Proof of concept for underwater localization, characterization, and excavation of partially-buried munitions using robotic perception and control

MR24-4529

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In-Progress Review Meeting

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Project Team

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Bottom Line Up Front

What is being evaluated:

underwater localization, characterization, and precise excavation of partially buried objects in low visibility conditions using the SHARC (SHared Autonomy for Remote Collaboration) framework

What is going well:

hardware integration and algorithm development

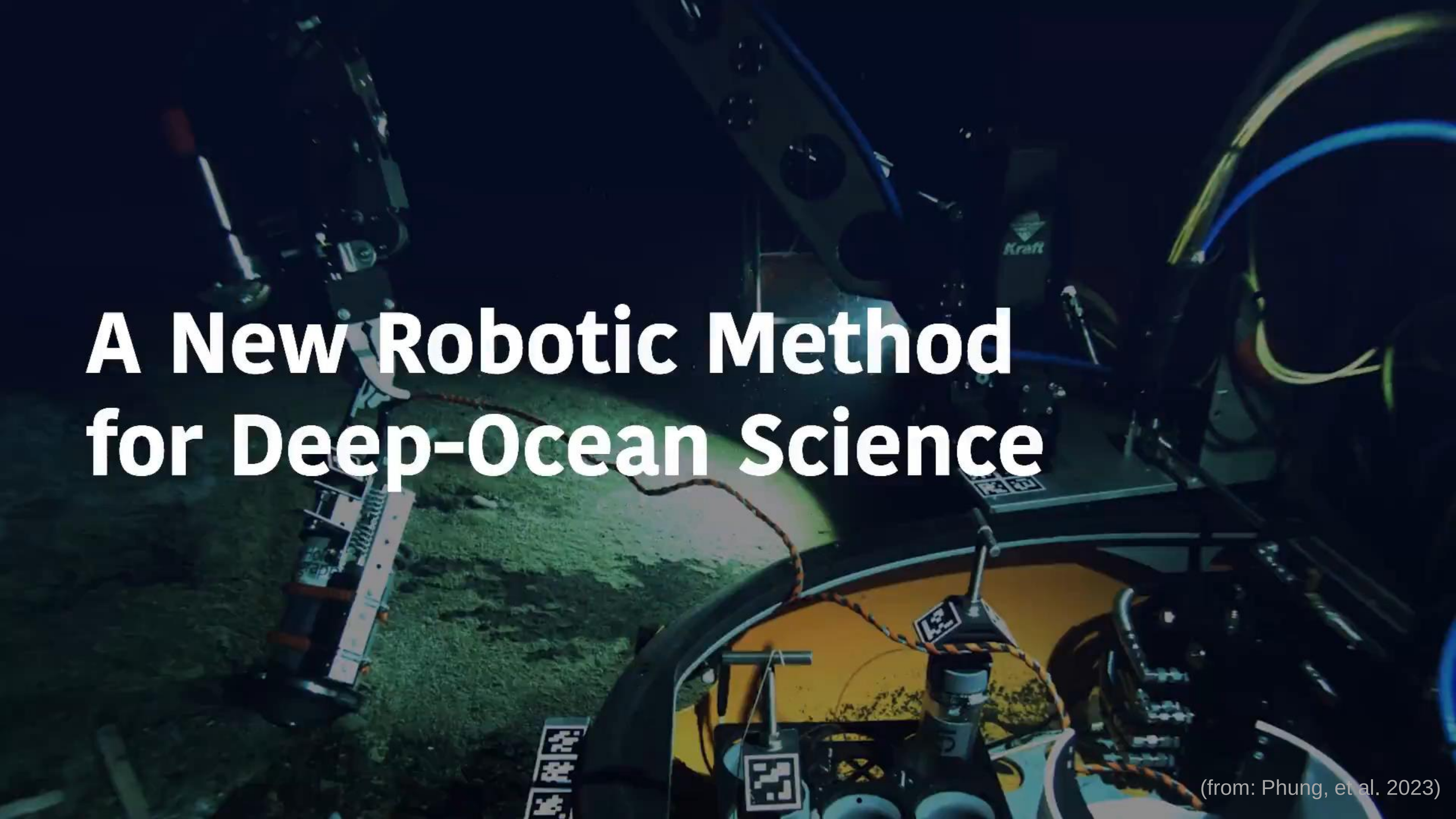
What is not working:

Computational complexity for real-time 3D reconstruction scales exponentially as a function of resolution. Centimeter-level spatial resolution has required abandoning conventional approaches (e.g., occupancy grid) and developing new computational methods based on ray tracing and 3DGS (e.g. Matsuki et al, 2024) .

What support is needed:

simulated munitions to seed testbed workspace in order to evaluate observability

A New Robotic Method for Deep-Ocean Science



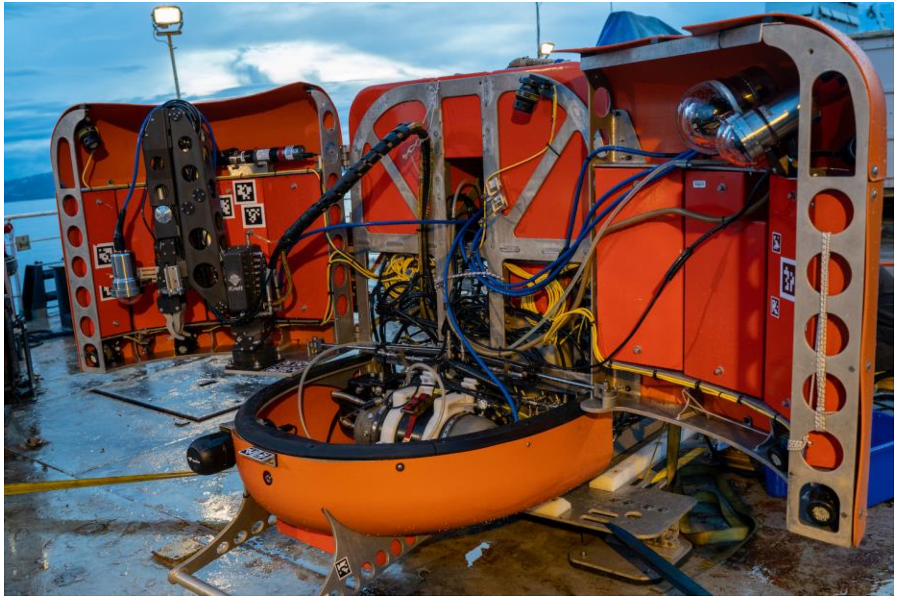
(from: Phung, et al. 2023)

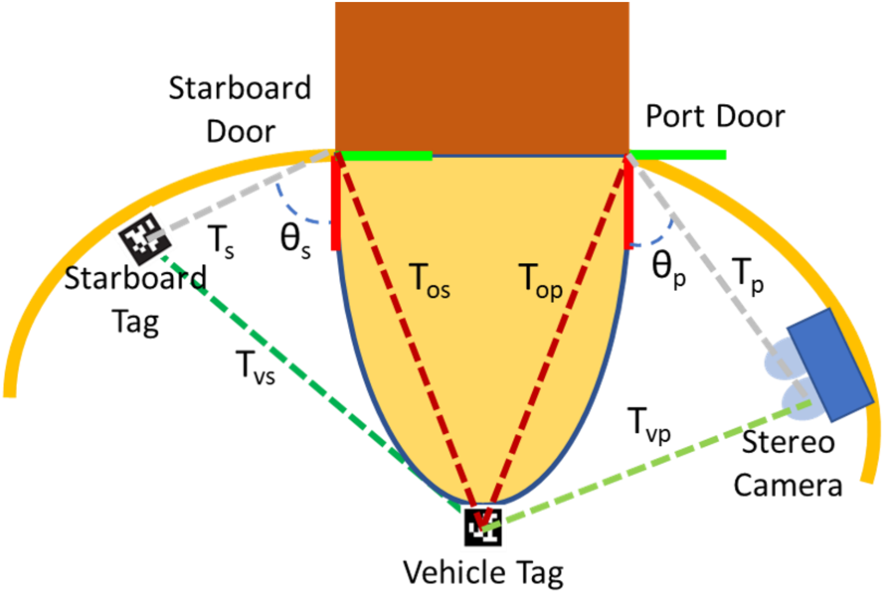
Technical Objective

1. Modify SHARC to incorporate ultra-high frequency sonar data while using jetting tool for excavation.
2. Develop a real-time process fusing optical imagery and sonar returns to generate 3D visualization of the workspace
3. Conduct tank tests to evaluate the utility of the method for localization, characterization, and excavation of partially-buried inert munitions in optically turbid water.

