INCREASING NAVIGATION EFFECTIVENESS IN GPS DENIED ENVIRONMENTS USING THROUGH-THE-SENSOR SAS TECHNIQUES

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1 INTRODUCTION

One of the common applications of unmanned underwater vehicles (UUVs) is to search for naval mines. In this application, the effectiveness of the platform is directly dependent on its navigation accuracy. Naval Mine Countermeasures (MCM) is defined around a set of phases including detection, classification, identification and neutralisation. When MCM is conducted using unmanned systems, these phases are typically executed by multiple, heterogeneous platforms. During the detection phase, errors in navigation will be reflected in the positioning of detected objects. This localisation error could result in the need for higher effort in reacquiring the detected object, effectively searching the area again, or never reacquiring the object. Therefore, accurate navigation is key, specifically in challenging seafloor environments where multiple mine-like objects may exist. Furthermore, an MCM mission requires the planning of a mission pattern which will achieve a minimum probability of detecting the target. When the variance on the navigation error is unbounded, the required performance may not be possible or only achievable with a considerable sensor overlap, resulting in increased mission time and resource usage.

Underwater navigation is challenging due to the medium in which the vehicle operates. While terrestrial and aerial unmanned systems can benefit from global satellite positioning systems such as DGPS for navigation corrections, this capability is not available underwater. In the underwater domain, positioning is typically provided by either simple dead reckoning [1], acoustic means, such as short-baseline (SBL) or long-baseline localisation (LBL) [2], and/or through the use of Inertial Navigation Systems (INS) [3].

Dead reckoning approaches use a measurement of distance traveled and heading. These measurements are integrated based on a known start position, resulting in a position and pose estimate. This approach is used in low-cost UUV applications, and can be combined with velocity sensors such as a Doppler Velocity Log (DVL) and/or inertial sensors to increase accuracy. Furthermore, operational techniques such as GPS surfacing at the beginning and end of each search leg are used to minimise the error. Although dead reckoning is a simple and low cost solution, without some other method of error correction the accumulation of errors in the solution can continue without bound, and therefore is not applicable to underwater search where a high level of precision is required .

Acoustic means such as LBL and SBL require the placement of additional infrastructure to allow a positioning update to be calculated. This typically takes the form of a set of deployed buoys equipped with either a fixed position or a GPS which can provide positioning updates through transmission and reception of acoustic pulses. This infrastructure requirement constrains the utility of the acoustic methods. For large or potentially dangerous areas, it may not be feasible to deploy a series of transponders for navigation.

INS provides a method for underwater navigation which does not require the placement of external assets such as bouys. INSs are devices in which a pose and position estimate is developed and maintained through the integration of measurements from accelerometers and heading sensors. These systems can further be aided through external sensors such as DGPS and DVLs when available. Although INS based positioning systems can provide an improvement in positioning accuracy, these systems still suffer from measurement error, composed of both drift and bias [3]. The result in the accumulation of this error is a potentially unbounded growth of positioning uncertainty.

One technique for navigation which has gained widespread use is through-the-sensor (TTS) approaches. In these approaches, the vehicle will employ sensors to gather a set of features which can be used to localise the vehicle. Two of the most common and related techniques are Terrain Based Navigation (TBN) [4] and Simultaneous Localisation and Mapping (SLAM) [5]. While these techniques have been shown to be effective for navigation, they are dependent on a sufficient set of seafloor features to develop a positioning estimate. Recent work in exploiting SAS processing has shown potential in providing navigation corrections in benign environments where traditional feature extraction based methods may be ineffective [6] [7]. These techniques leverage the micronavigation methods used for SAS beamforming, deriving a set of motion estimates which can be applied to the navigation estimate.

In this work, we show the potential improvement in navigation which can be gained through the exploitation of SAS micronavigation and repeat pass processing. We will examine these techniques over a typical MCM mission, and consider fusion of micronavigation and repeat pass navigation estimates to further decrease the positioning uncertainty. From an MCM perspective, this increased navigation accuracy can result in increased object positioning accuracy, increasing the probability of reacquisition, and a higher achievable MCM performance.

