Collaboration of multi-domain marine robots towards above and below-water characterization of floating targets

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***Abstract*—This paper reports on a method to obtain a multi-domain (environment) awareness on a floating target (non-responsive ship, iceberg, other floating structure) using a heterogenous collaborative team of above, surface and underwater robots. This allows, for example, a ship approaching a non-responsive floating target to get information on the target from a safe stand-off prior to getting closer to further investigate or to attempt a boarding. This information enhances the safety of the boarding party. The ship can be a horizon (6 km) away from the floating target. The above-water unmanned aerial vehicles (UAV), integrated with optical cameras, obtains measurements of the above-water geometry using visual imagery to create an above-water three-dimensional model using photogrammetry methods. The below-water unmanned underwater vehicle is integrated with an imaging and profiling bathymetric sonars to capture the submerged hull geometry and features. An unmanned surface vehicle (USV) hosts an intelligent node which centrally controls the robotic collaboration by autonomously planning and distributing the mission for both the UUV and UAV. The results from the two are fused to yield a more complete picture of the floating target. We present results from simulations and a controlled in-water trial with an UUV, USV and UAV. The contributions from this work includes the robotic collaboration and autonomy across multiple domains, autonomous mission-planning and the fusing of multi-domain data. The scheduling of inter-dependent multi-robot task allocation is addressed in the autonomous mission-planning. The approach is validated in simulations and tested in-water. The in-water trials highlight the challenges and value of integrating sensors on distributed multi-domain robots towards a more complete picture on a floating target.**

***Index Terms*—marine robotics, autonomy, multi-robot collaboration, UUV, USV, UAV, autonomous mission-planning, acoustic propagation**

I. INTRODUCTION

When ships approach a non-responsive floating target (derelict or non-responsive ship, iceberg, floating container, large wreckage, etc.) they are cautious as they have no data or information on its state, origin or why it is there (situational awareness). At its worse, there could be incendiary devices or a hostile reception on-board the target. This situation is relevant to Dept. National Defence, Coast Guard and other ships with policing and rescue functions.

Floating targets simultaneously occupy the underwater, surface and above-water domains. With floating targets, both the above and below water situational awareness is required. If a ship is the non-responsive target, below-water situation awareness would determine if there are objects attached to its wetted hull or bilge keels. It can also provide information on the target's propulsive capabilities. Measurements (sonars) could also be got on the geometry (underwater profile) and draft of the below water portions of the target (if boat/ship). If the target is an idling boat, sensors (hydrophones) can log and analyze the target's acoustic emissions with a hydrophone. If the target is a boat that is not idling, any notable on-board sounds that reach say an on-board hydrophone could be logged. A surface asset could opportunistically provide above-water (low altitude) target imagery but it mainly processes and assembles the above and below water data and information, respectively. Above-water situational awareness could yield information on the target structure, items on the deck and potentially, people on-board. This information would be useful prior to boarding the target or coming in closer to investigate.

A proposed method to obtain this multi-domain situation awareness on the target is for the ship to deploy heterogeneous marine robots. below, on and well above-water, to collaboratively characterize and observe the floating target(s). The heterogeneous marine robot team can include a hover-capable unmanned underwater vehicle (UUV) with upward-looking sonars and hydrophones, an unmanned surface vehicle (USV) with optical cameras and an unmanned aerial vehicle (UAV) with optical cameras. All three would be networked to share information. The desired outcome is data (better still, information) streamed to the ship, at a safe stand-off from the target, from the marine robots. This data/information can inform the ship on whether to proceed through the area (icebergs), continue to search for more wreckage (aircraft accident) or attempt a boarding of the target (maritime interdiction operation). The ship could be a horizon away from the target so it is possible for the robots to also collaborate with ship-board human operators who oversee the robots' high-level goals.

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This aspect is noted but not discussed in this paper.

