ADVANTAGES OF AUTOMATIC TARGET RECOGNITION MULTI-VEHICLE SYNERGY IN UNDERWATER ENVIRONMENTS WITH LIMITED COMMUNICATION

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Automatic Target Recognition (ATR) is a technology that allows Unmanned Underwater Vehicles (UUVs) to identify, classify, and take actions on specific targets without human intervention. In large areas of operation, single vehicle missions are slow and subject to mission failure if there are any issues with the UUV. To combat this, UUVs equipped with ATR capabilities can be deployed in swarms to achieve tasks with increased efficiency, redundancy, and resilience. However, the introduction of multiple UUVs simultaneously stress the mission due to the limitations of the environment. UUVs tend to suffer from low fidelity data, unreliable acoustic communications, and limited communications bandwidth. The introduction of multiple UUVs in a mission greatly exasperate these issues. We will be discussing how the limitations of underwater environments affect the performance of multi vehicle UUV mission, and we will propose a joint ATR and autonomy solution that limits the impact of underwater conditions on multi-vehicle UUV missions. The ATR solution leverages both low fidelity sonar images and high-fidelity camera images to make detections of various confidences that can be updated by any UUV. The autonomy solution leverages template behaviors to allow each vehicle to safely operate by simulating the behavior of other UUVs. These template behaviors reduce the growth of navigational uncertainty for other vehicles to provide better mission performance.

INTRODUCTION

Problems with Multiple UUVs Mission

The implementation of multiple underwater unmanned vehicles (UUVs) for a single mission presents a myriad of challenges across various environments. These challenges encompass technical, logistical, and operational aspects, stemming from issues such as communication (mainly acoustic) and coordination between UUVs, resource allocation, mission planning complexity, environmental uncertainties, and the need for robust autonomous decision-making systems. Furthermore, integrating multiple UUVs into a cohesive operational framework demands addressing concerns regarding power management, sensor fusion, navigation accuracy, and collision avoidance. Despite the potential advantages of deploying multiple UUVs for enhanced mission capabilities, the practical realization of such endeavors remains hindered by the intricate interplay of these multifaceted challenges.

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Challenges in Underwater Communications

The nature of underwater acoustic communications is inherently fraught with challenges, making it a uniquely difficult, low-fidelity, and error-prone method of data transmission. These challenges arise from the physical properties of water and the way sound waves propagate through it (Reference 1). Unlike air, water is a denser fluid medium with vastly different sound propagation physics, which affects the speed, range, and fidelity of acoustic signals. Furthermore, the underwater environment is cluttered often not accurately mapped in real-time with various sources of propagation noise, such as marine life, underwater terrain, and human-made structures, that can reflect, absorb, or scatter sound waves, leading to signal degradation and loss.

The variability in water temperature, salinity, and pressure at different depths also impacts the sound speed profile, causing refraction of sound waves. This variability can lead to multi-path propagation, where signals reach the receiver at different times and angles, causing phase shifts and temporal spreading. The phenomenon significantly complicates signal interpretation, leading to delays, distortion, and decreased data rates. Additionally, the presence of background noise from natural sources like marine life and wave action and anthropogenic sources such as ship traffic and industrial activities further obscures the signal, increasing the error rate and reducing the reliability of data transmission.

Bandwidth limitations are another critical issue in underwater acoustic communications. The usable frequency range for underwater communications is much narrower than that in above surface communication systems, like radio waves, constraining the amount of data that can be transmitted over a given time period. Higher frequencies, while offering better bandwidth and hence higher data rates, are absorbed more quickly in water, limiting their range. Conversely, lower frequencies can travel longer distances but offer limited bandwidth, leading to lower data transmission rates. This trade-off between range and bandwidth necessitates a delicate balance, often resulting in compromises on data rates, fidelity, and error rates in underwater acoustic communications.