Technical Objective

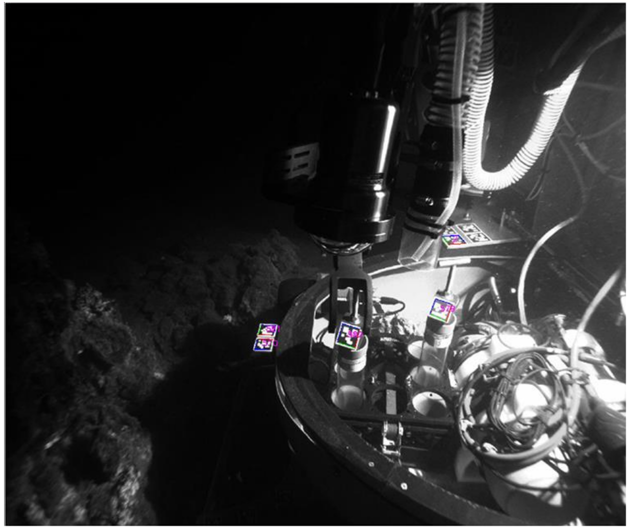
Concept of operation



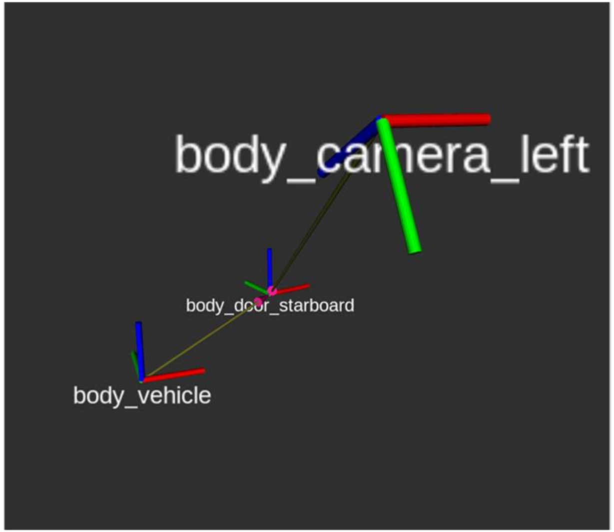


from: Billings et al. 2022

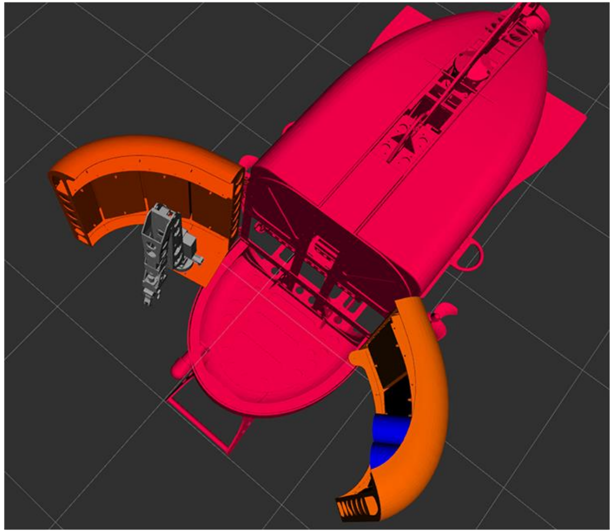
Technical Objective



(a)



(b)



(c)

(a) Fiducial-based visual SLAM using April Tags to estimate relative poses
(b) SLAM estimates of relative positions of vehicle components (door, arm, tools, etc.)
(c) Real-time update of vehicle model’s state for task and motion planning

from: Billings et al. 2022

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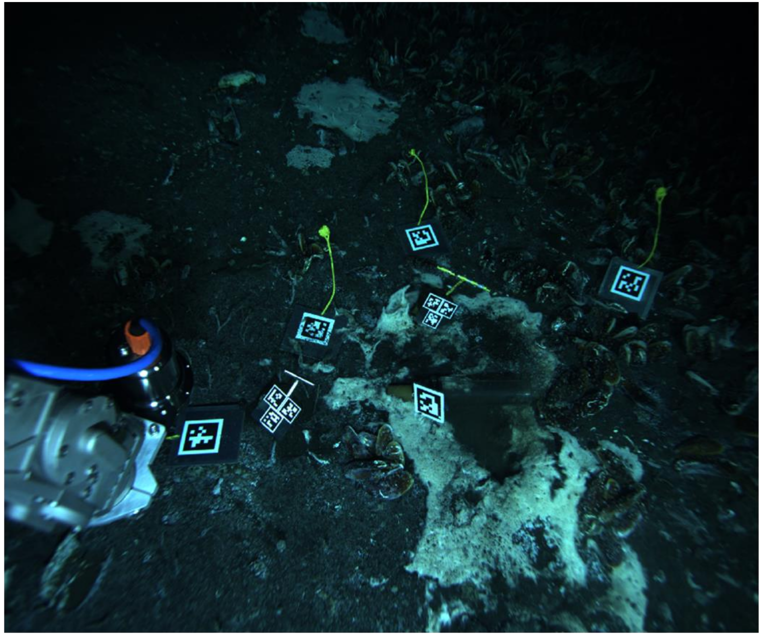
Technical Objective

Good



from: Billings et al. 2022

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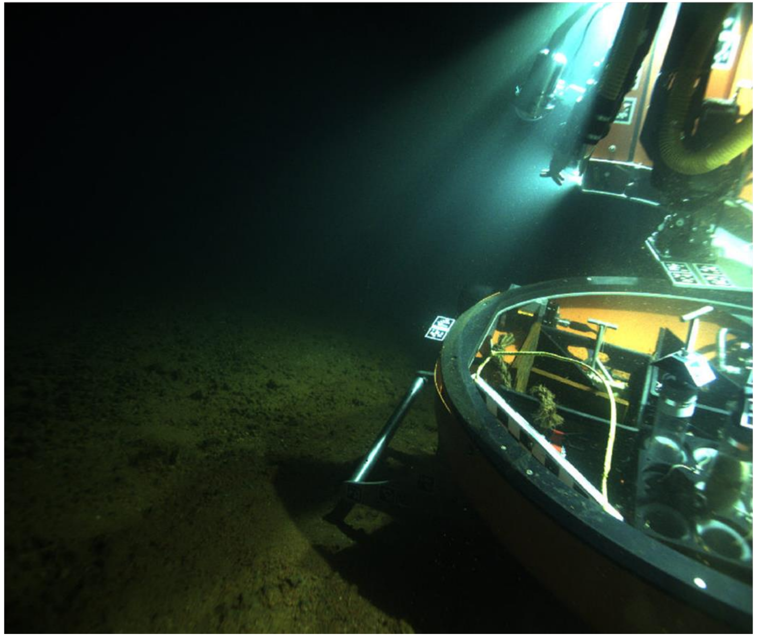
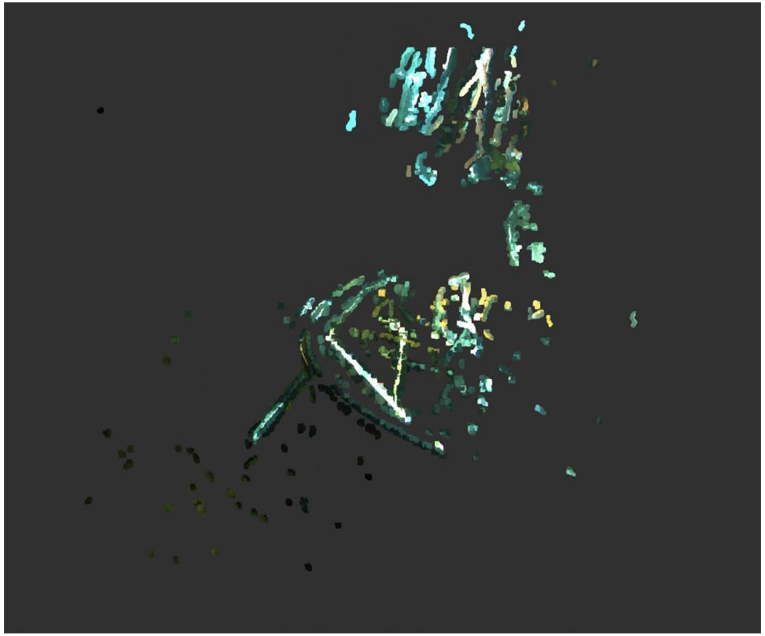
Technical Objective

Poor

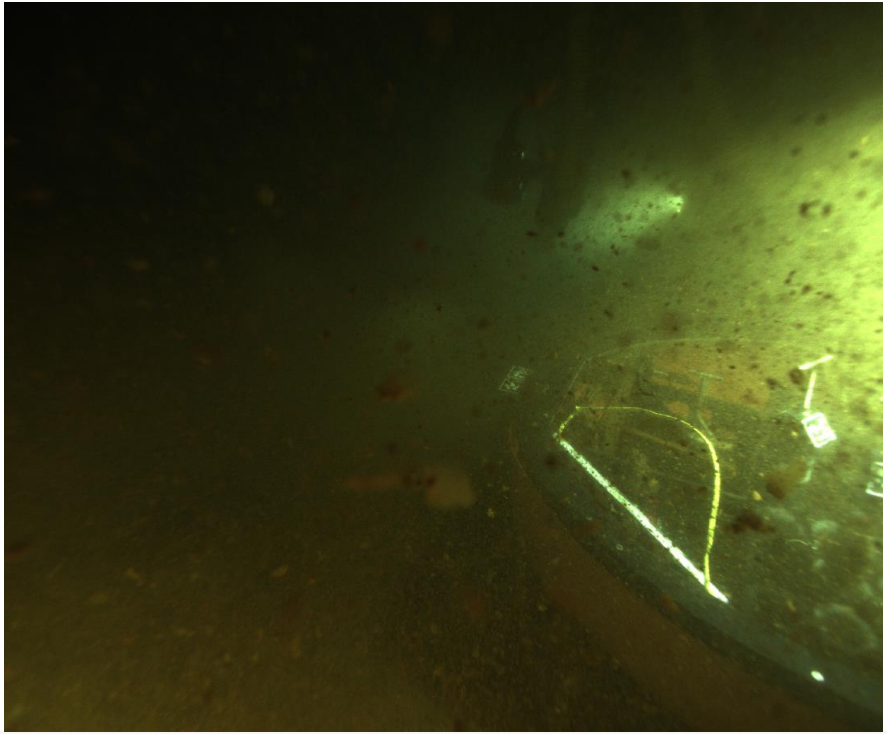




from: Billings et al. 2022

Technical Objective

Impossible



Technical Approach

Task 1 ☑
Build robotic intervention testbed

- **Task 1.1 ☑** Integrate 3D optical imaging system
- **Task 1.2 ☑** Fabricate robotic arm base & pedestal
- **Task 1.3 ☑** Integrate high-Frequency sonar
- **Task 1.4 ☑** Fabricate robotic jetting tool