Related work involves heterogeneous marine robots collaborating towards a common goal. The work of [1] uses a team of marine robots (UUV, USV and UAV) to obtain visual imagery of underwater features like coral reefs. Their objective was to assess the practicality of using such a robot team for repeat monitoring and inspection of coral reefs. Their robot team was guided in real-time with remotely located marine biologists. The level of interaction with humans for their system was greater than what is proposed here as our system autonomously determines the mission for the UUV, USV and UAV to survey the target. As well, their work does not address tightly coupling above and below water sensor measurements. [2] examines collaborative sampling with an USV that gathers high quality data in select regions based on transmitted cues from distributed low-cost drifting sensor nodes for coral reefs. Their system was more energetically favorable than exhaustively surveying an area. As well, the data logged is targetted towards information rich regions that contain coral reefs. However, their work focusses on just the surface domain and it is searching for the target. The proposed system assumes some knowledge of the target location. [3] uses heterogeneous UUVs to cooperatively map unstructured underwater domains. Their UUVs can adaptively reconfigure to sense in very different environments (ocean bottom to sea cliffs, etc.). Their contribution is a mission planner which uses a language built on primitives for each UUV as individual vehicles and then as a collaborative team. Their mission handler coordinates the team's behaviors and is able to receive waypoints, mission files and events from the central controller. This is a concept that is used in the mission-planner developed here. The proposed solution generalizes these concepts to apply to multiple domains.

The contributions of this paper are as follows:

1. a node that performs autonomous mission-planning for below, surface and above-water marine robots towards the common objective of obtaining information on a floating target,
2. robotic collaboration across multiple-domains and
3. fusion of below and above-water data on a floating target

This paper presents on simulations and an in-water implementation. The rest of this paper is as follows. The background section describes the individual autonomous systems used in simulations and the subsequent in-water implementation. Then, the *mRobot* mission-planning node is described. The objective of simulations is briefly presented. Then, the experimental set-up is described for in-water development and validation. Results from the experimentation are presented and discussed. Finally, the paper concludes with a few remarks.

II. Background

A. Heterogeneous Marine Robots

Previous work established communications between under, on and well-above the water marine robot communications [4]. The upward-looking imaging (or profiling) sonars on the UUV would survey (acoustically image) the below-water portions of the target. The optical camera on the UAV would gather imagery to create a photogrammetry reconstruction of the above-water portions of the target. The USV communicates with the UUV through underwater modems and the UAV with conventional RF radios. The USV relays UUV communications for the UAV. The USV, through its range and bearing from the UUV, helps localize the submerged UUV since it cannot access GPS. In the event of a GPS denied environment, the USV can aid the UAV in its positioning by determining its range and bearing from the USV in a similar manner. The USV could communicate with the UAV and be beyond the horizon of the surface target at sea level since at 200 ft altitude, the UAV has a horizon of 28 km compared to the surface target at sea level which has a horizon of 6 – 7 km. In addition to being a communications hub for the ship, UUV and UAV, the USV also processes the incoming data streams from the UUV and UAV into information to assemble the below and above-water information on the surface target and to potentially transmit that to the ship. Such a system was developed and tested at the Intelligent Systems Laboratory (ISL). To start, the concept of operation was developed in simulation using Gazebo [5]. Then, this was implemented and tested in-water in a large indoor tank test with an UUV, USV and UAV.

All three marine robots in the research use the service-oriented Robot Operating System (ROS) software framework as their middleware. The individual robots are described next.

1) Unmanned underwater vehicle: The IMOTUS UUV (Fig. 1) is a near spherically-shaped robot that differentially drives thrusters to actuate all 6 degrees-of-freedom. Its top speed is about 0.5 meters / second. This UUV was integrated with the Kongsberg M3 (500 kHz) and Flexview (1200 KHz) bathymetric sonars. IMOTUS with its low-speed hover capability was ideal for the submerged hull survey task. The sonars can insonify a target from a slant range of 150 m. In simulation, the upward-looking sonar was surveyed from 10 m below the target and for the in-water tests, the range was only 4 m. The objective of the tank tests were to assess the efficacy of acquiring and merging above and below-water imagery.

