

# Experiences with the Operation of a Commercially-Available Deep-Water AUV

J. L. Williams  
University of Southern Mississippi  
1020 Balch Blvd  
Stennis Space Center, MS 39529 USA

Dr. V. L. Asper  
University of Southern Mississippi  
1020 Balch Blvd  
Stennis Space Center, MS 39529 USA

G. H. Taylor  
University of North Carolina at Wilmington  
5600 Marvin K. Moss Lane  
Wilmington, NC 28409 USA

**Abstract**-The demand for autonomous underwater vehicles is increasing but applications are restricted due to complexity and cost of development and operation. We have acquired a commercially-available deep-water AUV and are presently operating it from vessels of opportunity. Experiences gained from both the development process and field operations are discussed and generally applicable recommendations are abstracted from specific events.

## I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are increasingly being deployed in response to heightened requirements for ocean and seafloor observations as demanded by commercial interests (e.g., mineral exploration), military interests, and academic research (e.g., seafloor geology, marine biology). Historically, vehicles capable of deployment on the continental slope (~ 2km water depth) have typically been operated by dedicated commercial companies (e.g., DeBeers Marine, C&C Technologies), the military, or vertically integrated research groups (e.g., MIT Sea Grant, MBARI). This has been in part because of the developmental and operational costs and because of the intensity of engineering and development required for each of these relatively unique systems. As a result, AUVs are not broadly used in relevant academic research, where alternative technologies and techniques are still favored. In order to more fully exploit the capabilities of AUVs, they more become more accessible:

- widely available
- transportable
- deployable from ships of opportunity
- operable by technician-level personnel
- cost effective

### A. NIUST and Its Goals

In 2004, the National Institute for Undersea Science and Technology (NIUST) at The University of Mississippi and The University of Southern Mississippi undertook a program to procure and operate an AUV program. Within NIUST, the Undersea Vehicle Technology Center (UVTC) applies technology to support the National Oceanic & Atmospheric

Administration (NOAA) mission as it relates to stewardship of natural and cultural ocean resources and understanding the ocean's role in climate. The Center partners with NOAA-supported scientists and others to develop, improve, support, and operate vehicles and associated instrumentation for undersea research. Its mission is to develop advanced vehicles and associated instrumentation for undersea research and exploration.

### B. NIUST AUV Requirements

From September 2002 to September 2003, NAUV managers polled various stakeholders in and outside NOAA to determine their priority scientific needs and desired capabilities for a new AUV program. The sixteen responses represent program needs versus individual science needs and include representatives from all the NURP centers, NOAA Office of Marine Operations, NOS, NOAA Fisheries, USGS, U.S. Navy and other academic institutions. Technical requirements were augmented to insure a multi-discipline-capable platform and to examine the segregation of vehicle manufacture and operation. Summary of the results (*Table I*) support purchase of a 1500-m AUV designed primarily for seafloor mapping.

The highest priority application, habitat characterization, is best served by at least a 1000 m depth capability. For example, out of 8 new proposed MPAs in the South Atlantic Bight, 6 are on the shelf edge between 100 and 600 m. Over half of the total area of the National Marine Sanctuaries is deeper than 100 m. At these depths, the resolution of surface-based acoustic mapping systems drops significantly. A significant investment for the initial purchase will be made by the NIUST Sensors and Observatories program, which is most interested in providing support for a new gas hydrate observatory and research program in the Gulf of Mexico at 1400 m. Many of NURP's research programs require diving below 100 m using costly in situ systems. These operations benefit greatly from availability of high-resolution charts and habitat maps to help guide subsequent exploration and

research diving. Other priority science applications and objectives that a 1500-m AUV may serve include:

- Plumes, water mass fronts and habitats: sampling and survey of convergence zones, habitats, and point source emissions into water column, such as from seafloor vents and seeps;
- Ocean observing systems: spatial extension of mooring and platform observations, and event-driven (e.g., seafloor slumps or storms) surveys;
- Homeland security: new sensing technologies and procedures related to safety of the nation’s ocean-based assets and infrastructure, for example, commerce, and oil and gas installations.

