A NEW PARADIGM FOR SHIP HULL INSPECTION USING A HOLONOMIC HOVER-CAPABLE AUV

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Keywords: Autonomous Underwater Vehicle, hovering, feature-relative navigation, inspection

Abstract: The MIT Sea Grant AUV Lab, in association with Bluefin Robotics Corporation, has undertaken the task of designing a new autonomous underwater vehicle, a holonomic hover-capable robot capable of performing missions where an inspection capability similar to that of a remotely operated vehicle is the primary goal. One of the primary issues in this mode of operating AUVs is how the robot perceives its environment and thus navigates. The predominant methods for navigating in close proximity to large iron structures, which precludes accurate compass measurements, require the AUV to receive position information updates from an outside source, typically an acoustic LBL or USBL system. The new paradigm we present in this paper divorces the navigation routine from any absolute reference frame; motions are referenced directly to the hull. We argue that this technique offers some substantial benefits over the conventional approaches, and will present the current status of our project.

1 INTRODUCTION AND EXISTING CAPABILITIES

The majority of existing autonomous underwater vehicles (AUVs) are of a simple, torpedo-like design. Easy to build and control, the torpedo-shaped AUV has proven useful in many applications where a vehicle needs to efficiently and accurately survey a wide area at low cost. As the field of underwater robotics continues to grow, however, new applications for AUVs are demanding higher performance: in maneuvering, precision, and sensor coverage. In particular, the ability to hover in place and execute precise maneuvers in close quarters is now desirable for a variety of AUV missions. Military applications include hull inspection and mine countermeasures, while the scientific community might use a hovering platform for monitoring coral reefs, exploring the crevices under Antarctic ice sheets, or close-up inspection in deep-sea archaeology. An autonomous hovering platform has great potential for industrial applications in areas currently dominated by work-class remotely operated vehicles (i.e., tethered, ROVs): subsea rescue, intervention, and construction, including salvage and wellhead operations.

Frequent hull inspection is a critical maintenance task that is becoming increasingly important in these security-conscious times. Most ships (whether civilian or military) are only inspected by hand, in dry-dock, and thus rarely - certainly not while they are in active service. Standards do exist for UWILD (Underwater Inspection in Lieu of Drydock), but divers have typically performed underwater inspections, a time-consuming, hazardous job. Additionally, there is a high probability of divers missing something important, because it is so difficult for a human being to navigate accurately over the hull of a ship, with their hands, and often in poor visibility. With a loaded draft on the order of 30m and a beam of 70m for a large vessel, debilitating mines can be as small as 20cm in size, and in this scale discrepancy lies the primary challenge of routine hull inspection.

Damus R., Desset S., Morash J., Polidoro V., Hover F., Chryssostomidis C., Vaganay J. and Willcox S. (2004).
A NEW PARADIGM FOR SHIP HULL INSPECTION USING A HOLONOMIC HOVER-CAPABLE AUV.
In *Proceedings of the First International Conference on Informatics in Control, Automation and Robotics*, pages 127-132
DOI: 10.5220/0001145701270132

The simplest inspection is a visual examination of the hull surface. Underwater however, (particularly in harbors and at anchor in coastal waters) a visual inspection must be performed very close to the ship. The health of a ship's skin may also be judged by measuring plating thickness, or checking for chemical evidence of corrosion. For security purposes, a sonar image may be adequate because of larger target size. For instance, the US Customs Service currently uses a towfish sidescan sonar to check hulls (Wilcox, 2003).

Some military vessels are now using small, free-swimming ROVs for in-situ inspection (Harris & Slate, 1999). This method eliminates the safety hazard of diver work, but retains the disadvantage of uncertain navigation and human load. The only commercial hull inspection robot, at the time of this writing, is the Imetrix *Lamp Ray*. *Lamp Ray* is a small ROV designed to crawl over the hull surface. The ROV is deployed from the vessel under inspection; the vehicle swims in and closes with the hull under human control, then holds itself in place using front-mounted thrusters for suction. The operator then drives the ROV over the hull surface on wheels. This limits the survey to flat areas of the hull; more complex geometry around e.g. sonar domes, propeller shafts, etc. must still be visually inspected with a free-swimming ROV. The *Cetus II* AUV is an example of a free-swimming autonomous system that has also conducted ship hull surveys (Trimble & Belcher 2002). Using altimeters to maintain a constant relative distance from the hull, and the AquaMap long baseline navigation system (DesertStar, Inc.), *Cetus II* records globally-referenced position information, and this (with depth and bearing to the hull) is the primary navigation sensor used to ensure and assess full coverage. The AquaMap system uses a transponder net deployed in the vicinity of the ship being inspected (see URL in References); clearly, a long baseline acoustic system could be used for any vehicle.