Neptune Autonomy Solution

Autonomous underwater vehicles (AUV), and more recently unmanned surface vehicles (USV), have grown in acceptance to the point where their relevance is unquestioned. The usage of AUVs in oceanography or mine-counter measures (MCM) applications is nowadays routine with dedicated teams trained to operate unmanned autonomous assets in day-to-day missions. The number of navies operating unmanned autonomous assets continues to increase, and unmanned maritime systems (UMS) are also starting to prove capable in other applications such as Anti-Submarine Warfare and intelligence gathering (Reference 2). Neptune autonomy software solution tackles these varying multi-vehicle UUV and provides a unified environment where collaborative and adaptive missions can be planned in an effective way. Notably, Neptune autonomy solution can efficiently manage the water space, handling dynamic mission objectives, asserting safety margins/collision avoidance between multi-vehicles, while empowering the operators.

Neptune provides efficient management of water space as a function of time, space, and energy by achieving the necessary shared objectives and avoid repeated objectives. The autonomy embedded software running on all the vehicles in the mission setups the most optimal route to accomplish a survey mission with input from the operator during the pre-mission stage. For example, an operator is aided setting up intelligent launch and recovery offsets during the pre-mission stage. The Neptune topside software during the upload process can automatically split vehicles in a squad to their respective launch and recovery (L&R) locations and set offsets. The L & R objectives are separated in depth and altitude following safe transit depth plane tolerances automatically

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determined by the software. The topside master mission file, which is disseminated to the all the vehicles before mission execution encodes all the vehicle safe transit planes, mission objectives, and respective vehicle surveys. All vehicles have a copy of the missions all the other vehicles are going to execute, in addition to their own.

Neptune can generate new dynamic objectives to be shared with the squad (i.e. re-tasking if a vehicle goes down) using only acoustic communication for information dissemination. Acoustic vehicle-to-vehicle (V2V) received messages include a vehicle's current objective and progress through the set of objectives. In order to avoid latencies in communication, the Neptune acoustic message schema does not require message acknowledgments instead each vehicle uses set timeslots to broadcast communication to vehicles within listening range. In addition, in the event a single vehicle has limited communication to the dry-side command and control (C2) station, but individual UUV communication is reliable. Vehicle message statuses can use the mesh network of vehicles to hop information to the topside C2 station. When communication is reliable between n number of nearby vehicles, the sub-squad of vehicles performs dynamic deconfliction of each other. The hive-mind knowledge of all the vehicles especially one's attempting to perform the same objective do the following: 1) Vehicle will not attempt to start an objective that it knows has been completed or is already being performed by another 2) When an acoustic message is received from another vehicle, current objectives are checked and ensured that the vehicles are not attempting to perform the same objective. Most importantly, algorithm logic focuses on vehicle safety is used to determine which of the vehicles should abort any superfluous objectives and which will continue.

Neptune most importantly empowers the operators to tailor mission for their squad and implement unique strategies based on preferred assets, and hierarchy to all assets in question. Once the mission is underway, the actual ordering of objectives is affected by generation of unplanned objectives (i.e. ATR hits), conflicting dynamic exclusion zones, time changes between GPS fixes, environmental anomalies, and unique behaviors for planned and unplanned objectives. Neptune hive-mind makes efficient use of all the vehicles in the squad by keeping them all busy performing mission objectives and when any vehicle is not engaged in an objective, Neptune searches for new objectives for them to perform (See Appendix 1 for more detail).

ADVANCED MULTI-MODAL ATR

Advancements in computer vision, machine learning and deep learning have evolved to a state where real-time detection and performance exceeds human abilities. SeeByte's approach to automatic target recognition in forward looking sonar (FLS) and electro-optical camera (EO) utilizes a convolutional neural network (CNN) and single-shot detector (SSD) backbone. SeeByte automatic target recognition (ATR) algorithm solution has been showcased in various underwater environments on various underwater vehicles using various combinations of camera and sonar fusion solutions.

