Abstract—This paper presents a survey and mapping strategy developed and simulated at the University of Idaho (UI). The UI mapping strategy utilizes low-bandwidth acoustic communication to populate and maintain a distributed representation of the search area among a small fleet of autonomous underwater vehicles. Using available acoustic communications, the individual vehicles create a multi-level representation of the search area. A low-resolution map contains information about the positions of other vehicles in the fleet, estimated coverage of the search area, low-resolution mine-like object (MLO) locations, and potentially dangerous areas for the autonomous underwater vehicles (AUVs). A high-resolution map contains significantly more accurate location estimates for MLO contacts. Maintenance of such a map of the search area enables certain advanced behaviors by the fleet of AUVs, as well as ensuring redundancy in the storage of important information; this redundancy provides assurance that, even if a vehicle were to be lost during a mission, much of the data obtained by that AUV would still be recoverable. These improvements allow for the more efficient and reliable conduct of autonomous mine countermeasure (MCM) missions.

I. INTRODUCTION

Previous research has shown that autonomous underwater vehicles (AUVs) are effective tools for various naval operations. Among other uses, AUVs have proven to be an effective tool for detecting and classifying underwater mine-like objects (MLOs) [1]. Using AUVs to conduct mine-countermeasure (MCM) missions allows human personnel to remove themselves from the potentially dangerous endeavor, ensuring additional degrees of safety during a mission. AUVs provide a method of conducting MCM missions with less human involvement, allowing for more cost effective searches. The efficiency of MCM missions can be improved through adjustments to the behaviors and abilities of the AUVs. This allows for multiple approaches for using AUVs to locate and classify MLOs in a predefined search area.

While the simplest use of AUVs involves only a single AUV, or multiple vehicles acting independently, the efficiency of the search can be further improved by employing groups of AUVs that communicate and collaborate during the mission. One such approach to MCM missions involves using a fleet of AUVs to map search areas for subsequent investigation and clearance [2]. AUVs that conduct these missions must perform collaborative survey behaviors and store information about the MLOs detected in the search space. Because of the possibility of losing vehicles during a mission, reliability can be improved if the AUVs communicate and share MLO information. Inter-vehicle communication enables AUVs to store mission information redundantly, thereby reducing the loss of information if a vehicle is lost. Maintaining a representation of the search area also allows the AUVs to conduct a more efficient and thorough survey of the search area [3].

Building on previously tested MCM behaviors, the AUV research team at the University of Idaho (UI) has successfully simulated a complex survey and mapping strategy that uses low-bandwidth, acoustic communication to support the collaborative development and maintenance of a distributed representation of the search space. This distributed representation ensures data redundancy and facilitates more intelligent fleet control by supporting real-time updates of AUV activity.

II. SURVEY AND MAPPING STRATEGIES

A. Available Mapping Strategies

Extensive research has been conducted on the development of and uses for maps of specified exploration areas. The creation of maps by autonomous agents is used in many fields, such as autonomous exploration [4]. The creation of such maps enable a more efficient and thorough search of the explored area. AUVs can also use the maps they build to determine their position. Because of these valuable applications, research into the use of decentralized, simultaneous localization and mapping (SLAM) has been conducted with multiple AUVs [5]. Successful efforts have been made to improve the capabilities of individual vehicles as well as collaborative groups of autonomous agents to search unexplored areas [6]. Work has been done to enable individual AUVs to draw feature information from the map they are maintaining using concurrent mapping and localization (CML) [7]. Using an augmented, state-extended Kalman filter as the map, an AUV was able to recognize and avoid obstacles using this method.