Our vehicle program has three unique aspects to address the needs of ship hull inspection: development of a *small* autonomous vehicle optimized for *hovering*, and of a *hull-relative navigation* procedure, wherein dependence on a deployed acoustic navigation system is avoided. The data product this vehicle will produce is a high-resolution sonar mosaic of a ship hull, using the DIDSON imaging sonar (University of Washington's Applied Physics Laboratory) as a nominal payload (Belcher *et al.*, 2003).

2 PHYSICAL VEHICLE OVERVIEW

The hovering AUV (HAUV, Figure 1) has eight hubless, bi-directional DC brushless thrusters, one main electronics housing, and one payload module. The symmetrical placement of the large number of thrusters makes the vehicle agile in responding to wave disturbances, and capable of precise flight maneuvers, such as orbiting targets for inspection or hovering steadily in place. The vehicle is intended to operate in water depths ranging from the Surf Zone (SZ) through Very Shallow Water (VSW) and beyond, up to depths of 100 meters; and to perform in waves up to Sea State Three.

Onboard non-payload instruments include a Doppler velocity log (DVL), inertial measurement unit (IMU), depth sensor, and acoustic modem for supervisory control. While we do carry a magnetic compass, this cannot be expected to work well in close proximity to a metal hull. As noted above, the nominal payload at this writing is the DIDSON imaging sonar. Both the DIDSON and the DVL are mounted on independent pitching servos at the front of the vehicle, because the DIDSON produces good imagery at an incidence angle greater than 45 degrees, while the DVL needs to maintain a normal orientation to the hull. The DVL can also be pointed down for a bottom-locked velocity measurement.

The vehicle is strongly passively stable, with a gravity-buoyancy separation of about 3cm. It has approximate dimensions of 100cm long, 80cm wide, and 30cm tall; it displaces about 45kg. Of this weight, about 12kg are for a 1.5kWh battery.

3 OUR APPROACH TO HULL NAVIGATION

We have chosen to attack this problem from a feature-relative navigation standpoint, as this has some advantages compared to current approaches. Our basic strategy is to measure tangential velocity relative to the hull being inspected using a Doppler velocity log (DVL), and to servo a desired distance from the hull, and orientation, using the individual ranges from acoustic beams.

The immediate impact of this functionality is the elimination of support gear for the robot itself; no localized network setup like LBL is needed. This reduces complexity and provides a simple, quick deployment where the robot can operate unattended; our long-term goal is that the mission focus could shift towards analyzing the data collected. The lack of a shipboard system presence also means the craft

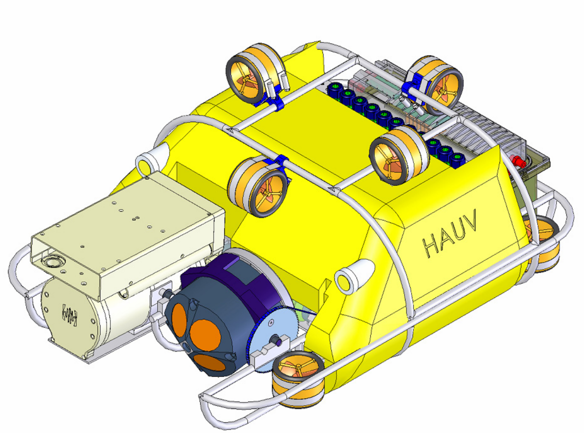

Figure 1: The HAUV, showing DIDSON (light brown) and DVL (dark blue) on the front, yellow flotation in the mid-body, and a large battery at the stern. Thruster locations are reconfigurable; the main electronics housing is underneath the foam

can be deployed quickly to respond to developing situations below the waterline.

As a second benefit, the proposed feature-relative control schemes should work when the ship being inspected is fixed within a close berth (where LBL navigation could be poor), anchored and moving slowly about its mooring, or moving freely at very low speed, e.g., adrift.

The key technical point to note about navigating relative to a fixed hull surface is that the vehicle is constrained absolutely in the DOF normal to the hull, but not tangentially. A featureless hull is a poor candidate for visual or sonar image serving, and the use of DVL velocity measurements for positioning invokes an obvious drift error over time.

3.1 Suitability of the DVL for this Task

The DVL (RD Instruments; see URL in References) comprises four narrow beam transducers, arranged uniformly at a spread angle of 30 degrees, and operating broadband in the frequency range of 1200kHz. The Doppler shift is measured for each beam, and an average sensor-relative tangential velocity vector is computed. We also have available the four ranges from the individual transducers: the device provides range by using the return times from each sensor and the speed of sound in water. Complete (four-transducer) measurements are available at a bandwidth of 3-8Hz, depending on signal quality and range.