SeeByte ATR system is a deep neutral network (DNN) framework that can rapidly evaluate multiple algorithms for a given application. These internal tools consist of open-source tools, custom built tools, as well as closed source tools from third parties. Many of the software solutions and processes were evaluated for this application, and a CNN with a backbone was selected after rigorous testing. The convergence of using a CNN with an SSD as SeeByte's chosen methodology provides the best balance between positive detections and inference time. Most notably, SeeByte ATR intended deployment is real-time on edge devices on underwater vehicles where it was optimized for minimal power consumption and controlled heat generation/dissipation. The SeeByte ATR solution model dataset development was generated by manually tagging footage stream, frame by frame, by subject-matter experts with great deliberation and trained-eye accuracy. This

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method resulted in a highly robust CNN that is vehicle agnostic, EO device agnostic, and viewing angle agnostic (with limits) that has been tested and verified to be able to detect an MLO target before an expert operator can.

Localization and Navigation Correction

The deployment of multiple underwater unmanned vehicles (UUVs) in a coordinated squad introduces a powerful dimension to enhancing localization and navigation correction capabilities far beyond the reach of single-vehicle operations. This collaborative approach leverages the strengths and capabilities of individual UUVs to achieve a synergistic effect, significantly improving the accuracy and reliability of underwater missions. For instance, when one UUV is equipped with advanced ATR capabilities, it can act as a beacon or reference point for other vehicles in the vicinity, facilitating a dynamic, real-time enhancement of navigational precision and spatial awareness among the fleet.

This collaborative framework operates on the principle of shared situational awareness. The ATR-equipped UUV can detect, identify, and relay information about underwater landmarks or objects of interest to its counterparts. The critical contact information, once shared, enables other UUVs to cross-reference their own positional data against the identified landmarks, allowing for immediate correction of navigational errors and drifts. Such an approach is particularly beneficial in GPS-denied environments, where traditional navigation systems are prone to cumulative errors over time.

The utilization of multiple UUVs in this manner enables the distribution of different sensing and processing tasks among vehicles, optimizing the use of available resources. For example, a UUV with enhanced ATR capabilities can focus on detailed object detection and identification, while others concentrate on mapping, environmental monitoring, or direct intervention tasks. Through inter-vehicle communication protocols, these UUVs can share critical data and updates, enabling the fleet to operate as a cohesive unit with enhanced spatial intelligence. This not only increases the operational efficiency and coverage area, but also significantly reduces the likelihood of navigational errors, as multiple data points and observations contribute to a more accurate and robust understanding of the underwater environment. Neptune autonomy solution is the ideal framework for solving these many challenges in an optimized, operator friendly, third-party compatible, and reliable/repeatable way.

Camera and Sonar Fusion ATR Single Vehicle Use-Case(s)

Recently SeeByte, Inc in collaboration of other ocean vendors have proved on-vehicle the capability of using SeeByte ATR for detection, localization, navigation, inspection, identification, and neutralization of mine-like objects (MLOs) on the seafloor, in the water column, and at the water surface. The project funded by Defense Innovation Unit (DIU) to develop and demonstrate an untethered prototype Autonomous EOD Maritime Response Vehicles (AEMRV) system that can locate, identify, and interrogate a subsea threat. The subsea robotics vehicle prototype derived from VideoRay, Inc.'s EOD Maritime Expeditionary Standoff Response (MESR) ROV Defender platform (includes a HD 1920 x 1080, 25 FPS camera, Oculus Binocular camera and Blueprint Subsea Oculus Dual Frequency Sonar). The ROV prototype was modified with additional payloads and systems, including the Greensea IQ, Inc OPENSEA Edge platform, Oceancomm M2 acoustic modems, Seatrac Ultra Short Baseline (USBL), and VideoRay lithium battery pods to meet AEMRV mission requirements.

