# Co-Multi-Robotic Exploration of the Benthic Seafloor

## New Methods for Distributed Scene Understanding and Exploration in the Presence of Communication Constraints

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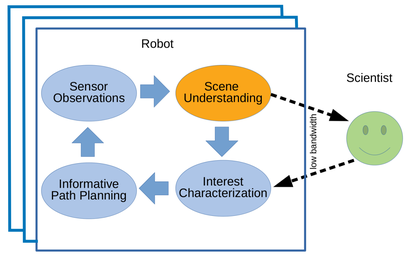
## Overview

This project is focused on developing new techniques to enable interactive exploration in unknown, low bandwidth environments, with a multi-robot team. The proposed approach enables new types of data collection missions that can target spatiotemporally sparse, and previously unknown phenomena, in extreme environments like the deep sea.




## Challenges

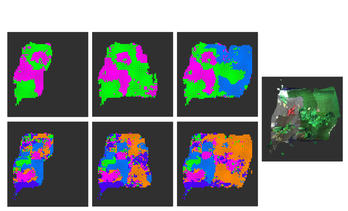
- The primary hurdle in autonomous deep sea exploration is the extremely **low bandwidth communication**.
- A vast majority of the oceans and the seafloor is **unexplored and unknown**, and hence there is very limited amount of data available for targeted autonomous missions.
- The **scale** of the oceans necessitate exploration using multi-robot teams. Strict bandwidth limitations mean they must coordinate with each other efficiently.
- **Informative path planning for robots when observations are categorical**, such as observations of species or tax types, is hard when number of species is large.

## Scientific Impact

- The proposed exploration approach **generalized to many other types of environments** beyond the deep sea such as: aftermath of a natural disaster, caves and mines, and other planets, where there exist communication bottlenecks.
- The proposed **distributed unsupervised scene understanding** and **active reward learning** is, to our knowledge, the first to enable interactive exploration in communication constrained environments.
- The proposed generative model for spatially distributed categorical observations is ideally suited for **modeling complex ecosystem**, habitats, and community structures, enabling new applications in ecology.

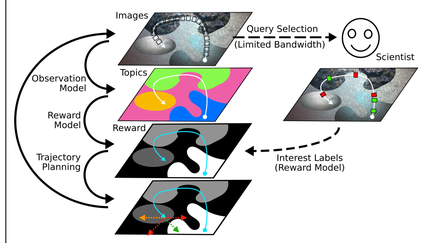
## Key Innovations

### Unsupervised semantic maps from streaming image data



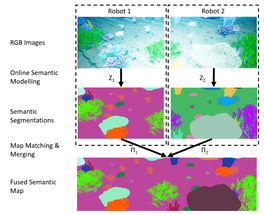
Girdhar, Y. et al. Streaming Scene Maps for Co-Robotic Exploration in Bandwidth Limited Environments. in 2019 International Conference on Robotics and Automation (ICRA) 7940–7946 (IEEE, 2019). doi:10.1109/ICRA.2019.8794132.

### Active reward learning over low bandwidth



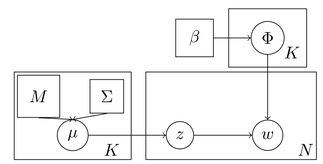

Jamieson, S., How, J. P. & Girdhar, Y. Active Reward Learning for Co-Robotic Vision Based Exploration in Bandwidth Limited Environments. in 2020 IEEE International Conference on Robotics and Automation (ICRA) 1806–1812 (IEEE, 2020). doi:10.1109/ICRA40945.2020.9196922.

### Distributed unsupervised semantic maps in low-bandwidth environments



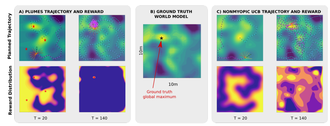

- Doherty, K et al. Approximate Distributed Spatiotemporal Topic Models for Multi-Robot Terrain Characterization. in IROS 2018. doi:10.1109/IROS.2018.8594442.
- Jamieson, S et al. Multi-Robot Distributed Semantic Mapping in Unfamiliar Environments through Online Matching of Learned Representations. in ICRA 2021.

### Enabling informative path planning with high dimensional categorial observations using GP and topic models



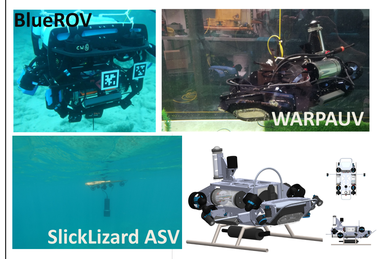
Soucie, J. S., Sosik, H. & Girdhar, Y. Gaussian-Dirichlet Random Fields for Inference over High Dimensional Categorical Observations. in International Conference on Robotics and Automation (ICRA) (2020).

### Informative path planning for maximum seek-and-sample missions



Flaspohler, G., Preston, V., Michel, A. P. M., Girdhar, Y. & Roy, N. Information-Guided Robotic Maximum Seek-and-Sample in Partially Observable Continuous Environments. IEEE Robot. Autom. Lett. 4, 3782–3789 (2019).

### Robot systems for distributed underwater exploration




McGuire, N., Cai, L., Belani, M., Claus, B. & Girdhar, Y. [poster] WARPAUV: A low-cost, vision-guided AUV for robotics research. in Northeast Robotics Colloquium (2019).

## Broader Impacts

### Impact on Society

- Potential applications to coral reef health monitoring in the face of climate change. The 2020 field trials will collaborate with coral reef scientists to study endangered stag horn corals
- Cross disciplinary work with marine ecologists.
- Use of methods by third party researchers/robots (NDSF AUV Sentry)
- Lowering barriers to using co-robotics to explore the ocean

### Education and Outreach

- Motivating STEM education in high school students through a summer volunteering in the lab.
- Training graduate students
- Robotics field trials with students
- Development of WARPAUV as an open research platform for vision guided AUVs

### Quantifiable Impact

- 5 refereed conference papers
- 1 journal paper
- Best paper award in service robotics at ICRA2020
- Finalist for best paper award at IROS 2018.
- First place prize at MIT Mechanical Engineering Research Exhibition 2019.
- 10 students trained (graduate, undergraduate, high school)
- Use of methods by third party researchers/robots (NDSF AUV Sentry)

2021 NRI & FRR Principal Investigators' Meeting
March 10-12, 2021

Award ID#: 1734400