MCM missions, however, offer a unique challenge for autonomous systems developers. The underwater environment places significant restrictions on the capabilities of the AUVs to navigate, communicate, and detect/classify important objects. As such, AUVs must be capable of building and interpreting maps based on infrequent and inaccurate information. A.J. Shafer used simulations and experiments to model two-vehicle MCM missions in which the vehicles constructed and utilized dynamic maps of the search area [2].
Shafer's strategy allowed one vehicle to search an area following a predefined path, with the second vehicle following behind providing enhanced coverage for poorly covered areas. This work provided a method in which multiple AUVs could act collaboratively to explore a predefined area; it was, however, conducted using surface vehicles that were not subject to all of the restrictions inherently placed on AUVs used in an MCM mission. Rajala used the Autonomous Littoral Warfare Systems Evaluator–Monte-Carlo (ALWSE-MC) simulation environment to simulate a fleet of AUVs collaborating to build maps while conducting an MCM mission [8]. Each vehicle builds its own map by using data transmitted to it from other vehicles in the fleet. Again, however, little consideration was given to the limited bandwidth available to AUVs conducting MCM missions using acoustic communications.

B. UI Mapping Strategy

The mapping strategy adopted at the UI was developed to accommodate the complications involved in using AUVs to conduct MCM missions. This paper describes the UI mapping logics used to develop a dynamic, decentralized representation of the search area. To facilitate the creation of a decentralized map of the search area by multiple AUVs working collaboratively, the UI logics rely on acoustic communication among the AUVs. The communication scheme and logics used by the fleet of AUVs allow for the creation of a multi-layered map. This map is split into two parts: the low-resolution map and the high-resolution map. The low-resolution map is based upon smaller, more frequent communications among AUVs, and includes position estimates for other vehicles, search area coverage, estimated MLO locations, and potentially dangerous areas. The high-resolution map utilizes larger, less frequent messages, as well as the information gathered by the individual AUV (and therefore unrestricted by communication) to record data about MLO locations and classifications.

The multi-layered approach adopted by the UI provides the benefit of data redundancy. Because of the potential for dropped messages and irrecoverable vehicles, it is possible for important information to be lost during the course of an MCM mission. Maintaining redundancy in stored data increases the likelihood that all significant information will be available to operators after a completed mission. This approach also enables the creation of autonomous logics that could allow the vehicles to react more quickly to changes in the search area.

Such reactions may include a vehicle adjusting its position to be better situated to inspect an anticipated MLO, using the low-resolution MLO location to anticipate the area it will be ordered to inspect.

III. AUVish-BBM and ALWSE-MC

The UI survey and mapping strategy was developed and simulated on the ALWSE-MC software. ALWSE-MC is an AUV mission simulator developed and maintained by the Naval Surface Warfare Center Panama City. ALWSE-MC runs behavior modules written in MATLAB to simulate AUV logics. The UI AUV research team designed a simulation to duplicate the behaviors that the five small University of Idaho AUV’s use, and modeled the environment and existing communications cycle. A behavior module was created to simulate the use of low-bandwidth communication utilized in the acoustic underwater environment.

Specifically, this module simulates communications involving a modified version of AUVish-BBM, a language developed for the AUVs which uses a time-division multiple access (TDMA) messaging scheme developed for the “UI mini-sub”. Messages between these AUVs are transmitted via the Woods Hole Oceanographic Institute (WHOI) acoustic modem [9]. This messaging scheme, simulated in ALWSE-MC, involves use of both the 13-bit and 32-byte message types supported by the WHOI acoustic modem. During the first 18 seconds of the 30 second communication cycle, each vehicle sends out a 13-bit message in turn with its ID, current task, a connection vector indicating which members of the fleet it has heard from, the vehicle's current formation role, and whether or not it is the leader. Included in the time allotted for each AUV’s 13-bit message is also a slot in which the AUV pings the long-baseline (LBL) buoys to attain a position estimate. During the next 6 seconds, the leader broadcasts a 32-byte message containing its progress along the search path, any MLO locations it has found since the last broadcast, and any vehicle assignments. The remaining 6 second slot and 32-byte message is assigned by the leader AUV to one of the other vehicles that requests it. A single AUVish-BBM communication cycle, lasting 30 seconds, is shown in Fig. 1.