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The SeeByte ATR AEMRV technological demonstration in September 2023 in San Diego, CA, USA showcased accurate, reliable and scalable MLO/non-MLO detection in ranges of up-to 40 m from the vehicle, in addition to close ranges of roughly 1 meter from the vehicle. Examples of SeeByte ATR detection on real-time data streams are seen in the Figure 1 and Figure 2 below:

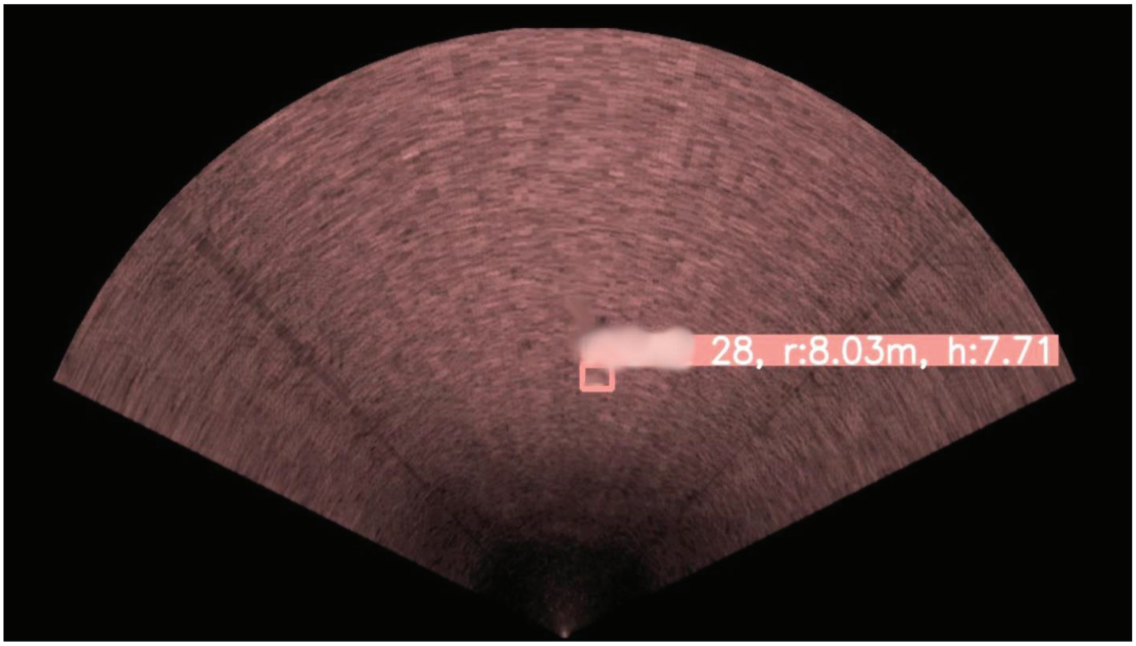

Figure 1. Sonar Frame Capture of Detected MLO with ATR Detection Overlay.

Vehicle range = 8.03 m and detected height of 7.71 m (Image Intentionally Blurred)

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Figure 2. Close Range Image of MLO Detection and ATR Overlay (Image Intentionally Blurred)

The most important takeaways from the demonstration was the ability to show accurate and reliable fused ATR solutions from streaming both the FLS data and camera stream from the Videoray HD camera/Numurus Stereo camera. The object of interest (MLO or non-MLO) in the sonar and camera stream was converted into a single landmark object in the vehicle referenced map and localization of the landmark was improved iteratively (based on spatial and temporal confidences of each ATR detection). The fused ATR solution allowed the AEMRV vehicle to autonomously navigate to new objectives in a mission to detect, track, and inspect an object-of-interest in real-time as seen in Figure 3.

