Ship Hull Inspection by Hull-Relative Navigation and Control

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Abstract - **MIT and Bluefin Robotics designed the Hovering Autonomous Underwater Vehicle with a focus on ship hull inspection missions for Anti-Terrorism and Force Protection. Our hull-relative navigation and control are primarily based on a Doppler Velocity Log that the vehicle keeps pointed normal to the hull by means of a tilt actuator. A Dual Frequency Identification Sonar (DIDSON) is used to inspect the hull. The sonar is mounted on a separate tilt actuator in order to control the grazing angle relative to the hull. The vehicle has been successfully tested on the decommissioned heavy cruiser "USS Salem (CA 139)". The results of a demonstration to the US Navy are reported in this paper.**

I. INTRODUCTION

MIT Sea Grant, MIT Mechanical Engineering, and Bluefin Robotics jointly developed the Hovering Autonomous Underwater Vehicle (HAUV) under funding from the Office of Naval Research (ONR). The objective of the project was to design a small and low-cost vehicle capable of precision maneuvering in very shallow water environments, with a focus on ship hull inspection for Anti-Terrorism / Force Protection missions.

The HAUV design combines the maneuverability of an ROV with the flexibility of autonomous operations. For navigation and control, other autonomous ship hull inspection vehicles rely on high-frequency long baseline transponders hanging from the ship being inspected [1]. Our approach aims at freeing the operator from any pre-deployment burden and at making the support hardware as minimal as possible. This high level of operational freedom is achieved by using a hull-relative approach to vehicle navigation and control. In this approach a 1200 kHz Doppler Velocity Log (DVL), mounted on a tilt actuator, is used to control the vehicle's distance and bearing with respect to the hull and to keep track of its path as it travels along the hull by integration of the relative velocity.

Depending on the section of the hull being inspected, two different inspection strategies are considered. For mostly vertical surfaces (like the sides of a ship), the HAUV executes horizontal slices by keeping normal to the hull, at a fixed distance and depth, while traversing along the hull. The vehicle progresses down the hull by increasing its depth in between horizontal slices. For mostly horizontal surfaces (like the bottom part of a ship), the vehicle performs vertical slices by keeping normal to the hull, at a fixed distance and sliding up and down while maintaining the bearing and the fore-aft position along the hull constant during a slice. The vehicle progresses along the hull by shifting either towards the bow or the stern by a predefined amount between vertical slices.

Control of the HAUV is achieved using an inner-outer loop controller design where the low-level controller depends only on the core sensors of the IMU (accelerometers and rate gyros), while a mid-level layer incorporates the DVL and depth sensor measurements, and a high-level controller manages the mission and desired pathlines.

The inspection sensor is Sound Metrics' Dual Frequency Identification Sonar (DIDSON). The DIDSON is mounted on its own tilt actuator which allows the vehicle to point it at the desired grazing angle with respect to the hull for good imaging.

This paper presents the vehicle and the two inspection techniques. Open water navigation and hull-relative navigation are then described followed by some details about the vehicle flight control system. Finally experimental results obtained during a demonstration to the US Navy are presented and commented.

II. VEHICLE DESCRIPTION

The HAUV chassis holds 8 hubless bi-directional DC brushless thrusters, a Main Electronics Housing (MEH), a Junction Box (JBox), a battery, 2 pitch actuators, 3 antennae, the DVL, the DIDSON, floatation foam, and ballast weight (Fig. 1).

Several components of the vehicle are standard Bluefin products, namely the battery, the MEH, and the antennae. The battery is a 1.5 kWh pressure tolerant, rechargeable, lithium polymer battery. The MEH is derived from the MEH used in the Bluefin12-class of survey vehicles. The WiFi, RF and GPS/strobe antennas are standard to all Bluefin survey vehicle classes (9", 12", and 21" diameter vehicles).

MIT Sea Grant designed the vehicle architecture so as to incorporate the existing components (thrusters, DVL, DIDSON, and Bluefin components). In addition, MIT designed the oil-filled JBox (that mainly houses the thruster controller board), the tilt actuators and mechanisms used to pitch the DVL and DIDSON separately. MIT performed the final integration of all the components.

