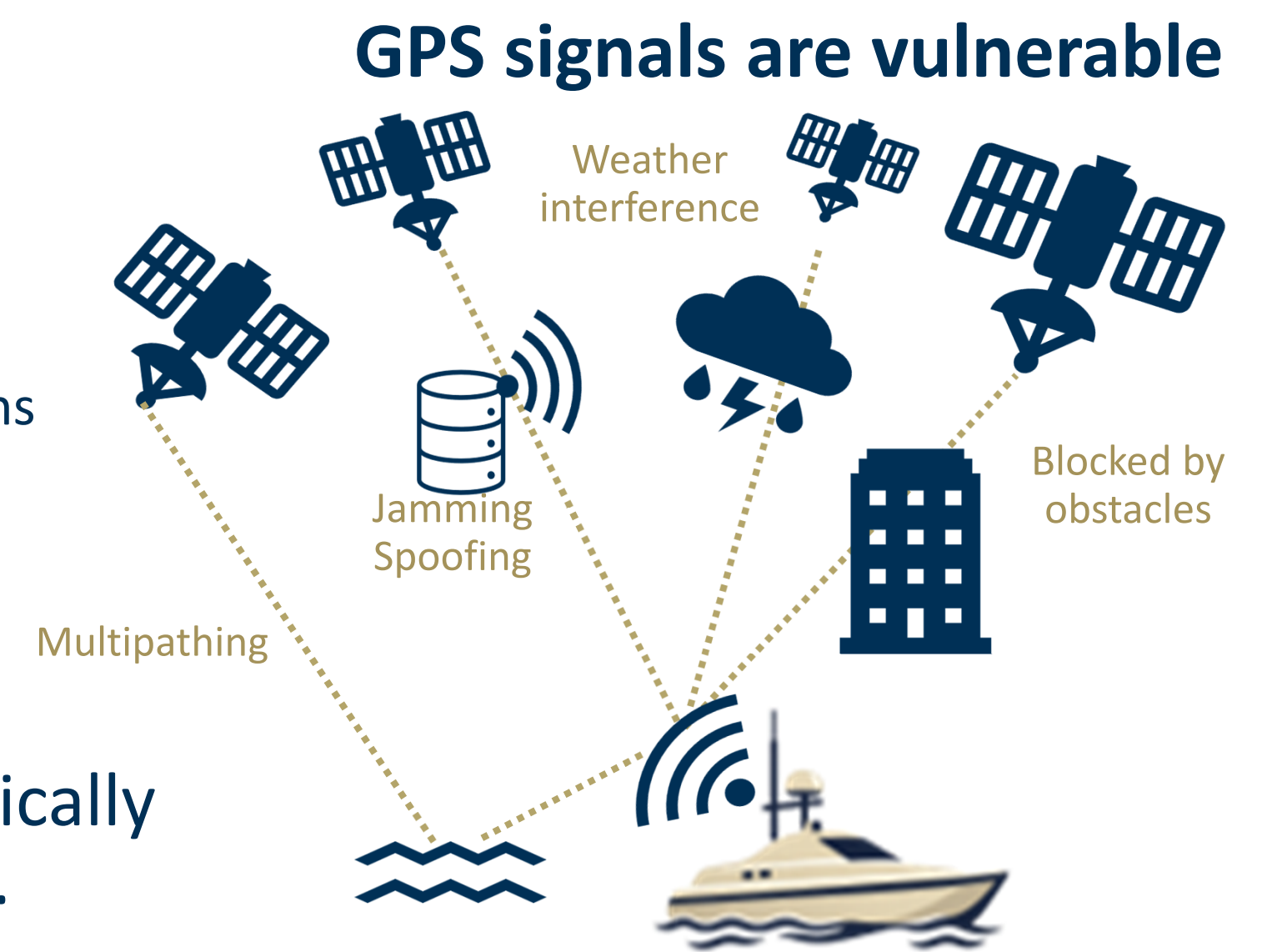
#### GPS navigation in unmanned maritime mission is vital

- **Maritime shipping** accounts for **80%** of world trade by volume and **70%** by value
- **13 of the 16 nations** critical infrastructure sectors are **reliant on GPS**
- **Unmanned surface vehicles (USVs)** heavily rely on GNSS for successful missions

#### Lack of benchmark for GPS-denied navigation methods for USVs

- GPS-independent navigation methods each have weaknesses when used in isolation but can be combined to provide a more robust system.