This TDMA message cycle allows the vehicles to collaborate and to exhibit the behaviors of formation control, vehicle replacement, leader replacement, and divert to waypoint. However, due to the low bandwidth of underwater

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<td>6 seconds</td>
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Figure 1. AUVish-BBM communication cycle consisting of five 13-bit messages and two 32-byte messages.
acoustic communications, the vehicles cannot simultaneously share their position coordinates, MLO coordinates, CAD/CAC information, and sensor area coverage with the other vehicles each communications cycle. Because of this, the AUVs cannot share a full updated map through acoustic communication. Through use of the UI mapping and communication logics, the fleet can share up to 12 MLO coordinates between the two 32-byte messages without sacrificing too much coordinate resolution. These communication restrictions require that a complex survey and mapping strategy be developed in order to let the AUVs share as much information as possible and build redundant maps.

IV. LOW-RESOLUTION MAPPING

The mapping logics developed at the UI utilize both 13-bit and 32-byte messages, with the 13-bit message supporting the production of low resolution maps of the search space. The 13-bit message has four fields, one of which is the “task” field used to communicate the task being conducted by the sending vehicle. The task field in the 13-bit message conveys information about the location and efforts of the transmitting AUV. The structure of an AUVish-BBM 13-bit message is shown in Fig. 2.

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<tr>
<th>Formation Position</th>
<th>Leader Flag</th>
<th>Connection Vector</th>
<th>Current Task</th>
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<tr>
<td>3 bits</td>
<td>1 bit</td>
<td>4 bits</td>
<td>5 bits</td>
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13-bit Message

Figure 2. AUVish-BBM 13-bit message structure.

The task field of a 13-bit message describes the task the transmitting AUV is currently undertaking, and can contain one of the following values:

- In Formation
- Out of Formation
- MLO Found – In Formation
- MLO Found – Out of Formation
- Inspecting MLO
- Inactive/Disabled

The tasks “In Formation” and “MLO Found – In Formation” are used when the transmitting vehicle is within a specified area around its ideal fleet location when it transmits its 13-bit message. This is determined by estimating the AUV’s ideal location based upon the leader’s progress and the AUV’s role in the fleet. With this ideal location known, the AUV is considered to be “In Formation” if it is within a specified region centered on the desired position of the AUV and defined by preset distances both parallel and orthogonal to the AUV’s path. Otherwise, the AUV is considered to be “Out of Formation.”

The “MLO Found” tasks are used by the AUVs upon discovery of an MLO. If the transmitting AUV has detected an MLO, it sets its task message to either “MLO Found – In Formation” or “MLO Found – Out of Formation,” depending on whether it is within the specified region around its ideal location, before transmitting the message. Implicit in both of the “MLO Found” messages is a request by the transmitting AUV to use the spare 32-byte message broadcast window so that it can communicate the coordinates of the detected MLO.

The 13-bit messages are transmitted between vehicles in binary form, with the task field occupying 5 of the available 13 bits. This allows for AUVish-BBM to maintain 32 distinct possibilities for the “task” field in the 13-bit message. Of the 32 possibilities, 6 of them (as shown in Table I) are used in the simulated UI mapping strategy, allowing for significant expansion if necessary to support additional collaborative behaviors.

Employing information communicated in this task field, AUVs construct a rough, low-resolution map that they use to estimate the location of other AUVs in the fleet and the fleet’s coverage of the search area, as well as to mark preliminary MLO locations and potentially dangerous areas in the search space.

A. Position Estimates

In order to act collaboratively and coordinate the movement of the fleet of AUVs, it is essential for a fleet of AUVs to maintain some knowledge of the locations of the other AUVs in the fleet. Because of the limitations of communication, this task becomes more difficult, as the vehicles cannot provide constant updates to fleet members of the AUV’s position. To compensate for the difficulties introduced by the operating environment, the UI mapping strategy allows the AUVs to estimate the positions of the other members of the fleet based on inferences made from the 13-bit message. The position estimates made by a single vehicle during the course of an ALWSE-MC simulation can be seen in Fig. 3.