MIT Mechanical Engineering completely designed and implemented in software the new vehicle flight control system needed by the vehicle.

The HAUV runs Bluefin's new vehicle software "Huxley". Although most of the HAUV software is identical to the other Bluefin vehicles, new behaviors had to be developed to address the specific needs of the HAUV. The vehicle's dynamic control software was also modified to include the HAUV flight control code.

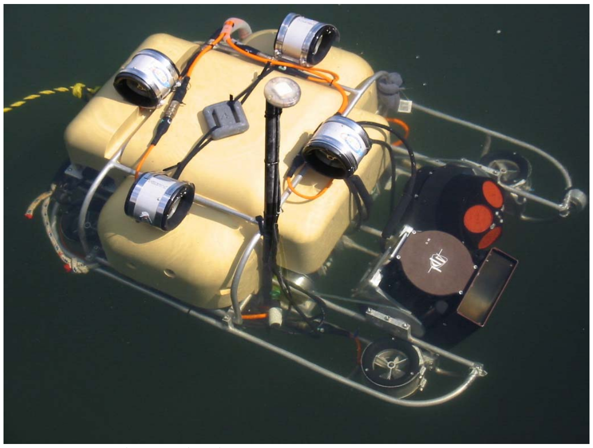

Fig. 1. The demonstrator prototype HAUV

III. INSPECTION STRATEGIES

Two ship hull inspection strategies are considered for the HAUV: "horizontal slices" and "vertical slices". Horizontal slices have already been extensively used. Vertical slices will be demonstrated in the next few months.

A. Horizontal slices

Fig. 2 (top-left) illustrates the horizontal slice inspection principle. The HAUV maintains zero pitch and roll and servos at the desired slice depth. The DVL is tilted with respect to the vehicle and the vehicle oriented in yaw so that all beams measure nearly identical ranges. This ensures that the vehicle forward axis and the DVL axis are normal to the local hull surface. The HAUV then surges to maintain the desired range to the hull. The vehicle's position with respect to the hull is then fully constrained except in the sway direction. The vehicle's sway velocity is then controlled to make the vehicle move sideways. As the HAUV sways, it collects DIDSON data. However, because the DIDSON needs to look at the hull with a particular grazing angle (15 to 20º), the DIDSON will look at the hull below or above the vehicle depending on the slice depth. Fig. 2 (bottom-left) is a view from behind the HAUV and illustrates the situation when the vehicle is looking at a vertical surface. The yellow circles represent the footprint of the 4 DVL beams on the hull. The green area represents the footprint of the DIDSON beams. A slice ends when the DVL loses lock meaning that either the bow or the stern of the ship has been reached, or the desired position along the hull has been reached. When this happens, the vehicle changes depth, re-acquires the hull, and executes a slice in the opposite direction. The depth change is chosen so as to allow some overlap between the DIDSON data collected on successive passes to help with mosaicking.

B. Vertical slices

Fig. 2 (top-right) illustrates the vertical slice inspection principle. The HAUV maintains zero pitch and roll, and maintains its position along the hull (no lateral motion). The DVL is tilted with respect to the vehicle and the vehicle oriented in yaw so that all beams measure nearly identical ranges. This ensures that the vehicle forward axis and the DVL axis are normal to the local hull surface. The HAUV then surges to maintain the desired range to the hull. The vehicle's position with respect to the hull is then fully constrained except in the heave direction. The vehicle's depth and surge velocity are then controlled to make the vehicle go up or down the slice. The vehicle then shifts by a pre-defined amount along the hull when it reaches the bottom or the top of the slice. The distance that the vehicle moved along the hull can be accurately measured by integration of the DVL sway velocity. If the previous slice was done with a depth increase, the new slice is done by decreasing depth and vice versa. Here also, the distance shift is chosen so as to allow some overlap between the DIDSON data collected on successive passes to help with mosaicking. Fig. 2 (bottom-right) is a side view of the vehicle that shows how the DVL and the DIDSON are pointed as the vehicle goes down the hull.