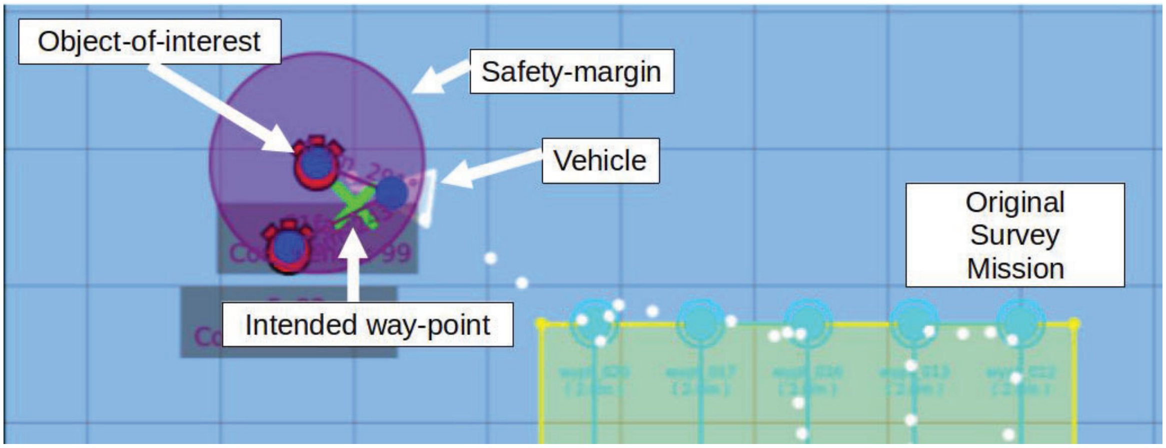

Figure 3. Screenshot of C2 Showcasing the Vehicle Detecting, Locating, and Tracking MLO within 5 m of vehicle.

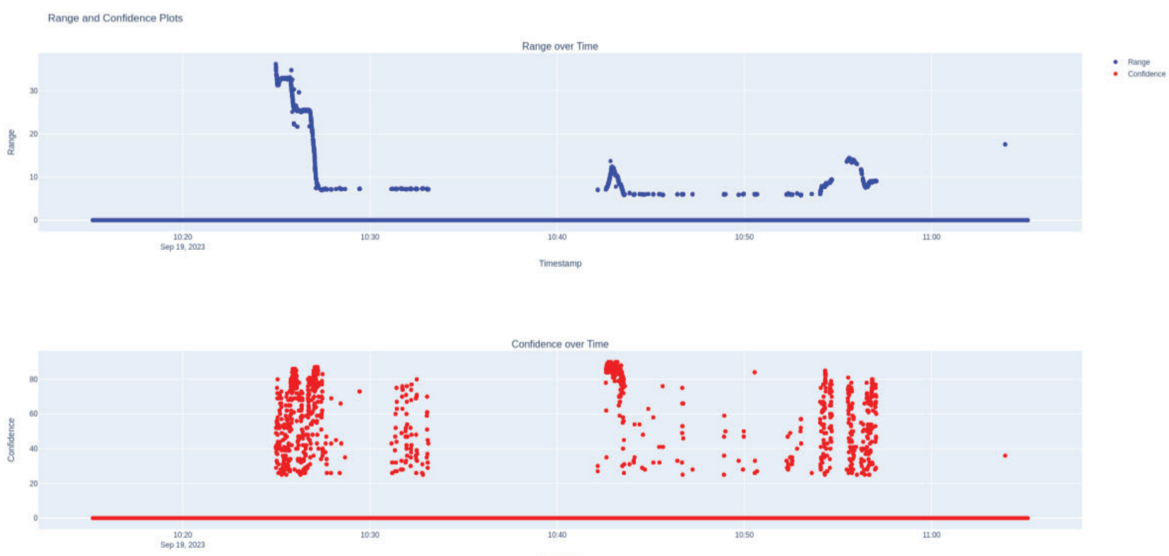

Figure 4. SeeByte ATR performance of estimated object range (on the top plot in blue) and detection confidences (on the bottom plot in red)

The SeeByte ATR multi-modal ATR tool shows detection confidence and classification performance immunity between 1m to 40 m. The detection confidence behavior is not biased or skewed as a function of range of the vehicle from the object of interest as seen in the bottom plot of Figure 4. The high confidences detection occurred at both 1 m away and 40 m from the vehicle. Front-seat end-users of the data stream were able to filter the data based on classification tag, detection confidence, distance, time consistency, and spatial consistency. In Figure 5, is an example

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of the capability provided by leveraging the SeeByte ATR data stream. End-users of the AEMRV dataset were able to accurately detect, track, and localize the location of a potential MLO in a survey mission with no a priori knowledge.

