REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 30-09-2006

2. REPORT TYPE: Final

3. DATES COVERED *(From - To)*: 01-09-2002 - 30-09-2006

4. TITLE AND SUBTITLE
Small Autonomous Vehicle for Precision Maneuvering in Survey and R-I-N Missions / Ship Hull Inspection and Harbor Security Autonomous Underwater Vehicle

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-02-1-0946

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Dr. Franz Hover

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Tom Swean
Navy-ONR 321 OE
800 North Quincy Street
Ballston Tower One
Arlington, Virginia 22217

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution unlimited A.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We designed, fabricated, and tested a new autonomous underwater vehicle system to carry out inspections of large ship hulls. The vehicle employs hull-relative navigation, so that operations can be performed without any absolute positioning data, and in poor acoustic environments. The primary payload sensor is an imaging sonar, whose data stream can be sent via fiber optic tether to a ground station for viewing. The system has been successfully demonstrated surveys and target detections on three vessels in Quincy, MA, San Diego, CA, and La Spezia, Italy. Work was performed in coordination with Bluefin Robotics Corporation, under separate ONR funding.

15. SUBJECT TERMS
autonomous underwater vehicle, hull inspection, harbor security

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	12	Franz S. Hover

19b. TELEPHONE NUMBER *(Include area code)*: 617-253-6762

FINAL REPORT

Small Autonomous Vehicle for Precision Maneuvering in Survey and R-I-N Missions

Franz S. Hover
Room 5-426A
Department of Ocean Engineering
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, Massachusetts 02139 USA
Phone: (617)253-6762 Fax: (617)253-8125 Email: hover@mit.edu

Chryssostomos Chryssostomidis
Director, MIT Sea Grant Program
Building E38-300
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139 USA
Phone: (617) 253-7131 Fax: (617) 258-5730 Email: chrys@mit.edu

MIT Award Number N00014-02-1-0946

LONG-TERM GOALS

We aim to facilitate autonomous underwater operations at low speed. These tasks include inspection and detailed survey of complex objects or surfaces, as well as intervention with high precision positioning. Examples are ship inspection, mine countermeasures, and water and soil sampling, in both shallow and deep water. Our intent is to provide cost-effective solutions that reach a broad military, commercial, and scientific market.

OBJECTIVES

Our technological objective was to create a new vehicle class enabling hull inspection and R-I-N (reacquire-identify-neutralize) missions, while maximizing the attributes of small size, low-cost, and high maneuverability. The project goals were:

- Design of a vehicle hull-form for maximizing maneuverability and station-keeping performance, as well as efficient payload sensor layout.
- Design, fabrication and integration of vehicle subsystems, including structure, actuators and sensor packages, flight controllers, power and communications hardware, and intelligent algorithms for mission execution in complex environments such as a rounded ship hull.

- Demonstration of hull/object/feature relative positioning and maneuvering.
- Quantitative testing of an integrated prototype vehicle in open water conditions, and a realistic R-I-N or inspection mission.

APPROACH

MIT Sea Grant's Autonomous Underwater Vehicle Laboratory worked in close collaboration with Bluefin Robotics Corporation on nearly all aspects of the prototype design and testing. Broadly, MIT Sea Grant (F. Hover, P.I.) performed the overall design of many mechanical and electrical components of the vehicle. Bluefin (S. Willcox, P.I.) provided batteries, the main electronics housing, navigation systems, and mission and control software expertise. We have employed tank tests, and to a larger extent, tests on the *USS Salem*, a 700-foot ship docked near Bluefin's Quincy facility.

WORK COMPLETED BY YEAR

FY03

1) A detailed Concept of Operations was developed.
2) The Functional Specification was defined.
3) Tests with two candidate Doppler Velocity Log units were performed, both in tank and open-water conditions, and on a steel hull.
4) Tests with the selected thrusters were completed in laboratory conditions.
5) A prototype battery was designed and assembled.
6) The Main Electronics Housing (MEH) was designed.
7) A comprehensive design review was held, in which seventeen participants were drawn from Bluefin, MIT Sea Grant, and MIT at large.