TABLE I  
SUMMARY OF NURP AUV REQUIREMENTS

<b>Priority applications</b>	<ul style="list-style-type: none"> <li>•Habitat characterization</li> <li>•Seafloor and water column mapping (e.g., chemical plumes or water masses)</li> <li>•Observatory support</li> <li>•Test bed for new sensor technologies</li> </ul>
<b>Vehicle capabilities</b>	<ul style="list-style-type: none"> <li>•1500 m depth</li> <li>•10 km range</li> <li>•2 day endurance</li> <li>•4 kt speed</li> </ul>
<b>Sub-system capabilities</b>	<ul style="list-style-type: none"> <li>•Payloads: side-scan sonar, CTD, obstacle avoidance/sector scan sonar, ADCP, multibeam/backscatter sonar</li> <li>•Modularity to permit connection to other optional sensors (e.g., various chemical, optical or acoustic sensors)</li> <li>•Electronic navigation system; 1 meter accuracy</li> <li>•Inertial navigation system</li> <li>•Tracking/positioning to &lt; 50 m accuracy</li> <li>•Heave/pitch/yaw detection system; accuracy of &lt; 1°.</li> </ul>
<b>Other operational considerations</b>	<ul style="list-style-type: none"> <li>•“Off-the-shelf” system or upgrade proven, existing design;</li> <li>•Deployable from vessels of opportunity of &gt; 25 m LOA</li> <li>•Handling system part of system package or standard equipment on most research vessels;</li> <li>•Dedicated team of no more than two persons (additional staff may be untrained and on as available basis, e.g., watchstanders) to handle operation and maintenance of the system and sub-systems.</li> </ul>

### C. Acquisition and Operation

Based on the survey, the UVTC acquired the International Submarine Engineering (ISE, Port Coquitlam, BC) AUV configured for both mapping missions and to serve as a platform for the development of new and powerful tools, sensors, and capabilities to support NOAA research. ISE has built over 200 undersea vehicles since its founding in 1974. The company engineers and develops vehicles, propulsion systems, and flight controls, and integrates commercial sensors such as inertial guidance systems and sonars.

In 2004, collaboration was established between NIUST and the National Undersea Research Center (NURC) at the University of North Carolina at Wilmington (UNCW) wherein a team of technical specialists was identified and tasked with supporting the development and operation of the vehicle. When the construction contract was let to ISE, the NURC team had responsibility for the program monitoring and

oversight, and for the refinement of specifications during the engineering and development at ISE.

## II. THE EAGLE RAY AUV

### A. Physical Description

The *Eagle Ray* AUV is the second in ISE’s Explorer line of AUVs. The vehicle is 5.1 m in length, 0.69 m in diameter, and weighs 882 kg dry. Aluminum pressure hulls rated to 2200 m (sea water) comprise approximately half of the vehicle length; the remaining fiberglass hull sections being flooded. The bullet nose and tapered aft section were designed to minimize hydrodynamic drag.



Figure 1. *Eagle Ray* AUV

The forward flooded hull section houses a bottom avoidance sonar, a pop-off buoy and recovery line, pressure (depth) sensor, inertial navigation system, multibeam sonar receiver, and conductivity-temperature-depth (CTD) instrument. The aft flooded hull section houses a retractable mast with communications antennae and the propulsion motor. Lead ballast is located in both fore and aft hull sections. The multibeam sonar transmitter is surface mounted beneath the center hull section.

Propulsion is provided through a two-bladed propeller, driven through a 3:1 reduction gearbox. Vehicle attitude is controlled through the integrated action of six control planes, two forward and four aft. Maximum forward speed is 2.5 ms<sup>-1</sup>; normal survey speed is 1.75 ms<sup>-1</sup>.

Within the main pressure hull are located 18 lithium-ion rechargeable battery modules, the vehicle control computer and interfaces, the multibeam sonar computer, and various power and logic control devices.

Vehicle telemetry and real-time pilot control communications utilize hardwired Ethernet, radio Ethernet, and/or proprietary acoustic channels, as appropriate and available.

### 1. Vehicle control system

The AUV’s Vehicle Control Computer (VCC) and the surface-based pilot station (Surface Control Computer, SCC) are built on an Ethernet backbone. Other primary sub-sea components include a network time server, multibeam sonar processing unit, and Ethernet radio modem. Surface components include the Mission Planning Workstation

(MPW), the Acoustic Tracking Computer (ATC), a wireless access point, and the Ethernet radio modem.

