Relative Autonomy and Navigation for Command and Control of Low-Cost Autonomous Underwater Vehicles

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Abstract—The underwater environment severely constrains robotic navigation and communications, making the use of traditional multi-robot control and coordination schemes very difficult. These challenges are further exacerbated on a new generation of low-cost autonomous underwater vehicle (AUV) that lack a Doppler velocity log (DVL), acoustic modem or high-end inertial sensors typically used for underwater robotic navigation and communications. This work demonstrates multi-robot operations for low-cost AUVs via a novel and user-friendly operating paradigm that allows intuitive command and control of an AUV group. Each vehicle is equipped with a low-power and inexpensive acoustic system that enables it to navigate and receive operator commands. This system consists of a passive array of hydrophones and a timed acquisition and data processing stack that allows each AUV to self-localize relative to a single time-synchronized acoustic beacon. Switching between different operational ‘modes’ on the beacon causes it to broadcast different acoustic signals which, when received by the AUVs, result in the vehicles switching between different autonomous behaviors. These behaviors are defined in a beacon-centric coordinate system using pre-defined parameters unique to each vehicle; as a result, the movement of the beacon itself allows the operator to control the group-wide movement of all vehicles concurrently. This work presents field experiments with three SandShark AUVs in which the beacon and operator are collocated on a motorboat, allowing both operational mode and beacon movement to be controlled manually. However, by installing the beacon on a conventional mid or large-size AUV or autonomous surface vehicle (ASV), this paradigm provides a method for the remote command and control of an arbitrarily large number of miniature, low-cost AUVs, without the need for sophisticated navigational sensors or acoustic modems.

I. INTRODUCTION

Autonomous underwater vehicles (AUVs) are increasingly used for a variety of defense, oceanographic, and industrial applications. These vehicles are generally commanded independently, and the combination of communication limitations and individual platform cost has made multi-vehicle operations rare. When multiple vehicles are used together, they have been commanded individually and generally operate in non-overlapping areas or depths. A new class of low-cost, miniature AUVs, including the Bluefin SandShark\textsuperscript{[1]} and Riptide microUUV\textsuperscript{[2]} vehicles, make multi-vehicle sensing and deployments more realistic from a cost perspective. With each vehicle in the tens of thousands rather than hundreds of thousands or millions of dollars, riskier autonomous behaviors and adaptive networks or formations of vehicles are a potential reality. These vehicles lack the strapdown sensors used on more conventional vehicles to improve navigation and communication, such as Doppler velocity logs (DVLs), high-end inertial measurement units (IMUs) or acoustic modems. Their limited payload space and on-board power mean that adding these devices would either be impossible because of size, they would significantly restrict vehicle runtime, or they would substantially increase per-vehicle cost. Scalability in communications is also a challenge, as the current generation of acoustic modems restricts the total number of vehicles that can operate in one area due to the need to time or frequency share the bandwidth-limited acoustic channel.

We propose a unique AUV operational paradigm, geared specifically for vehicles lacking high-fidelity navigation or communication hardware and operating in close proximity to each other. Instead of operating in an absolute coordinate system, we re-define the autonomy and sampling problem in relative coordinates: vehicle behaviors are defined, and missions are planned, in a coordinate system relative to a single acoustic beacon. Operating in this beacon-centric coordinate system provides two advantages: first, each AUV remains in close proximity to the single acoustic beacon which provides it with a navigational ability that degrades with distance; second, movement of the beacon itself results in the concurrent movement of all vehicles, allowing the operator to control the absolute position of all AUVs simultaneously. Vehicles carry acoustic receiver payloads that enable them to calculate their position relative to the beacon on-line.

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in real-time – this payload is acoustically passive, limiting power draw, restricting environmental acoustic noise, and most importantly, enabling operational scalability to large vehicle numbers. Navigation and communications are based entirely on the one-way acoustic transmission between this single beacon and each AUV. Communications are limited such that the signal broadcast by the beacon commands the behavior of all vehicles in the group. If the beacon position is known, absolute position can be found from relative vehicle logs, as first demonstrated in [3]. Vehicle position is not communicated back to the operator in real time – instead, vehicles must be trusted to operate correctly within their pre-defined behavior parameters; combined postprocessing of vehicle logs and beacon position then enables the accurate estimation of the absolute trajectories of all AUVs.