FY04

1) A second design review was held.
2) The MEH was packed with the vehicle processor and various other components.
3) Thrusters from TSL, with a controller board, were installed on the vehicle.
4) A joystick control system using LabView was developed, enabling us to operate the vehicle in a manual mode.
5) Essential operating system and software behaviors were specified.
6) The core flight control system was designed and coded.

FY05

1) Physical integration of the vehicle was completed, including power system, junction box, main electronics housing, and DVL and DIDSON payloads on pitching actuators.
2) Routine operation of the DIDSON was achieved for imaging tasks.
3) We developed, implemented, and tested low-level flight control routines for depth, yaw rate, pitch, and roll.

4) We achieved routine operation of the DVL – switching modes on the fly to work at different ranges. This included modifications by RDI to the firmware allowing us to employ only two out of four beams.
5) A GPS- and compass-based waypoint capability was implemented.
6) Behaviors were developed for acquiring a vertical hull, approaching the hull, and servoing attitude and distance to the hull.
7) We created horizontal and vertical slice behaviors for effecting systematic coverage of large areas.
8) Three demonstrations were given to Navy and EOD personnel (1/13/05, 5/4/05, 6/28/05) showing the waypoint capability, acquiring and approaching the hull, and vertical and horizontal slices. We showed 100% coverage of an area using ropes and balls attached to the hull, and that could be seen in the DIDSON imagery.
9) We implemented an enhanced vertical slice behavior that allows us to move all the way under a hull – this was tested under the *Salem* from zero to eighty degrees hull inclination.

FY06

1. We developed an HAUV simulator development for onboard software testing.
2. New survey behaviors simplifying mission planning were created.
3. SPAWAR's Fiber Optic tether was integrated.
4. We achieved a real-time DIDSON display over fiber optic and WiFi link.
5. Behaviors were developed allowing transition from the side to the bottom of a flat-bottomed ship.
6. We performed a HULSFest mission demonstration (see below)
7. We performed a NATO Harbor Protection Trials mission demonstration (see below)
8. Overall, survey work on five different hull shapes has been performed: the 719-foot heavy cruiser "USS Salem", a 200-foot barge, the 170-foot R/V Oceanus (WHOI), the 130-foot flat bottom ship "Acoustic Explorer", and a 190-foot Sauro-class submarine.

RESULTS

Concept of Operations Summary. We began with the important observation that most ship inspection tasks are made much more tangible and effective if they do not depend on an external, absolute navigation system. This relative navigation approach is useful for ships or structures that are moving slowly on a mooring, are adrift, or are in the neighborhood of other structures that would impede acoustic navigation systems. The model implies that the vehicle has the capability to perform the survey using only ship features, and, because close inspection is desired, the capability to position relative to the hull. In the simplest case of a vertical wall, if the vehicle can maintain range and orientation to the wall, horizontal passes using depth as a cross-track displacement sensor can be performed; see Figure 1. We recognize that, apart from these vertical faces, hull forms are complex (e.g., curvature, bow-thrusters, props and shafting, rudders) and may not always provide suitable information for accurate positioning (e.g., along a vessel's flat bottom). On the other hand, it is possible to employ hull features in navigation, such as paint marks or weld lines. Advanced approaches for these special conditions have to be developed as part of the mission software.

Functional Specification Summary. To accomplish the goals of the CONOP, we selected a Doppler Velocity Log as our primary navigation sensor. The unit provides range and orientation to a plane, as well as velocity relative to it. Hence, the DVL supports servoing range and orientation to a hull surface, and velocity. In the case of horizontal passes, cross-track error is controlled in an absolute sense by the depth sensor, whereas along-track uncertainty is estimated as less than one percent of distance traveled (based on our tests). For imaging, we implement a DIDSON acoustic imaging system; visual imaging with a digital still camera is considered a backup. These components are located on active-pitch mounts. The vehicle is also equipped with other core systems including an Inertial Measurement Unit, compass, GPS, wireless communications systems; the vehicle can support an acoustic modem. The vehicle is designed to be stable in waves and currents, and so has eight thrusters of very high authority.