Other devices and sensors in the vehicle are controlled by digital inputs and outputs or through asynchronous serial communications interfaces, all originating in the VCC.

## 2. Software Architecture

The VCC and SCC comprise PC-compatible hardware running the Unix-like real-time operating system QNX. The QNX OS provides a multi-threaded, deterministic scheduler with file system and network support. ISE has developed a highly structured application package – Automated Control Engine (ACE) – which runs on the QNX platform and which, when fully configured, provides the functionality that defines the *Eagle Ray* AUV.

The ACE Core consists of the generic scheduler engine and a library of *components*. Each component provides a prototype of a specific behavior or set of actions through a compliant interface made up of *attributes*. Attributes comprise a schedulable *event* and an optional *value*. The *configuration* is a list of all components declared and the interconnection of their active attributes through events (see Fig.2).

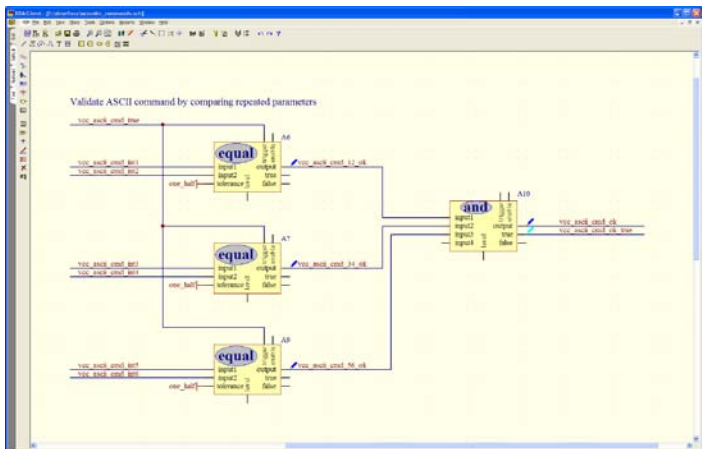


Figure 2. ACE Configuration Example

Custom components may be created to interface to unique devices (such as the Kearfott SEADeViL inertial navigation system) or to provide some specific new behavior.

The component/event system of design for ACE is so highly structured that the configuration is actually described using a schematic capture program. It is viewed and interpreted in a manner analogous to a hardware schematic diagram. Editing the diagram modifies the configuration and thus the vehicle behavior.

## III. DEVELOPMENT, TEST, EVALUATION, AND APPLICATION

### A. Development

Although the Explorer-class AUV is a commercial product, the numerous customer-specific requirements, features, and capabilities require a close working relationship with the manufacturer during this process. During the 20 months

between order and delivery, the operations team and the manufacturer interacted closely to discuss status updates, design adjustments, and to begin training of the operations team by exposing team members to the system components and assembly techniques.

While the initial goal was to have a system that could be operated from a graphical user interface (GUI), the complexity of the control system demands a certain level of familiarity with the underlying operating system and control software. To a great extent, this user interaction has been reduced to mechanical actions through an exacting checklist originally written by ISE and since elaborated by the operations team. Training then could be divided into three categories: vehicle mechanical, vehicle operations, and development engineering. Several personnel from the operations team participated in the truncated formal training sessions covering the former two categories. In reality, the complexity of the system as a whole and the plethora of complex sub-systems is beyond the simple training originally envisioned. Instead, operations and mechanical maintenance have evolved through time as team members gain experience in each area.

### 1. Pre-delivery Testing

Vehicle delivery was predicated on two distinct events, each with very specific criteria of performance: factory acceptance trials (FAT) and sea acceptance trials (SAT). Structuring the program in this way provided clear milestones for payment purposes, various opportunities for operations training, and melded well with the normal work-flow of the manufacturer. Factory acceptance trials consisted primarily of simple mechanistic demonstrations of each feature of the vehicle and the control system. For the most part, these criteria were established by the manufacturer and could be performed on the shop floor. Following FAT, the manufacturer spent several weeks at sea and in the shop completing development and preparing for sea acceptance trials. The criteria for SAT were also established during this period by both the manufacturer and the representative of the operations team. Whereas the manufacturer tended to focus on the operation of the vehicle itself, the operations team required criteria that demonstrated overall performance of the system in its intended use, i.e., as a multibeam data acquisition platform.

