Project Overview

• Develop undersea mobile sensor network for underwater target detection and tracking (This will be used for data collection and algorithm development in the early phases)

• The sensor network will perform passive listening to the undersea environment and mine sensory data from the environment, and response of various sea/ocean organisms

• The sensors will communicate with each other and to a central floating communication node through acoustic links, and the central node will communicate to command and control through stellate or RF link.

• Sensors will be autonomous and mobile to optimize their location with respect to monitored targets, region of interest, signal strength and location of detection organisms

Mobile Senor Network Concept

Develop undersea mobile sensor network that can detect and track presence and movement of M/UUVs through monitoring the behavior of certain organisms. The interaction of these organisms with their habitat in response to the moving vehicles/objects either through creating acoustic sounds, lights, bubbles, or changing location will be used as means of detection. The sensors will operate autonomously and will communicate with each other and command and control. Acoustic beamforming sensors, light sensors, and video cameras will be used.

Organism and/or Detection Hardware

The approach will be focused on sensor fusion using input sensed from multiple organisms and their various behaviors. Examples include acoustic signatures coming from snapping (pistol) shrimp, and whales, fish population movement, sonoluminescence emission pulses, and cavitation bubbles caused by pistol shrimp. Autonomous mobile sensors hardware that is capable of self navigation to optimal locations, listening to and watching of selected organisms’ behavior in their natural habitat and communicating with peer and central nodes and command and control centers will be developed

Team Strengths

• United Technologies Aerospace Systems, and its Sensors and Integrated Systems business unit develop aerospace and aircraft sensors and systems that are known across industry

•UTAS owns a 10,000 sq. ft. class-1000 MEMs facility and advanced environmental qualification testing and wind, icing, and supersonic tunnels

• The UOM & Cornell marine biology and acoustic sensing teams with years of experience in underwater testing in ocean and rivers, and access to knowledge of bio-organisms and bioacoustics Research, and data of Perennial Acoustic Observatory in the Antarctic Ocean

Teaming Goals

• We seek collaboration with teams of strong technical background and experience with Marine Biology, undersea organisms, and expected behavior and response to nearby moving targets, signals, and environment

• Current data regarding undersea organisms, bioacoustics, bio-organisms response signals, and behaviors would help jump start the effort

• Teams with experience of operation and challenges with unmanned underwater vehicles (UUV), unattended underwater sensors, and underwater acoustics would be a plus.

• Capabilities for extended under water testing and continuous data collection are required
Project Overview

The study of ambient biological soundscapes in marine ecosystems is an emergent & exciting field, using new developments in signal processing & data storage capability to characterize undersea biological processes. We have recently identified a number of environmental indicators in the acoustic spectra of coral reef sound. By better understanding the full range of contributing sources and content, i.e. an acoustic library, of marine soundscapes, we can monitor environmental changes autonomously in near real time.

Coral Reef Soundscape Study

Simultaneous time lapse photography of coral reef organisms and acoustic recordings show clear increase in both animal activity and sound level at night. Data from Hawaii 2012

Organism and/or Detection Hardware

- Hardware: Passive acoustic directional system, with alternate validation modalities (optical, active acoustic) if required.
- Possibility for complimentary optical detection in clear-water environments
- Target: Coral Reef Soundscapes
- Develop acoustic spectral library of sounds from biological and human activity
- Use rapid classification techniques with machine learning to detect and classify changes in coral reef environments in near real time
- A general technique applicable anywhere with biological soundscapes

Team Strengths

- Unique Coral Reef Soundscapes Expertise
- Multivariate Data Analysis
- Signal Processing
- Environmental Validation
- Coral Reef Ecology
- Oceanography
- Remote Sensing & Image Processing
- Rapid Instrumentation Prototyping
- Non-traditional Sensors & Sonar Development

Teaming Goals

- Access to tanks and facilities with coral reef husbandry capability
- Testing facilities near appropriate ecosystems

Summary

Soundscapes contain much information about the marine environment. Our team goal is to apply high level signal processing to acoustic signals coupled with rapid data clustering and machine learning programs to give near real-time indications of activity in littoral environments such as coral reefs. A key component will be development of a validating dataset of known bioacoustic responses to accurately match collected data with particular biological or human activities - an acoustic library.
Interpreting the Information in Coral Reef Soundscapes

Simon E. Freeman¹, Lauren A. Freeman², Jason E. Gaudette¹.
¹Code 15 Sensors Division. ²Code 85 AUV Division. Naval Undersea Warfare Center, Newport RI

Project Overview

**Goal:** To use variations in ambient biological sound to detect and classify organism behavioral changes due to the presence of man-made objects.