Fig. 1. IMOTUS hover-capable unmanned underwater vehicle used in the research

2) Unmanned surface vehicle: This was a catermaran hull form developed and built by the ISL (Fig. 2). It is propelled by a trolling motor which pulls the hull forward with a trolling motor. This drive train can provide a top speed of 3 knots for the USV. The USV has 150 lb of buoyancy and can be remotely controlled through a hand controller or autonomously controlled through the *mRobot* ROS node. The USV has an RF radio that can relay messages to/from its underwater acoustic modem. This modem is used for acoustic communications between underwater points (e.g. underway UUV and the submerged part of the USV). For this project, the USV hosted the *mRobot* node which coordinates the above, surface and below water robot missions and communications. Given the relatively small size of the Aquatron Tank for the in-water tests, the USV was not autonomously controlled. As well, since the tank was small, shallow and highly reverberent, the underwater modems for communications between the UUV and USV were not used.

Fig. 2. ISL high buoyancy unmanned surface vehicle used in the research. The USV is approaching the camera.

3) Unmanned aerial vehicle: It was necessary to design and build an UAV that had an interface that *mRobot* could communicate across, access the UAV's on-board position estimates and control the UAV. The on-board position estimates would be compared with the ground truth position estimates from the motion capture system. It was also necessary to have a marinized quadrotor that could tolerate being in the water as it is flying over water. The Pelican (Fig. 3) UAV is a marinized quadrotor designed with these capabilities in mind. Its payload sensor is an optical camera mounted on a gimble. Its mission was to acquire imagery of the target above-water using photogrammetry methods. The photogrammetry processing was not performed on-board the UAV. For the photogrammetry survey, the UAV performs a square spiral mission that descends towards the floating target. The imagery is sent back to *mRobot* for processing. In autonomous mode, *mRobot* controls the UAV but the operator can interrupt with the remote controller. The UAV receives its mission and sends back imagery along a separate wifi link.

III. Multi-Robot Task Allocation (*mRobot*)

mRobot is one of the ROS control nodes for the multi-robot (Fig. 4) path-planning part of the collaboration. It subscribes to the pose published by each robot in the collaboration and uses that information to manage the distribution of robot-specific tasks for a cross-domain survey mission.

Fig. 3. Intelligent Systems Laboratory's unmanned aerial vehicle, Pelican, designed to be marinized and networked through the motion capture system and controllable through *mrobot*.

mRobot first publishes a single waypoint to the UAV for an initial survey of a floating target. Using information from that survey (three coordinate points describing the exact pose of the target) *mRobot* generates an array of waypoints for the UUV and UAV that detail survey missions of the partially submerged target. Waypoints are then published sequentially to each robot every time the previous one is obtained – as determined by *mRobot*. Once all waypoints have been obtained, *mRobot* publishes a final waypoint to gather the team to a pre-determined rendezvous point. At this point data transfer between each robot can be completed and then delivered to a base station for post-processing.

mRobot is hosted on the unmanned surface vehicle, which requires that it also adaptively generates a path for the USV to best support the UUV and UAV. Specifically, *mRobot* uses pose information from the UUV to determine a USV heading to minimize the state-estimation error of the UUV. The path is also constrained by communication quality (range), a safe standoff distance from the target, and collision avoidance stand-offs from other robots in the system. This aspect of *mRobot* was proven in simulation only. It was not a priority for the in-water testing given the poor environment for acoustic communications.

IV. Simulations

The simulations served as a testbed to develop and validate the *mRobot* node for the multi-domain robotic collaboration. It was also used to investigate the data flow and data reduction needed. Finally, the simulation environment was used to analyze concepts of operation for the multi-domain robotic collaboration to characterize a floating target.