Tests with Doppler Velocity Loggers. We tested Sontek and RDI DVL units. The RDI performed much better and we selected it for the vehicle. We tested the RDI extensively at the MIT Testing Tank and characterized the performance over various speed ranges and grazing angles on concrete. At zero angle (that is, perpendicular to the surface) and speeds of 0.2-1.0m/s, we obtained 3-6mm drift per meter of distance traveled, or approximately 0.1m per minute; at thirty degrees, we found 20-50mm per meter drift. Hence, if the DVL can be maintained perpendicular to the surface during operations, we expect very good performance. Our second test with the RDI was in Boston Harbor, where we successfully obtained returns from a steel barge, showing that steel poses no specific difficulties for the DVL.

Tests with Thrusters. We made a vendor survey and found that the only available thruster technology that meets the operational demands of our vehicle – small, powerful, bi-directional – are a recently new product by TSL (UK), formerly Ohmex. These are 70mm ID ducted thrusters, utilizing an external motor. We obtained a 50mm ID prototype and subjected it to dynamic and static tests at the MIT Water Tunnel. We found steady power and thrust levels (200W and 26N) very much in line with TSL predictions, and designed the vehicle for about 50N thrust from new 70mm thrusters. The dynamic response of the thrusters is fast, with a rise time of about 125ms; this is an important aspect for the controllability of the vehicle in precision hovering.

Vehicle Components. (See Figure 2)

- The prototype battery tested at 1.45kWh and performed well in a 5m sustained dunk test. In flight tests, the brittle casing cracked; this was repaired with flexible Urelite polymer. The battery tested out electrically, and was reinstalled on the vehicle.

- The external frame was fabricated from welded 3/8" solid aluminum bar. It is very robust and protects some of the internal gear (e.g., junction box and battery); it also provides good access for clamps and wireways.
- The oil-filled junction box contains the thruster controller board (from TSL), DC/DC converters, and serial to Ethernet converters.
- Pitching mounts for the DVL and DIDSON payloads were completed; each unit has a geared stepper motor attached to the payload via a sprocket and chain assembly. Each unit is controlled by a custom printed circuit board in the same housing as the motor. The devices are accessed through a serial link.
- We leveraged the design of the MEH from the Bluefin 12" vehicle for the hovering vehicle. This saved a tremendous amount of additional development work and troubleshooting, while achieving a compact and robust result. The cylindrical form factor was integrated into the vehicle layout, as was the end-cap penetrators. The MEH contains the majority of electronics components on the vehicle, including main processor and peripheral boards, compass, inertial measurement unit, depth sensor, and various power supplies. Antennas for the radio modem, the wireless Ethernet connection and the GPS/strobe antenna are integrated.

Basic Behaviors and Vehicle Software. The vehicle uses Bluefin's real-time vehicle software Huxley. This software runs under Linux, and its development was supported by the Bluefin9 (Sealion), Bluefin12 (AOFNC) and HAUV projects. Given that the type of missions executed by the HAUV are very different from those of a survey vehicle, the implementation of "layered control" and "navigation" had to be revisited to accommodate for the specificity of the vehicle. Additionally, several HAUV-specific behaviors had to be developed in the Huxley framework. These behaviors include the acquisition, approach and lock of the hull using the DVL. Transit behaviors for the execution of waypoints were modified from the existing behaviors developed for the survey vehicles.

Core Flight Control System. Flight control for the vehicle was decomposed into two major loops. An inner loop uses high-bandwidth and relatively clean data from the inertial measurement unit and the depth sensor to control estimated attitudes and velocities. The DVL, which is used to position the vehicle relative to the hull, is included in an outer, slower loop, because the update rate of this sensor is sporadic and slow. Both loops contain integrated estimation and control algorithms.