**How:** Use directional passive acoustic sensors and transient-based signal processing to continually search, detect and classify transient biological sounds, using multivariate statistical analysis / look-up tables / trained classifiers to detect tell-tale behavior signals characterized in laboratory and controlled trial studies.

**Signal Processing:** Based on transient (short-duration signals) detection and classification algorithms. Each biologically produced transient contains unique information.

**Previous Application Success:**
1. Rapid environmental characterization of littoral environmental features using underwater biological soundscapes
2. Discovery of new sources of ambient biological sound

**Summary**
We have developed unconventional signal processing approaches for ambient biological soundscape analysis [1]. So far, they have yielded new and previously overlooked environmental information from reef sound [2].

*We want to apply these algorithms to detect and classify the subtle bio-acoustic signals associated with the interaction between organisms and man-made objects in strategically relevant, biologically soniferous underwater environments.*

2. Freeman SE., Freeman LA., Giorli G., Haas AF. PNAS (in review)

Organism and/or Detection Hardware

- Our techniques were developed for ecological survey in coral reef environments
- They can be applied in any environment where transient bioacoustic signals may be detected (estuarine, deep reef, mesopelagic, etc.) for environmental and tactical purposes
- Directional passive acoustic sensing systems (particle vector sensors, hydrophone arrays) are critical for spatial filtering and directionality in these high-noise environments.
- Optical, active sonar sensors will be simultaneously deployed for validation of our detector/classifier

Team Strengths

- Unique coral reef acoustics expertise
- Signal processing and multivariate data analysis
- Environmental validation
- Coral reef ecology
- Oceanography
- Rapid instrumentation prototyping
- Non-traditional sensors and sonar development
- NUWC: unique institutional assets (See Jason Gaudette’s poster)

Teaming Goals

We need:
- Access to tanks and facilities with coral reef husbandry capability
- Testing facilities near appropriate ecosystems
**GOAL:** The goal is to provide anomaly detection in the ocean environment with high spatial-temporal signal strength relative to ambient noise at some maximum distance from a target.

**METHODS:** The ubiquitous distribution of living organisms in the ocean on the scale of microns to millimeters allows the use of a simple, low cost detection system that would monitor and understand changes in plankton behavior, aberrant chemical signatures, light pulses from bioluminescent organisms, and far field sound emanating from a moving target, all integrated using deep learning to provide an understanding of the environment.
Advanced Underwater Sensor Development and Testing

Jason E. Gaudette¹, Simon E. Freeman¹, Lauren A. Freeman².
¹Code 15 Sensors Dept. ²Code 85 Vehicles Dept. Naval Undersea Warfare Center, Newport RI

**Project Overview**

NUWC Newport has extensive experience with underwater sensing hardware across many physical domains. This includes:

- Acoustic (e.g., piezo, fiber, vector)
- Optical
- Hydrodynamic
- Electromagnetic
- Chemical

**Team Strengths**

NUWC Newport has expertise in

- Acoustic and array signal processing
- Embedded electronics development
- Mechanical packaging for underwater systems
- Low-power, high-throughput data telemetry
- Piezoelectric and optical fiber transduction
- Environmental analysis and validation
- Sensor testing facilities (e.g., anechoic chambers, high-speed flow tanks, pressure vessels, electromagnetic sensing, optical equipment)
- UUV test assets and payload integration

**Teaming Goals**

- Academic partners with advanced underwater sensing research
- Industry partners sought for commercialization and transition of successful Phase I projects
- Current partners for bio-inspired technologies include:

**Summary**

NUWC Division Newport is well positioned to facilitate the prototyping and testing of PALS concepts with academic and industry partners.

A primary objective of the NAVSEA Science and Technology Enterprise is to partner with academia, industry, and government agencies to aid in the transition of basic and applied research to the future fleet of the U.S. Navy.

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Marine bacteria for engineered undersea sensing and reporting

Lina Bird\textsuperscript{1}, Chris Voigt\textsuperscript{2}, Sarah Glaven\textsuperscript{3}, \textsuperscript{1}NRC Postdoctoral Fellow, \textsuperscript{2}Massachusetts Institute of Technology, \textsuperscript{3}Naval Research Laboratory

Project Overview

Organism and/or Detection Hardware

We will pursue the marine bacterium, \textit{Marinobacter atlantica}, which our group isolated from an electrode enrichment with seawater from the Atlantic Ocean. We have been developing this organism as a marine chassis for synthetic biology applications in collaboration with Voigt Lab at MIT. \textit{Marinobacter} is naturally electrochemically active and a dominant taxa found in many ocean samples. It is considered to be an opportunist and will adapt to use many different substrates, including hydrocarbons, for growth.