Simulations were performed using Gazebo [5]. The packages used were *World/Environment* for the UUV environment [6]. The Imotus in-house simulator, with an upward looking bathymetric sonar, was used to simulate the UUV. The Clearpath Heron Simulator (based on the UUV Simulator) [7] was used to capture the USV. The UAV simulator was based on the Hector quadrotor package with an optical camera [8]. The targets used were the Heron [7] as the USV and a rectangular barge.

The USV simulator was based on the UUV simulator package and the Hector simulator did not require any of the buoyancy models. Therefore, they were easily integrated. The Imotus UUV simulator was not designed for integration with Gazebo and therefore to simplify its use the physical model

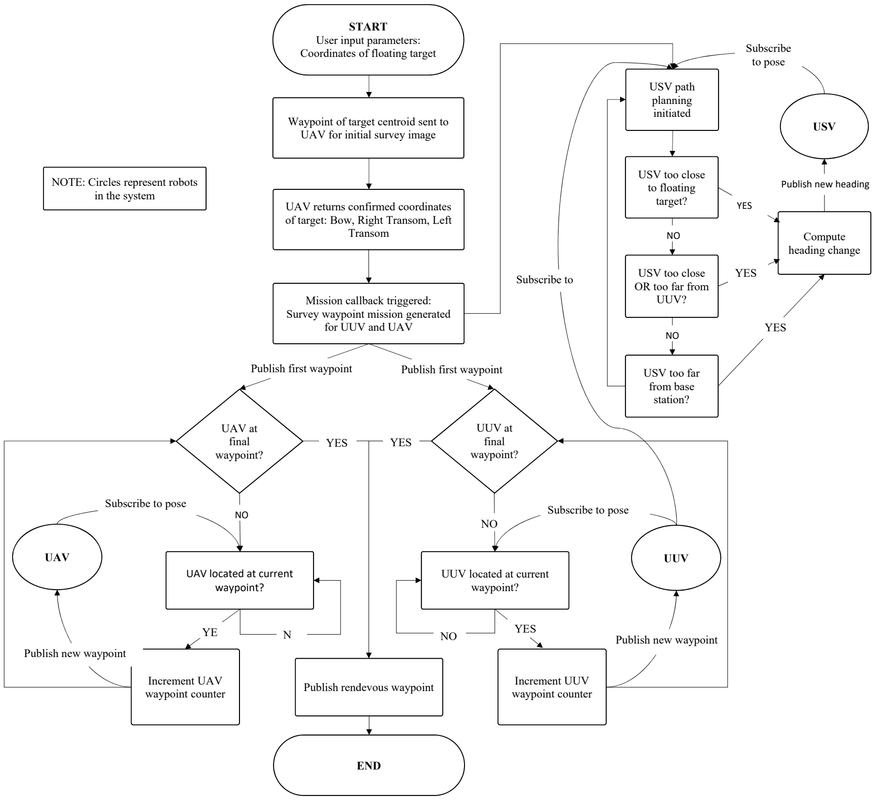

Fig. 4. Schematic of *mRobot* components for the UAV and UUV path-planning

TABLE I
SUMMARY OF MULTI-ROBOT SIMULATION PARAMETERS

marine robot	simulation parameters varied
unmanned underwater vehicle	survey distance and time UUV path, position and depth number of sonar passes sonar range and radius
unmanned surface vehicle	communication between UAV – UUV detection distance from target assistance to UUV localization
unmanned aerial vehicle	survey distance and time UAV path, position and altitude number and quality of images camera specifications

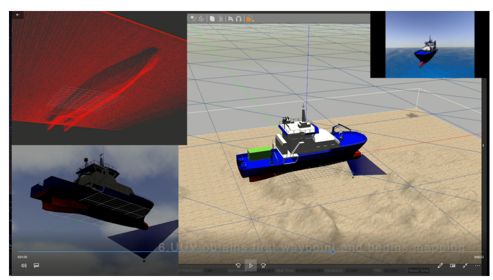

Fig. 5. From simulations, the ship is surveyed from below with the IMOTUS UUV integrated with a 256-beam sonar (bottom left, top left) and from above with the Pelican UAV (top right)

and sonar was manually set each time the UUV updated its position within its own simulation environment. The simulations were used to test primarily the path-planning for the marine robots. Some of the major parameters considered for each robot are summarized in Table 1.