Task 2.1 ☑
Develop real-time 3D workspace reconstruction using fused opti-acoustic data

Project is now here

Task 2.2
Integrate and test jetting tool

Task 3
Go/ NoGo decision

Go

Task 4
Demonstrate proof-of-concept operation

NoGo

End program

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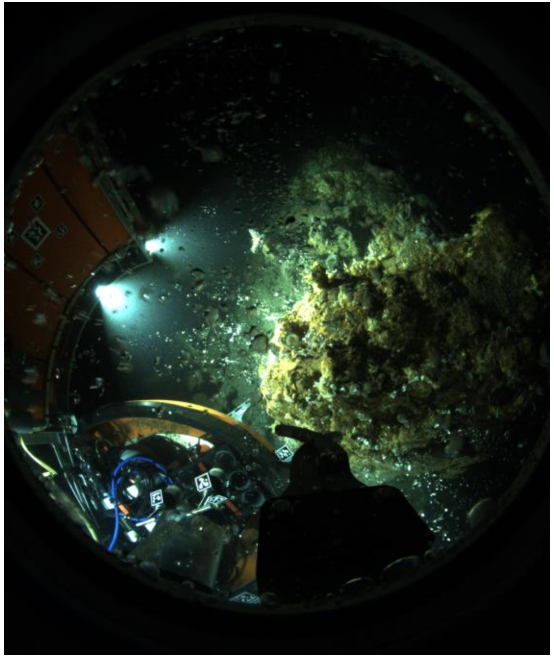
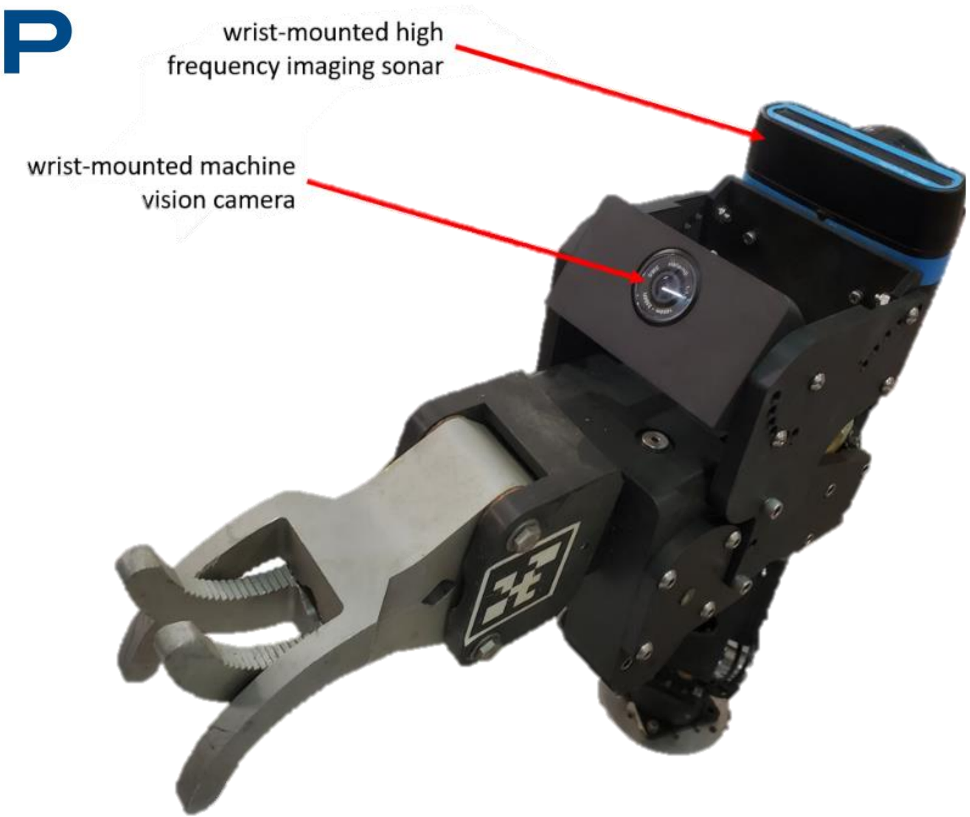
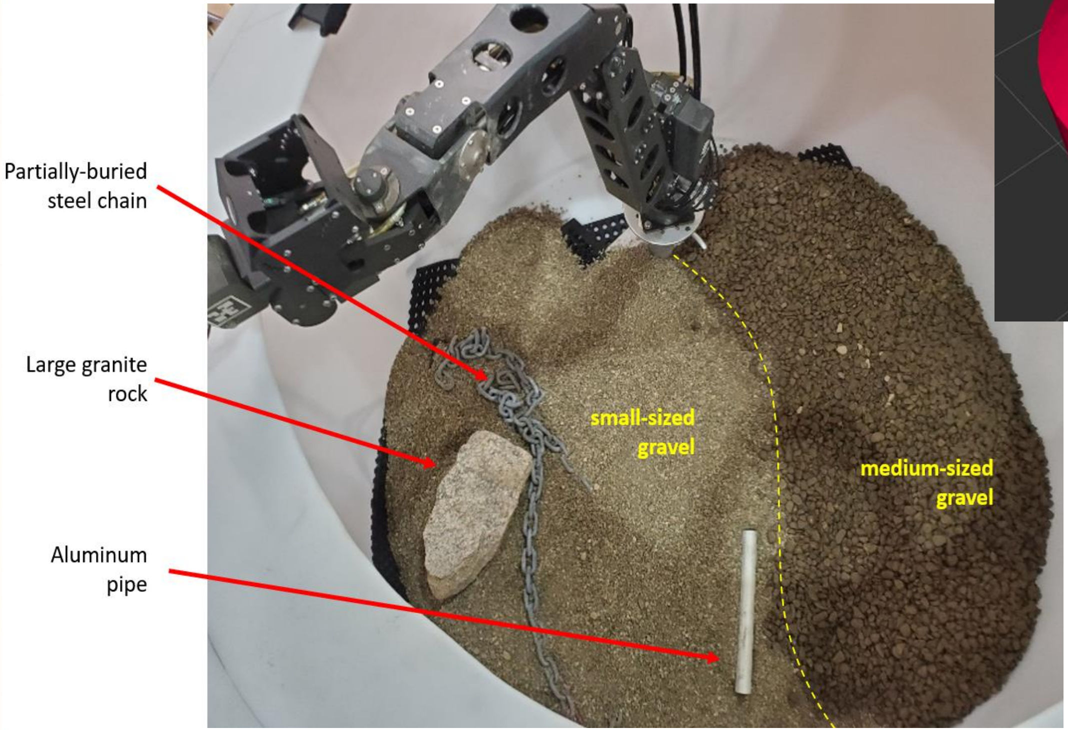
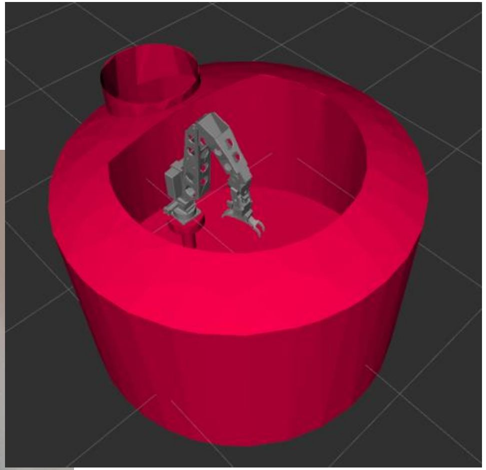


Task 1.1: Integrate 3D optical imaging system



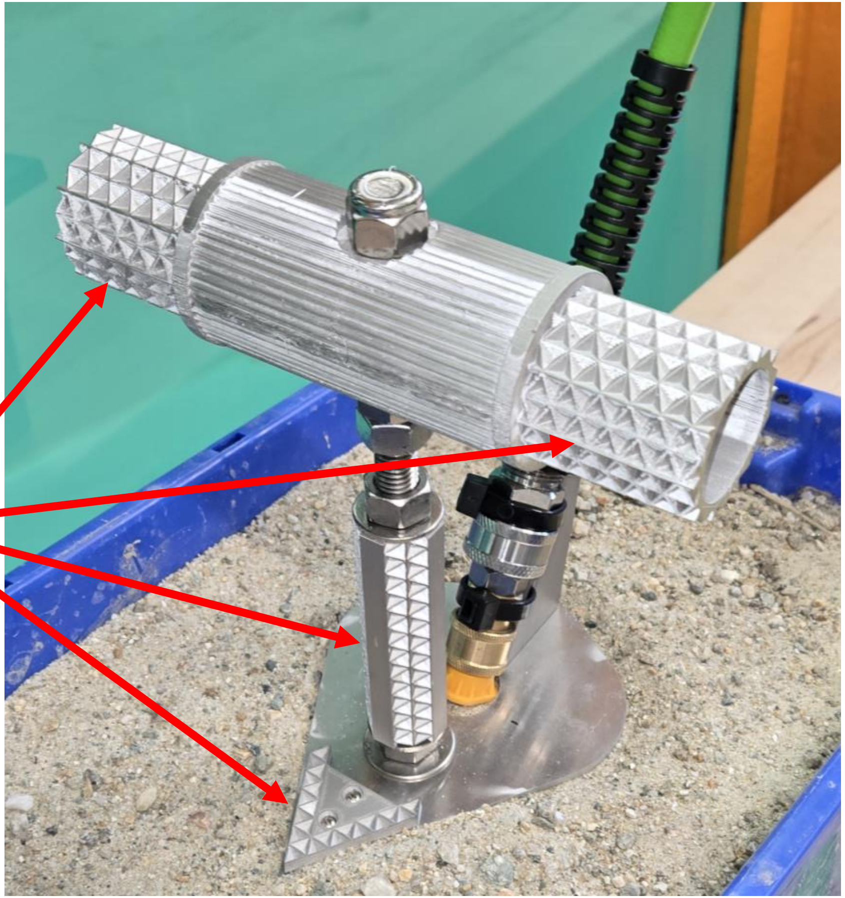
Tasks 1.1 & 1.3: Eye-in-hand optical camera and high frequency sonar