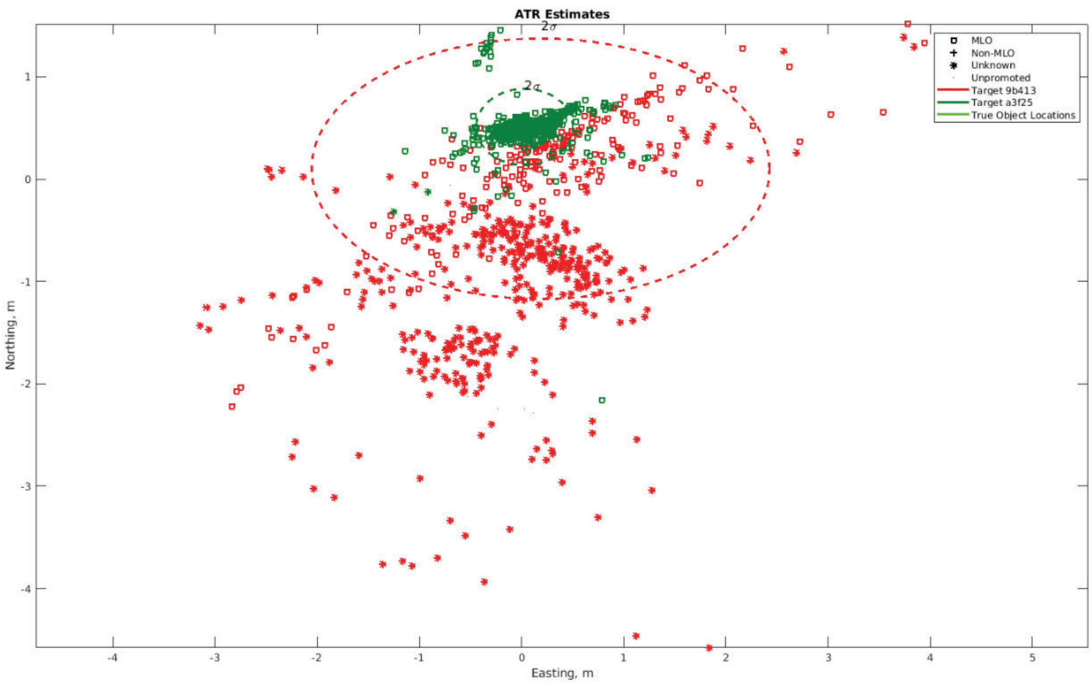

Figure 5. ATR performance showing high clustering of target observations are within +/- 1.5 m in Easting and +/- 0.5 m in Northing for the target a3f25, as seen by the green probability dashed circle

The determined object-of-interest (which happened to be a real MLO detected off the coast of San Diego, CA, US) based on the SeeByte ATR data stream and real-time temporal and spatial confidence modelling allowed the AEMRV untethered and fully autonomous accurately track and localize the object to within +/- 1 m of the actual position. Most importantly, the ATR data allowed the vehicle to identify, station keep within close range, and to deploy a neutralization charge (again all autonomously).

On a side note, the success of the fused SeeByte ATR solution proven on the AEMRV ROV vehicle, paved way for a similar application on an amphibious underwater crawler vehicle called the A2RV funded by DIU. The same SeeByte fused sonar and camera ATR solution was integrated into a the A2RV with no changes and despite the sonar viewing angle of MLOs being closer to 5 degrees with respect to the seafloor, instead of 25-35 degrees in the AEMRV ROV mission. The ATR accuracy and performance on the A2RV vehicle was equivalent to the original model set use-case being only ROV sonar and camera imagery training data. Shows the robustness of the SeeByte ATR CNN model.

