Autonomous Flocking μ-Sub (AFμS): Final Paper

ECE-497: Electrical and Computer Engineering Capstone I

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June 13, 2019

Abstract

Autonomous Underwater Vehicles (AUVs) is an emerging technology in the field of ocean exploration. They are praised for their ability to operate without human intervention and often for weeks to months at a time, with the ability to make decisions and modify trajectory as needed. Two dominant issues with commercially available AUVs are cost and difficulty in operation. Many AUVs can be several meters in length and weigh upwards of hundreds of kilograms, thus requiring expensive equipment and technicians just to move and operate them. They are often outfitted with complicated sensor suites and other expensive peripherals, which drives the price point to several thousands (or hundreds of thousands) of dollars. For these reasons and many others, a new class of AUVs have emerged called “micro AUVs”. These AUVs have a much smaller form factor and can often be hand-deployable, however the issue of price is still present. Therefore, there is a place in the AUV market for a low-cost automated exploration system with a comprehensive interface. The goal of our project is to design a scalable AUV system with a modular sensor suite and low-cost actuators, to be available to entities such as local governments or colleges that have a need for precise water body data but cannot afford systems that are currently available commercially. Our product can be used in a swarm formation and will have flocking capabilities in order to reduce the overall cost of a single sub without sacrificing the resolution or accuracy of the data. This paper outlines the existing technology in the field and existing state of the topic, design specifications, testing plan, considerations, standards, and project schedule.

Table Of Contents

Project Definition

Topic Overview

Nearly three quarters of the Earth's surface is covered by water- primarily ocean bodies. The biological and climatic cycles that occur underwater drive processes, such as photosynthesis and chemical weathering, that we as a species are dependent on. Underwater research has been an ongoing topic of study for decades now, however recent increased human activity has driven developments in the field.

Specific reasons for underwater research are vast and include aquatic organism(s) behavior studies, impact assessments of oil rig stations, ecological studies, and military submarine communications. Current technologies for underwater data acquisition include, but are not limited to sensor networks or stationary sensor systems, research vessels, submarines, remote operated vehicles (ROVs), and autonomous underwater vehicles (AUV's).

Due to the immense size of ocean bodies, technologies that are capable of rapid and wide data acquisition and little to no human intervention are desirable, making AUV's an attractive acquisition method. AUV's are unmanned, self-guided and self-propelled vehicles that are capable of fully autonomous data acquisition and navigation. They can range from several feet to several meters, and are able to traverse environments with difficult climatic conditions, such as underneath ice sheets. Compared to other motion-capable and water-based research vehicles, they are cheap and efficient, and are able to operate for hours or even days before needing to be retrieved.

Problem Definition

Modern AUVs are, for the most part, large, sophisticated and expensive pieces of machinery. All AUVs currently on the market are designed to be able to fulfill the customers full needs as an individual unit, and therefore contain a wide range of abilities and sensors to precisely measure its direct environment accurately. While the data collected from the sensor arrays is rich in detail, it often takes a great deal of time to cover the area of interest sweep by sweep, requiring these AUVs to also contain large power sources. To accommodate these advanced systems and ensure consistent performance, said AUVs tend towards multiple meters in length. However, as not all organizations need or can utilize such large equipment, some AUV companies have begun creating AUVs on the "micro-scale". These vehicles can be between 2 and 3 feet long, such as the Hydroid REMUS M3V or the Riptide µUUV. Though these are significantly more manageable than larger precourses, their form-factor is still unwieldy, and their sensor payload is uncustomizable. While the low cost of these systems makes them better suited for general research purposes, they are still very expensive for individual or institutional research, and the hardset sensor information may not suit the information that is desired to be collected.

Another issue with currently available AUVs is the retrieval factor. For the most part, AUVs can be programmed to complete a task but then must be physically retrieved so they can be reprogrammed for their next mission. Several of the large, extremely expensive AUVs can perform residency, the act of being able to remotely accomplish multiple missions, with the aid of charging and communication systems installed on the ocean floor for the AUVs to dock with. This system works very well for stationary endeavors, though it limits the use of residency to the zone around the charging station, an undesirable trait for many research use-cases.

Project Goal

The desired outcome of this project is to design and produce an AUV system that provides a highly portable modular distributed sensor network for low cost. This will be comprised of an n-sized system of small AUVs that are capable of transmitting information between them, as well as determining position and orientation in relationship with each other. By collecting information within a mesh of other AUVs spread out across an area, the system will be able to correlate it's data into a 3-Dimensional map of the area's properties, a task that takes many sweeps of the same AUV to collect. Parrelizing this process not only increases collection time, but ensures that all data was assembled within the same time frame, which can be an important factor depending on the research in question.