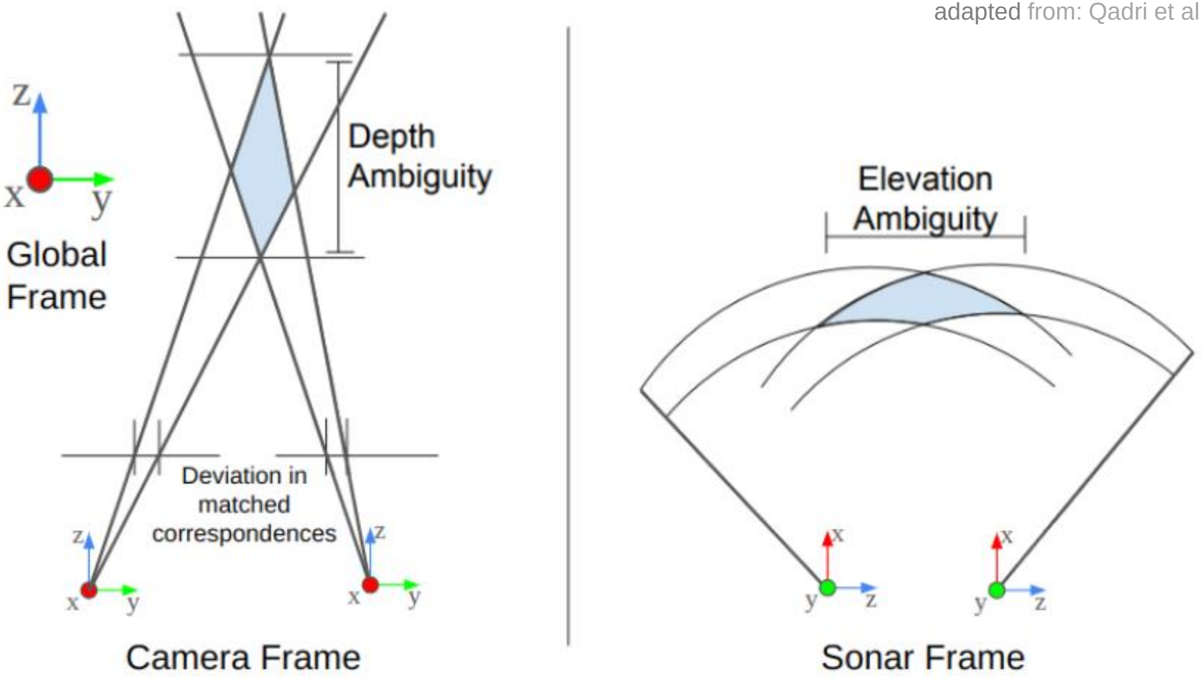
Task 1.2: Robotic arm testbed within 1500 gallon tank

frequency-tuned acoustic fiducial reflecting surfaces

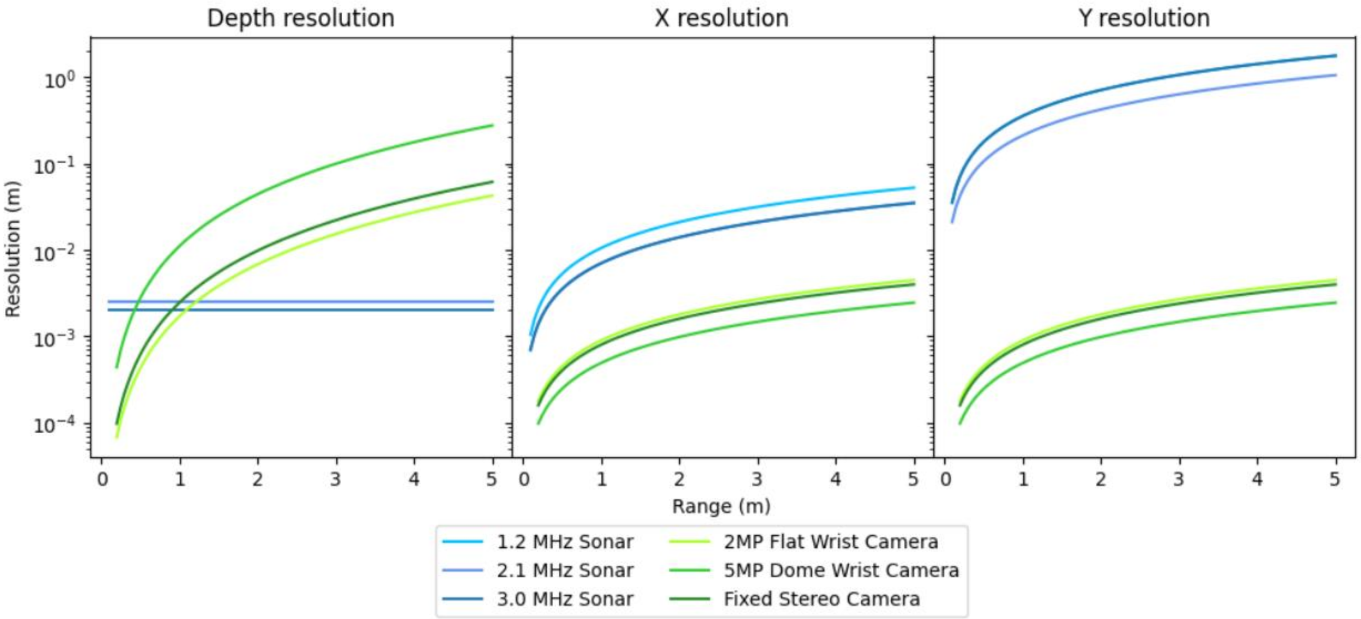


Task 1.4: Jetting tool

Differing modes of resolution uncertainty
adapted from: Qadri et al. 2024



Task 2.1: real-time 3D workspace reconstruction using fused opti-acoustic data



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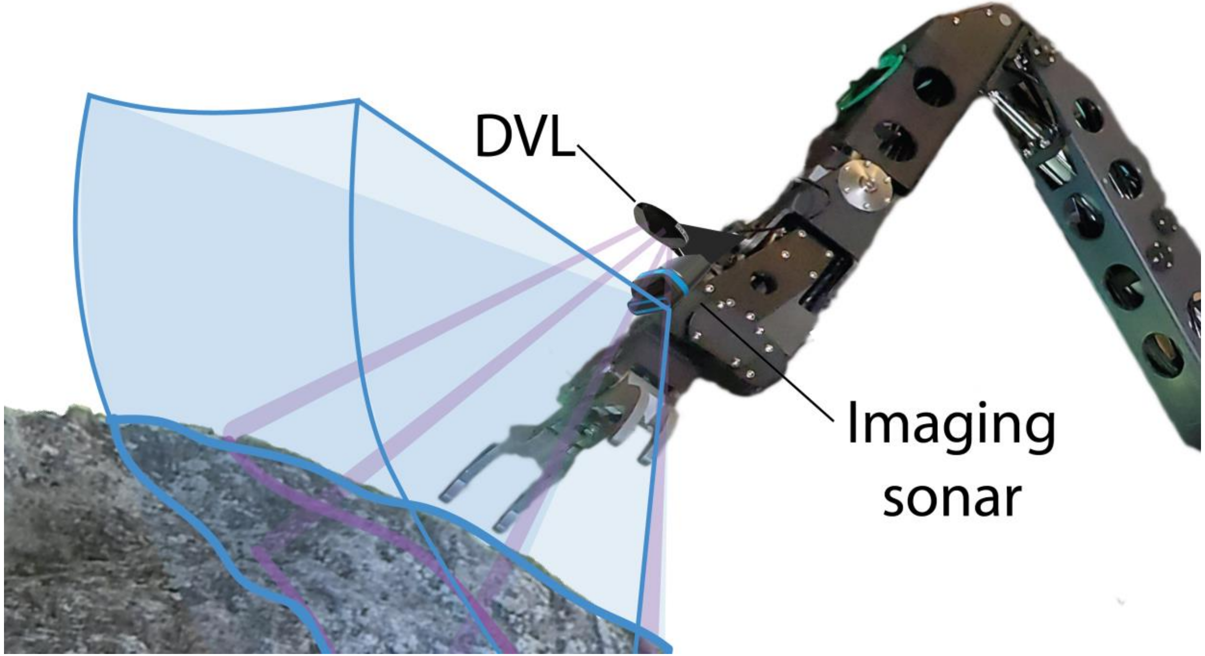