### 2. Operations – Launch and Recovery

While on the surface, an AUV is more vulnerable to damage from collision or wave action than while underwater, the transition from free-floating to ship-coupled motion being the critical moment in each evolution. Safety of personnel is a key consideration during launch and recovery operations; high-risk actions (swimmers, small-boat operations, hoisting of unstayed objects) are to be minimized. To address these requirements – and with consideration for operation from vessels of opportunity – the UNCW team designed and built a launch and recovery system (LARS).

The LARS consists of a *ramp* with a spreader bar lift point, on which the AUV rests, and a *truck* which rides along a set of

I-beam rails and is attached to the ramp by a pivot (see Fig. ??). The ramp has a remotely controlled, heavy duty 24-volt winch (Warn Industries, Series 9) attached to the forward bulkhead and carpeted rails on which the AUV slides and rests. The truck rides on four wheels inside the I-beam rails, and the ramp has six supports (or feet) that rest on plates inside and clear of the rails. The I-beam rails are attached to a custom ISO platform for ease of transport and mounting to vessels' decks. The platform is secured to the vessel at the stern by welding to the deck or to mounting plates which are themselves secured to deck fittings. The basic LARS is designed for vessels with a low freeboard (<2 m); LARS and deck extensions are used for vessels with higher freeboard (up to 3.3 m).

The LARS relies on the ship's A-frame or crane to lift and move the ramp out over the transom of the vessel until the truck reaches the end of the I-beam rails at the stern. A pipe through the rails secures the truck in place. When the vessel is in position at the launch site, it continues making way at ~3 knots through the water. To launch the AUV, the aft end of the ramp is lowered into the water. A depressor plate pulls the ramp down against the resistance of the water and prevents shock loading of the crane or A-frame cable. The winch, which is fitted with a sacrificial line passed through a lifting eye on the AUV and back to a cleat on the LARS, is activated to lower the AUV down the ramp. The AUV is released by cutting the sacrificial line near the cleat. The crane or A-frame then lifts the ramp, the locking pipe is removed, and the LARS is moved to its stowed position on the rails and locked in position.

For recoveries, the AUV is fitted with a pilot-activated pop-off buoy attached to ~16 m of floating tow line. The ship backs to position the AUV on its stern quarter close enough to recover the tow-line with a grapple. The buoy is removed and the tow-line is mated to the end of the winch line. The vessel then makes way forward to bring the AUV in line with the LARS ramp. The winch pulls the AUV to the ramp. When the AUV nose meets the ramp and begins to rise along the padded rails, the crane or A-frame lifts the ramp clear of the water decoupling it and the AUV from wave motion. The locking pipe is removed and the LARS with the AUV is moved to its stowed position on the rails and locked in position. Cables for communications and charging are connected to the AUV and the AUV is serviced and prepared for the next mission. The AUV generally remains on the LARS for the entire research cruise.

To date, Eagle Ray launches have proven to be easy and without problems and require only three individuals: deck supervisor, crane operator, and a deck hand to remove and replace the locking pipe. For recoveries, one or two extra deck hands are useful to help manage the grapple, mate the tow and winch lines, and operate the recovery winch. The low-cost Launch and Recovery System has proven to be a sound design concept and has enhanced the operation of the Eagle Ray AUV.

### 3. Mission Planning

Each mission plan begins with a conceptual layout using whatever bathymetric charts or other data are available. The concept is then transposed onto an electronic chart using the FleetManager program from ACSA (Meyreuil, France). FleetManager facilitates the layout of routine surveys using a basic "lawnmower pattern" defined within user selected boundaries, line spacing, run-in distances, turning rates, etc. The output of FleetManager is a text file containing all of the requisite waypoints in a format compatible with the AUV. Operators then manually insert this file into a preexisting *mission template* developed by the operations team which contains standard initialization and mission completion actions. In addition to providing a uniform structure to all missions, this method assures that certain standard operating procedures and emergency maneuvers, procedures, and entry points are included in the final mission file.