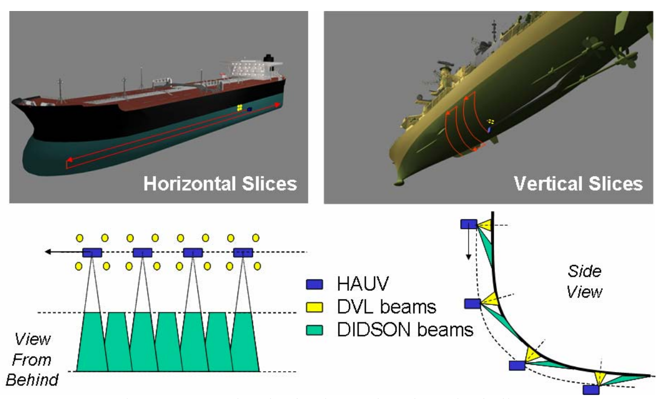

Fig. 2. Inspection by horizontal and vertical slices

IV. HAUV NAVIGATION

A. Open Water Navigation

Open water navigation is typically used during transit to and from the ship. In that case the DVL is pointed at the sea floor (using the DVL tilt actuator) and the vehicle navigates in earth-relative coordinates (UTM coordinates). The navigation approach is similar to that used by Bluefin's survey vehicles: the vehicle initializes its position with GPS, dives, dead reckons using the bottom-locked DVL and attitude / heading measurements. Once the vehicle reaches the desired waypoint within a given capture radius, it surfaces to correct its position with GPS before diving for the next waypoint.

The HAUV is fitted with a magnetic compass that can be used to determine the vehicle's heading. However, this compass is surrounded by 8 thrusters that draw relatively large currents and rapidly reverse their spinning direction. The varying magnetic environment in the vehicle makes the accurate use of a magnetic compass very difficult. A derivative approach is then used to maintain a more accurate vehicle heading: the compass was first calibrated in a parking lot using its internal calibration procedure. During the calibration, the thrusters were not spinning at all, but everything else was powered and operating as when the vehicle is floating on the surface while resetting its position with GPS. The calibrated compass then provides an accurate heading (within the accuracy of the calibration procedure) as long as the thrusters are not spinning.

The vehicle also carries a tactical grade IMU made up of 3 accelerometers and 3 Ring Laser Gyros. These gyros can be used to determine the vehicle's heading, pitch, and roll by 3-axis integration of the RLG angular rates measurements if an initial attitude and heading are provided.

When the vehicle is about to dive (before it starts spinning the thrusters), the compass heading is read, and the vehicle's pitch and roll are calculated based on the IMU's accelerometers. The measured heading, pitch, and roll are used to initialize the 3-axis gyro integration. From there on, and until the vehicle comes back to the surface at the waypoint, the integrated gyro heading is used to control the vehicle.

Although the navigation accuracy does not compare to what is achieved with Bluefin's survey vehicles, a substantial improvement can be observed when the same waypoint navigation box is run using either the magnetic compass or the gyro-integrated heading (Fig. 3).

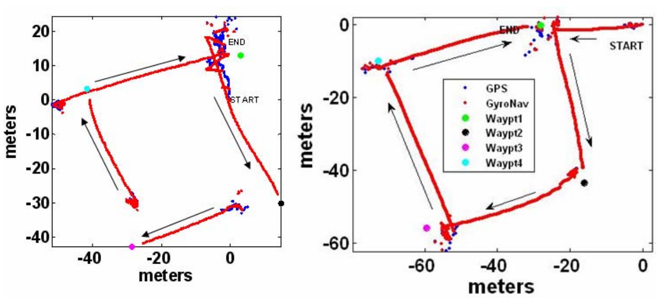

Fig. 3: Waypoint navigation. Left: using the compass heading. Right: using the gyro-integrated heading. The waypoints are shown as colored circle. GPS fixes are shown as blue dots. The vehicle's navigation is shown in red.

B. Hull-Relative Navigation

When navigating with respect to the hull, the vehicle bearing and the DVL pitch with respect to the vehicle are controlled so as to keep the DVL pointed normal to the hull. On small curvature hulls, this condition corresponds to the 4 beam reporting nearly identical ranges.