To ensure affordability, low cost communication, transportation and housing equipment will be utilized to construct the AUVs. The imprecision of the movement and the sensing will be made up for by using machine learning algorithms to ensure point to point control and high resolution data collection. Machine learning will also be implemented to allow for flocking of arbitrary AUV swarm sizes, ensuring that cohesive data will be collected for any size of swarm. To encourage maximal usability, the sensor array of the AUVs will be fully modular, and the software will be sensor-agnostic, meaning that anyone can use this system to measure with any research specific sensor that will fit on the AUVs.

As this system is optimized for data collection over a large area, the sub will be designed as to not be constrained by its power capabilities. Upon full battery discharge, the AUV will begin to passively recharge, and rejoin its flock before continuing to collect data. During the time that the AUV recharges, each will upload the collected data from the rest of the swarm, check if it has any updated mission plans, such as returning to a pick up location, and act accordingly. This allows the swarm to be released for an indeterminate amount of time and be re-instructed and monitored remotely.

Literature Review

There are several similar products being created by various AUV companies. Of these, the ones that are currently available for resale are the Hydromea Vertex[1], the ecoSUBμ[2], the Riptide μUUV[3], the Hydroid REMUS M3V[4], and the Bluefin SandShark[5]. There are dozens of other AUVs with similar characteristics, though they have significantly differing design goals from this project.

The largest of these are the ecoSUBμ, and REMUS M3V, both of which come in at a solid 3 feet. This puts them in the range of hand launching, but only barely, and severely limits

[1] https://wp.hydromea.com/wp-content/uploads/2018/08/VertexAUVBrochureR.pdf
[2] https://www.ecosub.uk/auvs.html
[3] https://riptideas.com/wp-content/uploads/2018/08/RipTide-Product-Data-Sheet-8-1-18.pdf
[4] https://www.hydroid.com/REMUS-M3V
[5]https://gdmissionsystems.com/en/products/underwater-vehicles/bluefin-sandshark-autonomous-underwater-vehicle

how many can be brought/used simultaneously. Neither of these have swarm capabilities, however both can boast impressive speed statistics, vast sensor capabilities, and around a full day of operation time.

The Vertex and Bluefin Sandshark are 27 and 20 inches respectively, both of which allow easy transportation and launching. The Riptide µUUV takes the approach of having reconfigurable lengths to accommodate various sizes of payloads. Its minimum length is 22 inches, which can be extended up to 62 inches. This AUV also has the option of utilizing a one time use aluminum seawater battery, which brings its standard endurance of 40 hours up to over 400 hours (without payload). While the µUUV offers impressive customizability and durability, it lacks any swarm capabilities, and the cost of the high endurance batteries make their use impractical for every day research solutions. The Sandshark does not offer off the shelf swarm capabilities, however this follows their design philosophy. The Sandshark is designed to be as easily integratable with automation suites as possible, and it is up to the user to decide if they want swarming capabilities.

The Hydromea Vertex comes with extremely advanced hardware specific swarm functionality. Each AUV communicates via short range radio, and coordinates their modular sensor data to efficiently locate the source of water condition changes, such as a pipeline leak or a vent plume. Each Vertex has a sensor bay with a standardized modular connection system, allowing for up to 7 individually chosen sensors to be integrated. This AUV is ideal for very precise use-cases, as it uses its swarm capabilities to gather extremely accurate and localized data.

AUV swarm robotics is a fairly small field. A key issue in attempting flocking behavior in an underwater environment concerns a lack of global positioning systems that function properly underwater. Many systems rely on an initial GPS reading (when surfaced, for example before a mission begins), and using an inertial measurement unit for position calculation with the initial reading as reference, however climatic variables (e.g. water current, collisions) cause errors to accumulate.[6] Many methods of flocking already exist[7], and this project will simply choose the one that works best.

[6] Liu, Jun, et al. "Suave: Swarm Underwater Autonomous Vehicle Localization." *IEEE INFOCOM 2014 - IEEE Conference on Computer Communications*, 2014, doi:10.1109/infocom.2014.6847925.
[7] Vásárhelyi, Gábor, et al. "Optimized flocking of autonomous drones in confined environments." *Science Robotics* 3.20 (2018): eaat3536.