For each mission, the sonar scans the underside of the target from the UUV and images from the UAV were extracted and transformed into point clouds from the UAV (Fig. 5).

A. Underwater Acoustic Communications

The viability of the proposed collaborative robotic solution depends on the underwater acoustic communications that is possible. This was studied in simulations. The underwater acoustic modems have a carrier frequency of 25 kHz and a bandwidth of 4 kHz. The modems would be mounted on the UUV and on the submerged portion of the USV. The concept of operation would have the floating target no further than 6 km (distance to the horizon) from the ship. The water depth considered in this analysis varied from 0 - 200 m. The modem that is on the UUV can vary from 3 – 4 m (in the Aquatron) to 10 m (in simulation) underneathe the submerged hull. The distance that the acoustic communications is possible over these parameters depends on the sound speed profile in the water column. The calculated transmission loss in the acoustic signals is the relevant quantity to monitor. 60 dB was

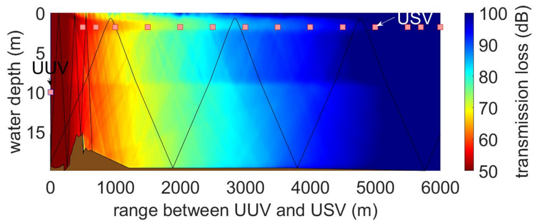

Fig. 6. The transmission loss for acoustic signals at 25 kHz in 20 m water depth with the USV modem at 1.8 m depth and the UUV one at 10 m depth. The threshold transmission loss was selected as 60 dB. This determines feasible ranges between UUV and USV as less than 1 km.

identified here as the threshold beyond which the mission was no longer possible. This was studied using acoustic modelling tools like Bellhop [9] to define realistic ranges between the UUV and USV. This analysis also informs on the level of data reduction needed given the information from the sonar, mission information that needs to be transmitted to the UUV from *mRobot*, etc. An example is shown in Fig. 6.

V. Experimental Set-up

Experimental testing was required to develop and validate the *mRobot* node and the Pelican UAV (not discussed here). Then, *mRobot*, the Pelican UAV and the motion capture system were mobilized to the Dalhousie University Aquatron Pool tank for in-water integration with the UUV and USV.

1) Laboratory Testing: *mRobot* was developed and tested on the UAV in the ISL flying space which is instrumented with a motion capture system (Motion Analysis, [10]) to provide the UAV ground truth localization to verify the *mRobot* and UAV on-board localization estimates. The motion capture system fuses visual information from 8 cameras, using the Motion Analysis proprietary software, to track markers on the UAV and USV to determine their pose.

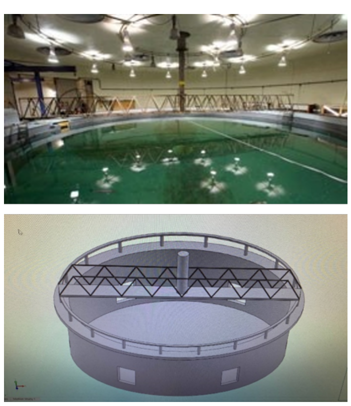

Fig. 7. Top: Pool tank at the Dalhousie University Aquatron Laboratory. Bottom: the Aquatron Pool tank model used in simulations.

