Adaptive Underwater Sonar Surveys in the Presence of Strong Currents

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Abstract— We consider the task of conducting underwater surveys with a sonar-equipped autonomous underwater vehicle (AUV) in environments with strong currents. More specifically, this topic is addressed in the context of mine countermeasure operations employing synthetic aperture sonar (SAS) sensors. Two complementary algorithms that allow the AUV to autonomously adapt its survey route based on sophisticated sensor data it collects in situ, while respecting the unique constraints imposed by the problem, are proposed. The algorithms allow the AUV to (i) adapt its survey heading based on the presence of currents to ensure quality data is collected, and (ii) adapt its survey route to reinspect the most suspicious objects at additional aspects. The flexibility to immediately react in situ to the environmental and tactical conditions sensed during the mission allow the most useful data for object recognition purposes to be collected efficiently. By obviating the recovery and redeployment of the AUV, as well as laboratory-based data-processing during the interregnum, the overall mission timeline can be greatly compressed and operational costs can be reduced. Experimental results illustrating the real-time execution of the proposed algorithms on an AUV are shown for a completely autonomous mission conducted in the North Sea.

I. INTRODUCTION

Various maritime applications share a common requirement to search with a sonar sensor an underwater area comprehensively, such that there are no gaps in coverage. At the same time, there is often also a desire to more closely inspect certain interesting objects or locations that are discovered in the first exploratory phase. Usually these two stages—global exploration and local reexamination—are executed sequentially, but importantly, separated by a significant time delay during which the sensor platform must be recovered; data downloaded, processed, and analyzed in a laboratory; a new mission-plan designed and programmed; and the platform redeployed. These intermediate tasks result in significantly longer times at sea that translate to substantially higher costs. Employing an autonomous underwater vehicle (AUV) as the sensor platform provides an intriguing opportunity to greatly condense the operational timeline and save resources. This work proposes methods to eliminate the time-consuming intermediate tasks by developing adaptive autonomy algorithms—in conjunction with real-time onboard processing—that exploit the through-the-sensor data collected on an AUV. In this way, the search and inspection tasks can be executed in a single, unified adaptive mission that requires no human interaction or manipulation.

The high-resolution imaging of underwater environments afforded by sonar has proven particularly useful for detecting objects in diverse applications, from archaeology [1] and habitat mapping [2] to pipeline inspection [3] and mine countermeasures [4]. Thanks to advances in marine robotics technology, the sonar data used to locate these various types of underwater “treasure” are very often collected by AUVs [5]. As these AUVs become more mature and robust, there is increasing interest in incorporating more flexibility into the data-collection process. At the same time, there is also a need to expand the universe of environmental conditions—in particular beyond calm seas—in which these surveys can be performed reliably. By enabling autonomous behaviors, the potential exists for an AUV to adapt to the conditions at sea in order to ensure the collection of useful, quality data and reduce survey times. This work addresses the issue of autonomous underwater surveys with an AUV, specifically in waters with strong currents, when the collected sonar imagery is to be exploited for detecting objects of interest. The proposed methods are relevant for numerous applications concerned with finding underwater objects, but here they are presented in the context of mine countermeasure (MCM) missions at sea. It should also be emphasized that the sensor data on which the adaptive decisions will be based is very sophisticated, extending well beyond simple scalar environmental measurements (such as temperature, depth, conductivity, etc.).

In calm water, an AUV can perform a desired survey with relative ease, but the presence of currents in the water column can make even a simple survey a struggle. Currents can push an AUV off its intended course or induce crabbing while the AUV maintains its track. Currents can also alter an AUV’s speed-over-ground, making it travel too quickly or too slowly. In general, the presence of currents introduces undesired vehicle motion that can greatly complicate sonar data collection, especially when the raw data is to be processed into high-resolution synthetic aperture sonar (SAS) imagery. SAS processing, which enables exceptional centimeter-resolution imagery and high area-coverage rates, relies on extremely accurate micronavigation and the coherent summation of sonar ping-returns of overlapping array elements [6]. The stringent requirements of the technique mean that undesired deviations from a linear track (of the platform, or AUV) can introduce errors that severely affect the quality of the resulting imagery [7]. Put simply, if currents are not taken into account, it is possible that a survey will result in essentially worthless sonar data.