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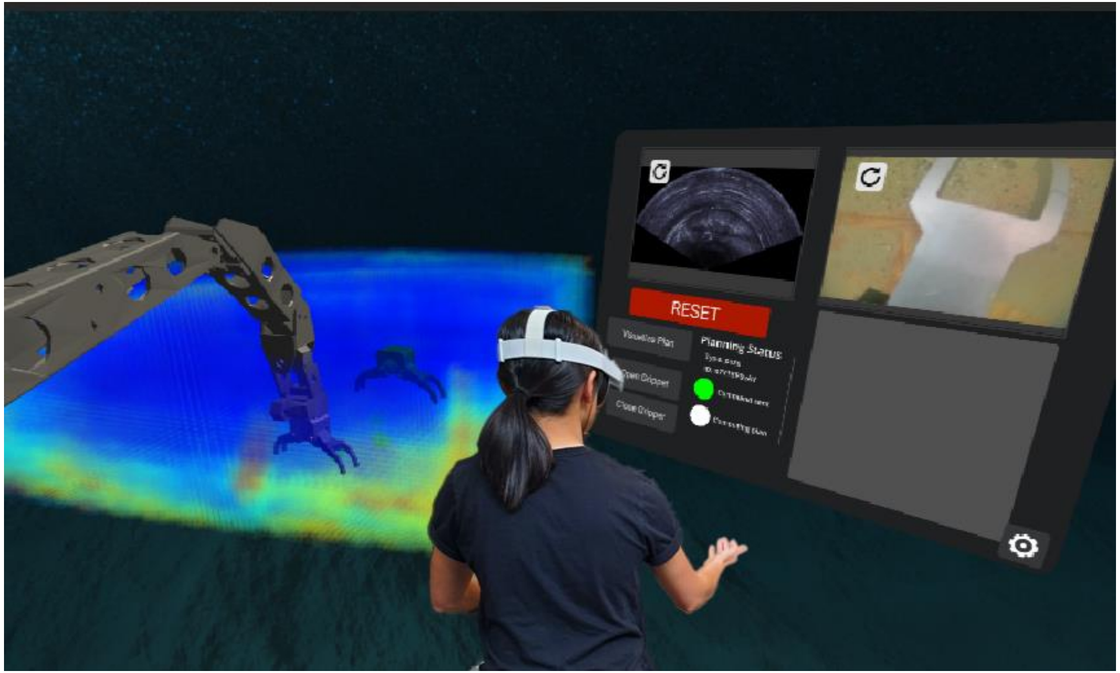

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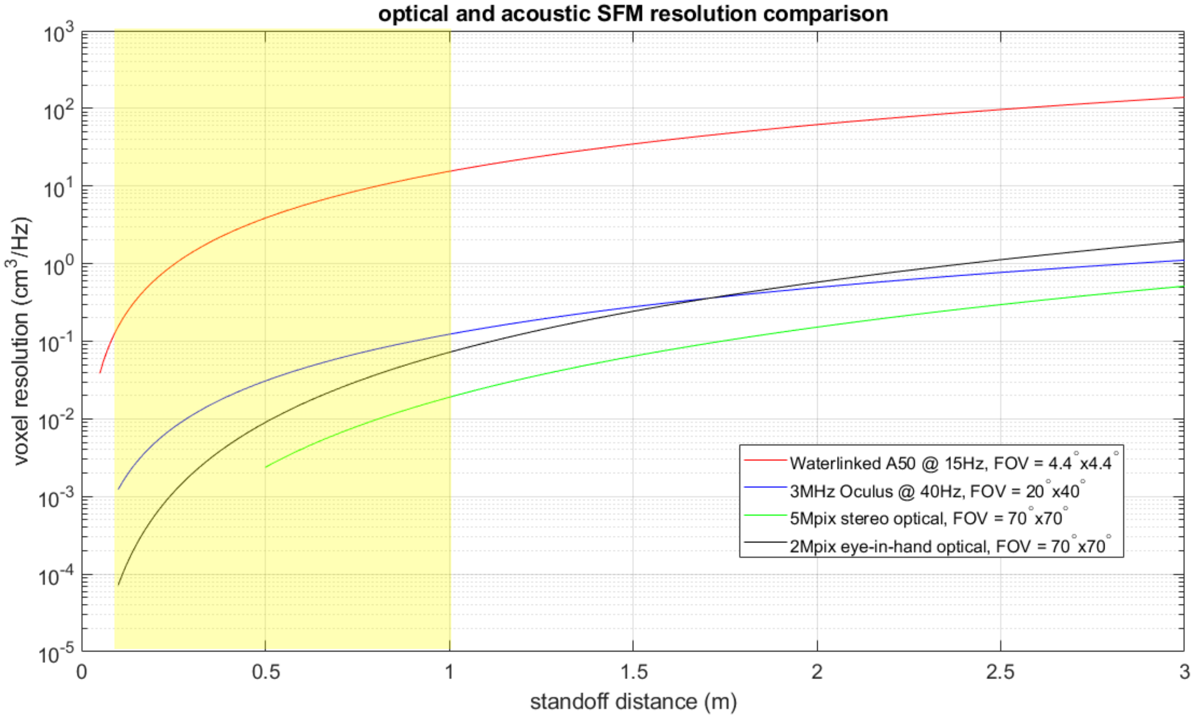
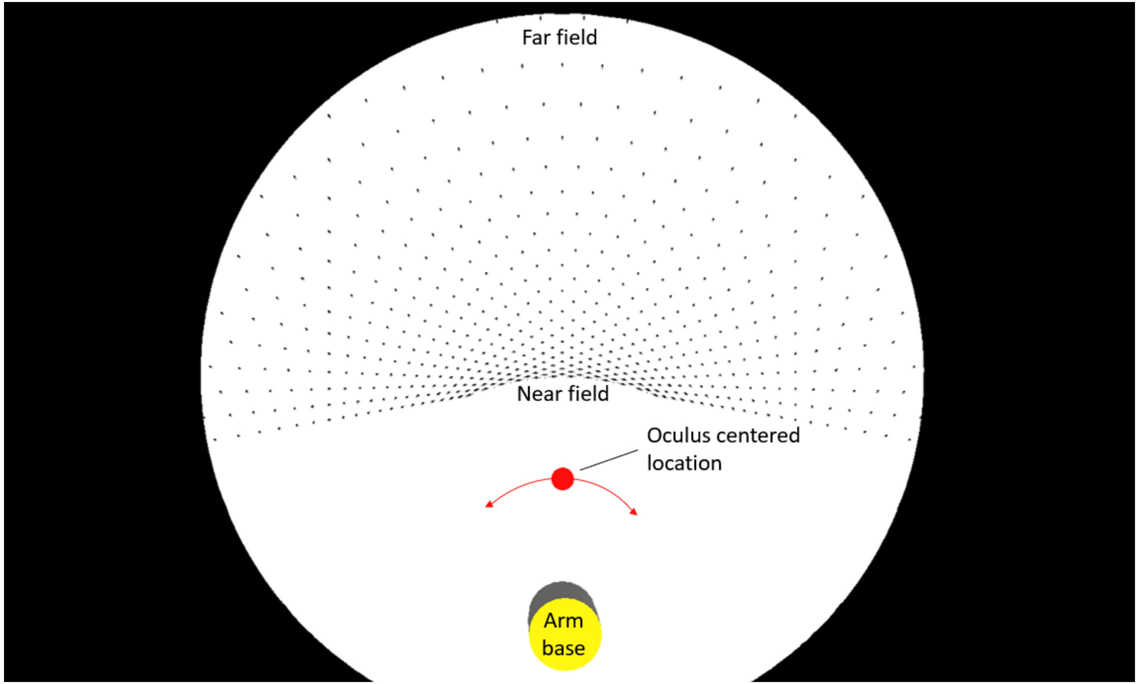


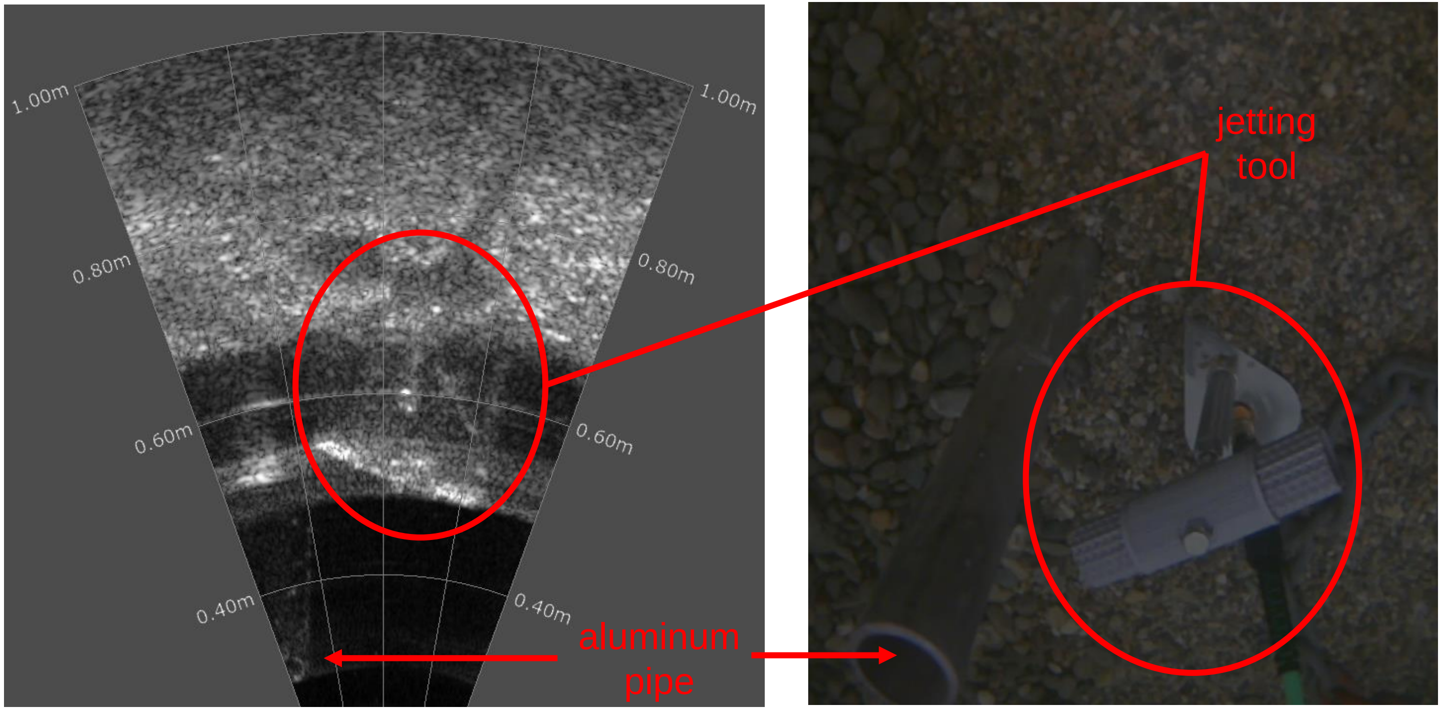
Task 2.1: real-time 3D workspace reconstruction using fused opti-acoustic data