The 4 DVL ranges allow computation of the distance between the vehicle and the hull (along the normal to the hull through the DVL head), the bearing (α) of the vehicle relative to the hull and the pitch of the DVL axis with respect to the hull (β) which we want to control to 0º (Fig. 4).

Note that α and β are quite noisy due to the noise on the DVL ranges. These are, however, the signals calculated by the navigation process and passed to the vehicle controllers for the control of the vehicle bearing and DVL pitch angle. For the control of the distance to the hull, it is possible to get a smoother estimate by filtering the range calculated with the 4 DVL beams with the relative velocity perpendicular to the hull. Similarly, the depth can be filtered using the velocity relative to the hull projected on the local vertical.

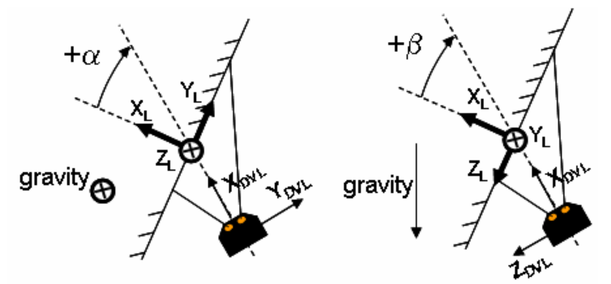

Fig. 4: Definition of α and β

The velocities reported by the 4 DVL beams are used to compute the vehicle's velocity relative to the hull. The along-hull velocity component is used to keep track of the vehicle's progress along the hull.

V. HAUV CONTROL

Dynamically, the vehicle is equipped with high-performance thrusters so as to operate in shallow waters, waves, and in proximity to walls. The primary sensor we have available, the DVL, however, is a comparatively low bandwidth device, which cannot provide robust measurements for direct control – the noise properties may be unpredictable, timing may vary, and missed data are not uncommon. Furthermore, loss of contact with the hull can occur in regular operation, and even be exploited as a landmark. As a consequence, the vehicle has to be capable of short-term autonomous navigation, through the IMU, and an integrated low-level control system.

The division of control can be stated as follows: The low-level controller depends only on the core sensors of the IMU, while a mid-level layer incorporates the DVL and depth measurements, and a high-level controller manages the mission and desired pathlines. This multi-level control system is to be of the inner-outer loop type, with the DVL and depth sensor providing setpoints for higher-bandwidth inner loops (Fig. 5).

Consider for example the case of yaw control relative to the wall. At the innermost level, a yaw rate servo runs at maximum update frequency and closed-loop bandwidth, employing a model-based estimator, i.e., a Kalman Filter for handling vehicle dynamics and sensor channels that are coupled due to gravity. The mid-level control has coupling, due to the fact that the DVL is like a velocity sensor on a moment arm, so that yaw and sway at the wall are kinematically coupled. This is one of many concepts from visual servoing that are appropriate here.

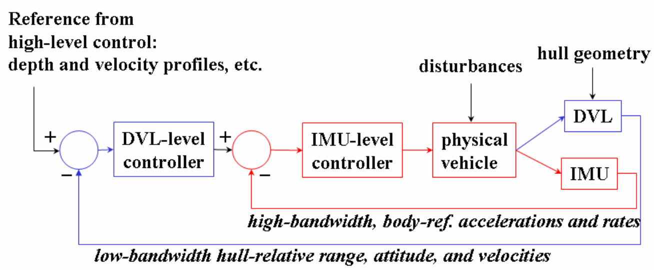

Fig. 5: Inner-outer loop control in the HAUV

VI. DEMONSTRATION

An HAUV demonstration has been performed in the presence of representatives from NAVEODTECHDIV, EOD-Mobile Unit 7, Mobile and Diving Salvage Unit 2, SPAWAR Systems Center San Diego, and EDO corp. The demonstration took place on the "USS Salem" [2] in Quincy Harbor, on June 28th, 2005 (Fig. 6).

Fig. 6: The USS Salem

A. Demonstration Objectives

The primary objective of the demonstration was to prove the vehicle's ability to achieve 100% coverage of a given section of the hull with its imaging sonar, with a good image quality.

Another objective was to demonstrate the vehicle's capability to autonomously switch from open water navigation to hull-relative navigation, which implies the capability to autonomously acquire and approach the hull.