To illustrate this fact, Fig. 1 shows two real SAS images—from the same area where the seafloor is characterized by large sand ripple dunes—whose main difference was the relative orientation between the currents and the sonar-
equipped AUV’s track during data collection. In Fig. 1(a), the AUV had traveled nearly perpendicular to the direction in which the currents were flowing. As a result, the SAS processing requirements were unable to be met, so the resulting imagery – blurry and defocused – is unsuitable for detecting objects of interest. In Fig. 1(b), the AUV had traveled nearly parallel to the direction in which the currents were flowing. In this case, the imaging was successful and the data could be used for performing object detection. Indeed, the vital importance of this outcome is underscored by the fact that two man-made (mine-like) objects can readily be found in the 90–95 m range at the top and bottom of the image in Fig. 1(b).

With this insight as motivation, in this work we develop algorithms that enable an AUV to adapt its survey – autonomously – based on data it collects in situ. Specifically, the real-time algorithms allow the AUV to (i) adapt its survey heading to travel at a favorable orientation with respect to the currents, and (ii) revisit automatically detected objects to obtain multiple views from new aspects. Experimental results obtained at sea, from executing the algorithms (and other real-time processing) onboard CMRE’s MUSCLE AUV, will be shown from a recent exercise in the North Sea. To our knowledge, these results are the first to demonstrate this type of at-sea AUV adaptation based on sophisticated high-resolution through-the-sonar imagery. (In [8], AUV target reinspection was performed based on only lower resolution side-scan sonar data.)

The remainder of this paper is organized as follows. In Sec. II, we provide necessary background information pertinent to AUV-based sonar-data collection to motivate the adaptive approach. In Sec. III, we briefly describe a family of algorithms we have developed that allow an AUV to adapt its survey route based on the data it collects in situ. An overview of the AUV employed and experimental results obtained at sea are presented in Sec. IV. A discussion of the results and topics for future work are given in Sec. V, before concluding remarks are noted in Sec. VI.
II. BACKGROUND: AUV-BASED SONAR DATA COLLECTION

The most common objective of MCM missions is to detect underwater targets (i.e., mines) on the seabed. The inherent danger of such operations has spurred the desire to distance humans from the minefield by instead conducting these mine searches with an AUV. Because of the time-sensitive nature of MCM missions, the next priority is to embed intelligence in the AUV so that it can immediately react to the data it collects. By adapting its survey route in situ and efficiently allocating resources, the AUV can collect the most informative data for the task at hand while simultaneously reducing mission times. In this work, we demonstrate as a proof-of-concept the successful use of a sonar-equipped AUV at sea to perform adaptive, autonomous MCM surveys. However, the framework and algorithms employed are readily applicable to a wide range of underwater research areas.

AUVs for MCM operations are typically equipped with two side-looking sonars, one on the port side and one on the starboard side. These sensors image in a direction orthogonal to the direction in which the AUV travels. Because of the geometry of the problem, a dead zone—from the AUV’s nadir up to a certain range on either side—between the two sonar swaths will lack sonar coverage [9].

The standard AUV survey plan used in practice [10]–[12] is a series of equidistant parallel tracks such that the swaths of consecutive tracks interleave, resulting in sonar coverage for the entire area of interest. (The adherence to traversing parallel tracks is partly because the collected raw data is subsequently processed into imagery, for which such data is preferable.)

But the rigidity of a preplanned approach introduces major inefficiencies that can extend mission times and increase costs. When currents are present, surveys at certain orientations will result in unusable (poor-quality) data. When objects of interest are present, it is desirable to have multiple views of them from different aspects, courtesy of a single AUV deployment. Therefore, we instead allow the AUV to automatically adapt its survey in situ based on data that it collects.

III. DATA-DRIVEN AUTONOMY ALGORITHMS

In this work, we propose two autonomy algorithms that are driven by data collected in situ onboard an AUV. The first, which exploits the measurements of an onboard acoustic Doppler current profiler (ADCP), adapts the heading of the survey to compensate for the presence of currents and thus ensure the collection of usable sonar data. The second, which exploits the actual through-the-sensor sonar data in conjunction with the results of an object-detection algorithm, adapts the survey to immediately reinspect the most suspicious contacts at new aspects (without having to recover and redeploy the AUV). Jointly, the two algorithms allow the collection of the most useful data for enabling successful object recognition in a timely manner.