II. BACKGROUND

There have been a number of prior studies on multi-AUV operations, as well as command and control. Several studies in theory or simulation look at different methods of coordinating vehicles, as in [9] and [10]. Real-world field trials using centralized command and control of multiple vehicles have also been published, in which each AUV is operated independently during a single experiment, such as in [11] and [12]. A technique of coordinated formation-based navigation has also been demonstrated in [13] and [14], in which range constraints between modems are used to operate multiple vehicles together in formations. This technique uses bidirectional acoustics, requiring each vehicle to both receive and send acoustic communication messages limiting its scalability for large groups of AUVs. Multi-vehicle coordination and adaptation has also been examined in the context of adaptive sampling, particularly for gliders. Gliders are a type of AUV that are deployed for months at a time, and Leonard [16], German [15], Paley [17] and others have demonstrated multi-vehicle coordination based on communication to the vehicles when they are on the surface, as well as adaptation to the environment. Since vehicles only communicate on the surface, this technique has limited utility for real-time in-situ command and control.

Multi-vehicle deployments underwater are significantly more difficult than deployments on land, the sea surface, or in air because of two major restrictions. Firstly, underwater positioning and navigation remains a significant challenge, because of the rapid attenuation of radio waves in water, thereby preventing the use of GPS; as a result, sophisticated acoustic navigational sensors like the DVL and IMUs with a laser-ring or fiber-optic gyro are typically used for high-grade inertial navigation. These sensors increase vehicle power-use, size, and ultimately price, meaning that the few operators that have access to multiple AUVs tend to be risk averse. Alternatively, external acoustic navigational aids can be used, but these usually require multiple transponders to be surveyed-in, limiting the operational area and the number of vehicles that can be deployed simultaneously. Secondly, the underwater acoustic channel is highly bandwidth-limited, which places a significant constraint on communication between vehicles, and also restricts scalability.

In this work, we elegantly sidestep both these issues and coordinate multiple underwater vehicles by using the acoustic system developed in [3] and [4] to provide concurrent underwater navigation for, and simple acoustic communication to, multiple vehicles using the one-way broadcast transmission from a single acoustic beacon and each AUV. This acoustic system is known as passive inverted ultra-short baseline (piUSBL) positioning, and is named so due to the fact that the system’s receive end is entirely acoustically passive, is located on the vehicle (inverted), and makes use of an ultra-short baseline (USBL) hydrophone array. Instead of bidirectional acoustics or surface radio communications, this piUSBL system with waveform detection is used as a basis for navigation and for autonomous behavior cuing of multiple AUVs together. The advantages of this approach are numerous: foremostly, the piUSBL system is a low-cost and low-power navigation solution ideally suited to the new class of inexpensive and miniature AUV that lack high-fidelity navigational sensors; secondly, the one-way, broadcast nature of communications allows the approach to scale to an arbitrarily large number of AUVs; thirdly, this centralized, single-beacon approach enables easy operational command of group-wide behavior on-demand through the broadcast of different acoustic signals without the need to send commands to individual vehicles; and finally, the use of a single beacon enables group-wide control of vehicle position via the unique operational paradigm of relative navigation – vehicle behaviors are defined within a beacon-centric coordinate system, allowing the movement of the beacon to dictate the overall movement of the AUV group. However, there are a couple of disadvantages: missions are constrained by the need to plan vehicle behaviors based on the relative position of the beacon; and the lack of communications from vehicles prevent the operator from obtaining direct feedback of vehicle status.

This paper describes the beacon-based relative navigation and autonomy method, the set of experiments used to develop and demonstrate that method, and the results. First the command and control scheme is presented, followed by vehicles and acoustic beacon used in experiments. The real-time processing chain is then described, along with the sequence of real-world experiments. Finally, results from these experiments, and conclusions and suggestions for future work are provided.

