

## Motivation and Challenges

Inspections and mapping are among the most fundamental underwater operations, with both academic and industrial interest, supporting infrastructure maintenance resource utilization, public safety, and archaeological and ecosystem monitoring.

Logistical challenges in underwater operations involve:

- Sensing and SLAM degradation
- Developing and tuning robust controllers
- Re-tuning the controllers after load changes
- Time/energy-efficient area coverage



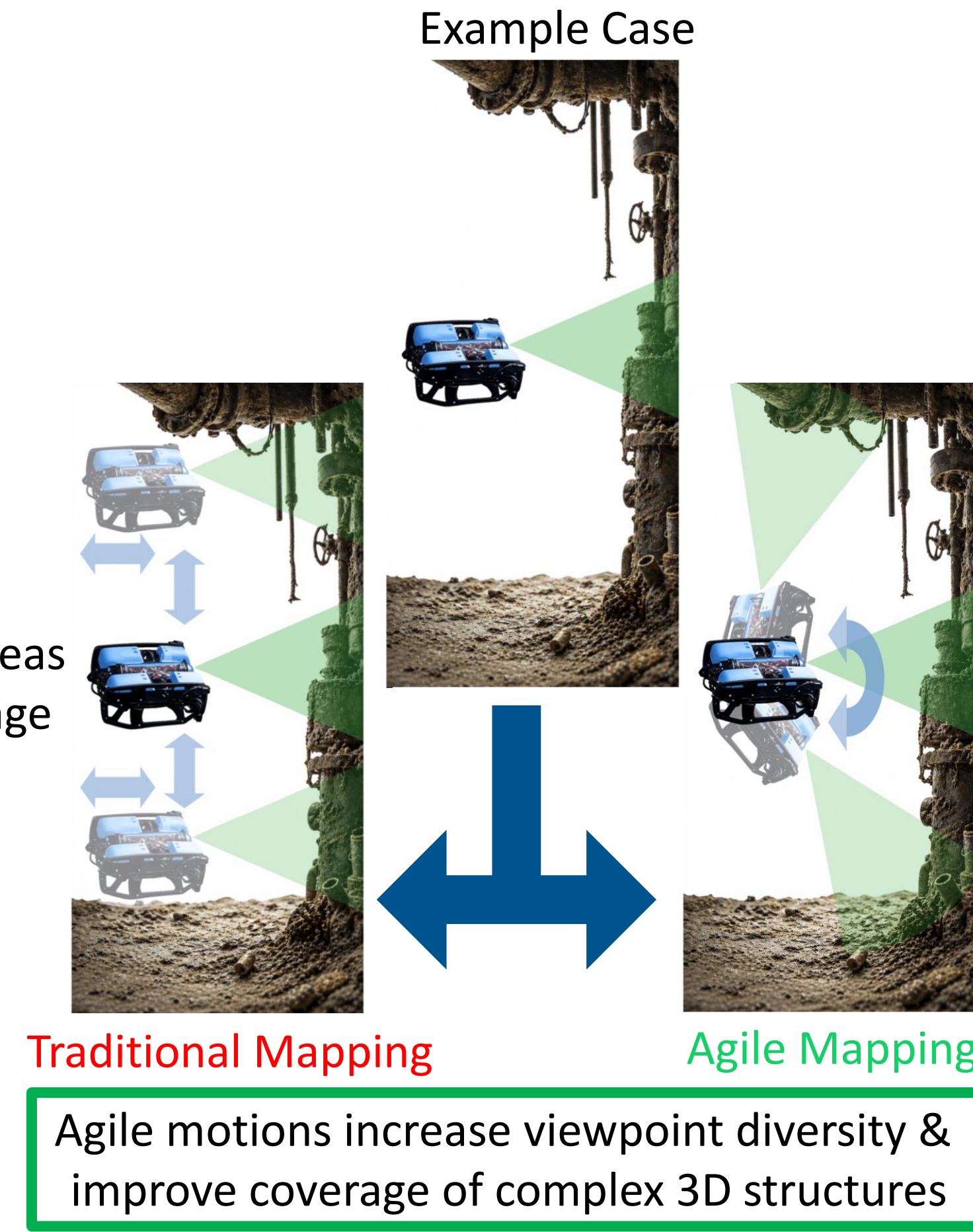
## Key Observations and Ideas

Observations:

- Traditional development and tuning of controllers:
  - Tedious and time consuming
  - Control simplicity over agility
  - Re-tuning after changes in weight load
- Most mapping and inspections are handled by ROVs:
  - Simple box-shaped over-actuated systems
  - Bottom-heavy with built-in stability
  - No capacity for pitch or roll
- Overhead and complex geometries in underwater areas
- Low level simplicity in controls VS efficiency in coverage

Ideas:

- Improve control logistics with learning:
  - Massively parallelized DRL
  - Agile full 6D mobility
  - Domain randomization for resiliency
- Improve mapping logistics with agility:
  - Make coverage easier and faster