A. Adaptive Survey-Orientation

The first onboard algorithm we employ adapts the AUV’s survey heading based on the orientation of water currents present.

An ADCP embedded in the AUV exploits the Doppler effect of acoustic waves scattered from particles in the water column to estimate the water current velocity. Raw 3-component sensor measurements are produced for several depths below the AUV at regular time intervals (here, every 0.2 seconds for 50 depth cells, each 25 cm deep). We use the measurements in only 7 cells, from 1.0 m to 2.75 m below the AUV, as a compromise between proximity to the vehicle (and the currents it actually experiences) and ADCP sensor fidelity (vis-à-vis noise). Various processing steps—coordinate transformations, subtraction of vehicle velocity, etc.—are performed to convert the raw data into a clean format expressing measurements of the current velocity (i.e., magnitude and direction) in the appropriate coordinate system.

The median direction of the current is deemed to be the dominant current orientation, \( \theta_c \), in the mission area. If the median magnitude of the measured current is sufficiently strong, above a predefined threshold \( \tau_c \), the current-adaptation behavior is triggered. (In the experiments, \( \tau_c = 0.25 \text{ m/s} \) was used.) Importantly, to ensure that the measurements are stable and consistent, the algorithm also requires that the standard deviations in direction and magnitude are both sufficiently small.

The adaptive current orientation phase of the mission then proceeds with the AUV surveying the area at an orientation of \( \theta_c \) (and \( \theta_c + 180^\circ \)). An adjustment to the speed of the AUV, to maintain comparable speeds-over-ground when traveling with or against the current, is also made based on the estimated magnitude of the current. By surveying at an orientation parallel to the current’s orientation, adverse effects of the currents should be minimized and the resulting sonar data should be of the highest possible quality.

B. Adaptive Target-Reinspection

The second onboard algorithm we employ adapts the AUV’s survey to reinspect at additional aspects the most suspicious objects detected. This exploits the detection algorithm we developed in [13] and the environmentally adaptive classifier we developed in [14].

The aspect at which an object is imaged can have a profound effect on its ability to be detected. For example, cylinders viewed at endfire (where there are fewer pixels on target) are significantly more challenging to detect than cylinders viewed at broadside. For this reason, it can be valuable to collect multiple views, at different aspects, of an object. Doing so can provide a more complete picture of the (unknown) object and also reduce the likelihood of observing the object at only one unfavorable aspect.

For each sonar image generated during the mission, a target-detection algorithm [13] is applied, resulting in a set of contacts. The contacts from all images in the mission are then pooled. For each contact, a small set of features are also
extracted from a “mugshot” of the object extracted from the wider sonar image scene. These features are then weighted statistically via a (pre-trained) relevance vector machine classifier [14] that produces, for each contact, its probability of being a mine. This probability – the “classification score” – is then used, along with the contact’s geographical position, to determine the AUV’s target-revisit survey.

Specifically, the contacts are reinspected based on their classification scores, with the most mine-like objects being reinspected first. If the classification score of a contact is sufficiently higher than those of subsequent contacts on the list, it can be reinspected multiple times (at different aspects) before the lower-scoring contacts are reinspected. Formally, the strategy is determined as follows. Let \( p_j \in [0,1] \) be the classification score of the \( j \)th of \( J \) contacts detected, and 
\[
    u_j = \frac{p_j}{\sum_{k=1}^{J} p_k}
\]
be the utility of reinspecting this contact once. It is deemed to be more beneficial to reinspect the \( j \)th contact \( i \) times before reinspecting the \( k \)th contact if 
\[
    u_j > (2i-1)u_k.
\]

The aspect at which each object is reinspected is determined as follows. Let \( \theta_0 \) be the aspect at which an object was imaged when it was initially detected. The desired aspect at which the object is to be imaged on its \( i \)th reinspection is defined as \( \theta_i = \theta_0 \pm 30^\circ / i \), where up to 4 revisits are allowed. (The maximum allowable deviation is set to 30°, rather than 90°, because the image quality would be poor from a survey perpendicular to currents.) Next, the range at which the object is to be reinspected is selected based on the image-quality success history [15], namely, where across the sonar swath the image-quality had been most-consistently good during the survey. (This “sweet spot” is typically near the middle of the swath.)