III. RELATIVE AUTONOMY FOR COMMAND AND CONTROL

The objective of this architecture is a vehicle command and control methodology that is easy to maintain as vehicle formations scale up in number, while providing accurate acoustic navigation for a new generation of miniature, low-cost AUV that lack high-fidelity navigational sensors (i.e. a DVL-aided INS). This method was demonstrated in field trials in which three SandShark AUVs (Fig. 1) were placed in the water, and were commanded to different patterns based
on the broadcast acoustic waveform and position of a single beacon in the Charles River in the summer of 2018.

The implications for this operational paradigm are to make multi-vehicle operations easier on the operator. Each AUV has a unique identifier assigned automatically on launch, and which determines parameterized offsets in \(\Delta x\), \(\Delta y\), depth (\(\Delta z\)), range (\(r\)) and heading (\(\theta\)) retrieved from a pre-defined look-up table. Desired vehicle state in each operational mode is then determined by the estimated relative position of the beacon, the autonomous vehicle behavior assigned to the mode, and the set of retrieved offset parameters. Since depth is also configurable with offsets, vehicles may be stacked in depth using these behaviors.

From an operator perspective in the field, in the experiments described here all vehicles are launched with a single script, after which a centralized dial connected to a single acoustic beacon commands group-wide AUV behavior by switching between different operational modes. Note, however, that this methodology can be extended for use with a beacon carried by an intelligent ‘leader’ vehicle, such as a conventional AUV outfitted with high-fidelity navigational sensors or an autonomous surface vehicle (ASV), resulting in a deployment paradigm that enables the operational command and control of AUV groups autonomously or remotely. The autonomous behaviors commanded by the dial in these experiments were ‘Default’, ‘Relative Loiter’, ‘Relative Line’, ‘Return and Surface’, and ‘Abort’, as shown in figure 2. An illustration of how these behaviors are configured using the parameterized offsets in the \(x-y\) plane is shown in figure 3. ‘Default’ is a pre-determined AUV behavior in a local, absolute (non-moving) frame of reference – it is used at the start of the deployment when the beacon is not transmitting in order to launch multiple AUVs in preparation for the operator (in a motorboat carrying the beacon) to get into the field for relative operations; during this time, the AUVs navigate without acoustics by dead-reckoning using propeller speed and IMU heading, resulting in a navigational accuracy that degrades rapidly. For the presented experiments a racetrack behavior was used, automatically shifted based on the per-vehicle parameterized offsets as shown in figures 2 and 3. All other behaviors are defined in coordinates relative to the beacon and navigate using the beacon as an acoustic aid. For the ‘Relative Loiter’ behavior associated with mode 1, the vehicle sets a circular loitering pattern with radius \(r\) at a distance of \(\Delta x\), \(\Delta y\) from the estimated beacon position. For the ‘Relative Line’ behavior associated with mode 2, the desired track is set to move the AUV along a line that is of length \(r\) and at a heading of \(\theta\), with a distance from the beacon to the center of this line of \(\Delta x\) and \(\Delta y\). Of the other two behaviors associated with modes 3 and 4 (not illustrated), ‘Return and Surface’ has all vehicles return along a track of length \(r\) and heading \(\theta\), and surface at a configurable \(\Delta x\), \(\Delta y\) offset from the beacon; ‘Abort’ has all vehicles stop and surface at their current position. For all relative behaviors, the desired track moves with the beacon, so that all deployed vehicles will continue to behave in the commanded mode in a moving path that follows the beacon. Note that for each of these behaviors, the vehicle attempts to converge to, and follow the desired spatial path at a constant speed, without any temporal constraints as a conceptual demonstration – in the future this can be extended to include time-parameterization in order to synchronize the positions of multiple vehicles.

With these operational modes, multiple vehicles may be commanded to collect data using different behaviors relative to an operator with minimal configuration in the field. The primary power of this approach is scalability: any number of vehicles can be added, each with different parameterized offsets specified in the look-up table to perform mission-specific sampling. By recording source position and logging the relative position of the beacon estimated by each vehicle, we can accurately estimate the trajectories of all AUVs in an absolute (global) frame of reference in post processing – either on-deck when all AUVs have returned and data downloaded, or after the fact. An advantage of this technique is ease of configuration and intuitive operation: the user need only specify offset parameters for each behavior per vehicle in a single look-up table to get easily understood beacon-centric multi-AUV operations.