Design Specifications

Performance

1. (D) Can operate for at least a week at a time
2. (D) Can travel against currents
3. (W) Can travel against the Gulf Stream (5.6 Mph)
4. (W) Able to stay in one piece while in the ocean with wind speeds up to 40mph. (Tropical Storm)
5. (D) Must have data agnostic collection capabilities
6. (D) Must be able to operate individually or in a group.
7. (D) Must be able to operate in the presence of obstacles.
8. (D) Must be able to share data

Economic

1. (D) Must cost less than $500 per sub
2. (W) Must cost less than $150 per sub

Environmental

1. (D) The sub has to not destroy the surrounding area

2. (D) The communication method's interference with wildlife must be minimized.

Energy

1. (D) Must be able to recharge itself within a day
2. (W) Must be able to recharge itself within two hours

Materials

1. (W) Will be made of biodegradable materials
2. (D) Will be made of non-polluting materials

Usability

1. (D) Can be deployed by a human from a vessel or shoreline (with enough depth)
2. (D) Can be retrieved by a human from a vessel or shoreline
3. (W) Can report back without physical presence

Engineering Standards

1. Will follow the principles of Green Engineering, as defined by the US Environmental Protection Agency (EPA), 2011:
    - (W) Minimize depletion of natural resources
    - (D) Strive to prevent waste

- (D) Use life-cycle thinking in all engineering activities
- (W) Conserve and improve natural ecosystems while protecting human health and well-being

Testing Plan

Note: Each number in parenthesis refers to that design specification number under that header (i.e. Performance, 1. Can operate for at least a week at a time)

Performance - Endurance (1, 2, 3, 4)

- The AUV will be placed in the Balltown lake once completed and left to collect data for a week. It will be tethered to land by fishing line to ensure that it can be retrieved in the case of failure.
- During one test, flippers will be worn by an experimenter and both the AUV and experimenter will submerge. While underwater, the experimenter will kick their feet to create currents toward the AUV.
- As an experimenter has a house on a lake nearby, as well as several motorboats, a test will involve going to said lake with the AUV to emulate the current speed of the Gulf Stream. The boat will be positioned stationary against a rigid object and its motor will be turned on. A flow meter will be used to determine the current velocity and the motor will be adjusted so it creates a current of roughly 5.6 Mph. The AUV will then be placed behind the motorboat and we will be able to see if it can edge closer to the motor boat against the current.
- We do not have the resources to simulate 40 Mph winds, unfortunately. Deterrence will be calculated.

Performance - Behavior (6, 7)

- Minimum Viable Product based testing will be done on all aspects of the AUV as it is built. This includes tests of all sensors and communication systems in an enclosed aquatic environment, as well as basic motion and control testing within tanks and the pool.
- Tests will be run in the Balltown lake with multiple AUVs and a single AUV. The tests will pass if the AUVs are capable of data agnostic data collection and autonomous navigation in either a group or alone.
- Large sticks and rocks will be situated in the Balltown lake to create obstacles for the AUVs. If the AUV can navigate around or through the obstacles without collision, the test will pass.

Environmental (1, 2)

- During all tests, the AUV must not collide or contact directly with any objects found in the water body. In depths exceeding 2 meters, the AUV must also not disrupt the sediments that make up the water body floor.
- Multiple available acoustic frequencies will be tested as the active channel for communication. A feeder fish will be placed in the water body between two AUVs. Any noticeable discomfort or agony will result in a failed test; otherwise, it will succeed.

Energy (1, 2)

- An AUV with a critical battery will be placed in the water body. It will have to rely on its renewable energy generator to gather power. A timer will start. Once the AUV is fully recharged, the time will be recorded and it will be known how quickly it can recharge itself.

Engineering Standards (1)

- In a controlled test environment (i.e a pool), the AUV will be deployed with water quality sensors. After moving around for several hours, the data will be collected once more to ensure that the water quality has not been changed due to the introduction of the AUV.

Ethical Considerations

The largest area of potential ethical impact on this project is related to environmental concerns. Not only could a powered sub knock into something fragile and physically harm it, but if one happens to break open due to impact or malfunction, it is unethical to not do everything possible to reduce pollution potential. Depending on the strength and frequency of communication methods, it's possible that they could interfere with or confuse local wildlife's communication methods. Another issue that could arise is the sub could be mistaken for food by a large enough animal, and consumed, presumably causing biological harm. These issues are being addressed in the following ways: for the issue of collision/destruction of the swarm, motors will be custom designed to be minimally polluting and active obstacle avoidance will be employed to avoid collision. Should this fail, final safety will be ensured by including a water contact failsafe, that will trigger a relay to open the main power circuit and kill all power in the system. For the issue of communication interference with local fauna, a frequency band will be selected that will minimize any noise pollution underwater. For the issue of incidental consumption, extensive research will be conducted into behavior of animals large enough to consume them and the swarm will take steps to avoid consumption (for example: sticking to a depth along the water column, moving through more convoluted environments, take a separate path to avoid predators if possible).

