Collaborative Research: NRI: INT: Cooperative Underwater Structure Inspection and Mapping

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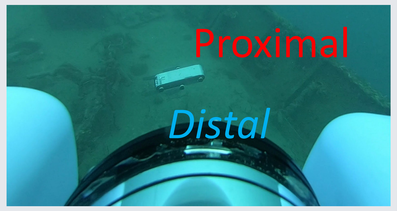
The problem

Underwater structure modeling is crucial for operating in different natural and manmade environments. These environments are diverse and include shipwrecks, oil-rigs and hydroelectric dams, submerged historical sites, and cave systems. Operating in the underwater domain is dangerous, tedious, labor intensive, and physically exhausting for humans. Underwater robots can enable such operations; however, the underwater domain poses unique challenges, including absence of localization systems (e.g., GPS) and communication infrastructure (e.g., WiFi). This collaborative research funded under the NSF-NRI program has the objective to address such challenges, answering to four important Research Questions:

(RQ1) How to robustly achieve cooperative localization with occlusions?
(RQ2) How to fuse the different sources of information on-board in real time for reconstruction?
(RQ3) How should the co-robots cooperate for the mapping task?
(RQ4) How to efficiently and robustly use limited resource communication channels to share information between a team of robots and between robots and operator?

Concept overview

The main idea of our solution is to have a team of co-robots collaborating with a human operator. There are two types of robots: **proximal observer**, which will operate close to the structure to map, and **distal observer**, which will be at distance maintaining the global picture of the structure and the pose of the proximal observer.



Intellectual merits and broader impacts

The **intellectual merits** of this project will be in several areas of computer vision, robotics, learning, and communication, including:

- Robust state estimation and cooperative localization, fusing several sensors.
- Cooperative exploration and planning of underwater vehicles in the presence of obstacles
- Cross-layer optimization approach for transmitting reconstructed models and vehicle positions under limited communication resources.

Having such a team of robots allows for **lowering the barrier to entry in underwater robotics**, as the robot design can be simplified by complementing their capabilities.

This project plans an extensive evaluation and application to underwater archaeology, consisting of

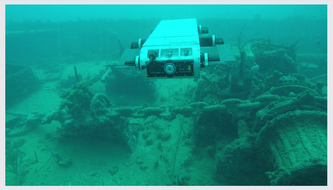
1. tests in a realistic 3-D simulator;
2. data collection in different environments and tests of the algorithms on the collected data;
3. tests directly on the computer onboard of the robot.

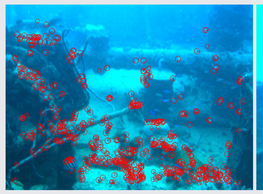
The project will have **broader impacts** in several high-impact applications, including infrastructure inspection and archaeological sites mapping. The project includes plans for engaging a diverse set of students, for example from Benedict College, the fourth largest Historically Black College or University in the country.

Map of the Carolinas with multiple shipwrecks

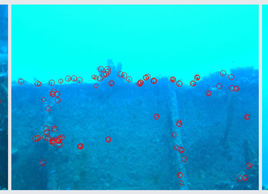
Robust State Estimation for AUVs

Vision based state estimation is prone to failure underwater due to poor visibility conditions. As AUV traverses over the deck facing blue water, very few features are detected and visual inertial odometry diverges.





Enough features - AUV seeing the deck

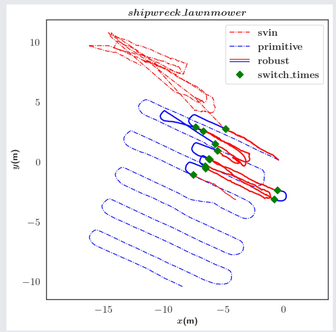


Number of detected features decreases - AUV looking at the side of the wreck

Very few features detected - AUV is at the edge of wreck and switching occurs

We propose [1]:

- "primitive estimator" - a model-based state estimator that fuses inertial data, water depth, flipper configuration, and velocity commands
- health monitoring of Visual Inertial system - no. of triangulated keypoints, no. of feature detections per quadrant, and feature detector response.
- Switching between the model-based estimator and the Visual/Inertial estimator based on health monitor.
- Results show robust pose estimates even when VIO diverges using primitive estimator. Loop closures improve the overall trajectory.