During underwater operations FleetManager provides simultaneous display of:

- ship's position, speed, and heading
- AUV position from acoustic telemetry
- AUV position from USBL tracking
- predicted AUV position from simulator software

The FleetManager display is repeated on the ship's bridge. The ship's position relative to the AUV is monitored by the AUV pilot and maneuvering requests are radioed to the bridge.

## IV. EXPERIENCES

Prior to delivery of the AUV, discussions with operators of other vehicles identified three likely scenarios that any operator would have to deal with during operations:

- Losing the vehicle (temporarily)
- Planting the vehicle on the sea floor
- Recovering a dead vehicle

In spite of attempts to prevent these, all three circumstances, plus an entanglement with a crab trap buoy, were encountered within the first six months of operation.

Each of the following events demonstrates the highly-integrated, tightly-coupled, and complex nature of the vehicle, its control system, and its operation – a nature that can produce behaviors which, while predictable in retrospect, represent such convoluted chains of events as to appear random at the time of occurrence.

These scenarios all exhibit characteristics of complex systems:

- while behaviors may be deterministic in retrospect, system complexity precludes *a priori* knowledge of all possible failure scenarios
- when observing some specific effect (fault induced or otherwise), disambiguation of cause may not be possible without large quantities of information about vehicle state

### *Loss of vehicle*

During our first deployment, as the pilot was preparing the vehicle to dive in mission mode he neglected to switch the navigation source from GPS to inertial. This was an easy mistake to make, simply overlooking one of many buttons and indicators on the GUI.

As a result the AUV dove and continued to use the last good GPS fix as its current position to determine the required heading to reach the next waypoint. The effect was for the AUV to proceed in a straight line on the bearing to the first waypoint, and to continue on this heading *ad nauseum*.

When the vehicle neglected to make the first turn of the planned survey it became evident that something was wrong. Unfortunately by this time the vehicle was out of range of the tracking system and, until further investigation identified the likely source of the problem, the ship was unable to be directed in any sensible fashion to look for the vehicle. Essentially, the AUV was lost.

Within fifteen minutes the mistake was recognized and it was then possible to plot the likely heading and speed of the AUV and to start the ship moving in that direction. Because by practice we wrap all motive verbs with failsafe timers, we were able to predict precisely when and roughly where the vehicle would surface.

Which it did.

Several important lessons were distilled from this experience:

- The need for a pre-Mission checklist, similar to the thorough pre-dive checklist already extant
- The value of color cues on the GUI in affirming correct configuration for a dive
- The importance of having the tools and skills necessary to change software in the field (in this case to inhibit diving with GPS selected as the navigation source)
- The value of an aggregated “Mission Ready” status condition to quickly alert the pilot to an anomaly

#### *1. Planting the vehicle on the sea floor – of the importance of proper buoyancy and trim*

An AUV must be ballasted close to neutral buoyancy and specific trim values for safe and efficient operation. If a vehicle’s buoyancy is too far off it may not dive or, worse yet, float. During flight, improper buoyancy will lead to biases in the control surfaces, increasing drag and reducing efficiency.

The Eagle Ray AUV relies on static positive buoyancy of 8 to 12 pounds for floatation and for returning to the surface in the event of a loss of propulsion while underwater. Ideal trim is level with a slight (5°) roll bias to compensate for the rotational torque of the propulsion system. ISE provided a detailed spreadsheet identifying all components in the vehicle, their weight and buoyancy, and the location of their centers of gravity and buoyancy. By manipulating this spreadsheet according to water density and/or changes to the vehicle, the operator is able to predict the required lead ballast (or foam flotation) required for proper buoyancy and trim. In practice, this methodology is valuable in obtaining a first-attempt

ballast regime. However it is still necessary to empirically demonstrate proper buoyancy and trim in confined water, extrapolating final ballast values to the expected water densities in the operational area.

On one early mission, the buoyancy was correctly adjusted but the trim was not, resulting in an uncommanded encounter with the seafloor. Review of the vehicle logs after the mission showed that the vehicle was significantly heavy in the nose, resulting in a dive attitude for which the planes were unable to compensate. Under normal mission operations, this error would have gone undetected but, for unrelated reasons, the vehicle was recalled to the surface and its “Surface Fault Response” resulted in an unplanned dive. This response was defined to set the planes to angles calculated to steer the vehicle in a constantly rising spiral and the thruster to a low, safe RPM. Unfortunately the nose-heavy trim caused the vehicle to pitch at an angle that was greater than could be overcome by the low forces generated on the control surfaces at this low speed.