This reinspection strategy means that more resources will be devoted to the most suspicious objects. And by permitting multiple reinspections of certain objects, the AUV will return with very detailed composite pictures of those objects, greatly aiding subsequent identification endeavors. The target-reinspection phase of the AUV survey proceeds until a pre-specified (maximum) number of total object reinspections has been completed.

IV. EXPERIMENTAL RESULTS AT SEA

A. Sea Trial

In May 2015, CMRE conducted the North Sea MCM Experiment (NSMEX’15) from the NATO Research Vessel Alliance in the North Sea. More specifically, the trial took place off the coast of Ostend, Belgium. This area is characterized by a sandy seabed with large sand ripple dunes and significant water currents up to about 2 knots (about 1 m/s). The water depth is about 30 m. Additionally, the area contains several other interesting features that make mine-hunting challenging, such as large rocks, man-made objects, and trawl marks. At the beginning of the trial, several man-made targets were also deployed on the seabed in this area.

B. MUSCLE AUV

As part of this larger sea trial, several adaptive survey missions were executed by the CMRE-owned MUSCLE AUV. This experimental, state-of-the-art AUV is a 21-inch diameter vehicle from Bluefin that is equipped with a SAS system developed by Thales; it is shown in Fig. 2. The center frequency of the SAS is 300 kHz, and the bandwidth is 60 kHz. The system enables the formation of high-resolution sonar imagery with a theoretical along-track resolution of 2.5 cm, and a theoretical across-track resolution of 1.25 cm, typically out to a range of 150 m. The standard speed setting of the AUV is 3 knots.

![Fig. 2. The SAS-equipped MUSCLE AUV (in mid-recovery).](image)

The AUV has two processing units, a GPU and a CPU. The GPU is devoted to the onboard processing of raw sonar ping returns into SAS images. The SAS imagery is then used as input to the algorithms for image-quality assessment, target and ripple detection, feature extraction, and object classification, and in turn, AUV survey route adaptation. These algorithms were originally implemented in Matlab® [16] and then modified slightly in order to run in Octave [17] on the CPU of the AUV in real-time. It is the ability to execute all of these algorithms onboard the AUV that makes possible the immediate adaptation of the survey route based on the through-the-sonar data collected in situ.

A MOOS interface [18] is used to handle communication of commands from the CPU to the AUV’s low-level controller. Since the AUV is not the focus of this work, we intentionally avoid giving more detailed information regarding its specifications here.

Several successful adaptive MCM survey missions were conducted with the MUSCLE AUV during the NSMEX’15 sea trial. Due to space constraints, we present and analyze the results from only one representative autonomous mission.

C. Preliminaries

In each mission, the objective was to collect the most useful SAS data to inform the detection and classification of targets within a specified geographical area. (Targets detected outside the delineated mission area were to be ignored.) The only information given to the AUV prior to each mission was
the coordinates of the desired area to survey, the maximum number of target-revisits to execute, and the final recovery location to proceed to when the mission was complete. The AUV autonomously decides its route in two sequential phases by (i) adapting its survey heading based on the presence of currents detected, and (ii) adapting its survey route to reinspect the most suspicious objects at additional aspects.

It should be noted that the side-looking geometry of the sensor means that sonar data is collected not directly under the AUV, but rather at a stand-off distance away from the AUV (specifically, over swaths 40 m to 150 m away from the survey path, in both port and starboard directions). The AUV tracks consistently extend beyond the mission area because each track requires “lead-in” and “lead-out” segments for vehicle stability purposes. (The quality of the sonar data in these segments is insufficient for successful SAS processing.) Additionally, the length of each target-revisit track was fixed at 200 m as an extremely conservative guard against potential vehicle navigation errors (in the along-track direction) and stability issues.

For the experiment, all orientations are defined by the convention that $0^\circ$ points in the east direction, with orientation increasing counterclockwise.

