Results of the Naval Oceanographic Office's 1997 AUV Workshop

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Abstract - The U.S. Navy has been developing Autonomous Underwater Vehicles (AUVs) for operational scenarios for many years. The maturity of this technology has reached a point where it is both feasible and economical to transition AUVs to the collection of environmental data for the Navy. With this in mind, the Naval Oceanographic Office (NAVOCEANO) has established an AUV program with the goal of matching different AUV capabilities to meet specific Navy requirements.

During September 1997 NAVOCEANO worked with scientists from the Woods Hole Oceanographic Institution (WHOI), the Massachusetts Institute of Technology (MIT), and the Florida Atlantic University (FAU). Operating onboard the Texas A&M research vessel GYRE, these scientific teams collected a wide variety of environmental data in Mississippi coastal waters.

This paper compares the AUV technology and the data collected by these institutions with data collected by traditional hydrographic survey techniques, and concludes that each AUV has characteristics that provide excellent quality survey data. The differences in capabilities (size, weight, mission duration, etc.) point out that no vehicle can be expected to meet all survey requirements. The best solution is a suite of vehicles, using common processing techniques, targeted to specific operational scenarios.

I. INTRODUCTION

The Navy's goal is to transition AUV technology into survey systems that can collect environmental data in a cost-effective manner. To meet this goal, the first objective was to define those parameters and survey scenarios that were appropriate to AUV capabilities. We established a working relationship with academic, commercial, and governmental agencies to accomplish this assessment and assure state-of-the-art technology in our data-collection systems [1].

One of the first steps in this process was NAVOCEANO's sponsoring of an AUV evaluation and technology demonstration. These tests were conducted during 5-11 September 1997 in the Gulf of Mexico near Gulfport, Mississippi (Figure 1). With strong support from the Office of Naval Research, AUV teams from MIT, FAU, and WHOI staged their equipment onboard the Texas A&M research vessel RV GYRE. The low-stern freeboard onboard the 185-ft GYRE (built in 1973) provided excellent AUV operational support. Operations were completed at 2200 hours on 10 September 1997, and the GYRE returned to Gulfport on 11 September 1997.

The evaluation process was based on International Hydrographic Office-(IHO-) based shallow-water survey techniques. Each team was provided a copy of the IHO survey specifications as a benchmark to NAVOCEANO's standard survey requirements. Also embarked onboard GYRE was a team of NAVOCEANO scientists and engineers who were tasked with evaluating specific operational areas, including:

- Safe vehicle launch/recovery, and over-the-side support
- Data processing and system compatibility
- Maintenance, training, and mission planning/simulation
- System robustness—high seas, shipping, and long-term reliability
- System costs, manpower, spares, and commercial off-the-shelf availability
- Navigational accuracy—inertial, Differential Global Positioning System (DGPS), and transponder
- Propulsion—motors, batteries, and propeller

II. SURVEY AREA

Two survey sites were selected off the Mississippi Gulf Coast (Figure 1): test area A (4 to 5 meters deep) and area B (10 to 15 meters deep), both areas being 1/4 mile wide and 1 mile in length. Because of the high winds and rough sea conditions on 6 and 7 September 1997, area A was occupied first in the lee of Ship Island in the Mississippi Sound. While data were collected in this area, this time proved to be primarily a shakedown period for all AUV systems. The launch and recovery procedures from the GYRE's Nautilus crane received serious attention from a safety perspective in the rough sea conditions.

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On the evening of 7 September 1997, conditions moderated, and the GYRE repositioned in area B. At area B, two 450-ft Liberty ships (Figure 2) were sunk in 1957 next to each other in 14 meters of water. NAVOCEANO personnel also positioned two minelike targets within the same area. Upon arrival at area B, the AUV teams launched and calibrated their transponder arrays and began survey operations.

In the Mississippi Sound, current patterns, while complex, generally move toward the west. Currents immediately south of the barrier islands flow counterclockwise in the fall months. Current velocities generally range from 1 to 2 knots. Bottom topography throughout this area is relatively flat, with sand ripples in the shallower waters and more muddy sediments in water depths greater than 10 meters. These waters are extremely turbid because of high volume of suspended sediments and particles from various river outputs and the resuspension of silt-sized bottom sediments.

III. BASELINE SURVEY

The week before the AUV teams arrived, a NAVOCEANO survey team conducted a groundtruth survey in both areas A and B. Using IHO survey standards, the survey team aboard a hydrographic survey launch (HSL) (Figure 4) collected environmental data with the following systems:

- EG&G side scan (100 kHz)
- Seabird CTD (SBE 10)
- Differential Global Positioning System (DGPS)
- HYPAC survey planner and data logging system
- Echo Track Single Beam (200 kHz)
- Bottom grab sampler

Both areas were surveyed with eight (75-meter line spacing) east/west-trending lines to provide complete data coverage. Bathymetry data were postprocessed for corrected sound velocity and corrected tides. Sidescan was in an analog format so that the data and coverage were manually matched and positioned. A side-scan image (100 kHz) of the Liberty ships are presented in Figures 2. These data were used for comparison purposes against the data collected by the AUV teams. Copies of the sound velocity and tide predictions were provided to the AUV teams to allow for onboard data corrections.