2) Aquatron Pool Tank Testing: The Pool tank at Dalhousie University's Aquatron Laboratory (Fig. 7) was used to perform the initial in-water tests with the UUV, USV and UAV. This tank is 15 m in diameter × 4 m in depth and filled with sea water. The tank is inside a concrete and steel building so it was not easy to bring a GPS repeater into it or to cleanly access magnetic north for the compass of either the UAV or USV for their localization solution. Consequently, the Lab motion capture system was used in the Aquatron Pool tank.

A. Floating Targets

Two floating targets were used. The first was a barge of 96 inches long × 56 inches wide × 15 inches deep. This is a good target as it is a cylinder in the vertical direction so its water planes do not change with barge draft. The barge top and bottom-side surfaces have fine textures and are identical. The approach was to merge the above and below water solid models about the water plane. To make the barge more responsive to the 500 kHz and 1200 kHz sonars, part of the barge underside had a black metal roof panel attached to it. The panel has ridges and stiffeners to provide larger scale features. A blue panel was sometimes placed on the top-side of the barge to test the the UAV optical camera photogrammetry. The second target was the unmanned surface vehicle (Fig. 2). It's expression at the water plane are the two pontoons, the propulsor and the brackets that hold the pontoons together.

B. Inter-Robot Communications

Given the relatively small Aquatron Pool tank, wifi was used between the UAV and *mrobot* for data transmission. IMOTUS communicated with *mrobot* through a tether integrated to its topside vehicle control computer. This facilitated the transmission of incoming sonar images for development purposes. Given the shallow depth of the tank and its concrete walls and floor, acoustic communications was not implemented. Underwater communications was emulated by sending the missions and messages using the UDP (user datagram protocol) common to underwater communications.

C. Translation Node

A ROS translation node (not shown) was written for the communications between *mRobot* and the UUV topside vehicle communications. Lua was the mission format that the UUV uses. Therefore, all the ROS topics and messages pertaining to the UUV mission and navigation were translated to that.

1) Indoor UAV Navigation: The Pool tank facility is in a concrete and metal building so a reliable compass heading for navigation was not possible. Therefore, the Lab motion capture was installed at the Pool tank to provide the UAV heading. The UAV performs its on-board position estimation with this.

D. Experimental Procedure

During the in-water validation, the UAV would determine the size of the target that to be imaged. Then, it sends this information to *mRobot*, which would determine an UUV and a UAV mission that would image it from their respective domains. Then *mRobot* would distribute the mission to the UUV and UAV as shown in Fig. 4 and Fig. 8.

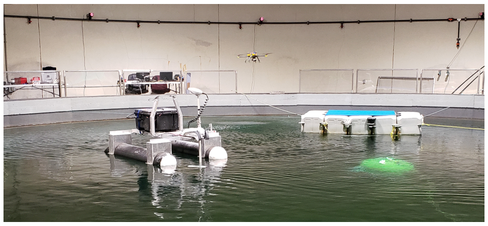

Fig. 8. All 3 marine robots in the experimental validation. The USV is left in the foreground. The surfaced UUV is right in the foreground. The barge is behind both. The UAV is left of the barge. On the wall, the red LED rings are 3 of the 8 motion capture cameras installed in the Aquatron Pool tank.

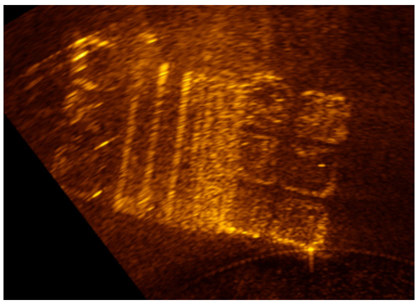

Fig. 9. Flexview sonar imaging of the **barge underside** from the IMOTUS UUV. Notice the roofing panel ribs running top to bottom are captured.