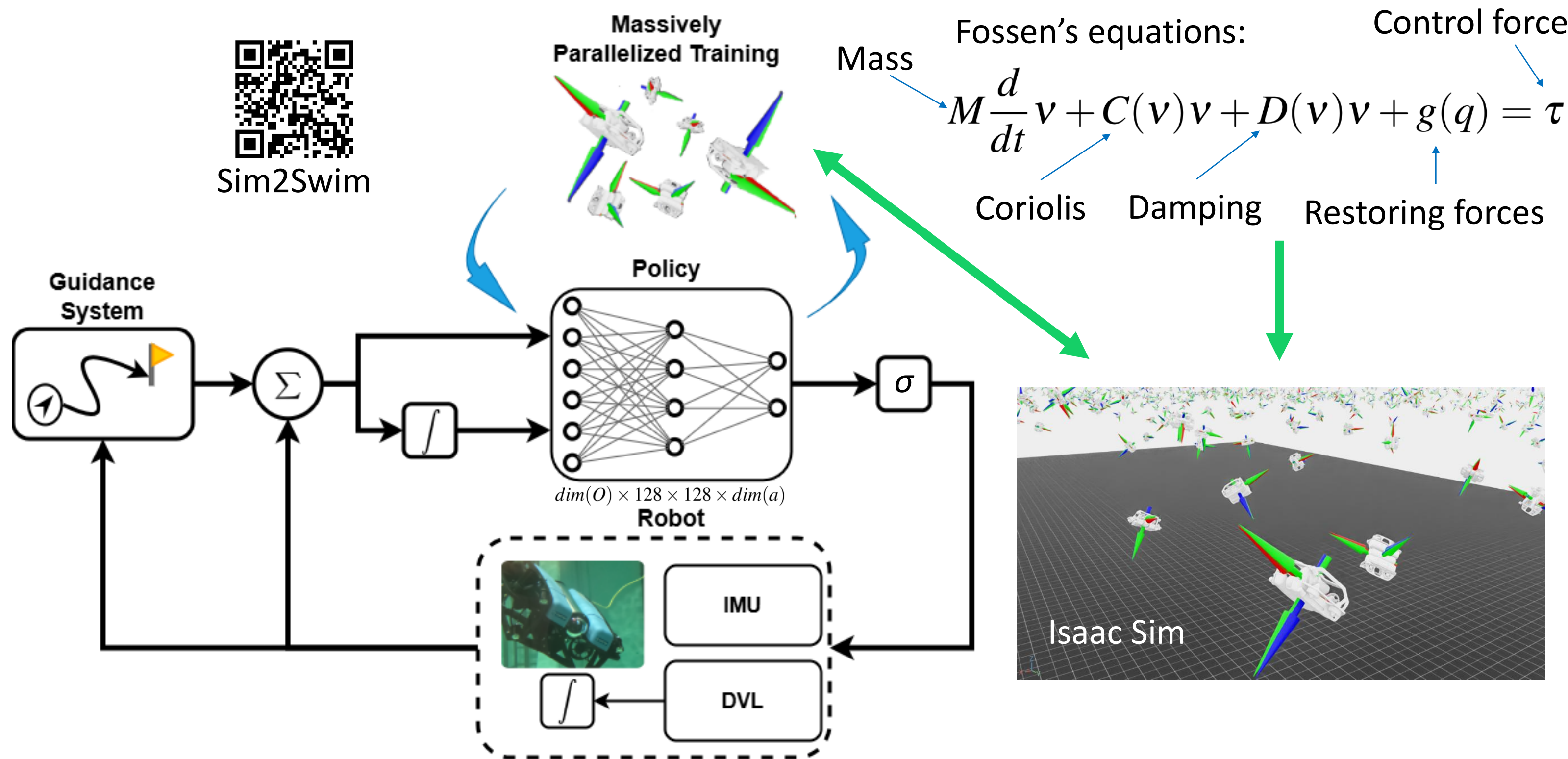


## Contributions

1. A fast (3.5 min) zero-shot sim-to-real DRL framework for robust 6-DoF hydrobatic control
2. A dynamics-informed (Fossen-based) policy enabling stable control with minimal onboard sensing
3. A new paradigm for underwater mapping: leveraging agile mobility to improve 3D coverage
4. Extensive real-world validation in both controlled in-pool experiments and tidal port deployments with no policy retuning or rebalancing of the platform

## Proposed Method

- Enhanced prior work:



- Observations and actions:

$$O = [q_e, v_e, \omega, z_v] \in \mathbb{R}^{13} \quad a = [F_x, F_y, F_z, \tau_x, \tau_y, \tau_z] \in \mathbb{R}^6$$

- Reward:

$$r = w_\omega e^{-\|\omega\|^2} + w_v e^{-\|v_e\|^2} + w_q e^{-\angle(q_d, q)} + w_a e^{-\|a\|^2}$$

- Objective function:

$$J(\theta) = \mathbb{E} \left[ \sum_{t=0}^{\infty} \gamma r_t \right]$$

- PPO clipped surrogate training objective:

$$L(\theta) = \mathbb{E} [\min(r(\theta) \hat{A}_t, \text{clip}(r(\theta), 1 - \epsilon, 1 + \epsilon) \hat{A}_t)]$$

- Domain Randomization:

$$r_g, r_b \sim \mathcal{U}(\mathbb{S}^2), \quad V \sim \mathcal{U}(V_{min}, V_{max})$$

$$m \sim \mathcal{U}(m_{min}, m_{max}), \quad d \sim \mathcal{U}(d_{min}, d_{max})$$

(center of buoyancy, center of mass, volume, mass, damping)

- Guidance: 3D line-of-sight

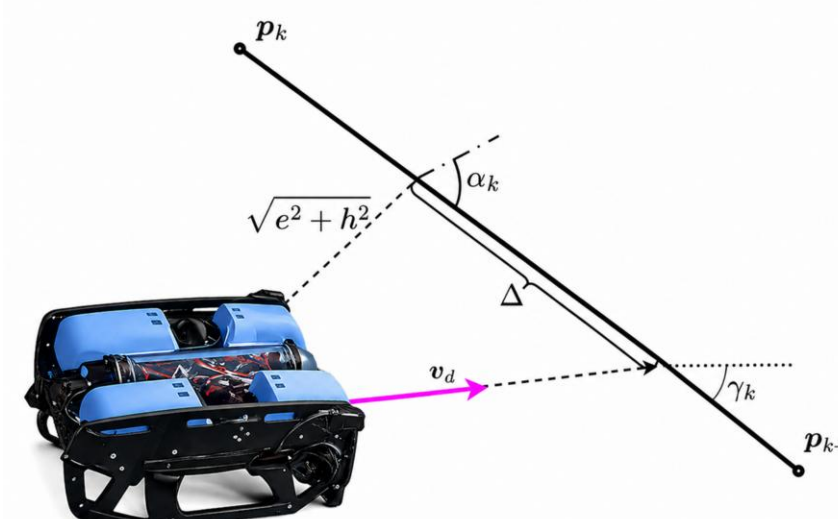
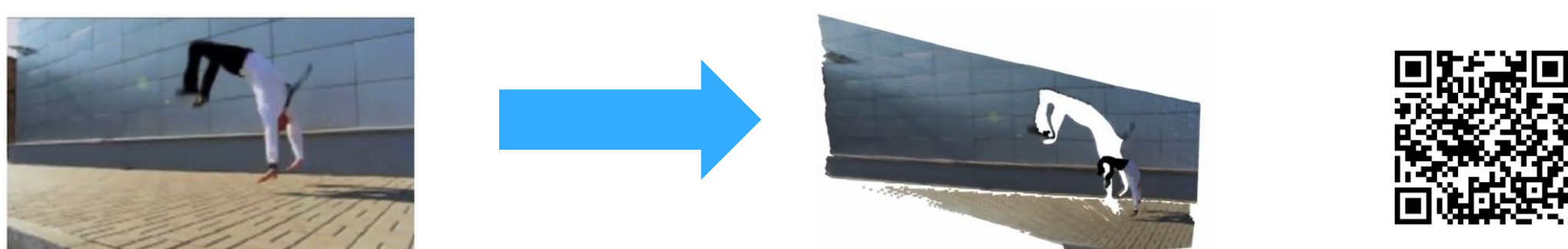
$$v_d = R(q)^\top R_z(\chi_d) R_y(\Gamma_d) \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} U_d$$