B. Demonstration Preparation

Since we could not instrument the entire hull to prove 100% coverage with the DIDSON, we defined a 10 m long by 6 m down the hull as the target area in which 100% coverage had to be proven. This section of the hull has been instrumented as shown in Fig.7. Twelve ¼" polypropylene lines have been attached to the hull with magnets at 0.5 m spacing. The tight spacing between the lines was chosen to make sure that we would see several lines in a given DIDSON image. Each line is identified by a certain number of tennis balls (visible in the DIDSON images) held against the hull by magnets. Additionally, 2 cylindrical shapes and 2 rectangular shapes have been placed as indicated in Fig.7.

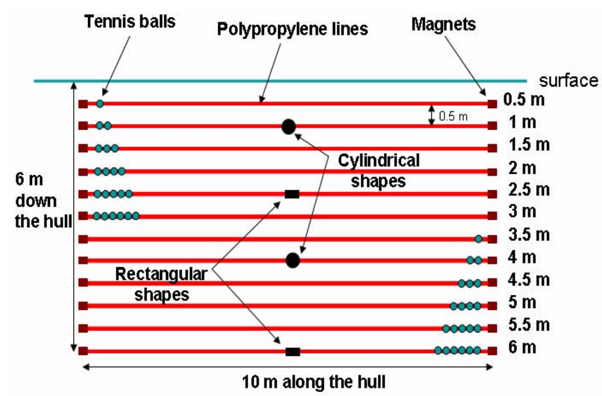

Fig. 7: Hull instrumentation to prove 100% coverage with the DIDSON

A demonstration mission including transit in, hull acquisition and approach, and transit out has then been defined to demonstrate the vehicle's capability to switch navigation modes. The vehicle was programmed to:

- Initialize its position with GPS,
- Dive to a first waypoint closer to the ship (WPT1),
- Surface to reset its position with GPS,
- Dive to another waypoint 15-20 m away from the hull (WPT2).
- Without surfacing, acquire the hull
- Approach the hull
- Execute the hull survey
- Move away 4 m while staying normal to the hull
- Rotate 180º
- Move away from the hull
- Surface to initialize its position with GPS
- Execute a first short waypoint (WPT3), surface
- Reset position with GPS
- Execute a long waypoint away from the ship (WPT4).

The hull survey consisted of 7 horizontal slices of 25 m length to make sure that we would cover the 10 m long grid (Fig. 8). During the first 3 slices (at depth 2.5, 3.5. and 4.5 m), the DIDSON was pointed up in order to image the top part of the instrumented section of the hull. During the last 4 slices (at depth 4, 3, 2, and 1 meter), the DIDSON was pointed down in order to image the bottom part of the instrumented hull section.

Fig. 8: Hull survey over the instrumented section of the hull

C. Demonstration Results

1) Open Water Navigation

Fig. 9 shows the vehicle's trajectory as it transited in and out before and after the hull survey. The vehicle initialized its position with GPS ("Start"), then dove to reach the first waypoint ("WPT1"). Upon reaching "WPT1", it surfaced to reset its position and dove towards "WPT2". At "WPT2", the vehicle did not surface, but instead started to look for the hull with the DVL, approached the hull and execute the hull survey (Fig. 8). Upon reaching the end of the survey, the vehicle moved away from the hull and surfaced very close to "WPT3". It dove to reach "WPT3", surfaced, reset its position and dove towards "WPT4".