Team Strengths

- TA1 is this group’s strength. We also have expertise in electrochemically active biofilms deployed to power existing underwater sensors.
- Microbial electrochemistry group, Laboratory for Autonomous Systems Research – littoral high bay, scalable testing of microbial fuel cells (MFCs), biologically powered sensors in collaboration with Dr. Lenny Tender.

Teaming Goals

- Seeking to collaborate with researchers interested in integrating TA2 device with living electrical reporter.
- Mobile sensor device for bacterial bioreporters. We have a sentinel platform but may need long range communication of recorded biological signal.
- Possibly build a biological sensor for a biological sensor, i.e. detect secondary signal from M/UUV.

The NRL has isolated and developed a genetic system for biofilm forming bacteria from seawater and the benthic interface. In collaboration with MIT, these bacteria have been transformed with a number of simple genetic circuits and coupled to electron transfer pathways for sensing and electrical reporting.

Flexible bacterial platform for marine sense and respond

1) Concentration dependent, inducible gene expression in seawater

Gene expression controlled by M/UUV signal

Example: Concentration dependent fluorescence response to antibiotics

2) Inducible gene expression during biofilm growth in seawater

Induction of expression of fluorescent reporter gene using the small molecule IPTG following biofilm formation. Fluorescence observed as soon as 30 minutes post exposure.

3) Reporting by electrical current for machine integration

4) Potential Sensing Space

- Changes in impedance in biofilm caused by changes in electromagnetic field change current.
- Respond to chemicals or ions off-gassed from M/UUV with electrical signal
- Integrate directly with electronics of detector.

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Project Overview

Blue-green light color sensing occurs in the marine unicellular cyanobacterium *Synechococcus*, the second most abundant photosynthetic organism on Earth, with an estimated global population of \( 7 \times 10^{26} \) cells (Flombaum et al. 2013. PNAS 110: 9824-). Many different color phenotypes of *Synechococcus* exist (Fig 1), each the result of a different combination of photosynthetic light harvesting pigments. The most abundant group, representing 40% of the total, carries out a process called Type 4 Chromatic Acclimation (CA4). During CA4, cells detect the ratio of blue to green light and, in response, alter transcription of specific genes up to 45-fold higher in blue light than in green light.

*Synechococcus* cells are widespread throughout the world’s oceans (Fig 2) as are the two known forms of CA4, A and B (dark and light blue).

**Organism and/or Detection Hardware**

We will use naturally occurring strains of marine *Synechococcus*, as well as strains that we genetically engineer to more strongly amplify signals, for their light color and light intensity sensing capacities. These sensing systems already control transcriptional responses, which we will use to drive the expression of appropriate reporter genes that produce proteins which can directly or indirectly be used for regulating processes in TA2.

**Team Strengths**

TA1 highlights our strengths. We can engineer *Synechococcus*, which exists throughout the world, to respond to (1) the blue to green light ratio (2) the blue light irradiance level (3) the green light irradiance level. The output is transcriptional activity, so we can use any reporter gene protein as the transmitting signal in our system. This light-activated response is extremely fast, sensitive, and reversible. Also, no external energy is required since *Synechococcus* is photosynthetic.

In the past decade, we developed molecular genetic tools to routinely genetically modify strains of marine *Synechococcus* from around the world. We are using these tools to reveal how blue-green light regulates transcriptional activity. We are also investigating responses to other environmental signals with these tools. Our goal is to create synthetic biology tools for use in industry and biotechnology.

**Teaming Goals**

We can provide the sensing requirement for TA1 and can create many different protein output signals as needed. However, the signals produced must be selected to be detectable by a secondary system that will amplify and transmit the signal as part of TA2. Thus we seek collaborators who can provide a system(s) that will accomplish the goals of TA2.

We are capable of creating all TA1-required organisms, including the appropriate biotechnological constraints on genetically engineered organisms, and testing them in small-scale environments. However, we will also require partnering with groups who have access to M/UUVs and facilities where larger scale testing can be carried out.

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1 PNAS 2018; published ahead of print February 12, 2018, https://doi.org/10.1073/pnas.1717069115
2 PNAS 2016; 113: 6077–6082
Detection of M/UUVs using reflected marine animal sounds

Brett M. Tyler\textsuperscript{a}, Jack Barth\textsuperscript{a}, David K. Mellinger\textsuperscript{a}, Joe Haxel\textsuperscript{b}, Xiaoli Fern\textsuperscript{a} and Raviv Raich\textsuperscript{a}

\textsuperscript{a} Oregon State University; \textsuperscript{b} National Oceanic and Atmospheric Administration; Corvallis & Newport, Oregon

Project Overview

Objective: We will develop technology that can use reflections of sounds produced by marine animals to detect M/UUVs.