$$\chi_d = \alpha_k + \arctan\left(-\frac{e(t)}{\Delta}\right)$$

$$\Gamma_d = \gamma_k + \arctan\left(\frac{h(t)}{\Delta}\right)$$

- 3D reconstruction:

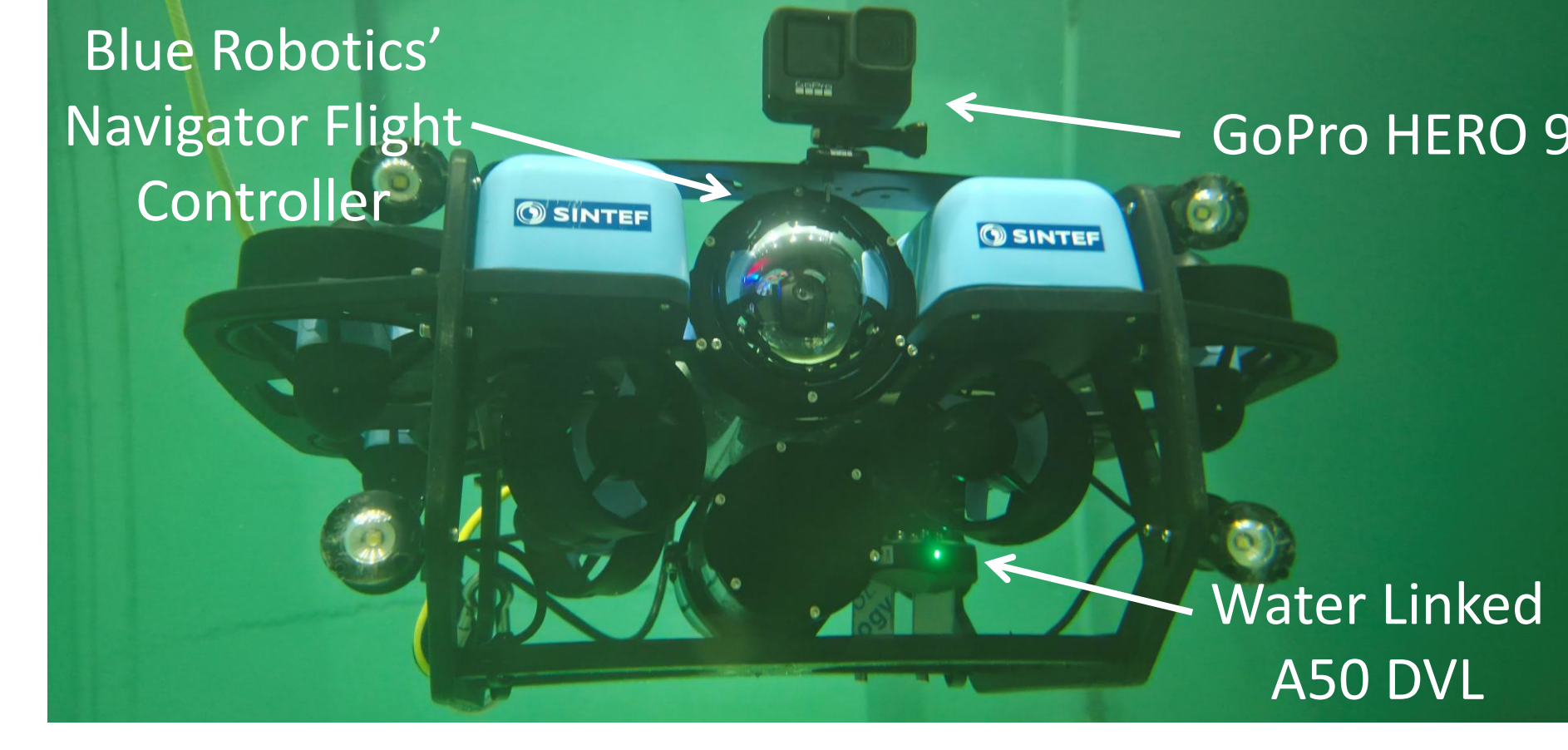
- Preliminary results utilized Map Anything from monocular input :



Sonar 3D-15 (Water Linked)

- On-going work employs acoustic range sensors tolerant to zero-visibility conditions, such as compact 3D Sonars

## System Description



Training in 3.5 minutes:



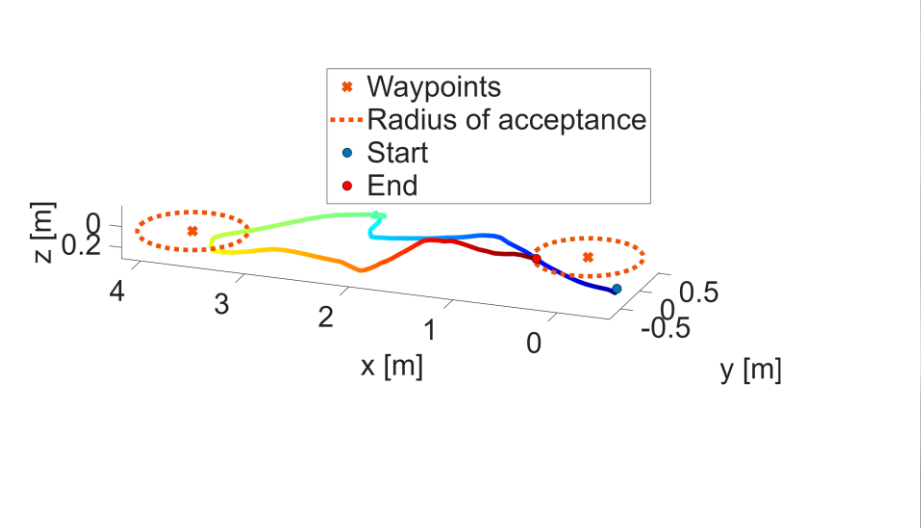
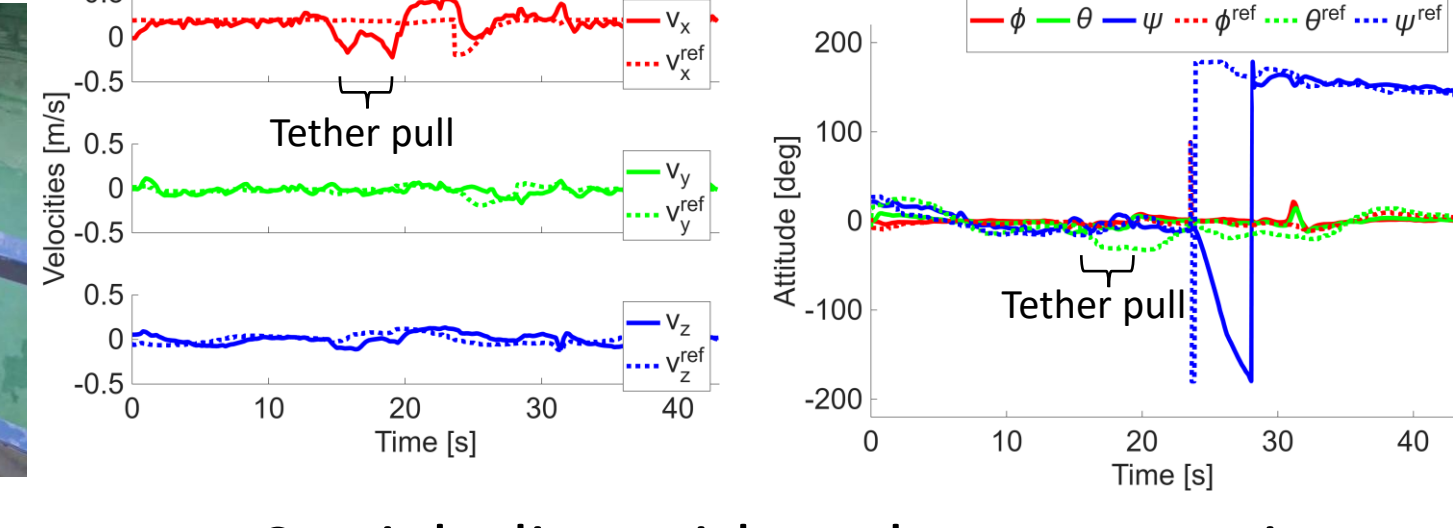
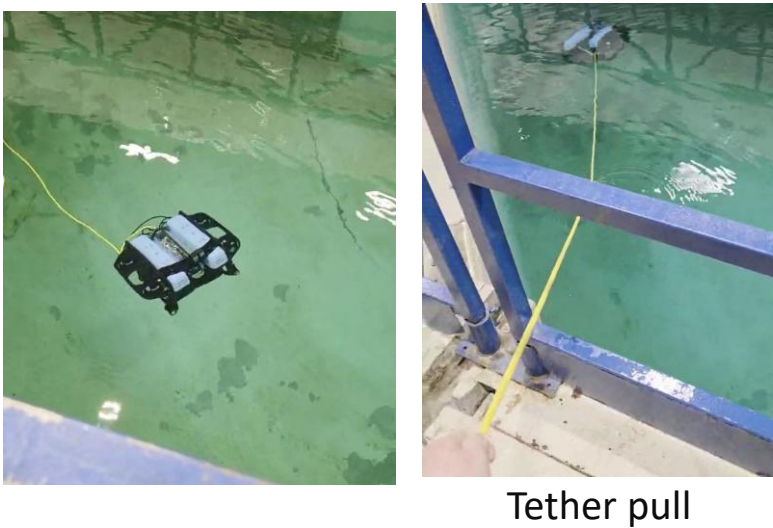
GPU: Nvidia A2000 GPU / 8GB VRAM  
CPU: Intel Core i7-12800HX at 2.0G Hz  
OS: Ubuntu 20.04.6