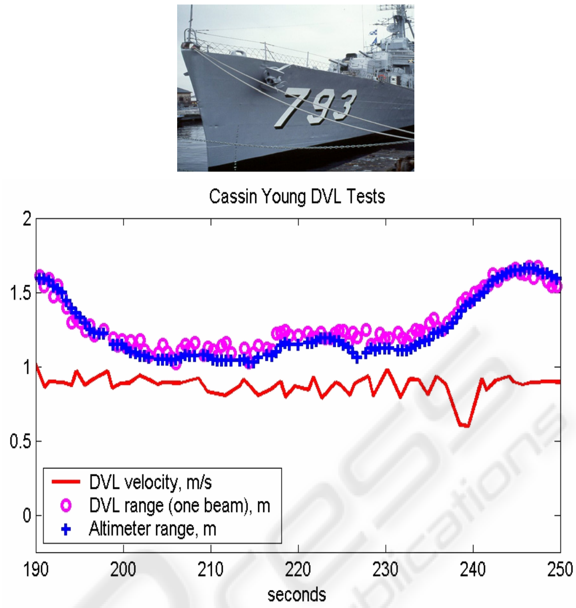

Figure 2: DVL performance when towed along the hull of the *USS Cassin Young*

We performed a series of tests with the DVL, with the specific goal of determining suitability for the hull-relative inspection task. Specifically, we have considered: a) what is the drift rate of the integrated velocities? b) What is the noise characteristic of the independent range measurements? c) What is the effect of a metal hull, with biofouling? d) Does the DIDSON acoustic imaging system interfere with the DVL?

- On a cement and glass wall at the MIT Ocean Engineering Testing Tank, the position error in integrating velocity was confirmed to be about 0.5 percent of distance traveled. The error goes up substantially when the sensor is oriented more than 30 degrees from normal to the hull.

- We performed field tests along the hull of the *USS Cassin Young*, at the Navy Shipyard in Charlestown, Massachusetts. As shown in Figure 2, the range and velocity measurements are well behaved.

- We performed controlled tests at the Testing Tank, with simultaneous operation of the DIDSON and the DVL. DIDSON images (at 5fps) show the DVL pings as a faint flash, but the image is by no means unusable. Conversely, there is a slight degradation of the DVL's velocity performance. The drift rate approximately doubles, but remains below 1cm per meter of distance traveled, which is sufficiently low enough to satisfy our concept of operations.

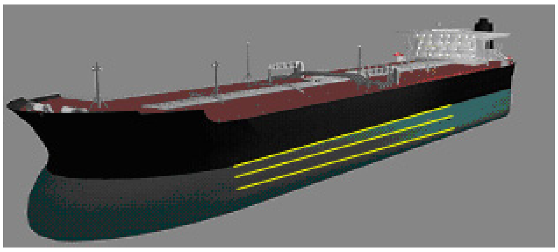

Figure 3: The horizontal slice method; the vehicle makes passes at constant depth

3.2 Two Approaches Using "Slicing"

The DVL can be used to servo both orientation and distance to the hull (through the four independent range measurements) and to estimate the distance traveled, with reasonable accuracy. When coupled with an absolute depth measurement, two plausible inspection scenarios emerge for the majority of a large ship's surface: vertical and horizontal "slicing." For the purposes of this paper, we confine our discussion to the large, relatively smooth surface of the hull sides, bottom, and bow. As with other existing automated inspection methods, the stern area with propellers, rudders, shafting and bosses cannot be easily encompassed within our scheme.

In the case of horizontal slicing (Figures 3 and 4), paths in the horizontal plane are performed. The absolute depth provides bounded cross-track error measurement, while the integrated velocity provides the along-track estimate of position. This along-track position, with depth, is recorded for each image.

Defining the end of a track at a given depth is a sensing challenge to which we see several possible approaches. First, there may be landmarks, such as weld lines, protuberances, or sharp edges as found near the bow or stern areas. These landmarks, especially if they occur at many depths, can be used to put limits on the search area, and to re-zero the integrated velocity error. Certainly prior knowledge of the ship's lines and these features can be incorporated into the mapping strategy at some level.

On the other hand, the complete absence of features is workable also: operate at a given depth until the integrated velocity safely exceeds the circumference of the vessel, then move to another depth. When an object of interest is detected, immediate surfacing must occur in this scenario since location along the hull would be poorly known.