An example application is in oceanographic sampling of fronts. An operator could deploy many AUVs in a single area, at which point they command a ‘Relative Line’ behav-
ior, with vehicle tracks crossing the front. When the operator determines that the front has moved, they change modes so that vehicles enter the ‘Relative Loiter’ behavior to follow and circle the beacon, and moves the vessel to the new front location before switching the mode back to the ‘Relative Line’ behavior. Upon mission completion, ‘Return and Surface’ brings all vehicles back to the operator. If the beacon is housed on an ASV or conventional AUV outfitted with a DVL-aided INS, the operator can command the beacon remotely via a single acoustic or radio modem installed on this intelligent ‘leader’ vehicle. Collected data can be globally geo-referenced by using the beacon position from GPS (in the ASV case) or DVL-aided INS (for a ‘leader’ AUV) to correct AUV fleet trajectories in postprocessing.

Experiments were conducted to demonstrate these principles in the Charles River in Cambridge MA in the summer of 2018. A beacon was used to command three submerged AUVs in-situ and in real-time based on broadcast waveform.

IV. VEHICLES AND ACOUSTIC BEACON

Three Bluefin SandShark AUVs [1] with piUSBL receiver payloads shown in figure 1, named Platypus, Quokka and Wombat, were used in these experiments. The experiments used a custom acoustic beacon that consisted of an acoustic source box with corresponding underwater speaker.

A. SandShark Autonomous Underwater Vehicle

Production-model Bluefin SandShark AUVs [1] from General Dynamics were used for testing acoustics and autonomy in experiments. Unlike conventional AUVs which typically navigate using an expensive DVL-aided INS, the SandShark AUV is a miniature, low-cost alternative that navigates by default via dead-reckoning using propeller speed and vehicle attitude from a MEMS IMU; as such, its positional error without external acoustic aiding accumulates at a rate of about 3 m/min, unless on the surface where it receives GPS. The manufacturer provides a tail section with thruster and control fins, including sensors (IMU and GPS) and actuators required for basic vehicle control. Users can then add a payload that interfaces to the tail via a cable that includes power and Ethernet, as illustrated in figure 4.

B. Vehicle Payload and Configuration

The payloads added to the SandShark vehicles include the piUSBL receiver, previously described in [3]. This system consists of an external hydrophone array, and a dry bottle containing a data acquisition board (DAQ), timing, and autonomy system (Fig. 4). The data measured by the pyramidal array is collected using a Measurement Computing 1608FS-Plus DAQ. A Microsemi Chip-Scale Atomic Clock (CSAC) provides a pulse-per-second (PPS) timing signal that triggers the DAQ to record data to the computer in sync with the acoustic transmission by the beacon. Collected data is processed on the computer to identify the broadcast waveform and to estimate range and bearing to the acoustic beacon. The payloads also include a NBOSI temperature/salinity sensor to be used in future oceanographic sensing missions. All data logging, signal processing, and MOOS-IvP autonomy [19] is performed in real-time onboard the AUV. All behavior configurations are tested in simulation that includes AUV dynamics prior to deployment to ensure expected behavior.

Data from the DAQ is processed on the computer to estimate range and bearing to the acoustic beacon as well as the waveform. The full details of this process are described in [4]. In brief, PPS triggers data collection such that the start of each data sequence corresponds to the beacon firing. The “most likely” waveform is determined by calculating the maximum of the matched filter with each possible waveform. Beamforming and matched filtering are then performed based on most likely waveform and coupled into particle filtering to estimate range r and bearing γ to the acoustic source from the vehicle. This is fused with vehicle heading h to estimate the relative location of the acoustic source, δx, δy.

\[
(δx, δy) = (r \cos(\pi/2 - h + γ), r \sin(\pi/2 - h + γ)) \tag{1}
\]