**The ask** Develop a comparative evaluation framework to systematically assess GPS-denied maritime navigation methods for USVs.



### Methodology

**Approach** Create a modular simulation platform to benchmark and evaluate navigation methods in realistic USV mission scenarios

#### Concept of Operations

- Search & Rescue Mission scenario in a coastal environment
- Operation in GPS-denied waters near the coastline
- Modeled to autonomously navigate to a series of waypoints

#### Benchmark Cases

GPS + IMU (Baseline)



IMU-only

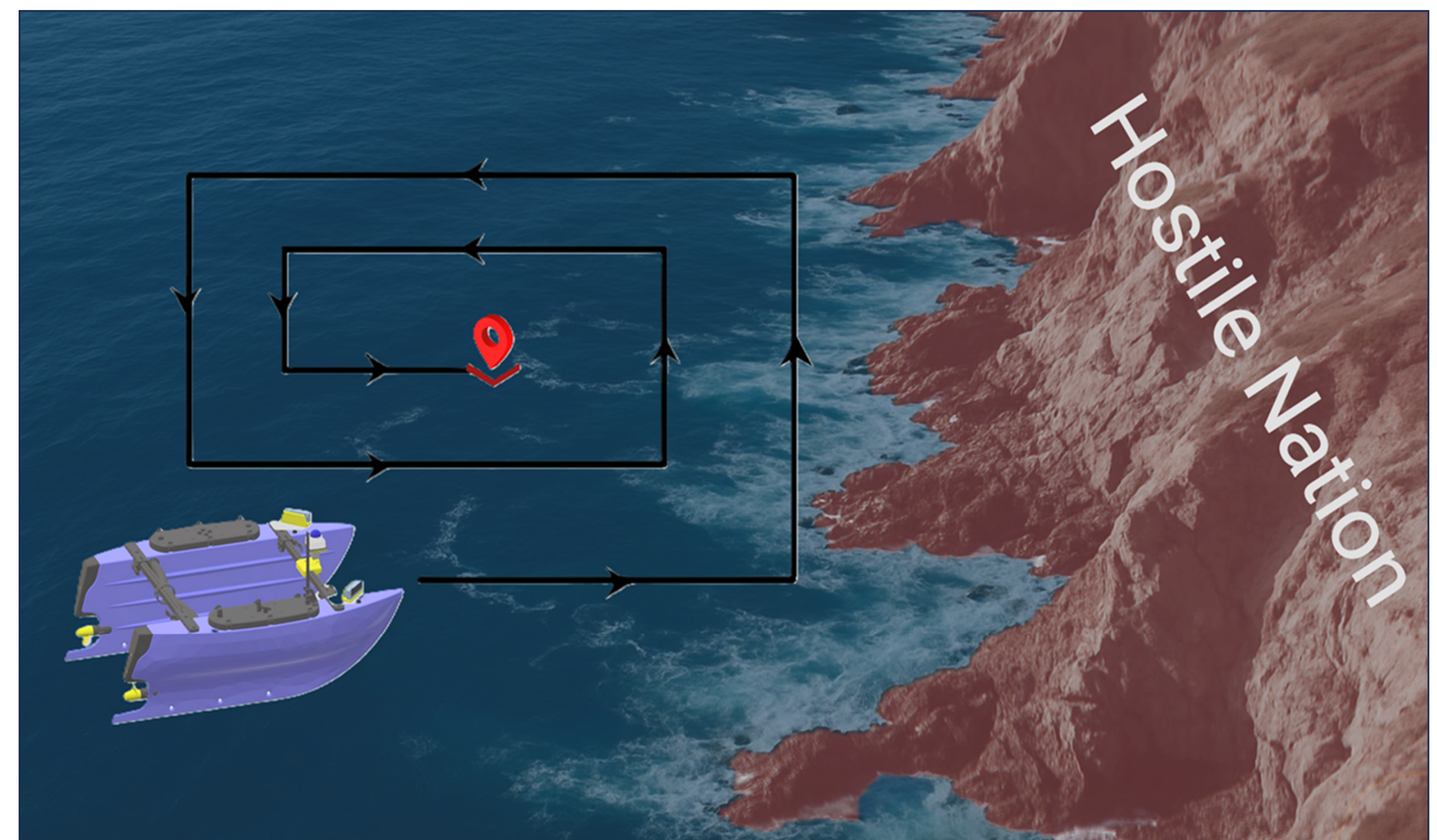


Visual Odometry



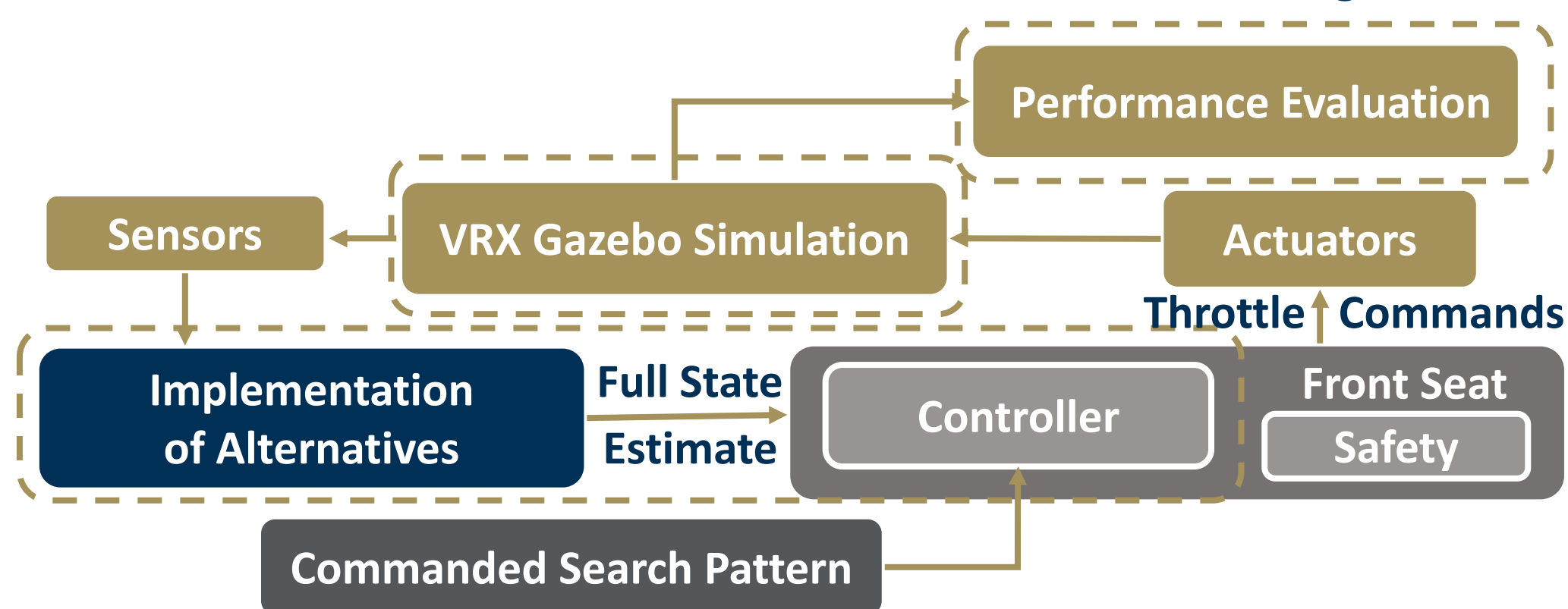