The single vehicle use-case (on ROV or crawler) shows the power and capability of the SeeByte ATR software solution for MCM applications for all types of vehicles, especially maritime vehicles. The lessons learned from the vehicle single use-case set the foundation for multi-vehicle ATR capability and with the Neptune autonomy software solution the value add for MCM is exponential.

SYNERGY OF MULTI-VEHICLE AUTONOMY WITH MULTI-MODAL ATR

The synergy of multi-vehicle autonomy combined with multi-modal ATR significantly amplifies the operational resilience and efficiency of underwater missions. The Neptune approach not only maximizes the use of available resources but also introduces a layer of redundancy that is critical for mission success in the challenging and unpredictable underwater environment. By distributing ATR capabilities across multiple vehicles, a joint ATR multi-vehicle solution ensures that even in the event of a vehicle failure, the mission objectives can still be met without substantial disruption. The section delves deeper into the advantages and mechanisms behind this innovative approach.

Hardware Redundancy and Mission Continuity

One of the most significant advantages of a Neptune multi-vehicle strategy is the inherent hardware redundancy software framework flexible architecture it provides. In a scenario where one vehicle experiences a failure, whether due to technical malfunctions, energy depletion, or environmental hazards, the remaining vehicles in the fleet can reassess the mission plan and redistribute the tasks among themselves. Figure 6 shows an example of the multi-vehicle coordination mission running within the SeeTrack C2 software dryside. This adaptive reassignment of objectives managed by Neptune allows the squad to facilitate shared ATR responsibilities/capabilities, where each vehicle is equipped with sensors and processing units capable of performing target detection and identification. Therefore, the loss of a single unit does not cripple the mission, as the collective capabilities of the fleet ensure the continuity and completion of objectives.

Distributed Sensing and Enhanced Coverage

The deployment of multiple vehicles, each with multi-modal ATR capabilities, also enhances the spatial coverage and sensing diversity of the mission. Different vehicles can be equipped with varied sensor modalities, such as sonar, optical imaging, and chemical sensors, enabling a comprehensive assessment of the underwater environment from multiple perspectives. The multi-modal approach to ATR not only improves the accuracy of target identification but also reduces the likelihood of false positives, as objects of interest can be verified through cross-modal validation.

Collective Data Fusion and Decision-Making

A joint ATR multi-vehicle solution benefits from the collective processing power and data fusion capabilities of the fleet. By aggregating and analyzing data from multiple sources in real-time, the vehicles can make more informed decisions about navigation, object identification, and mission strategy. The collaborative decision-making process is particularly valuable in complex or

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rapidly changing environments, where the synthesis of diverse data streams can reveal insights that would not be apparent from a single source.

Scalability and Flexibility

A multi-vehicle approach with shared ATR capabilities offers remarkable scalability and flexibility in mission planning and execution. Depending on the objectives and available resources, the number of vehicles and their sensor configurations can be adjusted to optimize performance. The scalability ensures that missions can be tailored to specific requirements, whether that involves covering a large area in a search-and-identify operation or focusing multiple vehicles on a single target for detailed analysis.