The robust switching estimator utilized the parts of **VIO** switching to **PE** when tracking was lost.

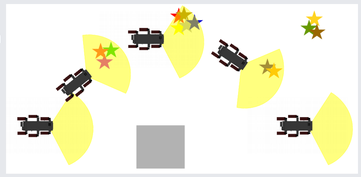
Proximal observer: Perception-aware navigation

AquaVis [2] – 3D Active Perception

- Observes multiple areas of interests from a desired distance
- Avoids obstacles safely
- Applicable to arbitrary multi-sensor configurations
- Strong potential for mapping complex structures
- Efficient and online

Approach [2]:

- Utilize robust SLAM
- Extract points of interest online
- Reconstruct 3D map
- Plan with path-optimization
- Use effective visibility and kinematic constraints
- Way-point navigation



The robot observes points of interest while avoiding obstacles

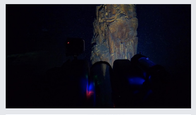
AquaVis used for mapping a shipwreck in simulation

Inexpensive 3D reconstruction

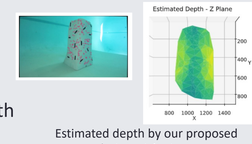
Non-stationary photometric stereo:

- Traditional approach: with a stationary camera and multiple light sources, estimate object's surface normal by observing changes in reflected light intensities at surface points

- Our approach [3]:
  - Relax the stationary camera constraint
  - Up-to-date underwater image formation model
  - Extract camera motion from monocular SLAM
  - Interpolate initial map points for dense feature matching
  - Solve the photometric consistency optimization problem
  - Export the 3D structure of scene
  - Freely explore shipwrecks and cave structures with a low-cost sensor suite – camera and lights only



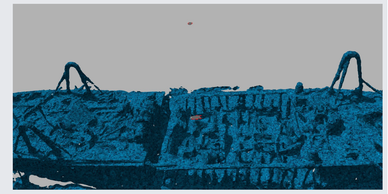
Individually controlled light showing changes in shadows and highlights used for reconstruction



Estimated depth by our proposed photometric stereo

Distal Observer: Active Positioning

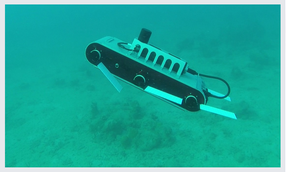
We are also working on the tight coordination of the proximal and distal observer, so that the distal observer has the general structure in view, as well as at least one proximal observer.
This step is to reduce the uncertainty of both the reconstruction and the cooperative localization process.



Distal and proximal observers in simulation tests

Low-Bandwidth Communication

The underwater domain is a very harsh environment for communication, which is primarily based on acoustic devices characterized by very low data rate (tens of kb), high packet loss, and distance-dependent performance.
We are investigating compact data representations and the optimal utilization of the communication channel. We are evaluating the acoustic channel performance with the real robot.



AUV with acoustic modem

Acknowledgments and References

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[1] B. Joshi, et al. Robust Switching Model-based/Visual Inertial Odometry for an Autonomous Underwater Vehicle. RAL/IROS 2022 (under review).
[2] M. Xanthidis et al. "AquaVis: A Perception-Aware Autonomous Navigation Framework for Underwater Vehicles". In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2021
[3] M. Roznere and A. Quattrini Li. Photometric Stereo for Non-Stationary Underwater Robots. In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2022 (under review).
[4] C. McKinlay, "Woodville Karst Plain Project (WKPP)," URL:http://www.wkpp.org, Apr. 2015.