Initial Flight Tests Summary. The completed integration of the vehicle and significant software and algorithm development allowed us to run the vehicle extensively on several hulls, from which we learned that the fundamental scheme of DVL-based navigation is tenable, i.e., the positioning and navigation errors are commensurate with the imaging task. We found generally reliable performance of the system on large areas of the hull, as well as reasonable resistance to current disturbances (< ½ knot). The completion of surveys at surface angles from ten to ninety degrees inclination, with the confirmation of 100% coverage, means that very large portions of a smooth hull can be surveyed; see Figure 3.

The work culminated in two major demonstrations, which are described in detail below.

HULSFest 2006. During HULSFest, on February 21st-22nd at SPAWAR Systems Center San Diego, the HAUV executed several inspection missions on the Acoustic Explorer. The mission consisted of:

- Two slices on the side of the ship
- Transition from the side to the bottom of the ship around the chine
- Inspection of the flat mid-section of the ship

The vehicle demonstrated:

- Real time DIDSON data display over the fiber optic + WiFi link
- Good DIDSON imaging that allowed the creation of super-resolution images and mosaics
- Accurate and consistent navigation, within a mission and between missions
- Mapping of the anode locations on the hull with 0.5 m accuracy
- A search rate of about 11.5 m^2 / min with 100% overlap (each point of the hull seen on two consecutive passes)
- The ability to reconstruct the hull shape in 3D from the navigation data

An overview of the HULSFest demonstration is given in Figure 4.

NATO Harbor Protection Trials 2006. During NATO Harbor Protection Trials 2006 in La Spezia Italy, the vehicle inspected a section of the side of a SAURO-class submarine. The mission consisted of five 30-meter long horizontal slices at various depths. The main challenge associated with this demonstration was the curvature of the submarine hull, which was higher than that of most of the ships the vehicle had been operated on. Nevertheless, the vehicle was able to execute its survey pattern and collect DIDSON images. The mine shape placed on the side of the rectangular keel by Italian EOD divers was detected. The DIDSON images were post-processed to create a mosaic rendered in 3D on the submarine hull shape reconstructed from the navigation data.

An overview of the NATO Trials is given in Figure 5.

IMPACT/APPLICATIONS

The vehicle technology we developed should benefit military missions of mine countermeasures and hull inspection, by providing capability to hover autonomously with high precision. It has a wide scientific and commercial appeal as well, as there are currently very few similar platforms available to the oceanographic and offshore industry communities.

RELATED PROJECTS

Work was performed in conjunction with a similar vehicle effort funded by Sea Grant, and F. Hover has performed maneuvering work of this vehicle under ONR Grant N00014-02-C-0202 (J. Valentine); he is also working with M. Triantafyllou of MIT on biomimetic flapping foil propulsion vehicles (Sea Grant and DARPA support), and has worked on application of artificial muscles to variable camber AUV propeller blades and control surfaces, through an ONR STTR (P. Bandyopadhyay) with Molecular Mechanisms, LLC. Current work in micro-pressure transducers for aiding underwater navigation may be relevant in future AUV development. F. Hover works with J. Leonard on the application of localization and mapping techniques in control of underwater vehicles, under ONR Grant N00014-06-1-0043 P00001.

TRANSITIONS

Bluefin is currently fabricating a second HAUV platform, the HAUV1B; this will allow Bluefin and MIT, as well as our other partners in the hull inspection group, to develop further capabilities in imaging and inspection. We have provided HAUV DIDSON data to SeeByte and Sound View Systems for mosaicking (see Figures 4 and 5). A proposal has been submitted by Bluefin in response to the "EOD HULS" request for proposal. This is a phased program with down selection of contractors at the end of each phase (demonstration, delivery of a prototype system, delivery of production systems).