#### Automation

Automated navigation under different environmental conditions



### Results

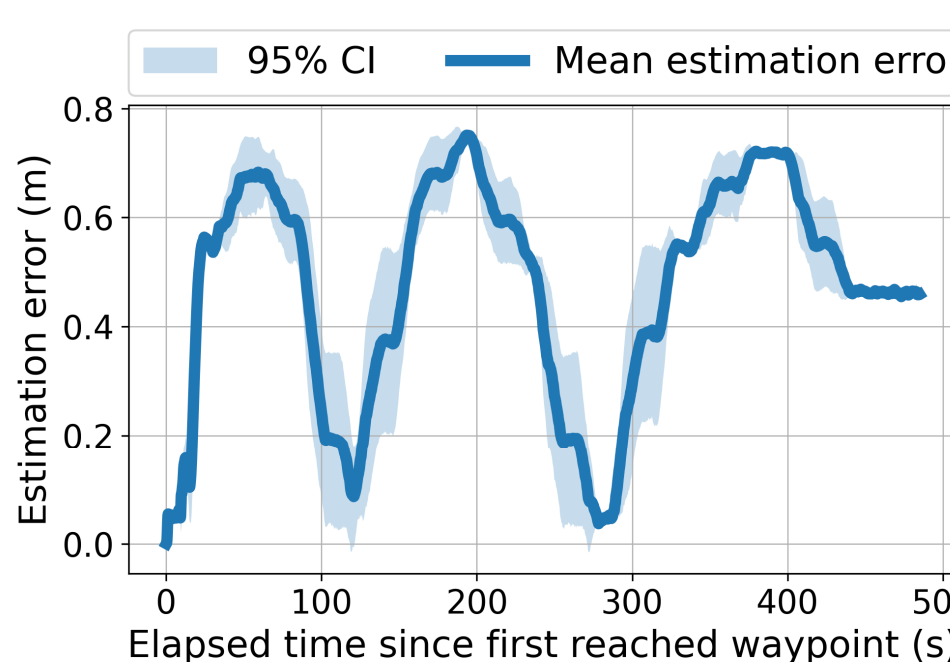
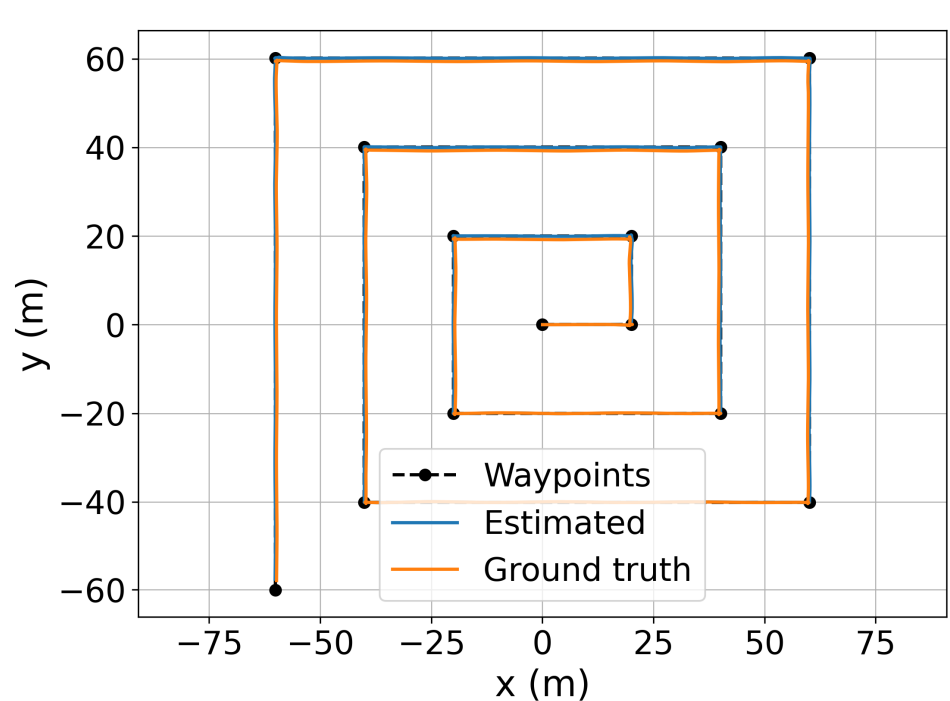
We created a toolbox that enables consistent benchmarking and comparative performance analysis of GNSS-denied maritime navigation