2 THROUGH-THE-SENSOR NAVIGATION USING SAS

TTS navigation is a set of data-driven techniques which leverage the vehicle sensors, such as a Side Scan Sonar (SSS) or SAS to sense the environment and select unique features such as underwater landmarks or bathymetry features in order to compare with apriori information to allow localisation of the vehicle. The most common of these techniques is SLAM [5], which is dependent on the selection of a series of features from the seafloor, which can later be re-sighted and used for correction of any accumulated error in the positioning system. TBN [8] is a related method to SLAM, however the initial map or seafloor feature set is provided to the robot apriori, allowing for sensed data to be directly compared to pre-existing knowledge. While both methods have been applied successfully to underwater navigation [4] [5], they are dependent on a set of seafloor features which provide sufficient fidelity for correlation. For many seafloor areas, a sufficient feature set may not exist for correlation with an apriori map, therefore the algorithm loses its effectiveness on benign, featureless environments.

The following subsections will introduce two SAS based techniques, micronavigation aiding and repeat-pass aiding, and consider the application of these techniques to limit the drift error in the INS.

2.1 Micronavigation Aiding

SAS beamforming is a technique for coherently integrating the collected signals along a synthetic aperture, which is formed as the sonar is moved in the direction of travel of the host platform [9]. SAS provides advantages over real aperture SSS by providing high-resolution seafloor images that are independent of both range and frequency [10]. One of the challenges of SAS is the requirement for sub-wavelength navigation precision in order to correct for any platform motion during the collection of the acoustic data. Failure to compensate for the platform motion will result in a defocused image or images containing artifacts from improperly aligned samples. While the ping to ping displacement can be approximated using the vehicle INS, the level of accuracy and resolution is not sufficient for focusing an image. To allow for the focusing of SAS images, data-driven methods such as Redundant Phase Centre (RPC) micronavigation [11] are applied to the recorded signals to estimate the displacement of the vehicle between pings. In order to determine corrections in sway and surge, which correspond to across track and along track motion respectively, RPC micronavigation forms an array from cross correlating signals between RPC arrays, which consists of the overlapping portion of the sonar array during subsequent pings.

While this technique has proven effective at forming a focused SAS image, these corrections can also be applied to navigation motion estimation for surge and sway, where surge corresponds to the forward component and sway refers to the lateral component of the motion vector [6]. These estimates offer higher resolution motion estimation than is available from an INS, while minimising two of the primary error sources from a DVL aided INS system, the velocity measurement noise and scale factor error. As shown in [6], when compared to a DVL, the SAS motion estimation for surge is not dependent on environmental factors such as the speed of sound, as the velocity is calculated by comparing the displacement along the array with the pulse repetition interval. While the SAS based motion estimation provides a considerable decrease in accumulated error (Table 1), these errors are not eliminated, and are dependent on the construction of the array and calibration of the system.

2.2 Repeat-Pass Aiding

In many TTS approaches for navigation such as SLAM or TBN, a re-sighting of a previously sensed area is required to correct the navigation estimates. As noted previously, this is dependent on a set of sensed features which provide sufficient fidelity to identify a patch of seafloor. One challenge with these methods is the requirement for these unique features. In benign environments, these features may not exist, therefore limiting the utility of these algorithms. SAS processing allows two passes to be compared coherently, providing a higher level of precision as compared to incoherent, image based methods such as SLAM. One method for coherent measurement between two passes, repeat-pass RPC [12], has shown potential for using resighting of a previously viewed area of the seafloor and applying RPC across the two sets of collected data to correct the navigation. This method allows for a technique analogous to SLAM, while not requiring a minimum set of features or landmarks in the data.

Repeat pass aiding for navigation is a processing technique which leverages RPC micronavigation across two independent passes over an area, effectively processing both passes together, rather than between pings as in SAS beamforming. Repeat-pass RPC micronavigation [12] is a generalisation of RPC micronavigation [11]. In addition to permitting sub-wavelength co-registration of SAS data for interferometry over repeated passes, it provides a means of precisely estimating relative position errors [13]. To enable repeat-pass aiding for navigation, repeat-pass RPC micro-navigation is performed at every opportunity to estimate and correct the measurable drift that has accumulated since the previous pass (i.e., at overlapping ends of the modified paired-track pattern) [7]. Although some measurement errors will be introduced during this procedure, we assume sufficient phase coherence such that the errors are sub-wavelength and therefore orders of magnitude smaller than the expected drift errors. Each RPC correction is modeled by resetting the position estimate to the value estimated in the previous pass. The correction is then back-propagated by time-reversing the accumulation of velocity measurements from the updated estimate.