PUBLICATIONS

1. C. Demirel 2002. "Quantification of Dynamical Behavior of a Ducted Thruster Unit." Diploma Thesis, Darmstadt University of Technology and MIT.

2. R. Damus, S. Desset, J. Morash, V. Polidoro, F. Hover, J. Vaganay, and S. Willcox 2004. "A New Paradigm for Ship Hull Inspection Using a Holonomic Hover-Capable AUV." Int. Conf. on Informatics in Control.

3. Hover, F.S., Vaganay J., and Elkins M. 2005. "Relative Inspection Under Ship Hulls." Proc. Unmanned Untethered Systems Technology Conference.

4. Hover, F.S., Desset S., Morash J., Polidoro V., Damus R., Chryssostomidis C., Vaganay J., Elkins M., Willcox S. 2005. "Zero-Visibility Relative Survey with an Autonomous Underwater Vehicle." Proc. Marine Technology for Environmental Sustainability Conference.

5. Vaganay J., Elkins M.L., Hover F.S., Damus R.S., Desset S., Morash J.P., Polidoro V.C. 2005. "Ship Hull Inspection by Hull-Relative Navigation and Control." Proc. IEEE/MTS Oceans.

6. J. Vaganay, F. Hover, M. Elkins, and D. Esposito 2006. "Performance of the HAUV Ship Hull Inspection System Prototype during HULSFest 2006", 7th International Symposium on Technology and the Mine Problem, Naval Post Graduate School, Monterey CA.

7. J. Vaganay, F. Hover, M. Elkins, and D. Esposito 2006. "Ship Hull Inspection with the HAUV: US Navy and NATO Demonstrations Results", IEEE/MTS Oceans.

8. F.S. Hover, J. Vaganay, M. Elkins, S. Willcox, V. Polidoro, J. Morash, R. Damus, S. Desset 2006. "A Vehicle System for Autonomous Relative Survey of In-Water Ships", Control Engineering Practice (submitted).

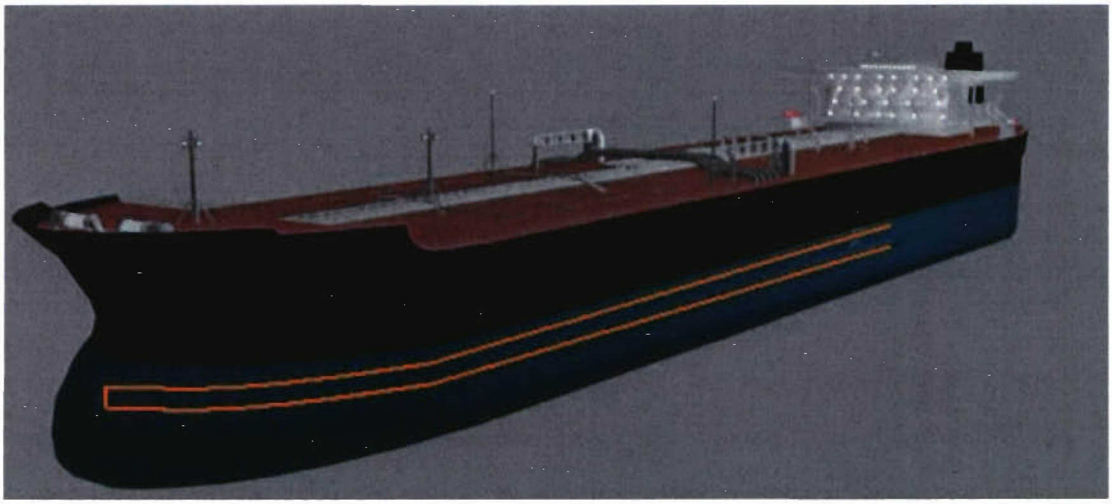

Figure 1. Schematic of the hovering vehicle performing a survey using horizontal slices on a large tanker. The concept of operations entails navigation only relative to the hull.