Upon receiving a 13-bit message with the task field set to “In Formation” or “MLO Found – In Formation,” the receiving vehicle estimates the location of the transmitting vehicle. To do
so, the receiving vehicle first estimates the current position of the leader AUV. This is done by adjusting the leader’s most recently broadcast progress message to compensate for the distance traveled by the leader in the time since the aforementioned message was received. This adjusted progress allows the receiving vehicle to estimate the leader’s current position. Using the estimated position of the leader, the receiving vehicle can estimate the position of the transmitting vehicle by adjusting the leader’s estimated position to that for a vehicle fulfilling the fleet role of the transmitting vehicle. This estimated position is then stored in the receiving AUV’s memory array, where it can be easily recalled should the need arise.

B. Area Coverage

Area coverage for the fleet is maintained on each vehicle, and is updated as the AUV receives additional position estimates for the other AUVs in the fleet. In a manner similar to that described in [2], an AUV will update the coverage of observed cells using an aggregate coverage based on the previous coverage of a cell and the sensor probability curve defined for the sensor in use. To estimate the value of the coverage of a cell when an AUV passes it, the AUV calculates the shortest distance between its path and the center of the cell in question. Using the simulated probability curve for the sensor, which provides a relationship between the distance from the sensor and the applicable coverage value, a confidence is calculated for the cell. This additional coverage is summed with the previous coverage, and the process is repeated for each cell close enough to yield a positive value on the probability curve. Fig. 4 shows the area coverage for a single vehicle during a simulated MCM mission.

The resulting coverage for each cell is stored in the low-resolution map in the AUV’s memory, which changes dynamically throughout a mission. Because of the method with which the coverage of cells is determined and the map is built, however, the coverage map can be rebuilt at post-mission using the more accurate and more frequent position estimates that each AUV is capable of maintaining for itself. Post processing yields a more accurate map, but this level of accuracy is not possible to attain during missions because of the communication limitations inherent in the AUV’s operating environment.

C. Low-Resolution MLO Locations

AUVs in the fleet also use the information communicated in the task field of the 13-bit message to estimate the locations of MLOs detected by other fleet vehicles. These estimations are based upon the estimated position of the transmitting AUV (described above) when it informs the fleet that it has found an MLO. This estimation can be made when an AUV transmits a 13-bit message with “MLO Found – In Formation” in the task field. When this occurs, the receiving AUVs estimate the position of the vehicle, as described above, and use this location to infer the area in which the MLO was likely to have been found. This estimation cannot be accomplished when an AUV transmits a message with “MLO Found – Out of Formation” as its task. Because no position estimate for the vehicle can be made when it is reported as “Out of Formation,” there is no method for estimating the location of the discovered MLO.

The area in which an MLO was likely to have been found is represented as a rectangle surrounding the area that would be covered by the AUV’s sensors between the new and previous position estimates. The area also extends slightly ahead-of and behind the two position estimates, respectively, to account for errors in the position estimates. A graphical representation of the low-resolution MLO location estimates can be seen in Fig. 5. This low-resolution estimate of MLO locations, while not nearly as accurate as the high-resolution estimates, provides...
redundant information concerning the location of MLOs. This redundancy is important to prevent loss of critical information in the case of lost communications or AUVs, as well as potentially allowing for quicker response by the fleet to an apparent minefield.

D. Dangerous Areas

The collaboration enabled by the AUVish-BBM communication language and the fleet-formation logics encoded on the AUVs allow for the fleet to recognize when a single vehicle fails to remain in contact with the rest of the fleet and can be considered lost [9]. This can happen for various reasons; one possibility is that the vehicle was disabled by a counter-counter-measure (CCM). In such a case, it is important for the remaining vehicles in the fleet to know the likely location of the CCM so that it can be avoided.

An AUV is considered to be inactive when no remaining member of the fleet has received a communication from that AUV within two communication cycles. The “inactive” designation requires the entire fleet to have lost communication to help ensure that a vehicle is not falsely declared inactive in the case of a failed transmission. Once any member of the fleet decides that another AUV is inactive, it updates its map to reflect a dangerous area in the area surrounding the lost vehicle’s last known location. To account for AUV travel after the last received transmission, the area is marked beginning just behind the lost AUV’s last known position and advancing a short distance ahead of it, as shown in Fig. 6.