Task 2.1: real-time 3D workspace reconstruction using fused opti-acoustic data

Preliminary Results

Example of observability of jetting tool



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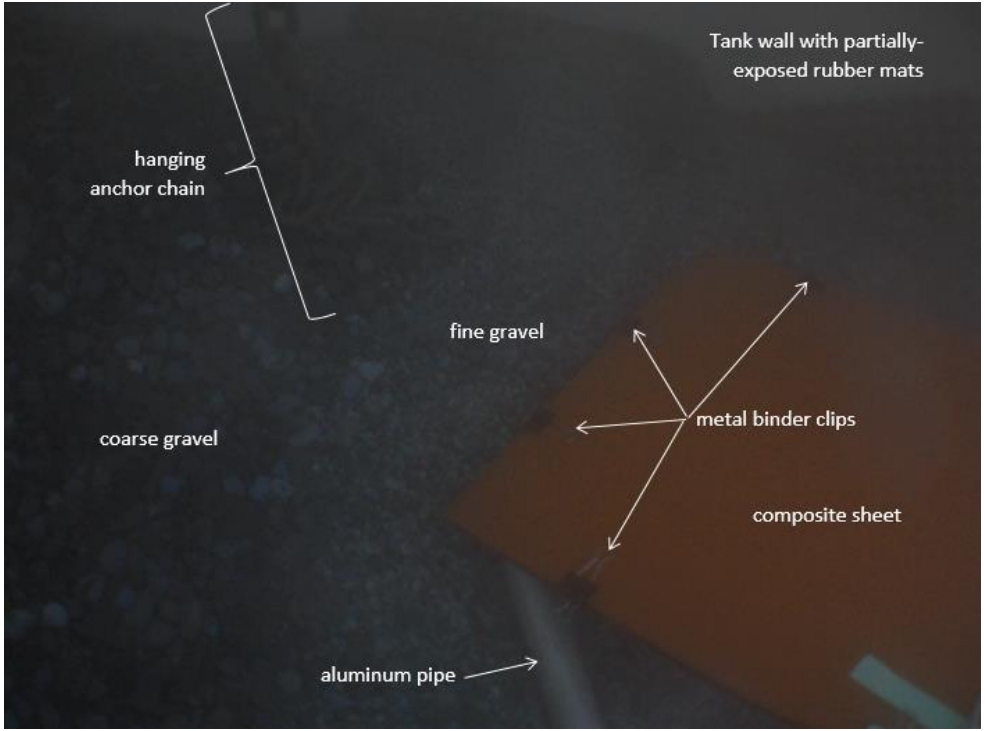
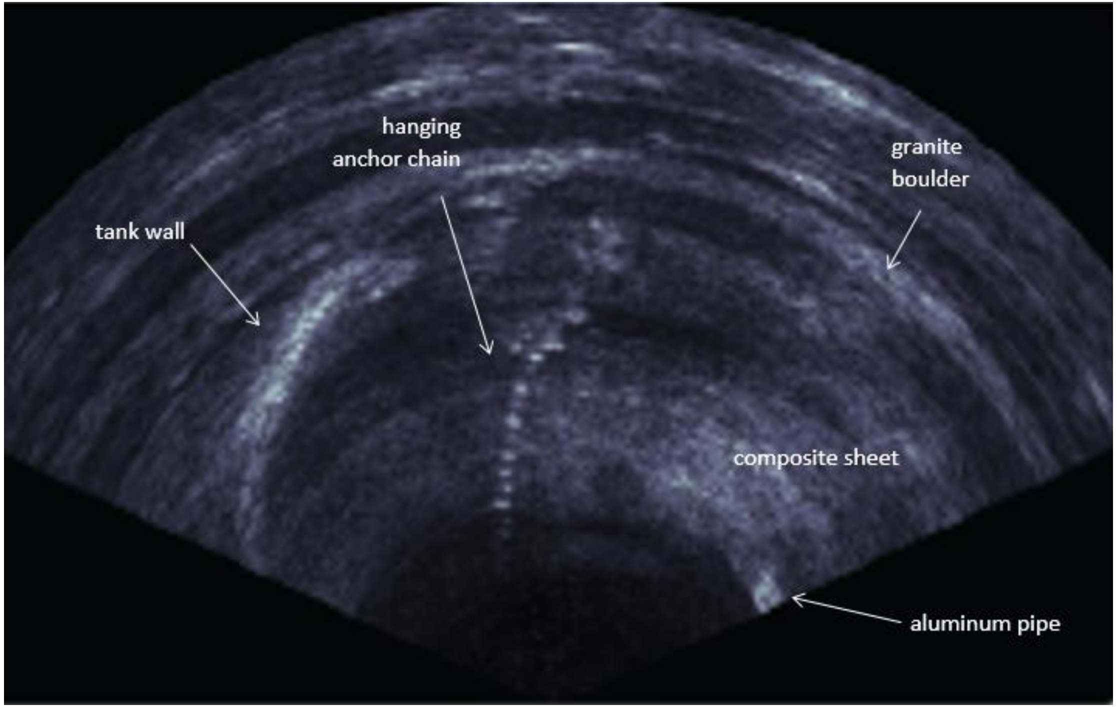
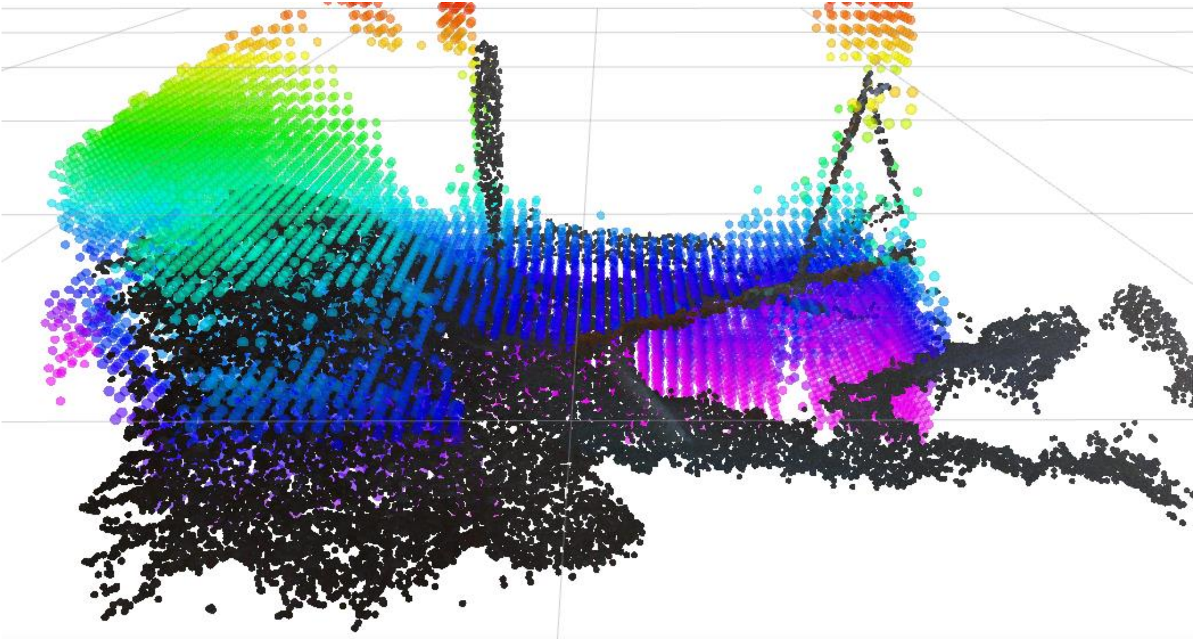