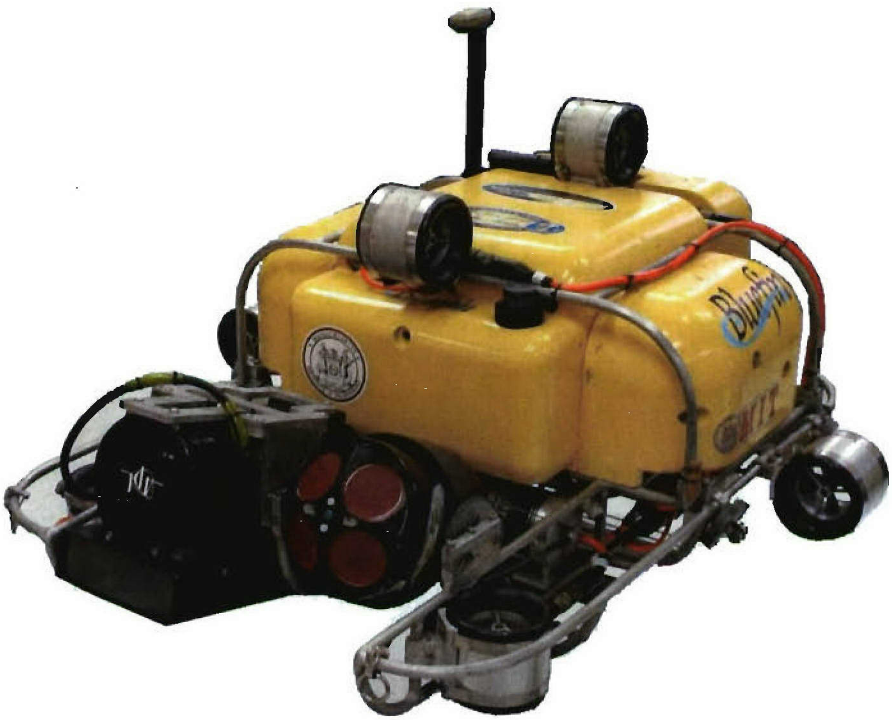

Figure 2. The Bluefin/MIT Hovering Autonomous Underwater Vehicle (HAUV).