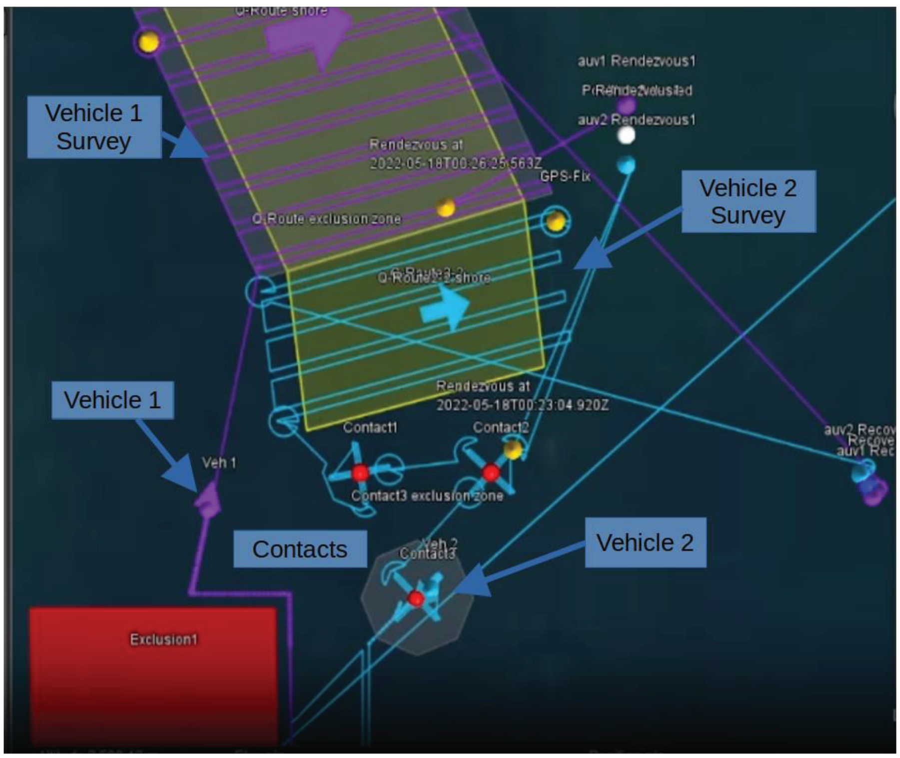

Figure 6. SeeTrack C2 Software with Multi-Vehicle Coordination during a Survey Mission of Potential MLO Threats

CONCLUSION

The implementation of multiple UUVs for a single mission in limited acoustic communication environment can be improved by synergizing the different multi-model with Neptune multi-vehicle autonomy solution. The demonstration of using multi-modal SeeByte ATR in a single use-

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case on an ROV with a FLS showed very fruitful potential for vehicle reliance, and reliability without operator-in-the-loop. The benefits are scaled exponentially when deployed on multi-vehicles via Neptune multi-vehicle autonomy solution. The SeeByte ATR has shown great potential on various vehicle hardware configurations in automating MCM and empower third-party hardware vendors and provide great value to the operator with minimal to non-existent interfacing. When deploying SeeByte ATR at scale for multi-vehicle deployment via Neptune's autonomy engine it strengthens the capabilities through hardware redundancy and mission continuity, distributed sensing and enhanced coverage, collective data fusion and decision-making, and mission scalability and flexibility. Future synergy of multi-vehicle autonomy with multi-model ATR will include deploying the Neptune and SeeByte ATR software on various types of autonomous multi-vehicles (including holonomic vehicles (i.e. ROVs), amphibious vehicles, unmanned surface vehicles [USVs]). The Neptune autonomy solution is not constrained by vehicle type and the SeeByte multi-modal ATR CNN model is flexible enough to be used on various types of sonars, cameras, magnetometer, Echoscope (Reference 4), depth-sensing cameras, and Li-DAR hardware solutions.

ACKNOWLEDGMENTS

Some images (i.e. Figure 3 and Figure 5) were provided by Greensea IQ. Figure 3 is a cropped screenshot of C2 front-seat software EOD Workspace.

APPENDIX:

1. Neptune Multi-Vehicle Implementation (Reference 2)

- Neptune constructs a list of objectives in from the mission file. The list is ordered the same as objectives in the Neptune mission file.
- Neptune removes from the list, objectives that are not available. An objective might be not available for the following reasons:
    - It has already been completed, by any vehicle in the squad.
    - It is current being performed by another vehicle.
    - It was previously attempted by this vehicle but failed. It will not be attempted again by this vehicle but may be attempted by another vehicle.
    - This vehicle does not have the capability to complete the objective. For example, reacquire objectives cannot be attempted by a vehicle that does not have a reacquire capable behavior.
    - It may be de-conflicted as described in section Implementation.
- Once these objectives have been removed from the list, objectives that remain in the list are available for the vehicle to perform.
- Neptune will tell the vehicle to attempt the first available objective in the list.

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