Raw optical image of workspace

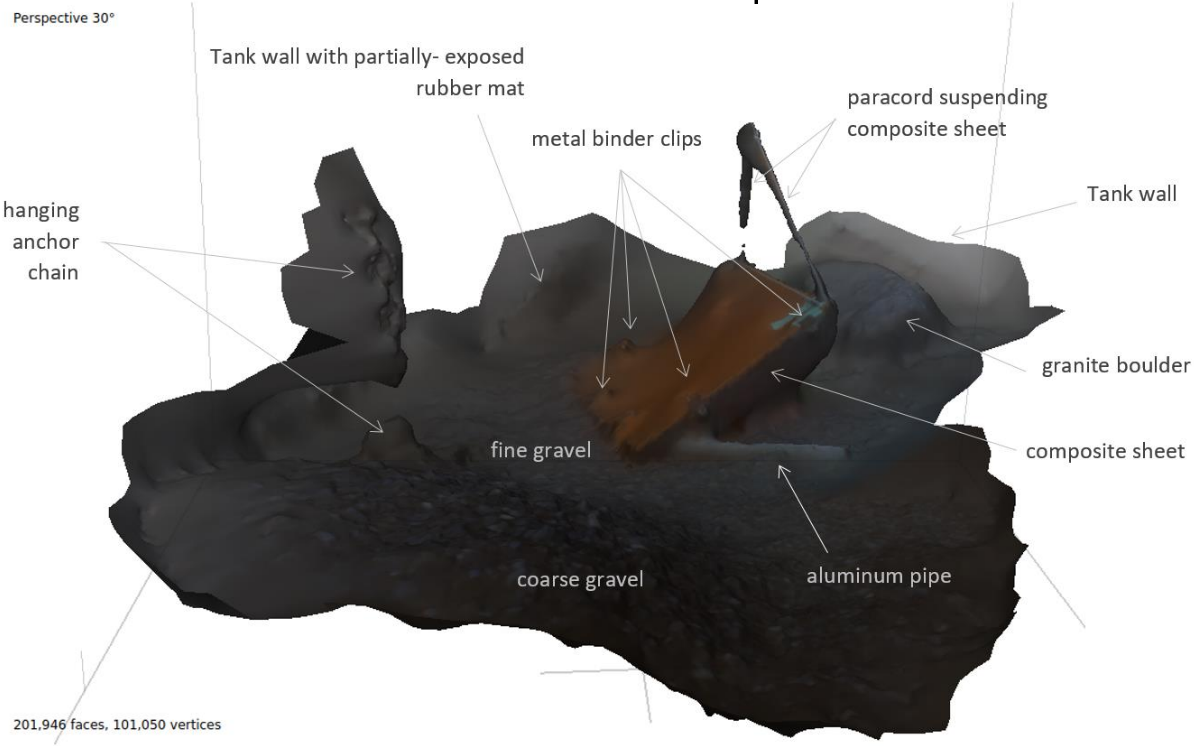


Raw sonar scan of workspace

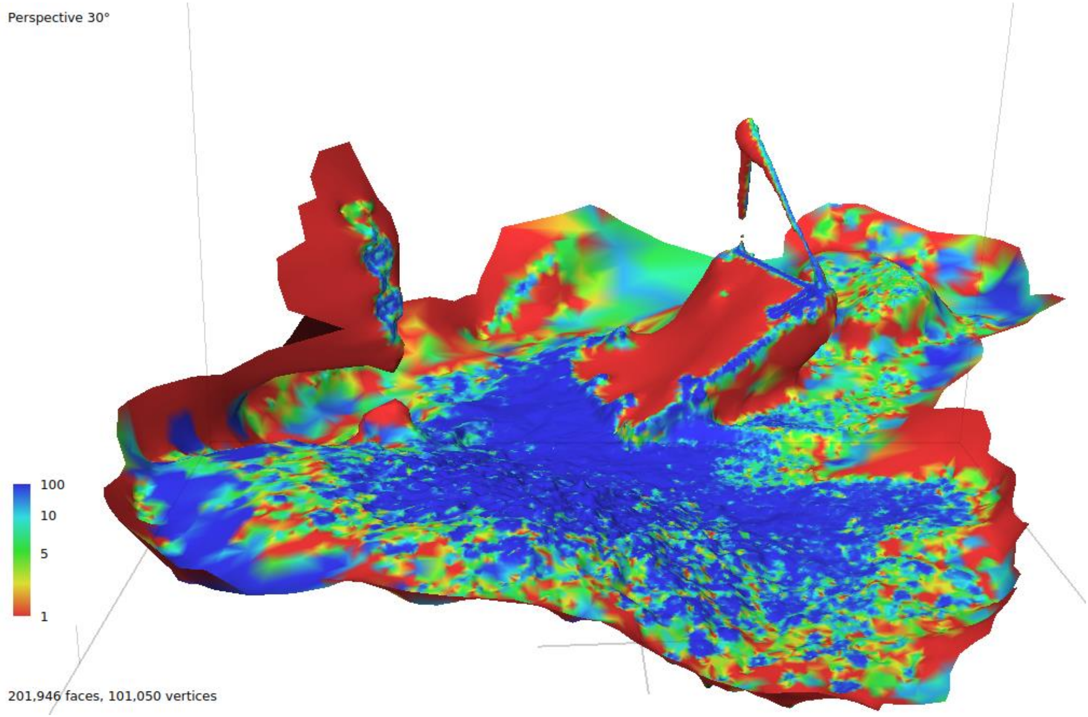


Decimated 3D point cloud of workspace (3MHz sonar data color mapped to elevation, 2Mpx optical points appear in gray without color correction).

Real-time 3D reconstruction using “eye-in-hand” fused optical and acoustic data.



Meshed 3D reconstruction



Confidence map (hot = low confidence, cool = high confidence)

Future Research

Near-term

- Research timeline remains on schedule and preparing for proof-of-concept demonstrations in the coming months.
- 3D reconstruction methods continue being refined to enable accurate estimation of workspace uncertainty and iterative improvement in workspace understanding
- Develop a modified April Tag using frequency-tuned acoustically reflective surfaces to automated tool pose estimation in low visibility environments.

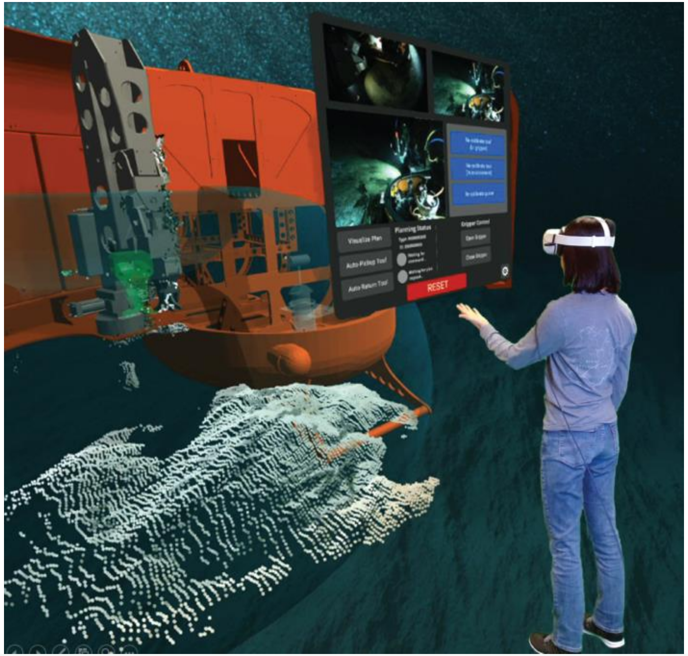
BACKUP MATERIAL

Technical Objective

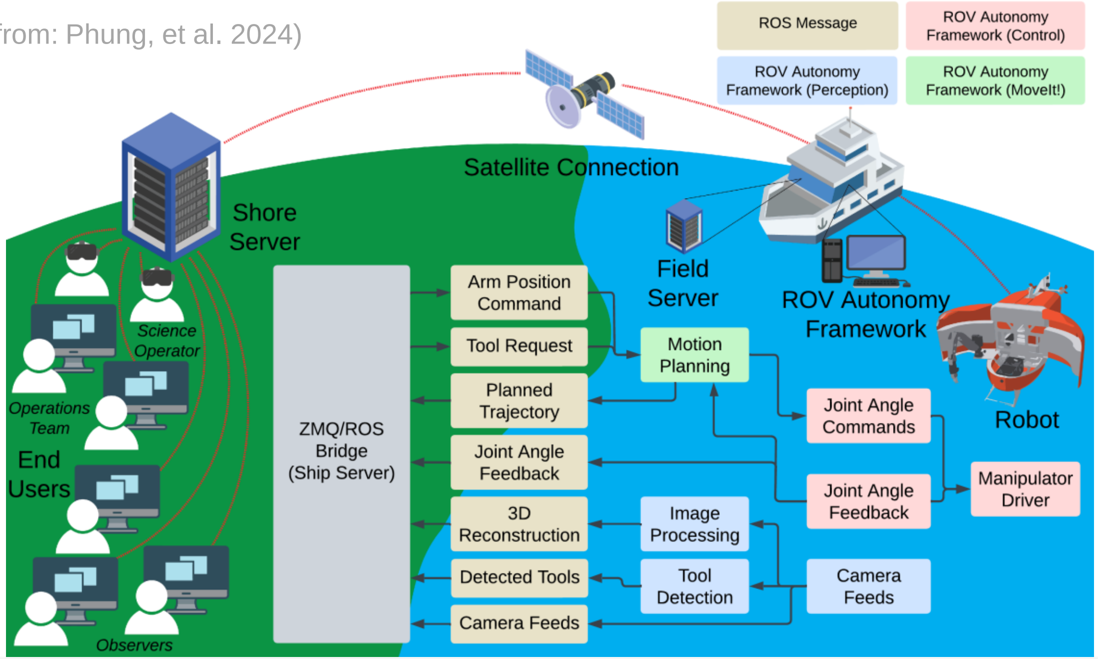
Conventional operations

Technical Objective

What is SHARC? …. (SHared Autonomy for Remote Collaboration)



(from: Phung, et al. 2024)