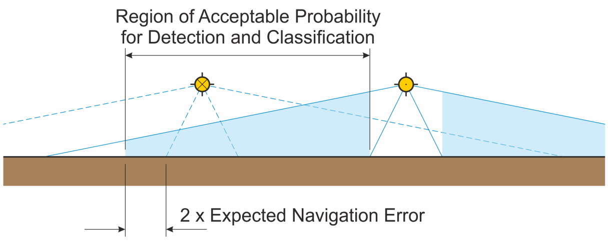
While this method has been shown to have potential in decreasing the overall global navigation error, it will still accumulate error in the navigation, however at a considerably lower rate than the DVL Aided INS system. One primary constraint demonstrated in [7] is the dependency on sway to ensure successful repeat pass correlation. This places a constraint on the track length of the mission, as the accumulated error when traveling along the track must be sufficiently low to allow for the repeat pass micronavigation. With the application of micronavigation aiding described previously, this accumulated error can be minimized, therefore increasing the likelihood that a successful repeat pass motion estimate can be made.

3 MODIFIED PAIRED TRACK OPERATIONAL CONCEPT

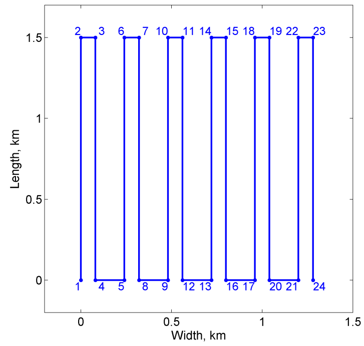
Detection and classification of underwater objects requires a consistent coverage of the seafloor which provides a sufficient probability of detecting the object being searched for. This probability of detection is composed of not only sensor factors such as signal to noise ratio and resolution, but also the development of a mission plan for the search area such that there are no gaps where sensor coverage is required. These gaps can result from the sensor footprint, but also the navigation of the vehicle. MCM mission planning must take into account both the sensor and the vehicle characteristics to ensure the required coverage.

For MCM missions, search patterns and mission planning techniques have been developed for traditional ship-based platforms. These planning techniques take into account not only the footprint and expected performance of the sensor, but also the expected variance on the navigation error for the ship. Due to navigation aids such as GPS, this variance can be relatively static, allowing for the development of a track plan which contains sufficient overlap to ensure coverage which satisfies the required probability of detection. UUVs, however, pose challenges to MCM mission planning. From a navigation perspective, the variance on navigation error is dynamic, varying with both the length and style of the search mission. This requires consideration of the track placement to ensure sufficient sensor coverage. Furthermore, if reacquisition of a target is required, the navigation error of both the detection and reacquisition assets must be considered to ensure a re-localisation of the target. Clearly, consideration of the navigation error is key for effective sensor coverage and to provide valid position estimates resulting from the search.

Recent work in MCM has considered mission planning techniques to enable the application of mod-



(a)



(b)

Figure 1: A paired-track survey pattern ensures that the swaths of track pairs cover the nadir gaps of one another, as illustrated in (a). The resulting mission pattern is shown in (b) with track offsets based on sensor footprint and expected navigation error.

ern robotic platforms in MCM. One of the techniques applied is paired-track planning, which includes the sensor footprint in planning the required seafloor coverage. The following subsections will examine paired-track planning, and introduce a modified paired-track planning technique to enable opportunities for repeat-pass corrections, while having a minimal impact on mission time. The RPC micronavigation and repeat-pass methods will be applied to this mission pattern to examine the potential increases in navigation estimates.

3.1 Paired-Track Pattern

The effective sensor footprint is also an additional challenge for mission planning. Many modern UUV based platforms use side looking sonars, such as SSS or SAS systems. This method of underwater imaging results in an area directly under the sonar, the nadir, where the sensor performance is low. In order to ensure this high quality coverage, either a gap-filling sensor or a specific mission pattern is required. In this work, it is assumed that a gap filling sensor is not used, and therefore techniques for mission planning which ensure coverage of the nadir must be employed.