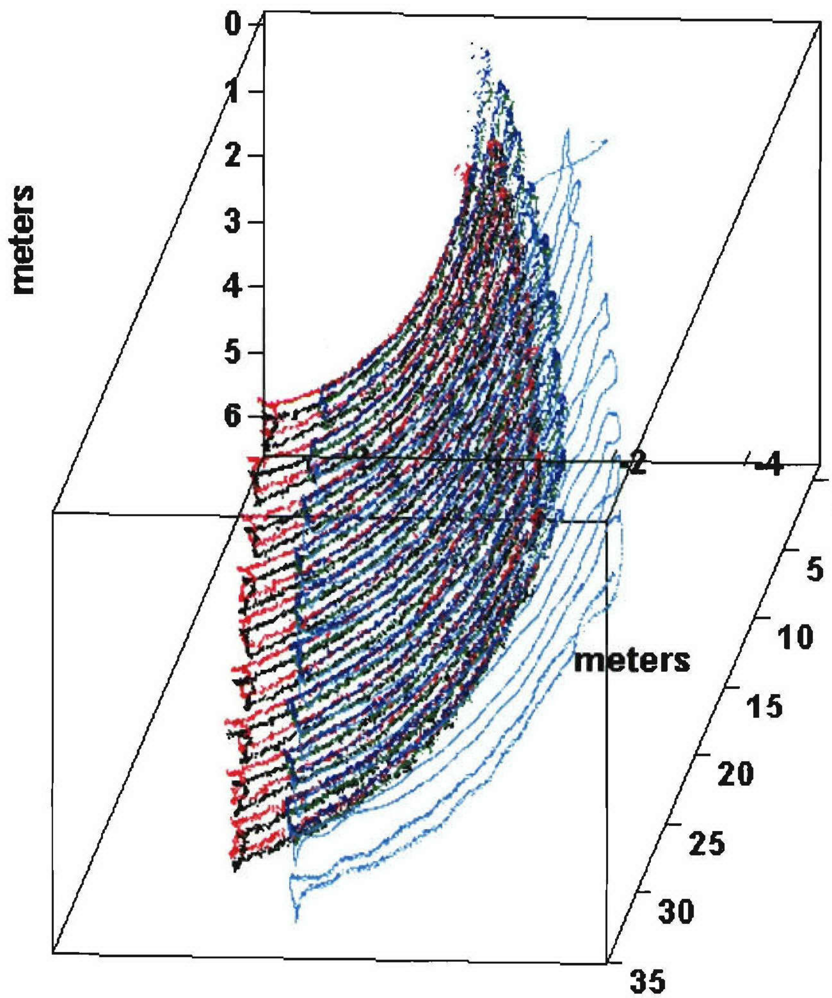

Figure 3. USS Salem hull shape reconstruction as inferred from the HAUV trajectory. This experimental run has twenty vertical slices down to an inclination angle of eighty degrees, separated by short horizontal slices. The blue lines indicate vehicle position, whereas the colored dots show the hull position.

