Final Research Performance Progress Report

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

ONR Award: N00014-18-1-2543

Project Title: Collaborative Adaptive Sampling and Mapping

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1. MAJOR OBJECTIVES AND GOALS

The major goal of this project was to allow multiple uncrewed underwater agents to perform collaborative and adaptive sampling and mapping in real-time in a scalable framework. By collaborative, we mean that data collected by one agent ultimately informs the behavior of other agents. By adaptive, we mean that the mission profile changes as a result of the data being collected. By real-time, we mean that this collaboration and adaptation occur within a single deployment as opposed to occurring in post-processing. By scalable, we intend that this framework extends beyond a pair to perhaps tens of uncrewed agents. Another major goal of this project was to demonstrate the viability of this framework through in-water experiments.

2. ACCOMPLISHMENTS TOWARDS GOALS

Through early discussions and whiteboarding sessions, it became clear that a distributed network approach to collaborative and adaptive sampling would not be truly scalable given the time-bandwidth limitation of acoustic modems. We devised a centralized approach based on work by collaborators Fischell and Rypkema that utilized acoustic "command pings" from a "leader" to control different behaviors of multiple "follower" uncrewed agents. Our major innovation was for the followers to reply to a command ping using an alphabet of signals that encoded the data being collected. An acoustic array on the leader would determine the angle of arrival (AOA) of each reply as well as the range to the agent from the acoustic two-way travel time (TWTT). In this way, the relative position of each measurement is resolved from the acoustic AOA and TWTT while the value of the measurement is resolved from decoding the signal. Different command pings can be used for different data streams (salinity, temperature, etc.), resulting in the dynamic of the leader "asking" for data on a certain channel and then receiving the data from a large number of nearby distributed sensors.

To demonstrate this framework in the water, WHOI (Woods Hole Oceanographic Institution) acoustic micromodems were integrated as payloads onto three SandShark autonomous underwater vehicles (AUVs). The signal alphabet consisted of 191 different up-chirps centered every 50 Hz from 22.5-32 kHz, each 40 ms long and having a bandwidth of 2 kHz. A planar acoustic array with six elements arranged in a 2x3 configuration and spaced 2.9 cm apart was also integrated onto a JetYak uncrewed surface vehicle (USV) to act at the leader. The command ping transmitted by the JetYak was a 20 ms 7-9 kHz up-chirp.

In February 2020, several tests were run in Great Harbor (Woods Hole, MA) from a small boat. Software and hardware issues prevented all three SandSharks from running simultaneously. An existing inverted ultra-short baseline (i-USBL) array previously integrated onto the SandSharks provided a surrogate sensor data stream, resulting in a transmittable data resolution for heading of less than 2°. Vehicle heading from an onboard inertial measurement unit (IMU) was used as ground-truth reference of bearing to the command ping source location. The platform configurations, data collected during testing, and analysis of the direct comparison and error histograms are shown in Figure 1.

These results are encouraging for this framework, showing good correlation between the transmitted and decoded sensors values and the ground truth. Additional testing was planned; however, the period of performance ended before a no-cost extension was submitted to the Office of Naval Research (ONR).

3. OPPORTUNITIES FOR TRAINING AND PROFESSIONAL DEVELOPMENT

Junior technical staff were able to work closely with senior technical staff, scientists, and consultants during the implementation and in-water testing phases of the project.

4. DISSEMINATION OF RESULTS

The concept and results were presented at the American Geophysical Union's Ocean Sciences Meeting 2020 (San Diego, CA; 16-21 Feb. 2020) in a special session on Ocean Data Management:

> **Kaeli, J.**, E. Fischell, A. Kukulya, and G. Gawarkiewicz (2020) "Closing the loop on sensor-based autonomy for swarms of underwater robots" (abstract OD42A-05).

5. HONORS DURING REPORTING PERIOD

Nothing to report.

6. TECHNOLOGY TRANSFER

Kaeli, J., and E. Fischell (22 Feb. 2021) "Device, System and Method of Adaptive Autonomy with Sensor Swarming." US Patent Application # 17/799,022.

7. PARTICIPANTS

The following individuals worked one (1) person-month or more during the project reporting period:

Dr. Jeffrey W. Kaeli, Principal Investigator (Research Engineer)
three (3) person-months worked
not a National Academy Member

Dr. Nicholas R. Rypkema (Research Engineer)
two (2) person-months worked
not a National Academy Member

8. STUDENTS

Nothing to report.

9. PRODUCTS

"Closing the loop on sensor-based autonomy for swarms of underwater robots" (abstract OD42A-05); Jeffrey Kaeli, Erin Fischell, Amy Kukulya, and Glen Gawarkiewicz; American

Geophysical Union's Ocean Sciences Meeting 2020; 16-21 Feb. 2020; San Diego, CA; Federal support was acknowledged.

"Device, System and Method of Adaptive Autonomy with Sensor Swarming" (Jeffrey Kaeli and Erin Fischell)

A sensing and transmitting system and method of using same, including a plurality of acoustically transmitting sensor (ATS) devices having a sensor, a housing, and a transmitter that, together, converts a physical quantity of the fluid body into a responsive signal measurable over long distances underwater by a central receiving node. The node having a receiver or receiver array, a controller and typically a logger. The signals sent by the ATS are modulated according to the sensor's measured parameter and in a manner known to and decodable by the node. This system may further have an autonomous node and the modulated signals of the plurality of ATS may influence the behaviour of the node.