D. Supplemental Animation

A supplemental multimedia file, submitted with this manuscript, shows an animation of the AUV survey route during the mission. In this animation, the moving circle is the geographical position of the AUV as a function of time, so the trail it leaves in its wake is the survey route history. The color of the trail fades in time (from dark blue to light blue) to improve visualization of the most recent survey positions (especially valuable toward the end of the mission). The green triangles marking detected targets appear in the animation when the AUV has finished the computation for determining the adaptive target-revisit survey route. The time-stamp (from the AUV’s clock) is also shown in the animation.

At this time, the reader is invited to watch the animation, as it will inform the remainder of this section’s discussion. In lieu of the animation, the reader can also refer to Fig. 3, which (statically) shows the mission area and the complete survey route that the AUV traveled.

E. Survey Explanation

A description and explanation of the AUV survey shown in the supplemental animation and Fig. 3 is provided here.

The mission area was a $450 \text{ m} \times 400 \text{ m}$ rectangular box rotated at an angle of $315^\circ$. The initial deployment and final recovery locations were both in the vicinity of the southern corner of the mission area. The AUV was programmed to fly at a constant altitude of 10 m above the seafloor. The mission was to obtain quality sonar coverage over the entire mission area, and then conduct 5 target-revisits. The experiment,
which took place on 27 May 2015, began at 6:20 and ended at 8:37.\textsuperscript{1}

The survey began with a series of parallel tracks oriented at 135° (and 315°), with the spacing (i.e., offset) between tracks determined dynamically based on the image quality of the collected data. During these preliminary tracks, currents were detected in the mission area via the onboard ADCP sensor; the current was computed to be at an orientation of 22.3° at a magnitude of 0.399 m/s. Reacting to this information, the AUV adapted its survey heading to collect data at a more preferable orientation, namely by executing a series of tracks parallel to the current, at 22.3° and 202.3°. After complete coverage of the mission area was obtained, the AUV executed a loitering circle in the middle of the mission area; this pause provided the AUV with additional processing time for developing the target-revisit survey plan. Then the AUV entered the target-revisit phase of its mission, conducting a set of tracks such that additional views would be obtained for the most suspicious objects detected in the SAS imagery collected in the previous phases.

\textbf{F. Current Adaptation}

The impact of the currents on the SAS data collected by the AUV can be observed in Fig. 4. While collecting sonar data that was processed into the 22 (poor-quality) SAS images shown in Fig. 4(a), the AUV was traveling nearly perpendicular to the currents. As a result, the currents were causing the AUV to crab as it attempted to maintain its desired track. The jagged nature of the (port and starboard) pairs of SAS images along the track reveals this. In contrast, while collecting data that was processed into the 20 SAS images shown in Fig. 4(b), the AUV was traveling nearly parallel to the currents. This anecdotal evidence illustrates one of the effects of currents on the data-collection process, and highlights the need to account for currents.

Reliable independent ground truth of the currents in the water column is unavailable, but the results from Fig. 4 suggest the onboard ADCP measurements were accurate. As additional corroboration that the onboard current estimates were reasonable, one can examine the forecasts of the currents for the mission area. (However, it should be noted that the forecasts are for surface currents, while the AUV experiences currents in the water column more than 20 m in depth.) The surface currents forecast near the operational area during the experiment [19] are shown in Table I. The general headings and magnitudes from the forecast seem to comport with the onboard measurements.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
\textbf{Time (AUV Clock)} & \textbf{Magnitude (m/s)} & \textbf{Heading} \\
\hline
6:00 & 0.28 & 8° \\
7:00 & 0.47 & 23° \\
8:00 & 0.60 & 31° \\
9:00 & 0.59 & 38° \\
\hline
\end{tabular}
\caption{Forecast of surface currents during the experiment}
\end{table}

More quantitative evidence regarding the impact of the currents on sonar data collection can be obtained by examining the correlation of consecutive sonar signal returns during the AUV tracks. This so-called ping-to-ping correlation has been shown to be a useful surrogate measure of SAS image quality, with good-quality imagery characterized by values above 2/3 [20]. Fig. 5 shows the distribution of ping-to-ping correlation values as a function of range for images collected during the first two tracks of the survey when the AUV was traveling nearly perpendicular to the currents, and during the six full tracks after adapting the survey orientation to be parallel to the currents. As can be seen from the figure, the ping-to-ping correlation values – and hence the SAS image quality – are higher when traveling parallel to the current,

\textsuperscript{1}These times are according to the AUV’s clock, which lagged local time by 2 hours during the experiment.
Fig. 5. Distribution of ping-to-ping correlation values as a function of range from SAS data collected during (a) tracks nearly perpendicular to the current, and (b) tracks nearly parallel to the current.

meaning the mission area covered by quality sonar data is larger. This result reinforces the justification for adapting AUV surveys based on currents.