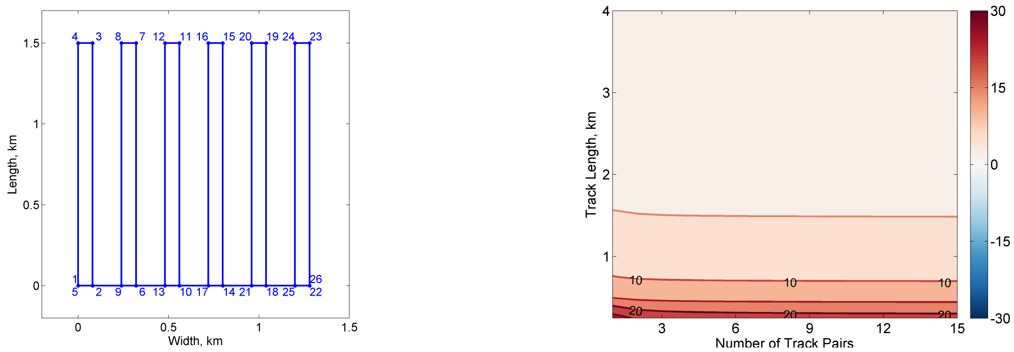
To allow for consistent imaging of the seafloor during a search, a method of planning missions named paired-track planning is used for platforms equipped with side looking sensors. Paired-track planning is based on the combination of two tracks, where one is offset such that the sensor footprint from one track is effectively covering the nadir of the other track. Figure 1(a) illustrates the concept of paired track planning.

This results in a mission style where the mission is split into a series of paired tracks, allowing full coverage of the seafloor with sufficient performance for the search task. Figure 1(b) illustrates a search mission based on paired tracks.

3.2 Modified Paired-Track Pattern

To allow for the application of methods such as repeat-pass or SLAM to limit navigation drift, there must be an opportunity to revisit previously sensed areas. The paired track pattern as illustrated previously does not provide any revisit opportunity with sufficient sensor footprint to allow for effective determination of navigation drift. In order to employ a method where some overlap in the imaging is required, a small modification to paired-track planning allows for a *loopback*, or a revisit to a previously imaged area.

Through a reordering of the waypoint order, overlap opportunities exist between the tracks at the end of the each track pair, providing opportunities for data-driven navigation correction with a minimal increase in mission time. As mission tracks are typically considerably longer than the turning duration, the increase is dependent on the offset between the paired tracks, where two times the offset distance is



(a) (b)

Figure 2: A modified paired-track survey pattern provides opportunities at each track pair to revisit a previously imaged area, as illustrated in (a). The resulting increase in mission time based on track length and number of track pairs is illustrated (b) showing minimal increase over legs beyond 1km.

added to each leg. This relationship is illustrated in Figure 2(b), which was developed for a 150m single side sonar range, a 40m nadir, and 5m navigation error. This plot shows a relative increase in distance traveled for short legs, however this relative distance decreases rapidly as the leg length increases.

4 EXPERIMENTAL RESULTS

As noted previously, both micronavigation and repeat pass techniques leverage the processing which is required to focus the SAS image. Although both have shown potential independently, this work seeks to examine the potential for a combination of methods to increase vehicle positioning and navigation. In this concept, the micronavigation based technique will be applied continuously during the tracks, then combined with the repeat pass corrections at the completion of the track, allowing a second correction step for each track pair. As noted in [12], repeat pass based navigation corrections are sensitive to sway between patterns, therefore limiting the possible track length. Through the incorporation of along-track micronavigation techniques, the goal is the lower the accumulated error, and therefore potentially increasing the likelihood for a successful repeat pass navigation correction.

In order to explore the potential gains in applying both TTS techniques, the repeat-pass navigation model used in previous work [7] was augmented to also include micronavigation aiding described in [6] for the along track segments. This model is based on a Monte-Carlo simulation which was validated with experimental data [7] . As demonstrated in [6], the application of SAS micronavigation provides a significant improvement on the noise and scale factors present in traditional DVL velocity measurements. The parameters for the repeated pass simulation are provided in Table 1.

As seen in Table 1, when micronavigation velocity estimates are used rather than DVL velocity estimates, both the measurement noise and scale factor are reduced. For a DVL such as the one illustrated in Table 1, two of the primary sources of scale factor error are the estimate of the speed of sound and beam misalignment [15]. Using a micronavigation technique, the surge measurement is independent of the speed of sound. In the case of the SAS scale factor errors, the precision in the machining of the array length is a contributor, which is assumed to be a constant scale factor error of approximately 0.1mm for a 1m array, resulting in a scale factor of 0.01%. Of note, as this error is due to the construction of the array, it does not vary with time. Additional contributions in the scale factor error include the slight variations in the receiver oscillator frequency, which would induce error, however oscillators with accuracy to within 0.001% are available, therefore it is not providing significant influence to the overall scale factor error.