In addition to the low-resolution mapping conducted through the 13-bit acoustic message, the UI mapping strategy utilizes the 32-byte message to create a high-resolution map of MLO locations. The modified AUVish-BBM communication scheme used to simulate MCM missions allows for the transmission of two different 32-byte messages during each 30-second cycle. The first message is used by the leader AUV, and the second message slot is available for other AUVs in the fleet. Each 32-byte message is composed of multiple, smaller packets that can be used to report information of various types. One such packet type conveys the location of a single MLO.

In order to minimize the size of individual MLO location packets and conserve space within the 32-byte message, MLO locations are transmitted as cell coordinates rather than absolute coordinates. Because of this, the high-resolution map for MLO locations is decomposed into cells. Each cell measures 5m on a side, and is assigned X and Y coordinates. The use of cell coordinates rather than absolute coordinates reduces the amount of data necessary to report a location, allowing a significant increase in the number of MLO location packets that can be transmitted in a given 32-byte message. Each packet is five bytes in size, allowing for six different MLO locations to be transmitted in a single 32-byte message. Fig. 7 shows the structure of an example 32-byte message including the locations of two separate MLOs.

Because of the inherent error in vehicle position estimates and the estimated locations of MLOs relative to the vehicle, the rounding necessary to decompose the absolute coordinates to cell coordinates (as well as the reverse) does not substantially decrease mapping accuracy beyond the error inherent in the detection of MLOs. While rounding the position estimates to cell coordinates introduces inaccuracy into the data, it is no greater than the inaccuracy involved in estimating the MLO’s location. Due to this inaccuracy in estimating MLO locations, it is possible for the same MLO, as detected by several different vehicles, to be transmitted multiple times with slightly different cell coordinates and be recorded in adjacent cells in the high resolution map. This occurrence is tolerable in MCM missions for two reasons: the first is that duplicate MLOs err on the side of false positives, which do not endanger the goals of the mission as false negatives would. The second

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<th>Packet Type</th>
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<td>MLO Location</td>
<td>[X1, Y1]</td>
<td>MLO Location</td>
<td>[X2, Y2]</td>
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<td>Packet 1 (5-Bytes)</td>
<td>Packet 2 (5-Bytes)</td>
<td>Additional Space</td>
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The remainder of the 32-byte message can be used for additional packets, including, but not limited to, MLO locations.

Figure 6. Graphical representation of vehicle position estimates and dangerous areas, as made by Vehicle 1 (red) for all AUVs in the fleet. The dangerous area determined for the loss of the tan AUV is marked in white.

Figure 7. An example of an AUVish-BBM 32-byte message containing two MLO location packets. Each packet begins with a 1-byte header identifying it as an MLO location packet, and contains the cell coordinates of a single detected MLO.
reason is that upon completion of a mission, post-processing would allow operators to interpret which MLOs may have been reported more than once.

Fig. 8 shows a high-resolution MLO map belonging to AUV 1 at the end of an ALWSE-MC simulation run. The red crosses indicate mines that this particular vehicle has found, while the blue squares outline the cell coordinates of the MLOs that have been transmitted in 32-byte messages from other fleet members. For comparison purposes, the actual locations of the simulated MLOs are shown as pink stars in the figure. In this case, the majority of the mapped MLOs were detected by other members of the fleet, and transmitted via the 32-byte message. The map in shown in Fig. 8 belongs only to vehicle 1, but the transmitted MLO locations will be nearly identical on each vehicle’s map, unless a 32-byte message was missed in a previous communication cycle. The figure also illustrates the estimation of an MLO in multiple, adjacent cells; this occurrence is shown where several neighboring cells are outlined in blue around a single MLO location (shown as a pink star).