The following changes resulted from this experience:

- The testing of in-water trim in addition to buoyancy
- Modified planes’ angles for aggressive climb
- The addition of an acoustic *Stop* command

#### *2. Recovering a dead vehicle*

In the preceding scenario, the method used to stop the propulsion system also released the pop buoy. When the vehicle eventually floated to the surface, we were unable to pilot it because of the risk of entanglement in our own recovery line.

In this situation, the ship had to perform all required maneuvers for aligning the two vessels, approaching for line recovery, etc.

It is worth noting that the ISE design includes a manual release for the pop buoy so that if the AUV is completely non-responsive at the surface the buoy can still be released for recovery operations.

The change recommended from this experience is:

- The need for an acoustically delivered command to stop propulsion without releasing the pop buoy.

#### *3. Gone walkabout*

At the end of a particular long dive the vehicle surfaced at the planned time and place, but instead of announcing its presence with radio telemetry was silent instead. Keen eyes on the ship’s bridge sighted the vehicle while the pilots in the lab were awaiting telemetry.

Nothing attempted by the pilots could establish telemetry with a vehicle that was within a few hundred meters of the ship. While still trying to establish communications with what was assumed to be a quiescent vehicle, the bridge radioed to say that the vehicle was underway and that they were following it.

The mission ended with a behavior that should have kept the vehicle in one location, but instead it was steaming full-speed in an easterly direction. After a few moments the bridge

radioed to say that it had stopped. Shortly thereafter the next radio call and it was moving again. Meanwhile, nothing could be done by the pilots to establish telemetry.

This seemingly arbitrary behavior of steaming and stopping, steaming and stopping continued for about an hour. Then with no intervention by the pilot, the vehicle suddenly raised its mast and started radio communications. The pilot took control and a normal recovery ensued.

Post-mission analysis of the vehicle logs fully explained the behavior in terms of a chain of events:

- 1)The Paroscientific pressure sensor used to determine depth had developed a clogged port and residual pressure remained in the sensor when the vehicle surfaced.
- 2)The residual pressure was interpreted as the vehicle still being below the surface and as a result, the normal surface events – raise mast, GPS enable, radio comms, satellite comms – were not invoked.
- 3)The Doppler velocity log used for velocity aiding with the inertial guidance system was set to only detect velocity relative to the seafloor, and not to perform watermass pings, this in an effort to reduce the likelihood of acoustic interference and due to recommended procedures when operating in areas of high currents. With no velocity aiding, the inertial system was running “free inertial” and began to drift
- 4)As the drift increased, the vehicle responded by attempting to “circle\_current,” i.e., to stay in the same geographic location. With the inertial system reporting a changing position, the vehicle attempted to return to where it thought it was supposed to be.
- 5)As the drift worsened, significant errors began to creep into the velocity measurements as well. At some point, the velocity reached the maximum possible numeric value allowed in the inertial computer’s memory and “wrapped” to the maximum negative velocity
- 6)The AUV is designed to not make reverse turns of the thruster (unless specifically commanded by the pilot) and so responded to the indicated velocities by alternately stopping the thruster (when velocities were too high) and running at full speed (when velocities were too low).

While the observed behavior is fully explainable in retrospect, the extrapolation of the observations to the explanation was impossible at the time.

Changes effected (or planned) as a result are:

- Cover the depth sensor port with an oil-filled bladder to prevent clogging
- Identify a separate means of detecting the surface (e.g., GPS reception)
- Set the DVL to automatically select either bottom- or water-lock during ascent

#### 4. Aquabatics – or the importance of tuning

The vehicle’s flight control surfaces and propulsion system comprise a complex, interrelated control system. Individual control loops establish setpoints for each process variable using some algorithm or heuristic. If the parameters for a

particular control loop are wrong, the observed response may oscillate, overshoot, wander, be sluggish, or otherwise exhibit undesirable behavior. Mechanical factors may also degrade vehicle dynamics, including unbalanced (asymmetrical) control surface responses and/or roll due to changes in thrust-induced rotational torque.