Another source of scale factor error for SAS micronavigation is the effect of terrain slope. Fundamentally, the surge measurement from ping-to-ping correlation is in a plane aligned with the seabed slope rather than either a body fixed or locally level navigation frame. However, seabed slope can be estimated and corrected using an interferometric SAS array with the technique described in [16]. Therefore, SAS micronavigation error due to terrain slope is not modelled in Table 1.

	Standard Deviation		Time Constant	
DVL Velocity				
Measurement Noise	$\sigma_{v,\text{noise}}$	5 mm/s	-	-
Bias Error	$\sigma_{v,\text{bias}}$	1 mm/s	$\tau_{v,\text{bias}}$	30 min
Scale Factor	σ_S	0.2 %	τ_S	30 min
Micronavigation Velocity				
Measurement Noise	$\sigma_{v,\text{noise}}$	0.5 mm/s	-	-
Bias Error	$\sigma_{v,\text{bias}}$	1 mm/s	$\tau_{v,\text{bias}}$	30 min
Scale Factor	σ_S	0.01 %	τ_S	30 min
Gyro Heading				
Bias Error	σ_θ	$\frac{0.02}{\cos\phi}$ deg	τ_θ	60 min

Table 1: Parameters used for the navigation error modelling. Standard deviation values for the DVL are taken from the Teledyne RDI-600 datasheet [14]; Micronavigation velocities are from [6]; a typical standard deviation for the gyro-compass heading bias error and typical time constants are from [3].

For measurement noise, SAS processing produces sway measurement noise of roughly two orders of magnitude lower than a DVL operating at a similar frequency [6]. The SAS surge measurement is noisier than sway because for sway, the phase of the ping-to-ping correlation coefficient provides a precise measurement of across track displacement, whereas surge is estimated solely from the magnitude of the correlation coefficient and its peak location along the receiver array. The measurement noise in Table 1 represents surge error and is estimated from the variation in measurements for independent range windows for two 300 kHz SAS systems (the CMRE MUSCLE SAS and Kraken's AquaPix SAS). Future work is planned to derive a theoretical expression for surge variance analogous to [11] with validation from numerical simulation and experimental data.

For the purposes of this study, both paired track and modified paired track patterns were employed, however the paired track patterns do not provide an opportunity for repeated passes, therefore only the micronavigation and unaided results will be presented for traditional paired tracks. Figure 3 illustrates the results of 10,000 Monte-Carlo simulations for navigation error. Figure 3 (a) and (b) are based on a paired-track as illustrated in Figure 1 (b), and (c) and (d) use the modified paired-track pattern from Figure 2(a). In plots (a) and (c), DVL velocity parameters from Table 1 are used, however (b) and (d) use the micronavigation velocity parameters.

4.1 Discussion

As can be seen in Figure 3(a), without an aiding mechanism such as micronavigation estimates or a correction mechanism such as the repeat pass correction, the error will grow without bound, resulting in an inability to reacquire detected objects on the seafloor. When considered independently, the micronavigation aiding mechanism provides a considerable improvement in the overall navigation uncertainty, and limits the rate of drift for the navigation solution as shown in Figure 3(b). Repeat-Pass corrections provide an opportunity to correct the navigation at the end of a track pair, resulting in drops in the error magnitude when the correction is made. The result of this can be seen in Figure 3(c). While this correction decreases the accumulation of error over the mission, the along track error that is accumulated between repeat-pass corrections can result in an inability to complete the correction. The combination of these two methods results in a considerable decrease in overall navigation uncertainty. Figure 3(d) demonstrates the modelled results over a $20km$ mission, demonstrating not only the impact of the repeat pass corrections, but also the lower accumulation of drift during the execution of the mission track pairs between corrections. While this improvement shows the potential of the methods, both still suffer from the accumulation of error, albeit at a lower rate than a traditional DVL-aided INS. While this plot clearly shows that the error will still accumulate over time, the overall magnitude of the error is substantially decreased, as well as the rate at which error is accumulated during the straight tracks. This can provide a coarse estimate of the worst case positioning variance for the mission.