VI. Results and Discussion

From the simulations, the timing for the UUV and UAV missions were determined as well as meaningful ranges between the UUV, USV, UAV and target. Insight was also obtained on mission parameters like the number of sonar sweeps for a given combination of sonar range from the target and the target dimensions at the water plane as well as the best UAV mission for photogrammetry purposes. The simulations confirmed the concept of operation with the collaborative marine robots across all three domains was feasible. As well, the missions generated by *mRobot* for the UUV and UAV achieved their goals and collected data at the required resolution.

Fig. 9 shows the insonification of the barge underside with the Kongsberg Flexview (1500 kHz) bathymetric sonar. Notice the sonar image was able to discriminate better than just the gross features of the barge (e.g. the 15 cubes that are the barge and their boundaries). A roofing panel was tied to the barge underside to give it different features (and better response at higher frequencies). The stiffeners in the roofing panel came out well. Fig. 10 shows the point cloud from a birds-eye view of the point cloud reconstructed from the photogrammetry. For this run, there was no roofing panel on the topside of the barge. The texture on the topside of the barge is captured well. Fig. 11 shows an isometric view of the point clouds. As per the hypothesized approach the merging was done on the common water plane. The merging was made more accurate by unique features on the common water plane (e.g. a piece of rope). This was easier with the 1200 kHz sonar that produced higher resolution images. The photogrammetry resolution was good and exceeded that of the sonar. As shown in Figs. 9 - 11,

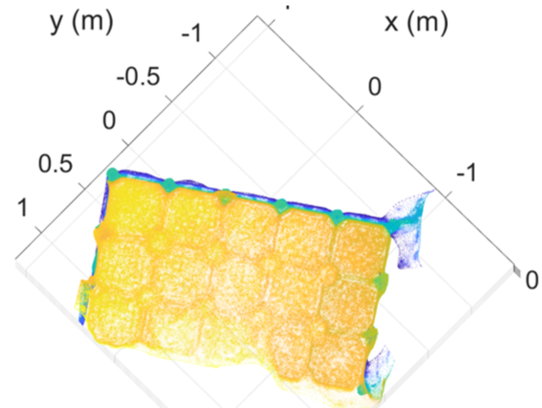

Fig. 10. Optical camera photogrammetry reconstruction of the **barge topside** with the Pelican UAV (birds-eye view).

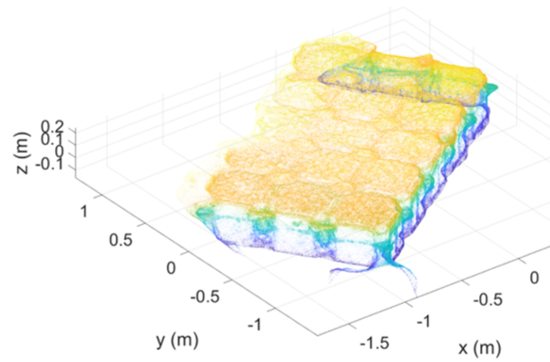

Fig. 11. Optical camera photogrammetry reconstruction of the barge topside with the Pelican UAV on top of the bottom-side sonar (isometric view).

dimensions can be extracted for features of interest on the top or bottom side of the floating target.

The ability to merge above and below water models of the target, well, depended on the uniqueness and fidelity of features common to water plane. This also meant that if there was wind on the water (as in the case of the UAV flying low) this created a noisy water plane to try and merge across. The UAV photogrammetry images were easily transmitted with in-air radio to *mRobot*. However, the extracted sonar images and resulting point clouds could not have easily been transmitted through underwater acoustic modems – especially at greater ranges between UUV and USV. Image compression and encoding techniques will help with this [11].

VII. Conclusions

Simulations and an in-water implementation with an UUV, USV and UAV validated the use of these marine robots working collaboratively to gain situational awareness on a floating target. The next phase of the project takes the heterogeneous collaborating robots into a larger in-water environment to test the underwater acoustic communications as well as how to represent the in situ sonar information so that it can be transmitted. With regards to the merging of above and below water models, more complex targets will be trialed.

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