The horizontal slice method is very good for the sides and bow of a vessel. Many vessels, for example, large crude carriers (LCC's) have flat bottoms, which must also be inspected. Here, aside from the fact that the vehicle or the imaging sensor and DVL must be reoriented to look up, there is no cross-track error available, since the depth is roughly constant. Long tracks parallel to the hull centerline would be subject to accrued errors on the order of several meters. The vertical slice approach (Figure 5) addresses this problem, by making paths down the sides of the hull and then underneath, in a plane normal to the hull centerline. Once at the centerline, options are to turn around and come back up on the same side, or to continue all the way under the hull to surface on the other side, after a 180-degree turn in place (which must be constructed based on rate gyro information only). In either case, the important property here is that the path length is limited, so that the cross-track errors are limited, and overlap can be applied as necessary. For instance, using a vertical path length of 130m implies a cross-track error on the order of 65cm, which is easily covered by overlapping images with field of view several meters, assuming no systematic bias.

Convex or concave, two-axis curvature of the hull also requires some overlap. For instance, in the extreme case of a spherical hull and the vertical survey, like ribbons around a ball, the imaged path lines converge at the bottom. These cases will require further study and mission design at a high level.

3.3 Role of Low- and Mid-Level Control

Dynamically, the vehicle is equipped with high-performance thrusters so as to operate in shallow waters, waves, and in proximity to hulls. 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.

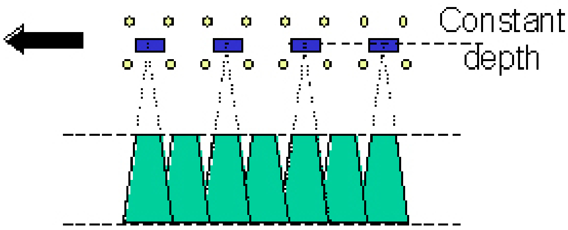

Figure 4: Operation during horizontal survey, looking at the side of the vessel. The vehicle is shown in blue, with the four DVL footprints in yellow on the hull. The DIDSON images (green) are taken looking downward as the vehicle moves

In waves, the depth sensor also fails as a high-bandwidth navigation sensor. As a consequence of these facts, the vehicle has to be capable of short-term autonomous navigation, through a high-end inertial measurement unit, 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 sensor, 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. As in most cases of inner-outer design, the outer loop bandwidth should be at least 3-5 times slower than the inner loop.

Consider for example the case of yaw control relative to the hull. 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 (e.g., Hutchison *et al.*, 1996). Figure 6 gives an illustration of hull servoing using nested low- and mid-level control, and DVL data.

4 SUMMARY

Doppler velocimetry with ranging facilitates a new feature-relative approach for autonomous ship hull inspection, one which allows several intuitive strategies that can account for the majority of the hull surface. The use of landmarks and ship's lines, as well as survey techniques for complex stern arrangements are still open questions.

Support is acknowledged from the Office of Naval Research (Dr. T.F. Swean) under Grant N00014-02-1-0946, and from NOAA and the Sea Grant College Program, Grant NA 16RG2255.

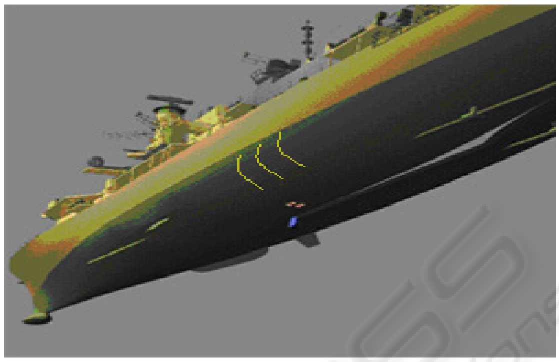

Figure 5: Vertical slice survey; the vehicle makes depth passes with zero sway velocity

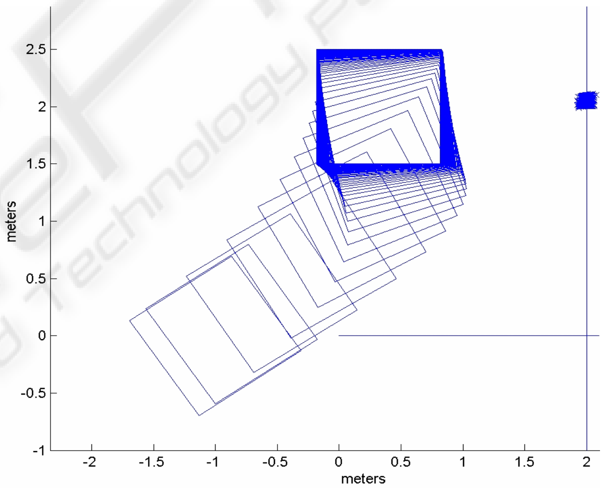

Figure 6: Example of low- (PID) and mid-level (LQG) coupled control in the yaw-sway hull positioning problem. Vehicle initially is at a 42 degree bearing, 3m range; final position is zero degrees bearing, 1.7m range. The controller keeps the tangential velocity small while reorienting, so that the excursion of the DVL "pointer" on the wall (line on right hand side) is 12cm

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