The likeliest source waveform and relative position, \((δx, δy)\), are used to control vehicle behavior during the experiment. This relative position can be combined with the logged GPS position of the beacon \((x_a, y_a)\), to estimate the geo-referenced vehicle trajectory \((\tilde{x}, \tilde{y})\) in postprocessing:

\[
(\tilde{x}, \tilde{y}) = (x_a + \delta x, y_a + \delta y) \tag{2}
\]

C. Acoustic Beacon

The acoustic beacon consists of a GPS unit, Arduino microcontroller with Wave Shield, 5-position rotary switch, and Lubell 3400 underwater speaker. The GPS PPS signal is used to trigger beacon firing. This firing is synchronized with data recording on the AUV. The rotary switch is used to control waveform, so that different waveforms may be used to communicate different vehicle behaviors. GPS logging is used to record the position of the source box, \((x_a, y_a)\).

The theoretical range of the existing system is 1 km based on the 1 PPS repeat rate and time-synchronized data recording limits. Further range limitations would be introduced by the low source level of the Lubell speaker and acoustic conditions introduced by shallow water and soundspeed profile. The maximum range used with this system for the two experiments was 300 m.
A. Dock-Based Beacon Experiment

In the first experiment, the beacon was located on the dock and used to command the vehicles to sample in the ‘Relative Line’, ‘Relative Loiter’ and ‘Return and Surface’ behaviors. Each vehicle first entered a ‘Default’ racetrack pattern for long enough to deploy each AUV sequentially. The beacon was then switched into mode 2 to command a ‘Relative Line’ behavior to all three vehicles; with all vehicles in this mode, the beacon was relocated 5 times to different locations along the dock moving from East to West, causing all three AUVs to shift their position along with it, as shown in the left of figure 5 (a). This behavior illustrates the power of this behavior and the relative navigation paradigm – by moving the beacon orthogonally to the behavior’s line direction, the AUVs are swept across and can sense a large area (this is especially useful for sidescan surveys). Mode 1 was then commanded to trigger a relative loiter pattern with a $\delta x$, $\delta y$ offset relative to the beacon, resulting in moving circular patterns as shown to the right of figure 5 (a). Finally, the ‘Return and Surface’ mode was commanded allowing us to recover one vehicle (Wombat) at the dock – unfortunately, a hardware issue with the other two AUVs (Platypus and Quokka) prevented them from returning, forcing an ‘Abort’ command. Otherwise, all beacon modes were correctly recognized by the three vehicles. Note that the tracks in figure 5 are generated using the real-time, online estimates of relative beacon position calculated by each AUV, but the tethered buoys (pink floats in Fig. 1) allowed visual confirmation of these tracks which were consistent with expected behavior.

B. Boat-Based Beacon Experiment

In the second experiment the beacon was located on an operator-controlled boat. The three vehicles were deployed directly into the ‘Relative Line’ behavior (mode 2), and operated relative to the boat as it moved between two locations from the North-East to the South-West. As in the first experiment, $\theta$ was 160 degrees for all vehicles, and offsets were set such that the tracks would be 30 m apart, resulting in the two triple parallel tracks clearly visible in the left of figure 5 (b). The “Relative Loiter” mode was then used to cue vehicles to loiter around the boat at different radii (15 m, 25 m, and 35 m) while maintaining parallel tracks; the beacon was then set to mode 1 for ‘Relative Loiter’ (right), resulting in the AUVs circling the boat with different radii; finally, mode 4 for ‘Abort’ was activated to prevent risk of imminent collision with a passing vessel.

V. EXPERIMENTAL RESULTS

Two experiments were undertaken to demonstrate these relative autonomy principles – the first mission involved autonomous behaviors relative to the beacon moving along a dock, and the second relative to the beacon on a moving boat. In both cases, the only communications and navigation link to the AUVs was the acoustic beacon that broadcasts information to all vehicles on desired operational mode, and whose signal is used by each AUV to calculate its position relative to the vehicle in real-time. Instead of each vehicle being individually configured at runtime, all vehicles are launched based on a unique identifier and operator-controlled via the command and control beacon. A single deploy script was run on each AUV, and vehicles were deployed in the water sequentially to begin operations. All vehicles were programmed to operate at a depth of 2.5 m and a speed of 1 m/s throughout both missions. To get visual feedback of vehicle behavior, tethered buoys were attached to each AUV.