IHO survey standards provided to the AUV teams not only described Navy survey techniques but, more importantly, gave detailed levels of accuracies required. A summary of these standards focusing on AUV survey requirements is presented in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Survey/Vehicle Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification/IHO</td>
<td>Order 1 – Harbors, Order 2 – Harbor</td>
</tr>
<tr>
<td>order of survey</td>
<td>Approaches, Order 3 – Balance of Areas</td>
</tr>
<tr>
<td>Horizontal accuracy</td>
<td>Order 1 – 5 m, Order 2 – 20 m, Order 3 – 150 m, +/-5% of depth to all orders</td>
</tr>
<tr>
<td>Depth accuracy</td>
<td>Order 1 – .5 m, Order 2 &amp; 3 – 1 m</td>
</tr>
<tr>
<td>Ensonification</td>
<td>100%</td>
</tr>
<tr>
<td>Maximum line spacing</td>
<td>Order 1 – 3X avg depth, but not less than 25 m, Order 2 &amp; 3 – 3X avg depth but not less than 200 m</td>
</tr>
<tr>
<td>Mandatory hydrographic factors</td>
<td>Conductivity, temperature, acoustic backscatter (side-scan sonar) depth</td>
</tr>
</tbody>
</table>
Desired hydrographic factors
Survey speed
Mission planning/simulation
Data viewing in the field
Vehicle

<table>
<thead>
<tr>
<th>Desired hydrographic factors</th>
<th>Sediment classification, optical, and currents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey speed</td>
<td>6-10 knots for 8-12 hours</td>
</tr>
<tr>
<td>Mission planning/simulation</td>
<td>Programmed tracklines, line spacing varies with depth, vehicle locations</td>
</tr>
<tr>
<td>Data viewing in the field</td>
<td>Near-real-time data quality/survey holidays</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Modular, easy to repair/train, lightweight</td>
</tr>
</tbody>
</table>

IV. REMUS - WOODS HOLE OCEANOGRAPHIC INSTITUTION

Woods Hole Oceanographic Institution developed its Remote Environmental Measuring Units (REMUS) to conduct scientific research in coastal oceans, bays, and estuaries [2]. The vehicle (Figure 3) was fairly small, with a body length of 53 inches and a diameter of 7.5 inches. The vehicle length could be expanded to accommodate other reasonable payloads. The base design weight was 68 lbs in air, and could be trimmed for operations in fresh or salt water.

Figure 3. WHOI's REMUS AUV

The REMUS vehicle control computer was based on PC-104 technology. The central processing unit (CPU) was mounted on a custom motherboard, and had eight 12-bit analog to digital channels, I/O ports, power supplies, and other interface circuitry. REMUS ran a DOS program written in C++ that executed out of an autoexec.bat file. The host program, running on a laptop computer, was designed to run on top of Windows 3.1 or 95 and was connected to the vehicle via an RS-232 link.

REMUS was an all-aluminum, air-filled pressure housing with a plastic, free-flooded nose section forward of the front endcap. Operating depth was expected to be 150 meters. All electrical feedthroughs were made through the forward endcap, and all the electronics, batteries, and control actuators were contained inside the air-filled cylindrical pressure housing.

Power was supplied to REMUS by sealed lead-acid batteries. The system used commercially manufactured 2-volt, 5-amp-hour cells with a maximum rated power density of 44 watt-hours/kilogram. Power can also be supplied externally through a deck cable.

Heading was maintained by an off-the-shelf triaxial magnetometer (Precision Navigation, Inc.) with an integral electrolytic pitch and roll sensor. It was connected to the main CPU via an RS-232 link and provided updates at a 10-Hz rate. Other sensors included Marine Sonics Side Scan (600 kHz), RD Instruments Acoustic Doppler Current Profiler (ADCP) (1.2 MHz), and Ocean Sensors CTD. An example of side-scan data is found in Figure 4.

Figure 4. REMUS Side Scan of WWII Liberty Ships

Vehicle propulsion was gained from a direct-drive DC brushed motor driving a small propeller shaft on internally mounted ball bearings. Both pitch and yaw control surfaces were aft-mounted fins. Each pair of fin shafts was cable chain and sprocket driven. Roll control was achieved via a stiff-gravity, buoyancy-induced righting moment. In flat, calm sea conditions, the vehicle was manually submerged to...
begin operations. In rougher sea states, enough control sur-
faces were exposed to the water to allow surface starts.