#### Vehicle control system

Two layers of control loops govern the actions of the propulsion system and six control surfaces. Each control loop relies on context-specific setpoints and real-time feedback. The planes control systems also incorporate a matrix operation for converting the simultaneous attitude and depth forces into plane-specific forces.

TABLE II  
PROPULSION CONTROL SYSTEMS

Speed	Layer 1 Pilot Control
RPM	Layer 2 Technical Control
Thruster Motor	Physical Layer

TABLE III  
PLANES CONTROL SYSTEMS

Heading	Roll	Pitch	Depth	Altitude	L1	
			Vertical Mode Select			
X			Maneuvering Matrix		X	
Plane 1 Angle	Plane 2 Angle	Plane 3 Angle	Plane 4 Angle	Plane 5 Angle	Plane 6 Angle	L2
Plane 1 Motor	Plane 2 Motor	Plane 3 Motor	Plane 4 Motor	Plane 5 Motor	Plane 6 Motor	Phy

#### Proportional-Integral-Derivative (PID) controls

A PID controller is a common control loop mechanism. ISE has implemented a PID component in their ACE software and in the Eagle Ray configuration every control loop is an independent PID controller with unique gains for each process variable. Using the same mechanism for all controls facilitates vehicle tuning through a uniform interface for operator manipulation and a commonality of dynamic response.

The control loops on Eagle Ray are tuned empirically and iteratively until the observed behavior is judged ‘acceptable’. Judgment is based on flight dynamics, where consistent, level flight at targeted depth (or altitude) and heading is the goal.

ISE spent several days during testing and SAT tuning the vehicle. In an effort to reduce attitude oscillations, this work was further refined with an additional 8 hours of tuning at sea. In those 8 hours over 40 dives were performed and the resultant data analyzed. Each dive consisted of three minutes of straight flight at 20 m depth, a 180° turn, and a straight line return leg. After each dive, tuning logs were downloaded from the vehicle, analyzed, and new control parameter values determined. Two tuning regimes were simultaneously investigated, allowing a set of new parameters for the one

regime to be tested while the data from the previous dive (and other regime) were analyzed. Vehicle speeds were between  $1.5 \text{ ms}^{-1}$  and  $2.0 \text{ ms}^{-1}$ ;  $1.75 \text{ ms}^{-1}$  being our nominal survey speed.

TABLE IV  
RESULTS OF SYSTEM TUNING

Observed	Before	After
Roll Rate	1.79 %/s	0.75 %/s
Pitch Rate	0.39 %/s	0.30 %/s
Yaw Rate	0.48 %/s	0.32 %/s
Depth Error	0.23 m	0.04 m

## V. AREAS FOR FURTHER STUDY

### A. Meta-data

The Eagle Ray AUV comprises a highly-integrated system of computers, sensors, flight systems, and control software. There are approximately 400 parameters in the control software that the pilot can change. The Kongsberg EM2000 multibeam sonar has dozens of configuration and run time settings.

The vehicle's position underwater is determined by the Kearfott SEADeViL inertial navigation system. Beyond the accuracy of the initial GPS-derived position, the inertial system drifts over time and it can be particularly influenced by water currents when not "in sight" of the seafloor.

Adjustments to the SEADeViL's position are performed with dynamic updates via acoustic communications using data derived from a USBL positioning system. The USBL tracking system has inherent limitations on accuracy, as does the ship's heading sensor and the (proposed) motion reference unit.

Taken together, these represent some of the meta-data associated with any data collected by the vehicle.

At present, there is no obvious means to reduce this meta-data to simplistic values; instead, the data are provided along with the total log files of the vehicle, the tracking system, the mission planning software, etc. As much as is known about the vehicle state is delivered with the raw data.

### B. Acoustic interference

The vehicle has four acoustic sources, three of which operate in the region of 200 kHz – the Kongsberg EM2000 multibeam sonar, the RDI Workhorse DVL as part of the SEADeViL inertial guidance system, and the Kongsberg 1007 Altimeter for bottom avoidance. The fourth acoustic source is the LinkQuest TrackLink transponder which operates at frequencies below 20 kHz.