(a) Dock-based beacon experiment – the acoustic beacon (white dots) is first set to mode 2 for ‘Relative Line’ (left) and repositioned from East to West in 5 steps, resulting in sensing coverage of a large area by the 3 AUVs; mode 1 for ‘Relative Loiter’ (right) was then activated, and the beacon repositioned once from West to East, resulting in moving circular patterns; finally, mode 3 for ‘Return and Surface’ was set, resulting in the blue AUV (Wombat) returning and surfacing, while issues with the other AUVs necessitated an ‘Abort’ command.

(b) Boat-based beacon experiment – the acoustic beacon (white dots) is set to mode 2 for ‘Relative Line’ (left), causing the 3 AUVs to follow the boat while maintaining parallel tracks; the beacon was then set to mode 1 for ‘Relative Loiter’ (right), resulting in the AUVs circling the boat with different radii; finally, mode 4 for ‘Abort’ was activated to prevent risk of imminent collision with a passing vessel.

Fig. 5: Tracks for SandShark AUVs Platypus (red), Quokka (green), Wombat (blue), and acoustic beacon (white dots) during both experiments: $\hat{x}, \hat{y}$ is represented in the absolute position plots overlaid on a map of the Charles River, and $\delta x, \delta y$ is shown in relative position plots (beacon-centric frame); relative plots are shown without a map overlay, illustrating the beacon-relative trajectories estimated online by each vehicle for acoustically-aided navigation; absolute trajectories are calculated offline by offsetting these vehicle-calculated relative trajectories by beacon GPS position.
30m, and 50m) as shown to the right of figure 5 (b). At the end of the experiment, the ‘Abort’ mode was commanded to ensure vehicle safety as an approaching tour boat was in danger of striking the vehicles. The tracks-per-behavior shown in figure 5 demonstrate how the beacon is used to control the vehicle: for the ‘Relative Line’, for example, the boat moves to the south-west during the experiment, but the overlapping tracks of the relative positions indicate that the vehicles all continue to perform the same behavior in a beacon-centric coordinate system. This is also observed in the loiter behavior. To more clearly show how the AUV tracks with the beacon, figure 6 illustrates how Platypus and the beacon move over time for the ‘Relative Line’ behavior.

C. Navigation

This system provides a good estimate of geo-referenced position after postprocessing with beacon GPS logs, and accurate relative navigation in real-time during operation, allowing the operator to understand vehicle motion relative to the beacon. Without piUSBL acoustic navigation, the SandShark AUV navigates using dead-reckoning by propagating its position from propeller speed and IMU heading, resetting its position to the GPS solution whenever it surfaces – this means that without acoustic aiding positional error accumulates rapidly. This is reflected in the magnitude of the ‘jump’ in position whenever the AUV surfaces and receives a GPS fix. Given AUV position from dead-reckoning \((x_{dr}, y_{dr})\) and piUSBL \((x_{pi}, y_{pi})\), the distance from the origin of the local geo-referenced frame for both methods is:

\[
N_{dr} = \sqrt{|x_{dr}|^2 + |y_{dr}|^2} \quad N_{pi} = \sqrt{|x_{pi}|^2 + |y_{pi}|^2} \quad (3)
\]

These distances can be used to measure ‘jump’ magnitudes to compare positional accuracy from dead-reckoning and acoustically-aided navigation. Figure 7 plots \(N_{dr}\) (gray) and \(N_{pi}\) (color) for the dock-based beacon experiment for Platypus (red), Quokka (green) and Wombat (blue), with the dashed black lines indicating GPS surancing events. These plots indicate that by the end of the 50 minute mission, dead-reckoning has accumulated an error of about 160m on Wombat and 90m on Quokka; the two surfacing events for Platypus show a dead-reckoning error of about 30 – 40m. In contrast, acoustically-aided navigation is consistent with GPS position upon surfacing, with negligible (< 10m) jumps in position across all vehicles. Without piUSBL acoustic navigation, these large positional errors would not only impact the quality of collected sensor data, but could endanger the vehicle as it might wind up outside of a safe operating area. Refer to [4] for an in-depth analysis of piUSBL accuracy.