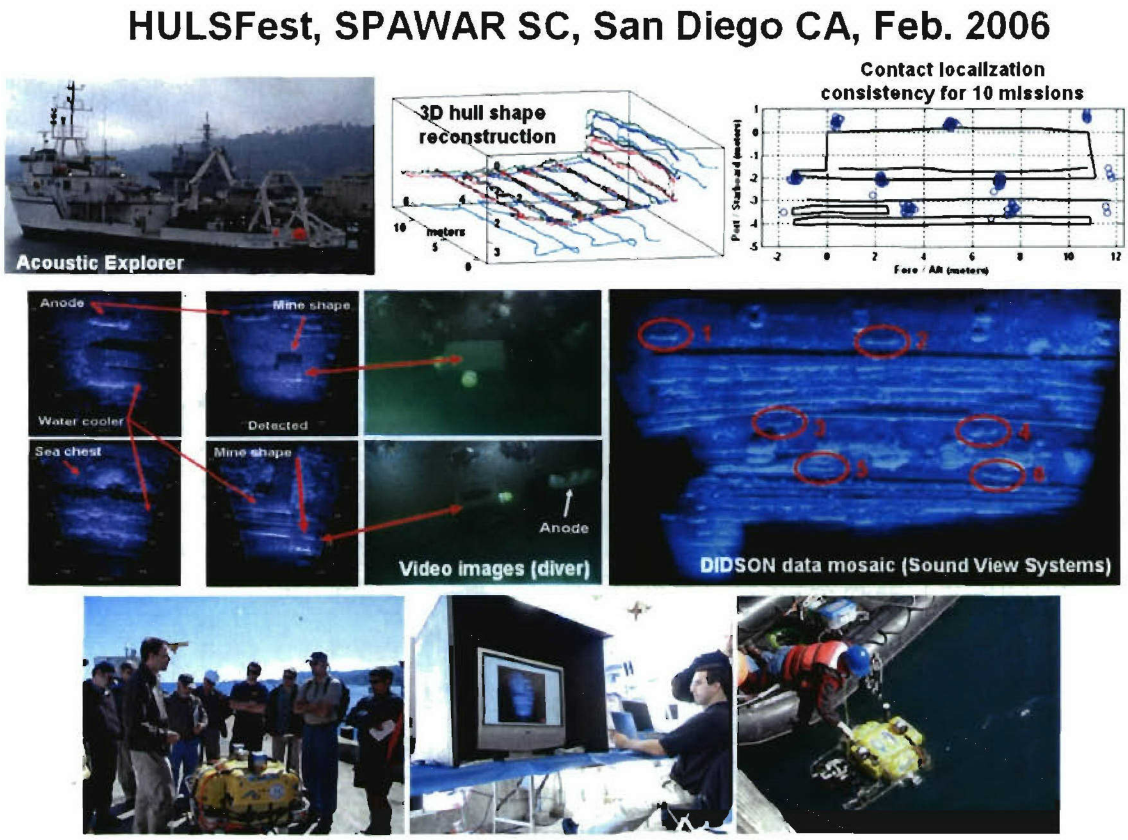

Figure 4. Overview of the HULSFest operation, San Diego, February 2006. The vehicle was deployed successfully nine times under the Acoustic Explorer, yielding high quality DIDSON imagery of the vessel's cooling channels, zincs, and the mine-like objects placed by divers. The repeatability of locating contact points was better than one meter over the nine runs performed.

NATO Harbor Protection Trials, La Spezia, Italy, Apr. 2006

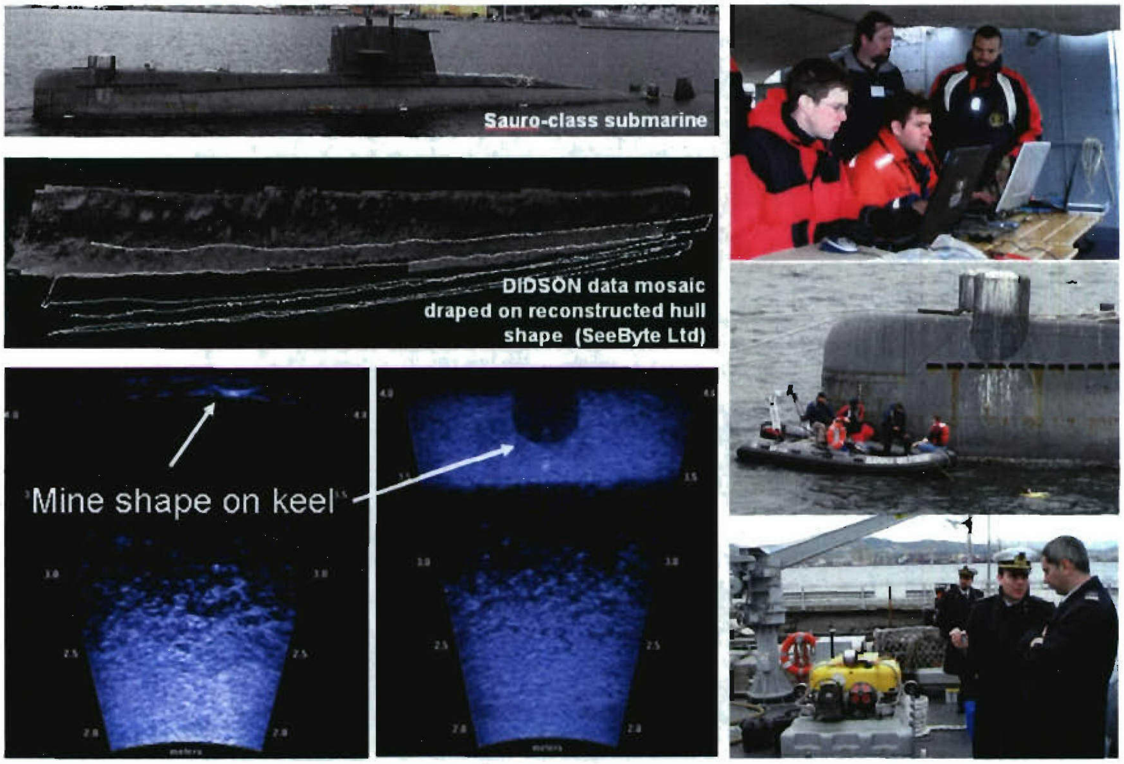

Figure 5. Overview of the NATO Trials, La Spezia, Italy, April 2006. A mine shape was detected on the keel of the submarine using DIDSON imagery.