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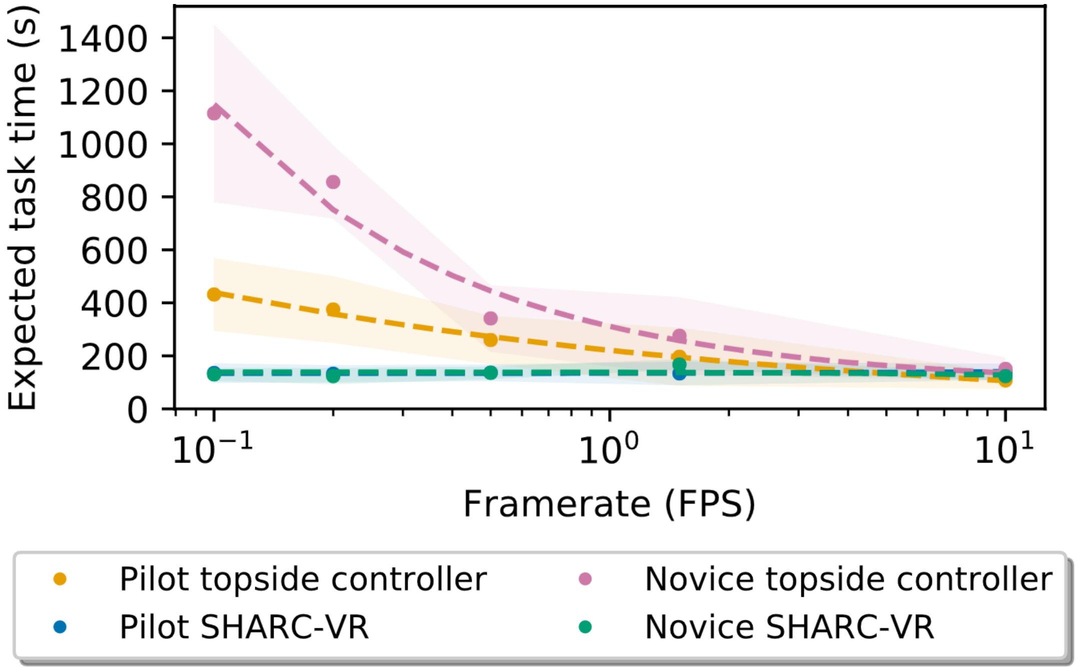
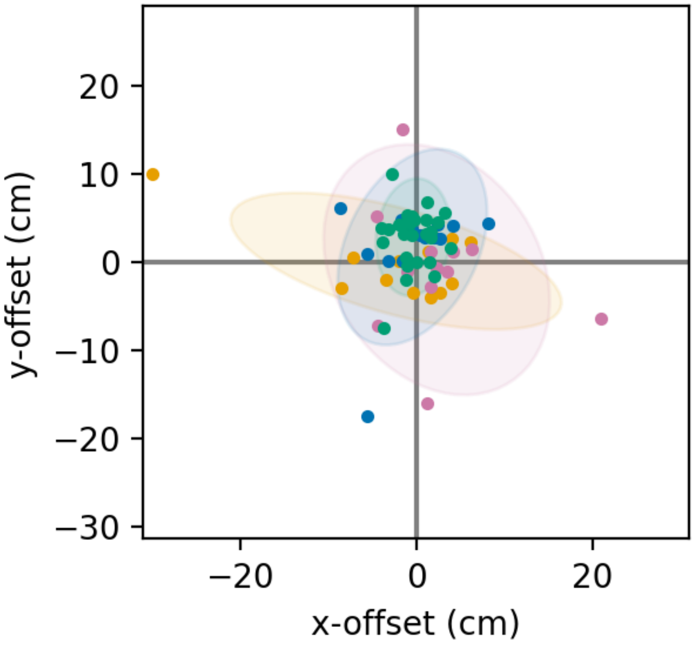
Technical Objective





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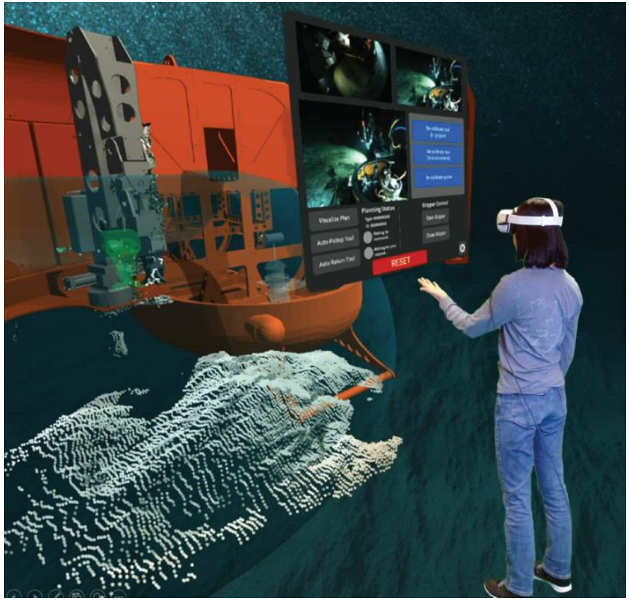
24-4529: Proof of concept for underwater localization, characterization, and excavation of partially-buried munitions using robotic perception and control



Technology Focus

- Develop a robotic process that can be used by remote operators to quickly detect, localize, classify and remediate proud and partially buried underwater munitions in low-visibility.

Research Objectives

- Fuse optical imagery with sonar acoustic data to enable real-time 3D situational awareness of workspace in varying lighting and turbidity conditions.
- Criteria for success: proof-of-concept demonstration, wherein remote operators collaboratively locate, excavate, and map in 3D a partially buried inert munition in water with visibility of less than 1m.

Project Progress and Results

- *Completed fabrication of testbed*
- *Demonstrated fused optical-acoustic perception for real-time 3D reconstruction*

Technology Transition

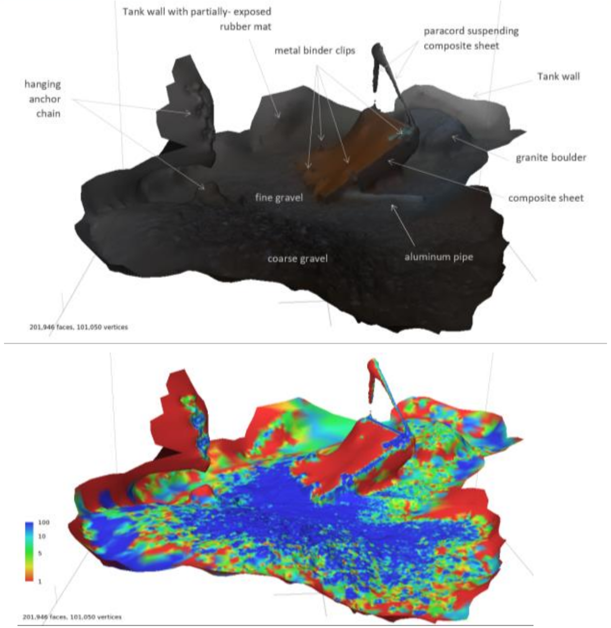
- Upon conclusion of this program, a critical design review will be conducted to identify technology components that require modification for further TRL advancement. The PI is currently in discussions with the US National Deep Submergence Facility to conduct engineering trials using the ROV Jason [https://ndsf.whoi.edu/jason/] during a cruise of opportunity conducting seafloor observatory node maintenance.

Plain Language Summary

- Remediation of underwater munitions is slow, costly, and potentially dangerous. Conventional approaches require on-site EOD teams using teleoperated robots and rely on 2D video camera feeds for situational awareness, which is inadequate for working in turbid environments.
- Our method fuses optical imagery with sonar acoustic data to generate a real-time 3D reconstruction of the workspace. This maximizes situational awareness, enabling safe and efficient intervention operations, regardless of water column visibility. The 3D reconstruction can be viewed by EOD team members located anywhere in the world using just a standard internet connection. This enables collaborative operation and guidance from off-site experts.

Impact to DoD Mission

- **Impact:** Developed a fused optical-sonar process for maintaining 3D underwater situational awareness of worksite.
- **Importance:** Can enable robotic remediation of munitions in low visibility conditions.
- **DoD advancement:** Intended to increase the efficiency and safety of munitions cleanup operations in coastal regions while lowering remediation costs.



Upper panel, fused 3D reconstruction of workspace using optical and sonar acoustic data; Lower panel confidence map (expressed in percent, where blue is high confidence, red is low confidence)

Publications

- A. Phung, G. Billings, A.F. Daniele, M.R. Walter, and R. Camilli, “A Shared Autonomy System for Precise and Efficient Remote Underwater Manipulation” *IEEE Transactions on Robotics*. in press 2024. DOI 10.1109/TRO.2024.3431830.

- A. Phung, G. Billings, and R. Camilli. "Sonar-Aided Manipulation in Low-Visibility Conditions by Novice Users." *OCEANS 2024-Halifax*. IEEE, 2024.

Literature Cited

- G. Billings, M. Walter, O. Pizarro, M. Johnson-Roberson, and R. Camilli. “Towards Automated Sample Collection and Return in Extreme Underwater Environments”. *Field Robotics*, 2, pages 1351–1385, 2022.
- A. Phung, G. Billings, A.F. Daniele, M.R. Walter, and R. Camilli, “Enhancing scientific exploration of the deep sea through shared autonomy in remote manipulation”. *Science Robotics*, 8(81) 2023.
- H. Matsuki, R. Murai, P.H. Kelly, A.J. Davison. “Gaussian splatting slam”. *InProceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 18039-18048, 2024.
- M. Qadri, K. Zhang, A. Hinduja, M. Kaess, A. Pediredla, and C. Metzler. “Aoneus: A neural rendering framework for acoustic-optical sensor fusion”. *In ACM SIGGRAPH 2024 Conference Papers*, pages 1–12, 2024.

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