The major means of navigation used was a Short Base Line
(SBL) system. Onboard the vehicle was a transducer array
called Relative Tracking System (RATS). This system con-
sisted of a small array of hydrophones that was precisely po-
positioned, thus giving the ability to measure the range and
bearing to the transponder which transmitted the sound. Be-
cause of the nose-mounted aspect of the REMUS array,
WHOI used at least two transponders oriented in the direction
of the survey to provide complete area coverage. In addition,
a Track Point system (range of 1.5 nmi) was hung over the
side of the support vessel to provide range and bearing of the
REMUS vehicle.

Also demonstrated was a subsurface navigation system,
which consisted of an ADCP and the magnetic compass.
While not measured during this demonstration, expected ac-
curacies should be approximately 1% of the distance trav-
elled. Bottom track velocities, altitude off the seafloor, and
depth below sea surface were the collected data types. The
shallower than optimum depths encountered probably pre-
cluded much usable current data from the ADCP system.

The light weight and size of the vehicle made maintenance,
launch, and recovery very easy. In fact, use of an HSL or
similar support vessel is preferable. The 1-meter prepro-
grammed mission turn-on system was fairly reliable, and
toward the survey's end, the vehicle was routinely tossed
over the side to begin its operation.

The WHOI mission-planning tool was very complete and
easy to use. The text mission planning files were made
mostly using the cut-and-paste features of an editor. Mission
playback was done with the same system. The manufac-
turer's acquisition and processing software was used in all
cases. Data were recovered from the vehicle at the end of the
mission by plugging an ethernet cable into the vehicle, which
downloaded the data into a laptop computer.

V. ODYSSEY - MASSACHUSETTS INSTITUTE OF
TECHNOLOGY

MIT's Sea Grant Laboratory Odyssey (Figure 5) was con-
structed about five years ago, and received many upgrades
since. The Odyssey, the only full ocean depth (6000+ me-
ters) AUV evaluated, is one of five currently being used.
With a length of 82 inches and a diameter of 22 inches, this
hydrodynamically efficient vehicle used lead weights and
syntactic foam to ballast (slightly positive) and trim prior to
launch. The 360-lb vehicle used a highly resilient polymer
exoskeleton. For strength, glass sphere pressure housings
were used to house operating systems and power source. The

battery sphere also helped to expedite battery swapping.
Seals and connectors were tar-coated and taped, producing a
very reliable deep system. Using Silver-ZincCells (3.2 kW-
hour) batteries gave the Odyssey approximately 12 hours @
3+ mph. The control surfaces were surfboard fins propelled
by a two-bladed propeller.

![Figure 5. Odyssey AUV](image)

Navigational instrumentation used for the tests were Trim-
ble NT200D GPS, a KVH gyro, and a magnetic flux gate
compass; they determined position, course changes, attitude,
and heading. Navigation data were in the sensor manufac-
turer's format and could be put into ASCII. Primary navi-
gation was with DGPS-positioned Benthos transponders (tx
on different frequencies; rx on the same frequency). Position
of the AUV relative to the support ship was determined with a
TrackPoint II acoustic system and Winfrog software. Posi-
tions were plotted in real-time on a computer display. MIT's
confidence in their total navigation/operations was evident by
the fast turnaround times and maintenance-free missions.

Other onboard sensors included a SeaBird SBE-25 CTD,
installed with a pump to flow water over the sensor and
maintain correlation of the temperature and salinity to reduce
errors. CTD data were logged in SeaBird format (ASCII
compatible). An RDI ADCP was used to determine altitude
and currents in the water, and to correct across the bottom
drift in a dead-reckoned position. A Para Scientific depth
sensor (pressure) (with a stated accuracy of 1 part in 10 to the
sixth) was used. The side scan was an Institute of Ocean
Science system (100 kHz), which produced a 16-bit digitized
analog signal as a function of time. An example of the side-
scan data is presented in Figure 6. The resolution of this im-
age is affected by the fact that this side-scan sonar was tuned
to observe oceanographic frontal features and not bottom
contacts.
The vehicle logged 6 Mb/hr of data for about 300 variables. All data logging was synchronized to GPS. Time was initialized in the ADCP, and then the computer’s clock kept the time. An ethernet cable was plugged into the vehicle to program its computer and to download data to the ship. Calculated waypoints and desired vehicle behaviors were converted to a text file, downloaded to the vehicle, and played back by the AUV. It was then viewed in a simple graphic simulator to check for accuracy.

The Oceanic Imaging Consultants (OIC) GeoDAS Geophysical Data Acquisition System was used for data acquisition, logging, and display. This software can be purchased in Unix version and handle systems made by SIMRAD, SEAMAP, EG&G, or Klein.