US Patent Application # 17/799,022 (22 Feb. 2021); submitted

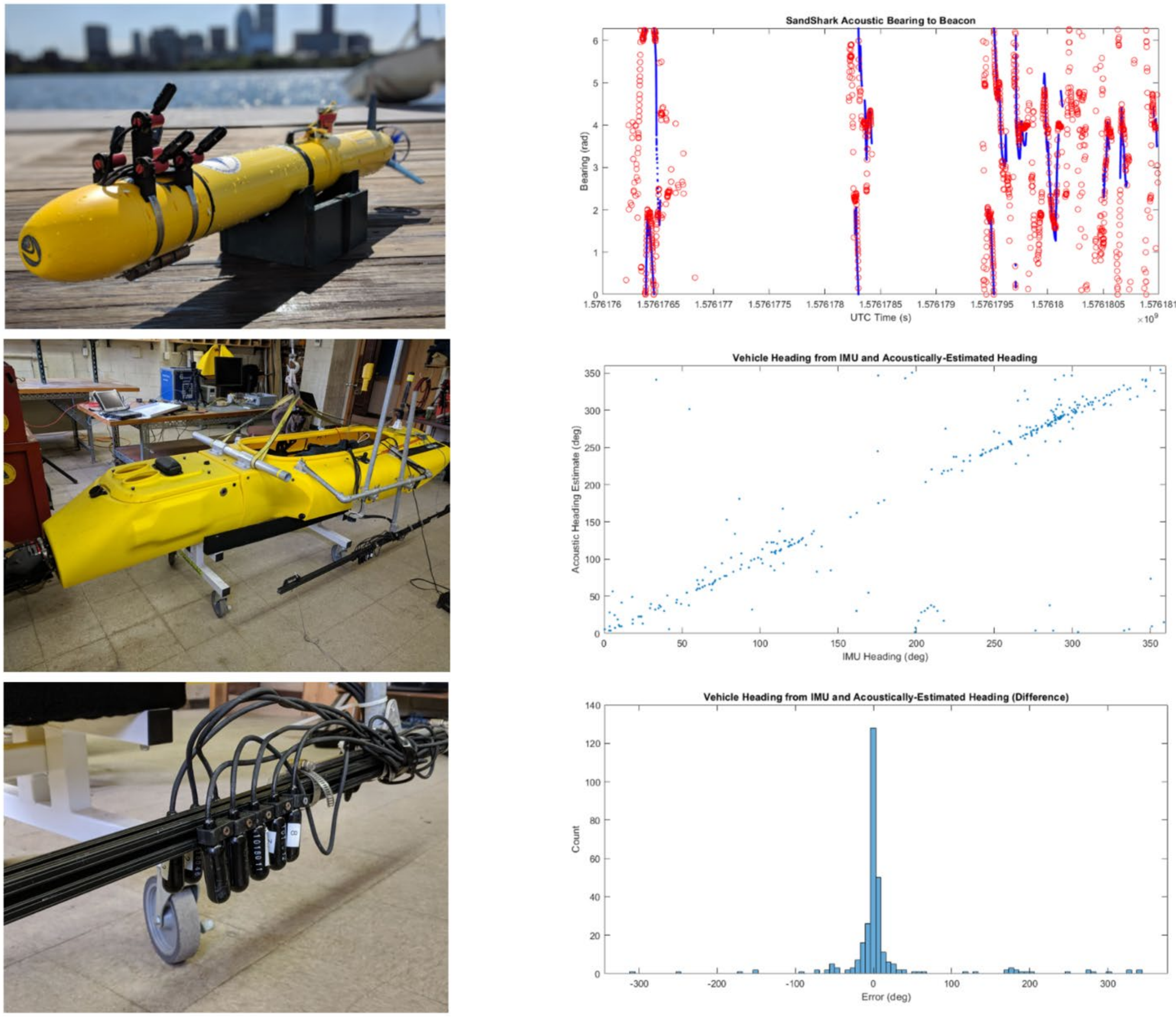

Figure 1. *Left:* one of the SandShark UUVs (*top*) with an acoustic array mounted on the nose. The JetYak USV (*center*) with close-up of acoustic array mounted on a rail (*bottom*). *Right:* Estimated heading from the decoded acoustic transmissions (*red circles*) and SandShark IMU heading as ground truth (*blue dots*) over the course of the mission (*top*). Direct comparison (*middle*) and error histogram (*bottom*) of the estimates show good correlation.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

We propose to develop and demonstrate the capability of a squadron of unmanned underwater vehicles (UUVs) to collaboratively and adaptively sample and map their environment. The simultaneous deployment of multiple UUVs is motivated by the desire to characterize dynamic structures in the ocean such as fronts, plumes, and currents. Specifically, we will address the areas of UUV navigation and adaptive map building with an emphasis on scalability to larger squadrons. Our efforts will focus on software and hardware integration into two small, man-portable UUVs. We will conduct local tests off of a small boat using simulated environmental data or a natural opportunity.

15. SUBJECT TERMS
Unmanned underwater vehicles, navigation, map building, scalability

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
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