D. Vehicle Safety

A key concept demonstrated by these experiments was how this system can be used to improve vehicle safety. During the boat-based source experiment, the operators modified vehicle behavior twice to prevent the AUVs from being hit by other boats. In the first case, the MIT sailing team began a race directly over the operational area being used to demonstrate the ‘Relative Line’ behavior. To respond, the beacon boat moved to the South-West as shown in figure 5, moving all three vehicles rapidly out of harm’s way. To perform a similar objective using acoustic modems in traditional AUV operations, it would be necessary for an operator to choose exact locations in the operating area for each vehicle, send individual commands to each vehicle, and then wait for a response. This is a slow way to respond to an urgent scenario: it can take up to 3 – 5 minutes for a vehicle to get a modem command to change behavior in shallow water, and it takes minutes rather than seconds for operators to decide on a new waypoint or path for each vehicle.

In the second case, a large tour vessel was passing close by, and operators were concerned that with all three AUVs circling the boat they could not both move the beacon to get the AUVs to safety and warn the tour vessel to stay out of the area. They switched to the ‘Abort’ mode so all vehicles would surface and become visible while they intercepted the tour boat. Again, sending abort commands via a conventional acoustic modem usually requires them to be sent separately to, and typically requires an acknowledgement from, each individual vehicle, which takes on the order of minutes —
the high latency of typical acoustic modems in multi-AUV operations can be a significant hazard in dangerous scenarios.

VI. CONCLUSIONS AND FUTURE WORK

These experiments demonstrated scalable and effective multi-vehicle navigation as well as command and control with low-cost AUVs using a single beacon. The vehicles operated successfully by navigating relative to the acoustic beacon during both experiments, and mission operation was intuitive and user-friendly since: 1. runtime configuration consisted only of running a single deploy script per vehicle and placing them in the water; and 2. the mission operator was able to easily and quickly shift vehicle trajectories as a group by manually moving the beacon. These results prove promising for the development of a scientist-friendly multi-AUV sampling system, in which non-experts can safely deploy many vehicles concurrently in a cooperative fashion.

The performance can be improved in several key respects. Instead of deploying vehicles sequentially, alternative methodologies for simultaneous AUV launching should be investigated. A more efficient method of automatically downloading, merging, and displaying vehicle and beacon logs on-shore would be another operational improvement. Additionally, the more sophisticated smoothing techniques demonstrated in [3] should be applied to improve the quality of geo-referenced trajectories in post-processing for future data collection. Because of the small operational size of the Charles River, the scale of the requested patterns resulted in tracks that are not straight or circular. Future experiments should look at larger-scale patterns (hundreds rather than tens of meters) which should ensure smoother spatial tracking of desired patterns by the AUVs, which is necessary for certain data collection methods such as sidescan sonar surveying.

The conditions for the Charles River experiments detailed here were near-ideal: limited current, a mostly-enclosed body of water, no waves, and few obstacles. Boats were the main impediment to smooth operation, and the ability to shift vehicle behaviors based on beacon position was effective in mitigating any danger to vehicles. Future experiments should assess the efficacy of these techniques in more challenging environments, with larger currents and areas to cover.

While the acoustic aiding provided by piUSBL enables vehicles to remain submerged indefinitely without navigation drift, there is a significant drawback in that the operator lacks any real-time feedback on submerged vehicle position. This requires trust in the autonomous behavior definitions, and in vehicle performance. Future work should look at ways to decrease operator stress by providing some indicator of vehicle position without increasing power draw or the sound put into the water per-vehicle: for example, the use of fish tags or acoustic reflections off the AUV body for tracking.

Overall, the system performed well and showed how multiple AUVs may be commanded and controlled cooperatively as a group. Future experiments will focus on using these techniques for collecting scientifically valuable data using multiple vehicles, for applications that involve sampling complex spatiotemporal oceanographic phenomena.

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