G. Target Revisit

By reinspecting suspicious objects detected in the SAS imagery during the initial survey, the overall mission timeline can be greatly compressed. During the experiment, the AUV adapted its survey route to obtain additional views (at new aspects) of objects of interest. The objects for which revisits were executed had been detected in the SAS imagery by the detection algorithm running in (delayed) real-time onboard the AUV.

With multiple views of the objects, target identification – performed either by trained human operators or by automatic target recognition algorithms – should be more reliable. One representative example of multiple views of an object obtained during the experiment via the revisit behavior is shown in Fig. 6. In the figures, interesting target features are visible in the second view that were absent in the first view. In general, the multiple views provide a more complete tactical picture of the object. Having these additional clues available would likely improve the confidence in target identification.

V. DISCUSSION

The experimental results from adaptive, autonomous surveys at sea demonstrated that the proposed methods were successful in collecting more useful data for target detection and classification objectives. It should be noted that collecting the same amount of high-quality data in a non-adaptive approach would take, at a minimum, many hours longer. Such a plan would first require AUV recovery, followed by data downloading, processing, and analysis. Only then could it be established whether there was even something of interest in the mission area to be reexamined. But then a new survey plan would need to be prepared for the AUV so that it could collect additional data (such as at a different aspect) over the region or object of interest, the AUV would need to be redeployed, and a whole new survey would need to be executed. The time it would take before the comprehensive set of data was available for examination would be significant. In our proposed framework, by contrast, the AUV returns with the most useful data after a single deployment. Future work will seek to provide quantitative performance comparisons – in terms of various metrics, including overall mission time and target classification success – between the adaptive approach and purely preplanned strategies.

This work was an initial proof-of-concept to experimentally demonstrate adaptive MCM missions with an AUV at...
Constraints imposed by the vehicle control software – e.g., when an adaptive behavior can be triggered – have limited the flexibility of the proposed approach. It is desirable to allow a more fluid transition between survey phases, rather than forcing the phases to be executed sequentially. For example, it might make more sense in certain missions to immediately reinspect each suspicious object as soon as it is detected, rather than first obtaining complete mission-area coverage. Furthermore, currents may change substantially during long missions, so modifications to address changing current conditions are also needed. Future work will be devoted to developing a more flexible autonomy architecture. More comprehensive strategies for handling extremely strong currents – e.g., when the magnitude of the current exceeds the AUV’s maximum speed – should also be developed to improve robustness.

More theoretical studies can be conducted on the target-revisit strategy. In particular, how to determine the best aspects (and ranges and AUV altitudes) at which to collect additional views of an object is an open question. The approach followed in this work is reasonable – seek aspect diversity while selecting a range that ensures good image quality – but alternatives exist. For example, it is possible to estimate the orientation of a detected object, so is imaging the object at broadside more useful than collecting looks with aspect diversity? Additionally, it is likely that the optimal revisit aspect should also be a function of the predicted target type [21]. The conclusions, in any case, will mainly depend on the manner in which the information from multiple views is to be exploited.

VI. CONCLUSION

A comprehensive approach for conducting autonomous MCM missions with a sonar-equipped AUV was outlined and demonstrated successfully via real experiments at sea. This proof-of-concept incorporated two forms of adaptivity that instilled the AUV with the flexibility to react \textit{in situ} to the through-the-sensor data it collected. As such, we believe it represents one of the most extensive demonstrations of autonomous, in-mission SAS-data exploitation onboard an AUV to date. The algorithms executed onboard allowed the AUV to (i) adapt its survey heading based on the presence of currents and (ii) adapt its survey route to reinspect the most suspicious objects at additional aspects. These strategies should prove useful for reducing survey mission times while simultaneously allowing the collection of the most useful data for performing object detection and classification tasks. Several directions for future work have been noted and will be pursued. More extensive additional experimentation at sea will also be conducted in the near future.

REFERENCES