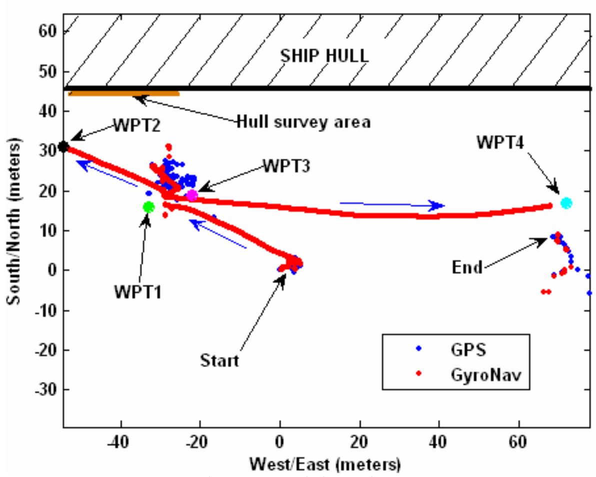

Fig. 9: Transit in and out

2) Hull Acquisition and Approach

During the "Acquire" and "Approach" phases, the DVL is rotated down so that the two upper beams are in the horizontal plane (the lower beams are then looking down and forward). Fig. 10 shows how the vehicle first rotated to make the reported ranges equal and then moved towards the hull while keeping the ranges equal. After reaching the desired range to the hull, the vehicle started to execute the hull survey.

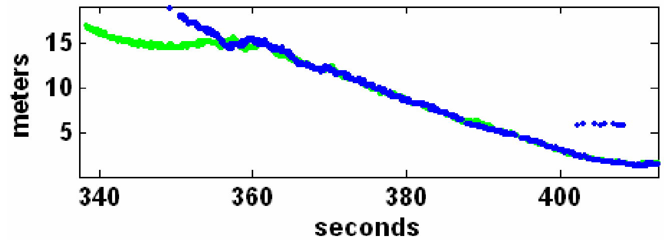

Fig. 10: Ranges reported by the two DVL beams in the horizontal plane during the "acquire" and "approach" phases

3) Hull Survey

Fig. 11 shows the vehicle's trajectory during the hull survey. This trajectory can easily be correlated with the intended vehicle path (Fig. 8).

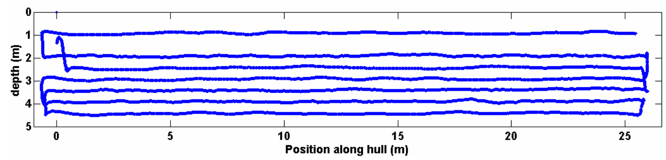

Fig. 11: Vehicle's trajectory during the hull survey

Fig. 12 shows various pitch angles as well as an estimate of the hull inclination with respect to the vertical, It can be seen that, at the deepest part of the survey, the hull is inclined about 40°. The inclination of the hull can also be observed on the 3D hull shape reconstructed from DVL ranges and dead reckoning (Fig. 13).

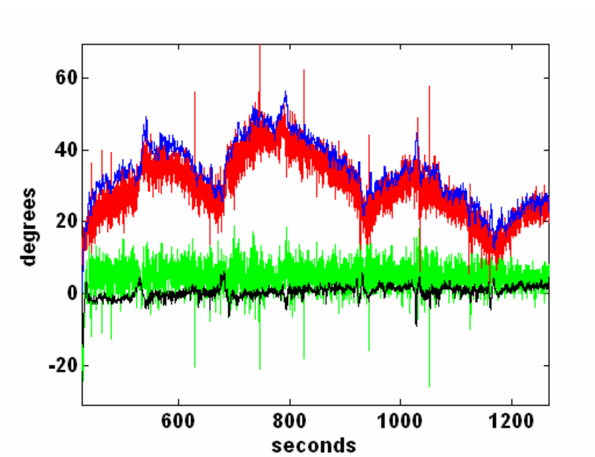

Fig. 12: Vehicle pitch (black), DVL pitch with respect to the hull (green), DVL pitch with respect to the vehicle (blue), hull inclination estimate (red).

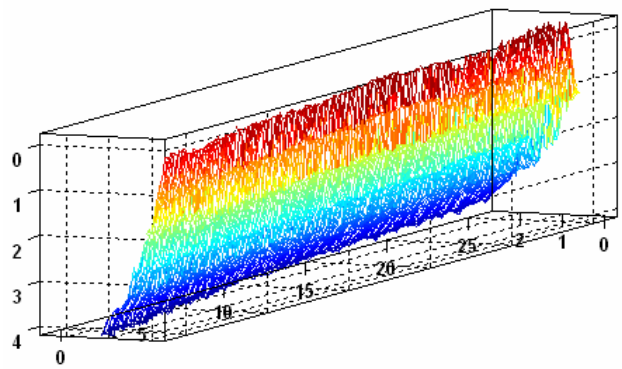

Fig. 13: 3D reconstruction of the hull section covered by the vehicle trajectory

4) DIDSON Imaging and Hull Coverage

Analysis of the DIDSON file shows that the instrumented section of the hull has been successfully covered at 100%. After analysis, we were able to determine that the same coverage could have been achieved with 5 slices instead of 7 by removing the first and fourth slices (Fig. 14).