Rationale: Marine animals extensively use sound for communication because sound travels further and omnidirectionally in water compared to light, magnetism or chemicals. Biological organisms have not evolved to sensitively discriminate between M/UUVs and confounder objects, nor to report them in real time. But many use echolocation to detect prey and other animals and objects. We will leverage the sounds that animals produce to detect M/UUVs.

Team Strengths

Technical Expertise

- Jack Barth (OSU College of Earth, Ocean & Atmospheric Sciences; CEOAS) Project Co-PI. Expert in sensor arrays and underwater gliders. Co-PI of Ocean Observatories Institute (OOI). OOI is a networked infrastructure of science-driven sensor systems to measure the physical, chemical, and biological variables in the ocean and seafloor. The OSU node includes sensors on the seafloor, buoys and underwater gliders.
- David K. Mellinger (OSU/NOAA Cooperative Institute for Marine Resources Studies; CIMRS) Project Co-PI. Expert in passive acoustic techniques. Analysis of long-term bioacoustics data sets; software and hardware for detecting, classifying, and locating animals acoustically.
- Raviv Raich (OSU EECS). Expert in statistical signal processing, machine learning, inverse problem, sparse signal reconstruction, manifold learning, and adaptive sensing; applications to bioacoustics.
- Brett M. Tyler (OSU Ctr Genome Res. & Biocomputing; CGRB) Project Co-PI. High performance computing facilities and research in support of data-intensive research in the life and environmental sciences.

Institutional Assets

- Sensor arrays of the Ocean Observatories Institute
- NOAA and OSU Research Vessels and on-board capabilities
- CGRB and CEOAS high performance computing clusters, including GPU arrays
- OSU artificial intelligence and data science group (16 faculty in EECS and Statistics)
- OSU’s CEOAS, CIMRS, and Hatfield Marine Science Center

Teaming Goals

Technical Expertise Needed

- Interpretation of reflected sounds into spatial information about M/UUVs (most important)
- Data on changes to marine animal production of sounds in the presence of M/UUVs (useful)

Institutional Assets Needed

- Capability for measuring sounds reflected from M/UUVs in laboratory and ocean environments

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Institutional Assets Needed

- Capability for measuring sounds reflected from M/UUVs in laboratory and ocean environments
**Project Overview**

- Persistent aquatic living sensors will need to sense their environment and communicate acquired tactical information to Department of Defense assets.
- Intelligent, distributed assets will link PALS and the DoD
  - Materials that mitigate biofouling
  - Materials that are compatible with marine distribution
  - Non polluting
  - Long-term, continuous operation in a marine environment
  - Assets can both receive and transmit information
  - Assets can process information to avert false positive reports
  - Mobility in the water column
  - Ability to obtain multiple depths

We envision a distributed set of PALS and sensing assets that can effectively monitor the marine environment for tactical adversarial information. The PALS and assets will need long-term operability at varying depths, the ability to communicate with each other vehicles/devices, and also demonstrate the ability to resolve information such that the DoD receives tactically relevant information.

**Organism and/or Detection Hardware**

Seeking Detection Hardware to couple with NRL's advanced functional materials.

**Preliminary Results**

NRL optical transparent Coatings

Functional polymers: a) control uptake of artificial sea water, b) pre-hydrolysis, c) post-hydrolysis

**Team Strengths**

- Antifouling Materials
- Polymeric Synthesis
- Materials for Marine Environments
- Test and Evaluation Facilities
- Integration and prototyping

**Teaming Goals**

- Seeking partners with demonstrated capability for sensing and reporting within the marine environment.

**Tunable Physical Properties for additional properties such as acoustic damping**

<table>
<thead>
<tr>
<th>Property</th>
<th>Range</th>
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<tbody>
<tr>
<td>$T_g$</td>
<td>-40.4 – 85.6 °C</td>
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<tr>
<td>Surface Energy</td>
<td>19.0 – 62.4 mN m⁻¹</td>
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<tr>
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<tr>
<td>Hardness</td>
<td>287 – 1350 g</td>
</tr>
</tbody>
</table>

Coneski, P.N. and Wynne J.H. *ACS Applied Materials and Interfaces* 2012, (4) 9, 4465-4469