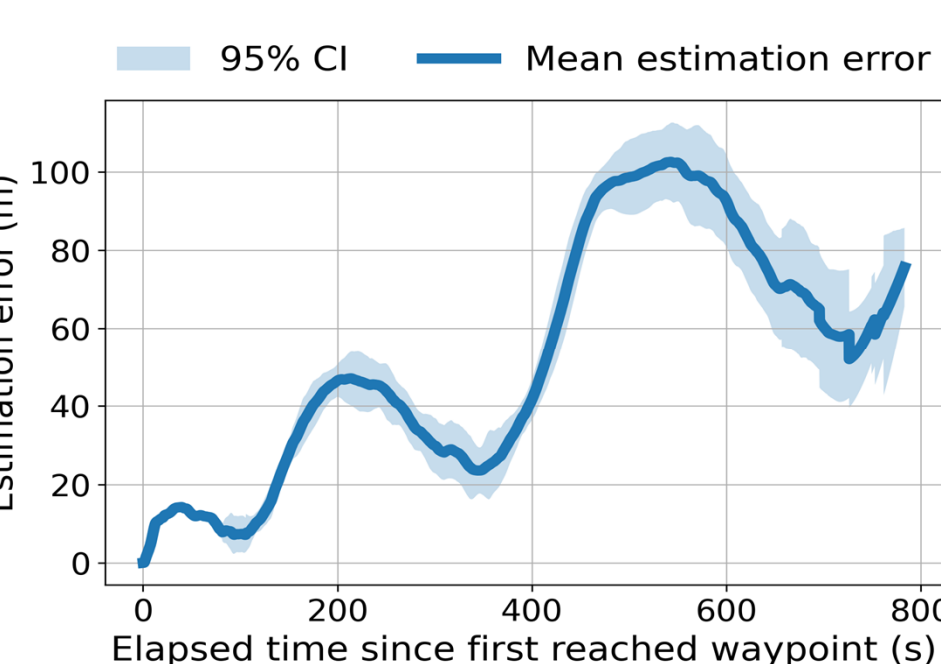
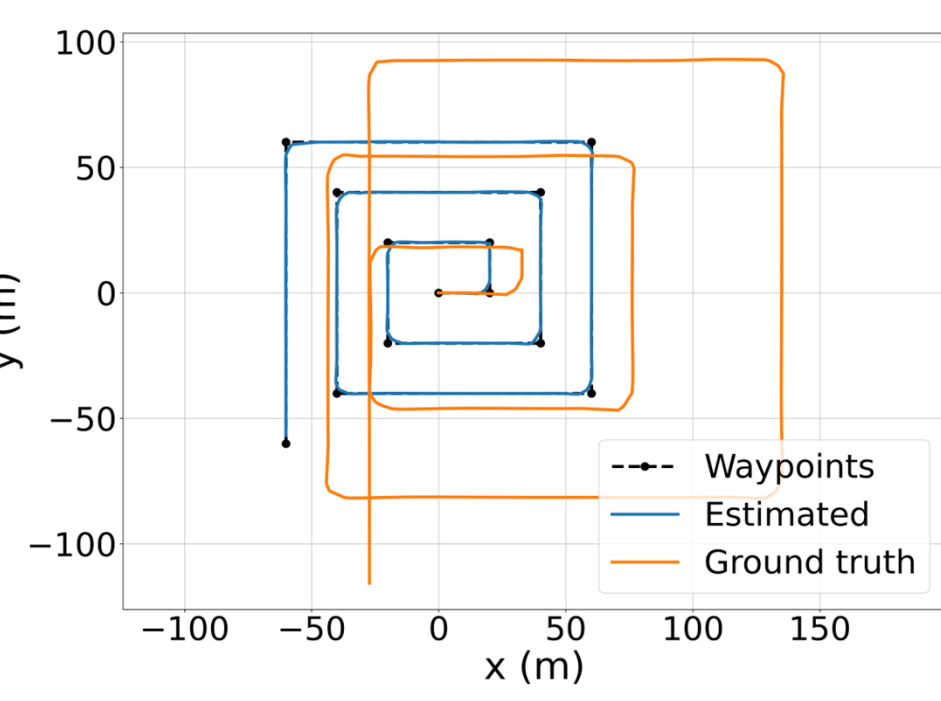
#### Software Used:

- ROS2 ■ Gazebo ■ Q Ground Control ■ Ardupilot/MPC ■ This GC ■
- Closed-loop framework integrating sensing, simulation, and control
  - Sensor inputs and simulation feed navigation alternatives
  - Navigation alternatives generate state estimates
  - Controller uses estimates with a safety layer to issue control commands
  - Actuators execute commands along a commanded search pattern
  - Navigation alternative is continuously evaluated for performance
  - Modular architecture allows modules to be easily swapped for uniformed comparison