While the 32-byte message currently transfers only the locations of MLOs, additional information, such as MLO type [10], could be included in the message and added to the high resolution map at the cost of decreasing the number of mines transmitted per message. Such information might prove useful in supporting autonomous fleet behaviors, such as MLO inspections. When debating the information to be transmitted, the cost in message capacity must be weighed against the benefit gained by distributing the additional information to the other vehicles in the fleet.

VI. APPLICATIONS

The multi-layered map created by the UI mapping logics during an MCM mission can be used both for human inspection and for enhanced behaviors by the AUVs during a mission. The information obtained from vehicle sensors and fleet communications is stored in a multi-layered memory array consisting of five overlapping matrices. Each matrix is a layer of the map, with one element per cell. The layers correspond to vehicle location estimates, estimated area coverage, dangerous areas, low-resolution MLO locations, and high-resolution MLO locations. Each layer is updated separately when the relevant information is made available to the AUV, either through the AUV’s sensors or through communications from other AUVs in the fleet.

As stored in memory, the map is not easily interpretable by human operators. For this reason, it is necessary to translate the memory array into graphical form. To this end, researchers at the UI have produced graphing functions using MATLAB to facilitate interpretation of the maps obtained during simulations run on the ALWSE-MC platform. Such functions could also be used to interpret and present data obtained from an actual MCM mission or test run, and can display the map obtained by a single vehicle or one generated through the post-process integration of the maps obtained from all the recovered vehicles. Fig. 9 shows a comparison between a map for
Vehicle 1 and a post-process map containing the data from all 5 AUVs used in the simulations.

The UI maps can also be used to facilitate decision-making by the AUVs during an MCM mission. Logics currently implemented on simulations at the UI utilize the leader’s map when assigning vehicles to conduct inspections of MLOs. When assigning vehicles to inspect MLOs, the leader uses the high-resolution MLO locations to determine the cells that need to be inspected. The leader also uses the area coverage layer of the map to determine which MLOs should take precedence when assigning inspections. MLOs in areas of poor coverage are more likely to require inspection than are MLOs in areas that are already thoroughly covered; with this in mind, the leader gives precedence to the MLOs in poorly covered areas when assigning inspections.

Though not currently implemented on the UI fleet of AUVs or simulation, other enhanced behaviors may be enabled by the map. Such behaviors include vehicles adjusting their paths to provide more thorough coverage of an inadequately searched area. Vehicles might be programmed to predict fleet commands or even MLO locations based upon prior knowledge contained within the maps. Such enhanced behaviors, though not yet implemented, are made possible by the UI mapping strategy.

Though not currently implemented on the UI fleet of AUVs or simulation, other enhanced behaviors may be enabled by the map. Such behaviors include vehicles adjusting their paths to provide more thorough coverage of an inadequately searched area. Vehicles might be programmed to predict fleet commands or even MLO locations based upon prior knowledge contained within the maps. Such enhanced behaviors, though not yet implemented, are made possible by the UI mapping strategy.

VII. CONCLUSION

An important aspect of MCM missions is the collection, compilation, and storage of information gathered by the AUV fleet. This necessity is complicated by the restrictive environment in which the AUVs operate. The UI approach to survey and mapping enables the creation of a distributed representation of the search area by a fleet of AUVs working collaboratively. The UI mapping strategy uses both the 13-bit and 32-byte acoustic messages available through the WHOI acoustic modem to transfer information among AUVs. The information transmitted, and the interpretation of that information, supports collaborative behaviors and distributed mapping by a small fleet of AUVs.

The UI strategy creates a multi-layered, distributed map of the search space that contains information about fleet AUV positions, area coverage, low-resolution MLO position estimates, dangerous areas, and high-resolution MLO position estimates. This map is used to enhance the autonomous behaviors performed by the fleet and its members, as well as creating a redundant storage system for important information gathered about the search area. The map created can also be graphically displayed in a form that is easily interpreted by human operators. The UI approach is unique in its capacity to create such a map based in highly limited communications among the collaborating AUVs.

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REFERENCES