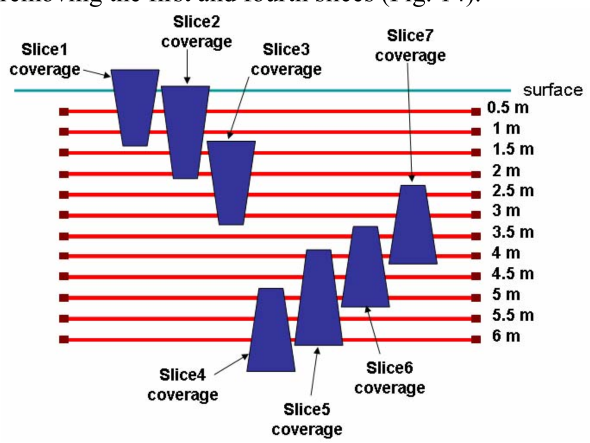

Fig. 14: DIDSON coverage for each of the slices from analysis of the DIDSON data file. Each of the trapezoidal shape slides along the lines as the vehicle executes the slice.

Fig.15 shows one image of the DIDSON file collected on slice 5 at the right-hand side of the grid. Note that since the DIDSON is pointed down, the surface is towards the bottom of the image. A section of the 5 visible polypropylene lines is highlighted with a yellow line to help visualizing those lines in the figure. The tennis balls on the lines at 4.5, 5.0, and 5.5 m from the surface can easily be spotted by their shadows. The 2 tennis balls on the line at 4.0 m distance are further on the right (out of the field of view of this image). The 6 tennis balls on the line at 6 m distance are not picked up by the sonar (they were picked up very clearly on slice 4). All 4 targets were clearly identified and seen several times due to the overlap between the DIDSON passes. Note that there is substantial bio-fouling on the hull which makes the detection of the features more difficult than on a clean hull.

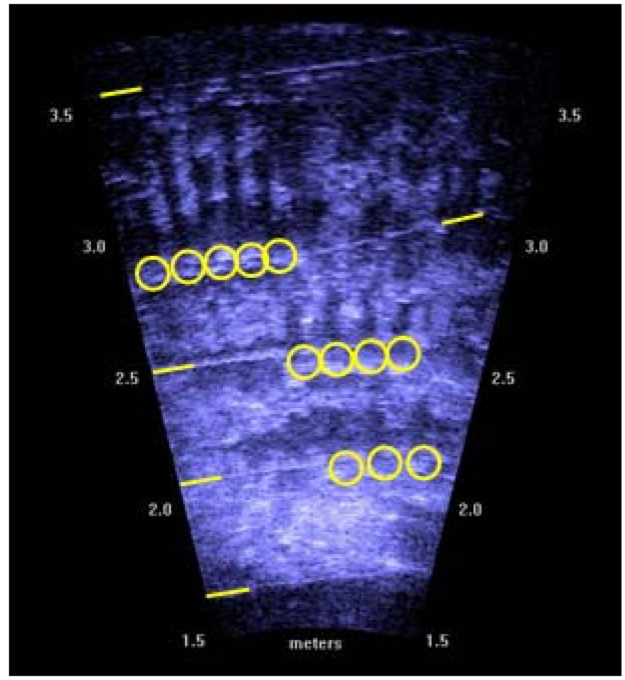

Fig. 15: DIDSON image at the end slice 5

VII. CONCLUSION

The HAUV conducted a very successful demonstration. The vehicle has demonstrated its ability to switch between open water navigation and hull-relative navigation. It has proven to be very robust when executing horizontal slices.

The next step for the project will be to go under the ship using vertical slices. We anticipate this capability to be available before the end of 2005.

Another big step will be the integration of a fiber optic tether developed by SPAWAR SC-SD to transmit DIDSON images to an operator in real-time.

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