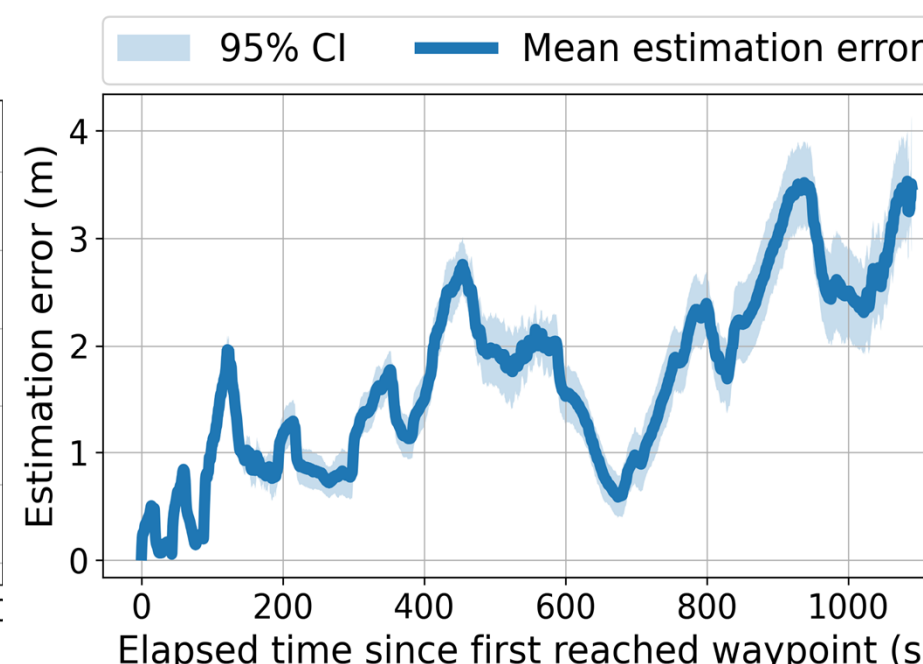
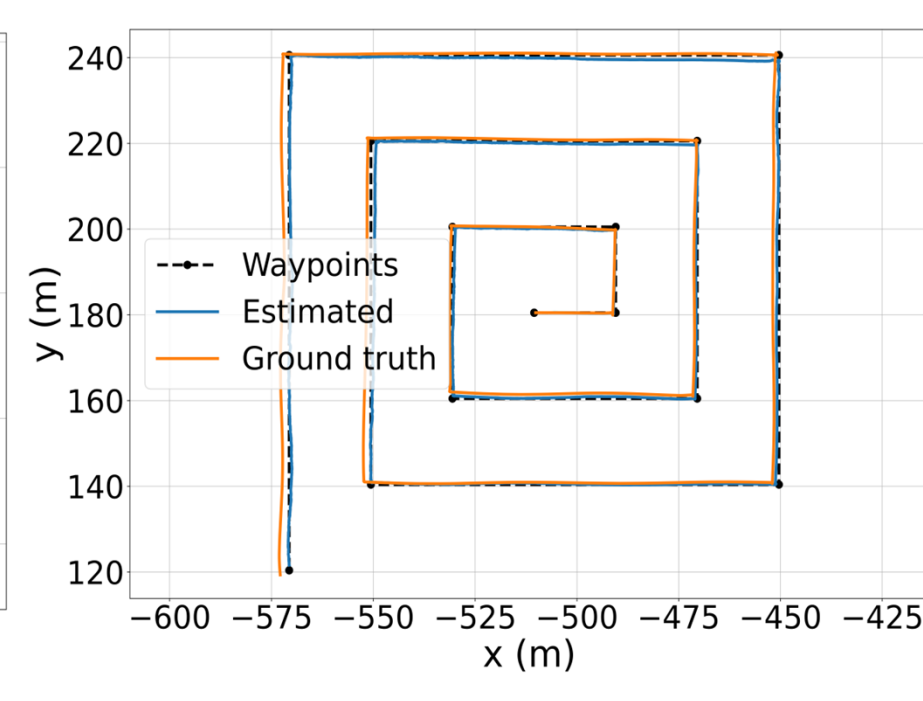
#### GPS+IMU (Baseline)



#### IMU-only



#### Visual Odometry



#### Performance Evaluation

- Mission completion:** Compare ground truth and estimated trajectories with the commanded trajectory
- **Ground Truth:** Reference trajectory representing the true state of the USV
  - **Estimated:** Trajectory estimated from sensor measurements and fused via navigation algorithm
- Error evaluation:** Estimation errors computed across multiple missions under varying environmental conditions

#### Key Findings

**GPS + IMU serves as a reliable baseline**, with estimates closely aligning with ground truth. In GPS-denied settings, **visual odometry functions as a reliable localization method**, whereas IMU-only estimation accumulates significant drift without external correction.

### Concluding remarks

- We propose a **unified platform to systemically benchmark GPS-denied maritime navigation methods**
- We assess **robustness** of each navigation method by evaluating performance across diverse environmental conditions
- Our architecture **allows consistent comparison** across navigation methods previously evaluated under different vehicle platforms and missions