In the field of data veracity, wrongly collected data could affect lives depending on what is being collected (i.e. radiation data near residential homes). The usage of swarm robotics will allow multiple confirmations of similar data to reinforce its validity, and as the sensor bay will be modular, multiple identical sensors can be installed to do per-sub error detection.

As with any new technology with navigation capabilities, it is entirely possible that someone with the intent of harm could utilize our device with an explosive payload. Additionally, the power supply for our system is not equipped to handle most any launching or deployment of exhaustive destructive payloads (i.e. missiles). The same goes for utilizing this to invade people's privacy. The usage of imprecise sensors and low communication rates make practically any other system better for this use case, and there are several devices on the market specifically designed to carry explosives.

In the field of artificial intelligence, there is a public concern regarding machine awareness, or incredible self-taught advancement. With the communication and mobility abilities that a single AUV will possess, this concern is not great for our application. However, inexpensive sensors will be used in our system and the state space will be capped to only what data is necessary in order to limit its capabilities to our use case.

In the field of algorithm bias, issues of biasing may arise, which could result in inaccurate data. This is addressed by implementing data agnostic algorithms only, many of which are scalable in the number of inputs (i.e. sensor datasets) which will further improve the neutrality of its outcome. Finally, these algorithms have also been tried in similar applications to ours with no reports of bias in any capacity.

The last field to examine for ethical consideration is monopolization of the AUV market and subsequent price point saturation. This system will be designed with a budgetary concern kept in mind and thus has a much larger customer base. This will be addressed by offering customizable modules that can scale to a desired price point. For example, a package with an Iridium satellite module may cost up to $1200 while a standard GPS/802.11 protocol module may only cost $50.

Standards

ISO 17208-1:2016

This standard concerns the measurement systems and methodology of underwater sound from ships. This includes the reception of hydrophones across many distances and how environmental factors can influence the perceived signal. It also includes general noise patterns found in common communication mediums underwater (i.e. acoustic technology) and how to address them. This will be vital to address for our project, as acoustical communication tends to be quite noisy and addressing common patterns through tried and true methods will save us time.

ISO 18405:2017

This standard covers the effects that underwater sounds can have on the surrounding environment. This standard will be critical to the development of the communication systems on the sub, as insurance that we are not harming local flora and fauna is a fundamental aspect of operating as a research vehicle. This is important for the scope of our project as environmental impact should be mitigated as much as possible, and this standard provides several practices and procedures regarding how to accomplish this goal.

ISO 12473:2017

This standard discusses methods for cathodic protection in seawater or marine mud applications. Specifically, this covers the criteria required to gain proper protection and complete waterproofing, as well as the implications of applying reference electrodes into a hull. While the exact material of our sub hull is unknown at this time, steel has been used as the primary material for mobile underwater applications for decades now and is a material that will be considered for our project. This standard provides insight into the difficulty and feasibility of creating a metal hull. Determining the proper methods for material preservation and selection will be essential once our mechanical engineers begin designing the hull of our sub.

Project Schedule for Fall Term

As there are a large number of factors being developed in parallel that will affect the development of the full system, the project schedule had to be designed in an atemporal manor. To ensure structure, the weighpoints are predicted not in dates, but in relation to what else has been completed and tested. This tentatively leans towards a minimum viable product development strategy, though it derives some features from test driven development.

The goal is for each of the team members who are capable of programming to begin testing and development of several individual programmatic systems over the summer, so upon return we will be able to immediately begin assemblage of the first system to test.

Following this initial sequence, the overall pattern will follow with each sprint cycle starting with the software development to accommodate the hardware features that will be implemented. Upon completion and initial testing, a minimum physical system to accommodate the new features will be designed using the simplest materials that will still enable full testing of this stage. The first of these cycles will focus on communication and movement algorithms, and therefore the first hull will only contain the necessary aspects to house these systems.

The second round will be related to relative position holding and group data systems, so artificial physical simulations of multiple subs will be constructed, or depending on resources, multiple sub test beds. Once the software development reaches the aspects of flocking, group movement and exploration, it may be deemed prudent to transition into a simulated system, and program in accurate models of our finalized physical design. This would allow interaction testing and iteration without risking physical resources. Once all of the core software aspects have been implemented, the first iteration of the final physical design will be tested in full amongst a variety of environments, and the design will be iterated upon based on actual performance.

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