As delivered, the ping regime has the three down-pointing sonars firing simultaneously. Prior to this ping control acoustic interference was prevalent in the multibeam data. With the imposition of this control no interference occurs at altitudes above 40 meters, with sporadic but increasing

interference evident in altitudes down to 10 meters (the lowest measured).

Work is ongoing to experiment with other cyclic and/or priority-based regimes to reduce or eliminate interference at lower altitudes.

### C. Inertial drift

Because of the particular method implemented by ISE for performing alignments of the SEADeViL inertial guidance system, it is difficult or impossible for the SEADeViL to complete a moving base alignment on a fast-moving ( $>5 \text{ ms}^{-1}$ ) ship or in the water where surface currents exist.

This has made operations in or near the Gulf Stream difficult and, in extreme cases, has compromised operations altogether.

This shortcoming is recognized as the primary deficiency of the system as a whole at this time and work is ongoing to directly integrate a GPS source with the SEADeViL inertial computer.

## VI. CONCLUSIONS AND RECOMMENDATIONS

### A. Commercially available yes, but not turn-key

Although ostensibly a commercial product and based in large part on commercial off-the-shelf (COTS) technology, the highly specialized nature of the *Eagle Ray* AUV has demanded the development of custom and/or leading-edge technology products (e.g., high energy density rechargeable lithium modules).

Our experiences with these various technologies have emphasized the prototypical nature of these subsystems and have led to the need for higher than anticipated vendor support both from the vehicle manufacturer and from primary suppliers.

#### 1. System complexity

The characteristics of complexity, high-integration, and tight-coupling lead to certain recommendations, including:

- Broad access to vehicle state information through acoustic telemetry
- Variety of acoustic commands available to the operator for dealing with unanticipated eventualities
- Real-time logging of as much vehicle state as practicable to facilitate post mortem diagnosis of anomalous events

While it is a worthy goal that operations be confined to a simple GUI, the truth is that the complexity of the system *in toto* demands a deeper understanding of the control systems by at least some members of the operations team. Anomalies occur with all computer operating systems – events which compromise the operation of the control system application or operating system in this case – and these must be dealt with immediately as they arise.

That being said, the value of a graphical interface cannot be overstated. The GUI presents information in an organized fashion with items collated by feature or purpose and status highlighted through consistent use of color. The GUI

facilitates pilot and watch-standing actions, reducing the need for specialized training for all team members.

## 2. *Software Issues*

### *Field changes to software*

Notwithstanding the GUI-based control, various faults and failures will occur during normal operations that cannot be foreseen and therefore cannot be accommodated within the limitations of the GUI. Software bugs may also be identified in the course of field operations. The capacity to change the control software is essential to field operations, as is the technical expertise to effect these changes.

Some means of controlling, documenting, tracking, and archiving software changes is essential to on-going maintenance and further development of the system.

### *Importance of software compartmentalization*

It is highly desirable that the control software be compartmentalized in such a way that changes to one area of the control system can be made confidently with no unanticipated artifacts of the changes affecting other areas of the vehicle's operation. The nature of actual operations is such that changes are made during periods of intense pressure without adequate oversight, review, and/or testing. To the extent that the effects of the changes are constrained to the area of interest, the likelihood of implementation errors is decreased.

### *Importance of structured software*

Similarly, the use of a structured software environment contributes significantly to the containment of effect within a

desired area and to the quality of the underlying components manipulated in any change.

## 3. *Tools and talents*

Mechanical damage to the vehicle is a realistic probability given the realities of the working environment. Areas of particular vulnerability are projections such as control surfaces and antennae. To the extent possible, spares of these items should be available and the ability to quickly replace (and calibrate as necessary) is a valuable aspect of vehicle design.

Clearly too, the appropriate tools and technical expertise must also be on board to effect repairs as needed.

## 4. *Environmentally controlled space*

An environmentally controlled work space is essential for effecting repairs that require the opening of any pressure hull. This requirement can be minimized through good design by the vehicle manufacturer, e.g., simplicity of plane replacement. Nevertheless, certain failures will require the opening of a pressure hull and without the appropriate environment available on board, the mission goals will be compromised if the ship must return to port to service the vehicle.

## ACKNOWLEDGMENT

This work is supported by NOAA contract numbers NA16RU1496 and NA06OAR4300227.