## Experiments

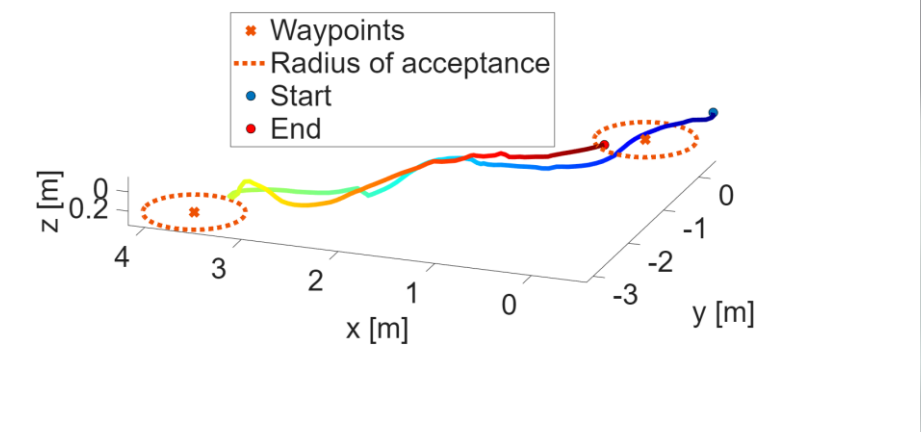
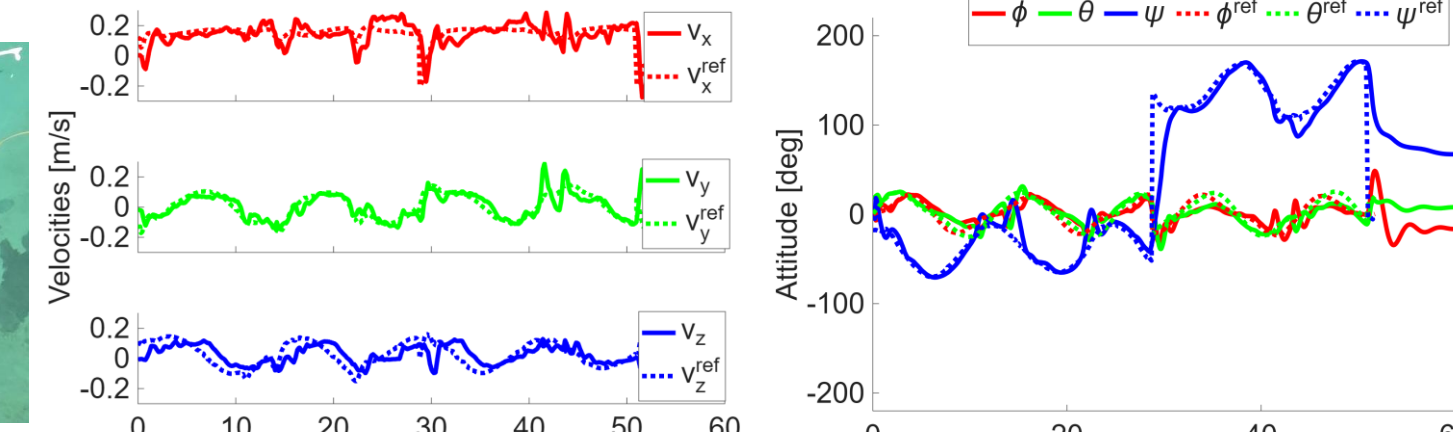
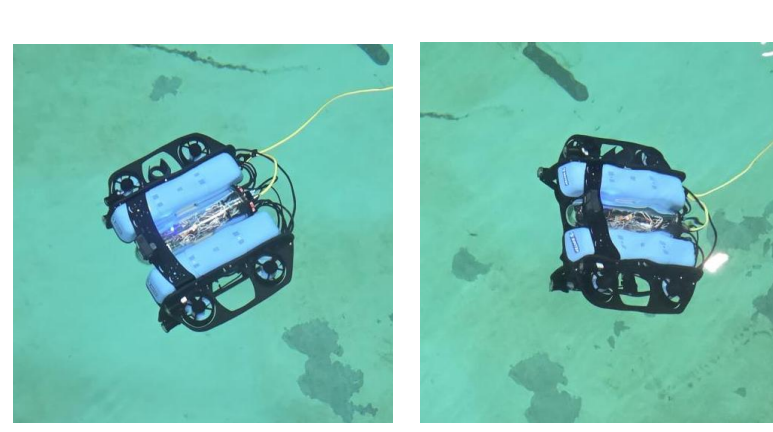
(10 trials per experiment, tested across two separate field deployments)

- In-pool zero-shot validation:

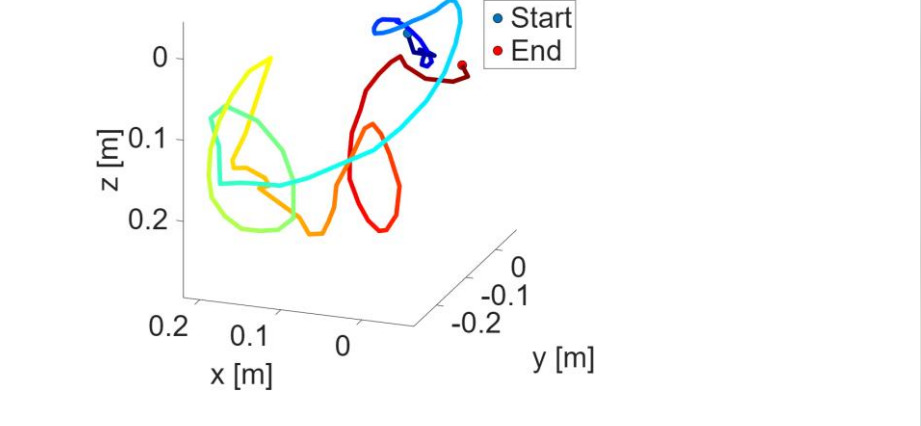
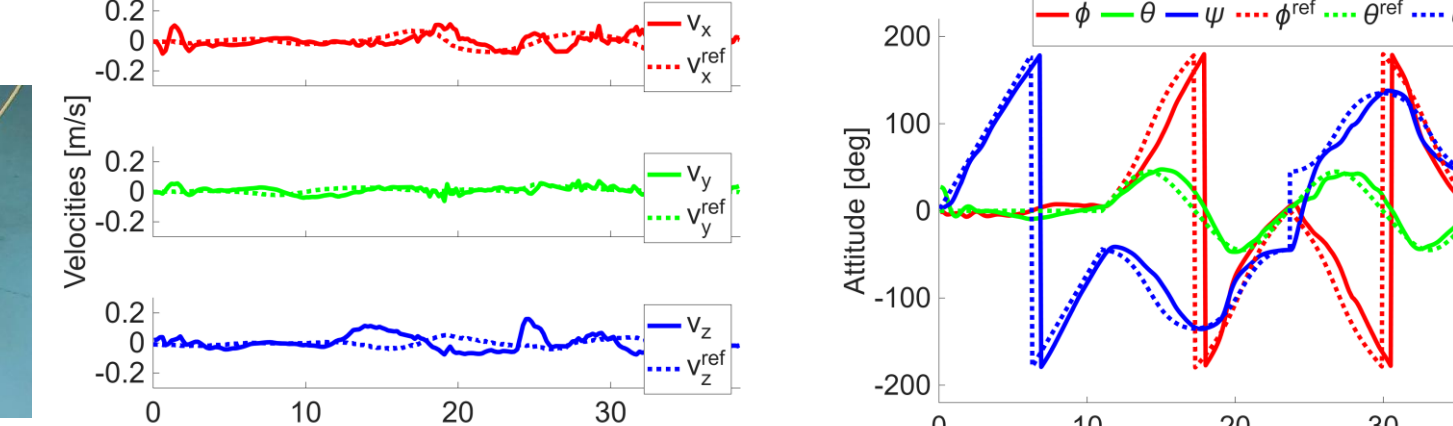
Straight line with disturbance:



Straight line with corkscrew rotations:



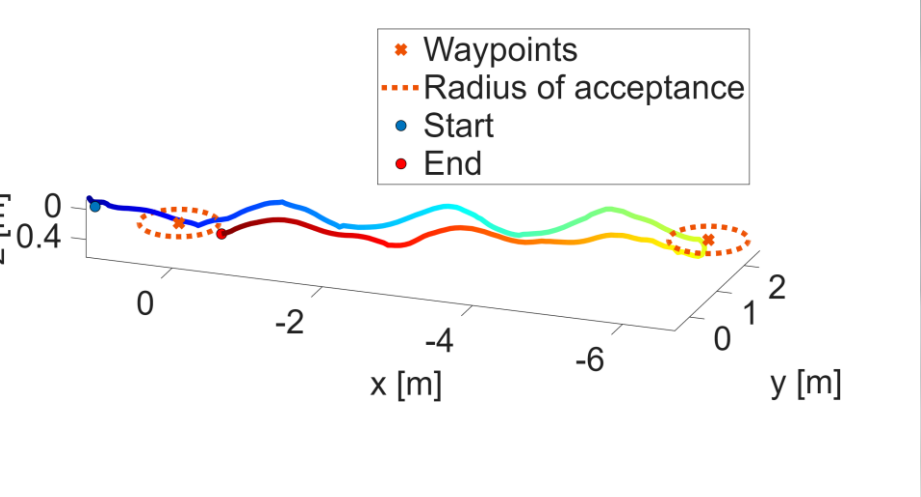
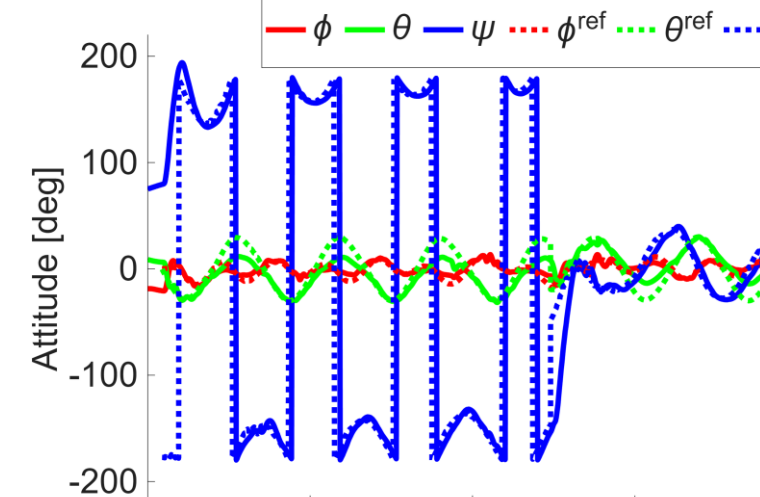
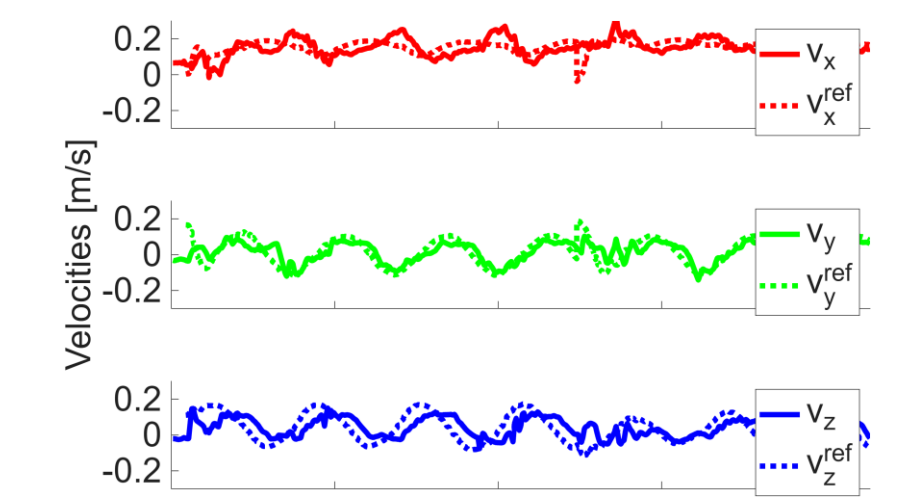
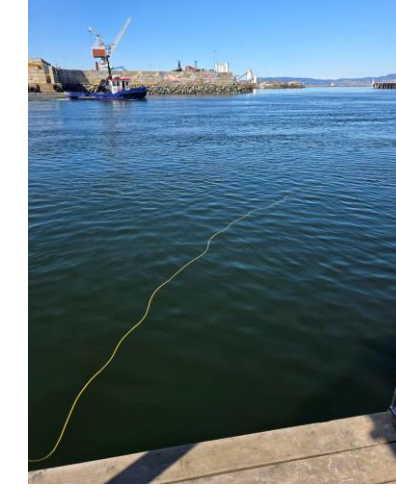
Yaw rotation with two perpendicular backflips:



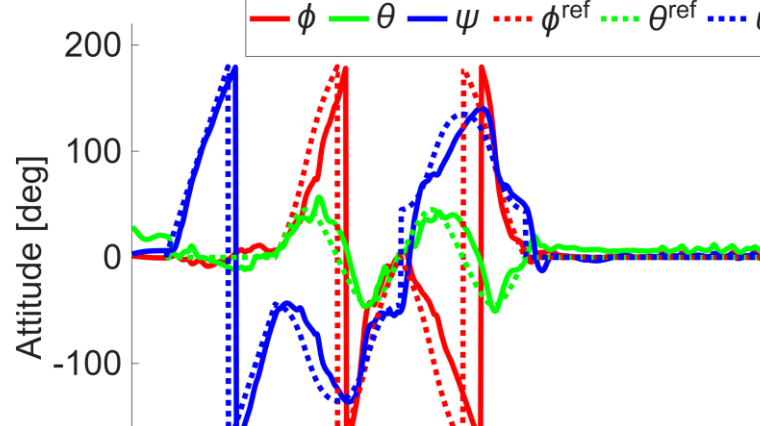
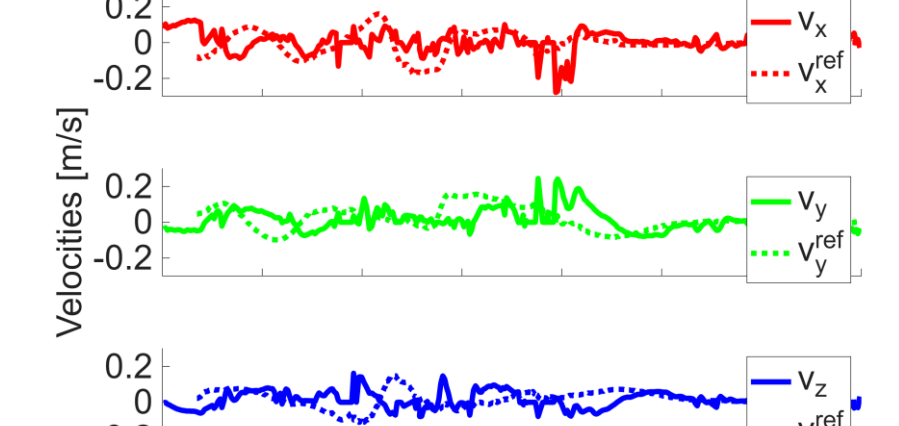
- Field deployments in Trondheim's port (tides with currents up to 0.5m/s)

\* Same policy, same platform, no balancing between clean water and seawater

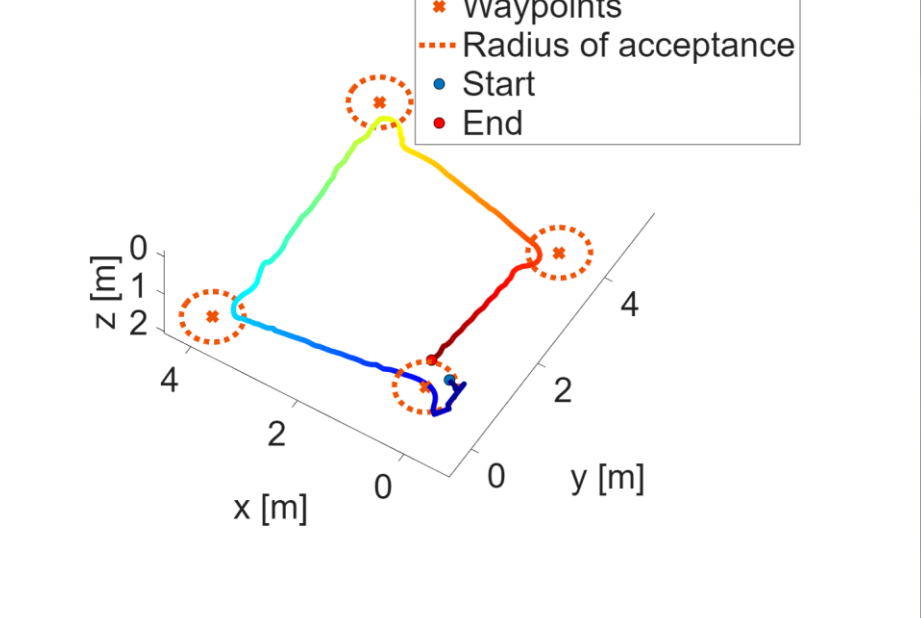
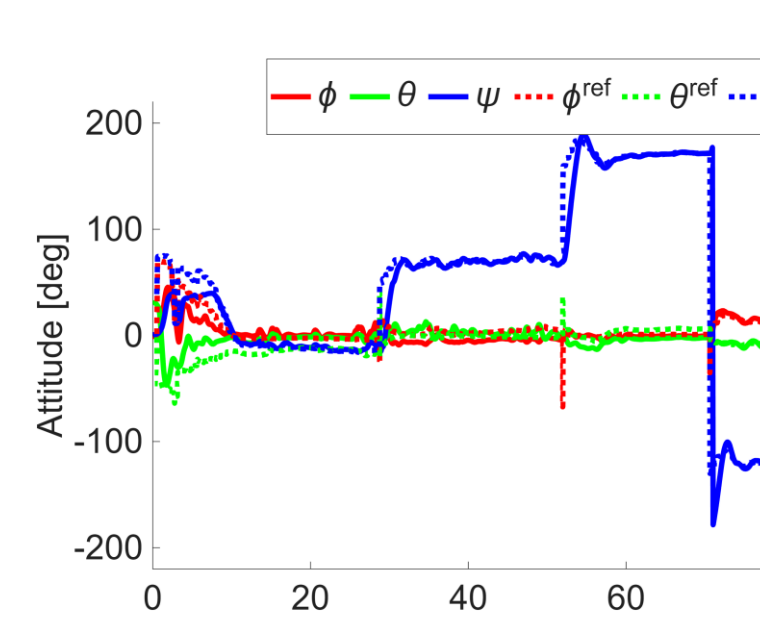
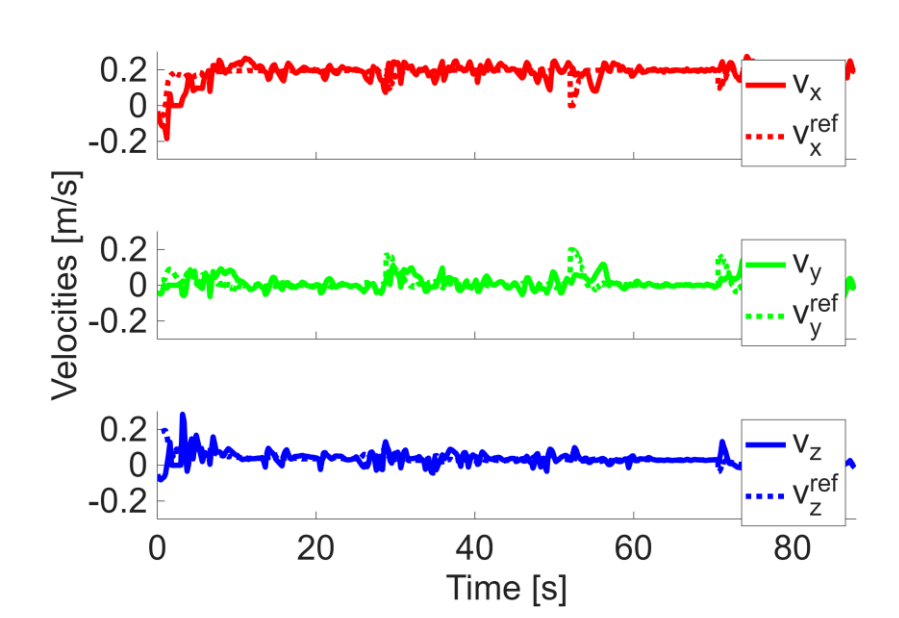
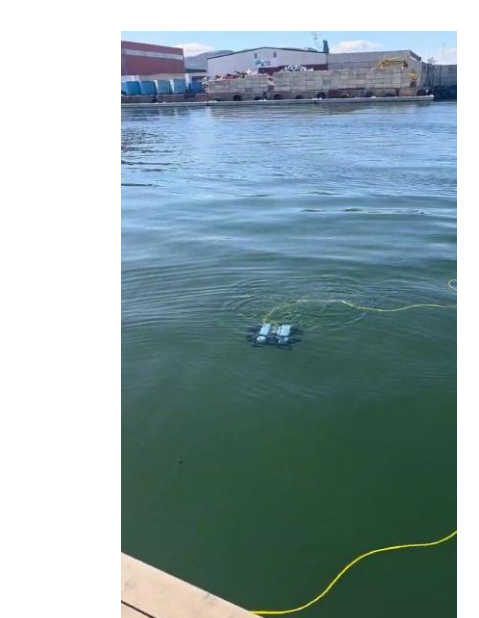
Straight line with corkscrew rotations:



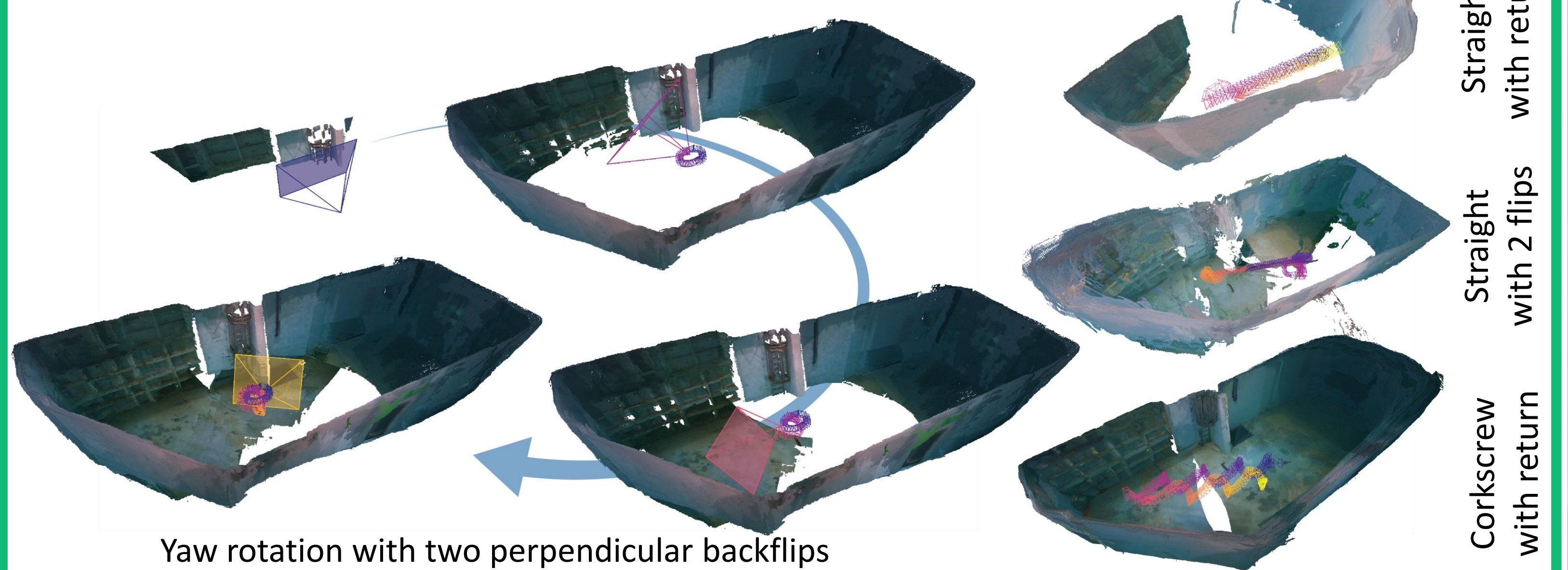
Yaw rotation with two perpendicular backflips:



Square pattern with straight lines (5 trials):



- Preliminary results verifying improved 3D coverage:



## Conclusions & Future Work:

A novel zero-shot sim-to-real DRL position & velocity control methodology is presented, incorporating Fossen's equations and enabling hydrobatic performance. Additionally, motion primitives were developed towards increasing viewpoint diversity in underwater operations. Extensive experiments display the robustness and effectiveness of the proposed concept for increased 3D mapping coverage. On-going work focuses on integrating a 3D Sonar to enable sensing in zero visibility and extend prior work for agile autonomous mapping of challenging underwater structures.

Underwater Active Perception:



3D Sonar Mapping:



3D Sonar Navigation:



## Acknowledgements:

We would like to thank Water Linked for assisting with recordings in the field trials. This research is funded by INESC.TEC.OCEAN Center of Excellence in Ocean Research and Engineering (#101136903)