Shipboard movement of the vehicle was accomplished with mobile carts. Launch, while requiring an overhead crane, did not require diver support due to the wire-mounted quick-release shackle. Recovery required a small boat to position the AUV within range of the crane.

VI. OCEAN EXPLORER - FLORIDA ATLANTIC UNIVERSITY

Florida Atlantic University (FAU) developed a series of AUVs known as the “Ocean Explorer” (OE) series [3]. Their vehicles (Figure 7) were the largest evaluated (7-10 ft long and 21 inches in diameter), with wet weights of over 900 lbs, a depth capability of approximately 300 meters, and a range 36 nmi (12 hours at 3 knots). The OE series offered some unique capabilities, such as a modular approach toward interchanging the aft propulsion/battery section with a variety of payloads and control systems.

The FAU vehicles were made with a hard fiberglass exoskeleton, internal handmade closed-cell foam floatation, and individual subsystem pressure vessels. The system used passive buoyancy; therefore, it was dependent on forward motion to maintain depth. The 48-volt battery (Nickel-Cadmium) container was positioned in the mid-body, securely joining the forward and aft sections. Propulsion was a DC brushless motor that drove either a three- or five-bladed propeller through a five-to-one gear reduction box. The rudder and dive planes were driven separately by a step servo and angular spline gears. These provided positive control surface movements for both pitch and yaw.

Onboard sensors included Precision Navigation, Inc. compass (± 0.5 degrees), EdgeTech side scan (100/390 kHz), RD Instruments ADCP (1.2 MHz), and a Falmouth CTD. When long baseline navigation was used, an EdgeTech transponder (11-13 kHz) was used. Examples of the data are presented in Figure 8.
User interface was through an umbilical for all data transfer. Mission demonstration and maintenance interface was not a simplified display, but a line-per-line program format. Vehicle commands and waypoints were entered into a text file and downloaded to the vehicle computer which played the mission. The mission text output is read, compared, and checked for accuracy. Vehicle speed logged in terms of revolutions per minute (RPM) in order to calculate battery life accurately. Data products required fairly complicated processing techniques, and much of it had to be postprocessed using MATLAB®.

Maintenance and mission initialization on the vehicle were accomplished via a small vehicle viewport, which gave the condition of the vehicle systems and also contained the magnetic switches to turn on and off the vehicle and its programs. Launch and recovery required a strongback being bolted to the snout of the crane. With the crane cable and hook running through the receiver, both launch and recovery were very smooth once the vehicle was pulled into the strongback. This process and program initiation required diver support.

FAU navigational emphasis focused on GPS/DGPS data to update their onboard navigational system. This ability to periodically update their position allowed the team to place less emphasis on the dead reckoning or transponders. Two configurations of the GPS/DGPS were used. In the first approach, problems with a tethered surface float that would continuously provide DGPS fixes were experienced. The second method used a vehicle pop-up antenna, which housed the GPS receiver. This method worked very well, and the resulting track plot clearly shows the updated position.

The FAU team also had the ability to communicate with the vehicle during operations. This was accomplished using an EdgeTech acoustic modem, which allowed the team to track the progress of the vehicle up to 1 nmi away and receive heading, speed, latitude and longitude, and GPS/DGPS status. They could also modify their survey program on the fly through this acoustic link.

VII. CONCLUSIONS

The NAVOCEANO team and numerous dignitaries who observed these evaluations were particularly impressed with the AUV technology and professional attitude of all concerned. As discussed, each system, while often taking a different approach to the same problem, had unique capabilities essential to high-quality survey operations.

What would we like the Navy’s AUV to look like? While the Navy’s mission extends from the shore to the oceans’ depths, AUVs seem to have their greatest cost efficiencies in the shoal waters (less than 200 meters), where big ship operations are often restricted. Current speeds of 2-3 knots are commonplace worldwide, so a vehicle speed of 5 knots is important. Our system should have standard IHO survey sensors, with the ability to add on additional parameters as required [4]. A range of 300 nmi would be a reasonable goal. A low-cost ring laser gyro (doppler compensation) navigator with the ability to update DGPS would provide navigational accuracy. Shipboard launch and recovery without diver support is required. Mission planning and vehicle simulation will allow the operator to review mission planning and replay mission accomplishments. Near-real-time data procession is needed to avoid costly area resurveys. While this sounds like a lot to ask for, the technologies for every one of these requirements currently exist. Putting them in a reasonably priced package will be the challenge.

The AUVs demonstrated off the Mississippi Coast provided an excellent benchmark for meeting Navy survey requirements. The AUV can act as a force multiplier to existing survey assets, provide low-cost survey mileage, and safely accomplish both day and nighttime operations. The Navy plans to transition AUV technology to meet these challenging goals.

VIII. REFERENCES