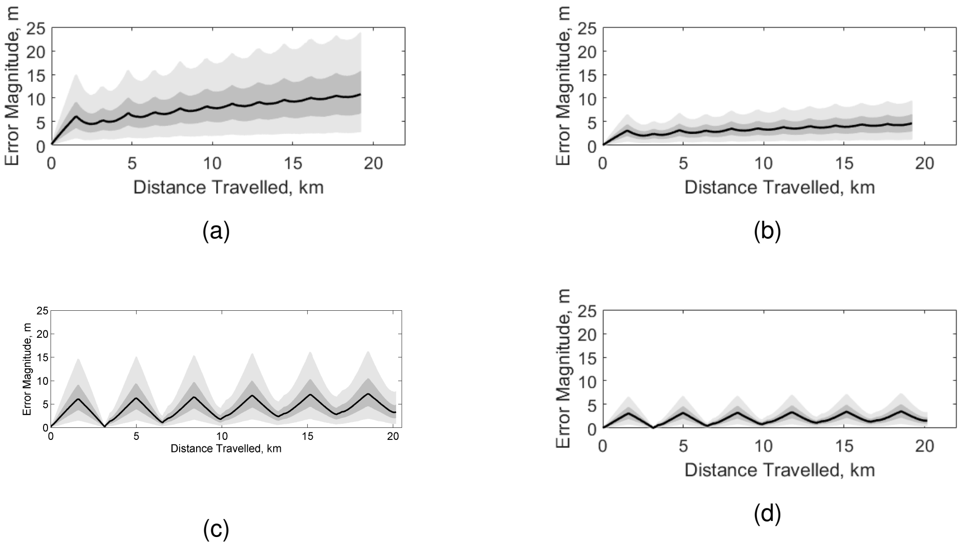


Figure 3: Navigation errors from 10,000 Monte-Carlo simulations for: (a) a paired-track pattern with six pairs and no corrections (total distance is $19\ \mathrm{km}$); (b) a paired-track pattern with micronavigation corrections ($19\ \mathrm{km}$); (c) A modified paired-track pattern using repeat-pass corrections (total distance is $19\,\mathrm{km}$); and (d) A modified paired-track pattern using micronavigation aiding and repeat pass corrections ($20\ \mathrm{km}$)

5 CONCLUSION

The proposed method aims to leverage SAS processing in order to constrain the drift and accumulated errors in current DVL-aided INS applications. Errors in DVL-aided INS systems can grow without bound, therefore resulting in an inability to properly navigate and localize objects on the seafloor. In this work, we aim to combine repeat pass and micronavigation techniques, allowing for along track measurements during the mission legs, and Repeat-Pass aiding during the turning between tracks. Repeat-Pass aiding suffers from sensitivity in sway when correlating the two images, which provides a limitation on the length of the mission tracks. One of the primary goals in combining the techniques is to increase the along-track motion estimates, as well as minimizing the accumulated error to increase the likelihood of a successful Repeat-Pass correction. In order to provide opportunities for repeat-pass corrections a modified paired track plan was proposed, providing an opportunity to revisit a previously covered area to apply TTS methods for navigation correction. This technique allows for the accumulated drift and bias to be corrected at the conclusion of each track pair. With the limitations of both methods considered, we proposed an operational concept which could employ both of these methods to minimize the accumulated error, and increase the likelihood of successful Repeat-Pass corrections. This concept was demonstrated using a Monte-Carlo model which was previously validated using at-sea data from the MANEX ’14 experiment.

While the method proposed in this work shows improvements in the overall navigation accuracy, the use of SAS processing still contains scale factor errors and measurement noise, which will accumulate over the mission, degrading the navigation estimate. These potential errors include array construction precision, oscillator precision and array alignment. Furthermore, in repeat pass processing, the likelihood of a correlation and therefore navigation correction is dependent on the accumulation of error since the last update. If the error has grown significantly over the track pair, it is possible that a repeat pass correction cannot be completed.

Future work is focused on the validation of this operational concept in an at-sea experiment using a SAS equipped UUV. Initial experimentation will validate the concept, and also consider the real-time implementation of the methods. Furthermore, more consideration must be given to alignment of the SAS systems, as well as navigation accuracy for long transit routes.

For MCM, accurate navigation and positioning is key to ensuring that detected objects can be reacquired and identified with a high probability and in a timely manner. Failure to understand the navigation error can result in either waste in resources or the potential for sensor gaps. In consideration of accurate underwater navigation, the proposed method leverages two techniques from SAS processing to address the challenges provided by unbounded accumulation of drift. Long transits still provide a challenge, but methods such as those described here in combination with other techniques can help to minimize navigation drift and allow for more accurate search through exploiting the SAS.

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