Advanced Technology in Motion: NIUST's AUV Fleet

Dr. A.-R. Diercks
National Institute for Undersea Science and Technology
Undersea Vehicle Technology Center
UM Field Station
15 CR 2078
Abbeville, MS 38601 USA

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

J. L. Williams
National Institute for Undersea Science and Technology
Undersea Vehicle Technology Center
University of Southern Mississippi
1020 Balch Blvd
Stennis Space Center, MS 39529 USA

M. Woolsey
National Institute for Undersea Science and Technology
Undersea Vehicle Technology Center
UM Field Station
15 CR 2078
Abbeville, MS 38601 USA

Abstract - **The National Institute for Undersea Science and Technology (NIUST) owns and operates two Autonomous Underwater Vehicles, an International Submarine Engineering built Explorer class AUV and a Woods Hole Oceanographic Institution built Seabed AUV. These two AUVs have completely different operational requirements and tasks based on their physical layout and propulsion. The torpedo-shaped explorer class AUV is used for multibeam mapping and carrying third-party or experimental instrument payloads. The Seabed AUV, propelled by three independent thrusters, is used for close-up sub-sea photographic and multi-beam site investigation which takes advantage of its slow speed and maneuverability. The high resolution digital photography can be used to construct spatial photomosaicis of the target area. Both vehicles will be introduced during this talk, highlighting their operational parameters and presenting some of the data collected with each results from previous deployments of the systems.**

I. INTRODUCTION

The use of autonomous vehicles in the oceanographic research over the last decades has become more widely spread, ranging from gliders to fully maneuverable vehicles with advanced control mechanisms. These AUVs are platforms for advanced research, and development of new technologies is in association with these vehicles is cutting edge science and engineering. The National Institute for Undersea Science and Technology (NIUST) was established in 2002 by the University of Southern Mississippi and the University of Mississippi in partnership with NOAA's Undersea Research Program (NURP) to develop and apply new technologies that enhance undersea research. NIUST is made up of three divisions: the Ocean Biotechnology Center & Repository (OBCR), the Seabed Technology Research Center (STRC), and the Undersea Vehicles Technology Center (UVTC) which broadly encompass the fields of biotechnology (e.g., biomedical and agrochemical products) and engineered technologies (e.g., instrumentation development) in the marine environment. NIUST is providing cutting edge technologies to NURP and their constituencies to further the nation's research capabilities in nearshore, deep water, and extreme marine environments. Program objectives are focused on exploration, research, and advanced technology development.

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A. AUV Facility

NIUST's AUVs are being housed at the University of Mississippi Campus in Oxford, MS at a new building, dedicated in October 2008. The air-conditioned shop provides a modern three-bay facility for working on the electronic and computing systems needed to operate the vehicles. The new shop provides NIUST with a central location to work on innovative technology development for its high-tech undersea vehicles. Integration and manufacturing of mechanical components takes place at the mechanical workshop of the Mississippi Minerals Research Institute (MMRI) a partner of NIUST's Seabed Technology Research Center also located in Oxford.

II. THE EAGLE RAY AUV

A. Physical Description

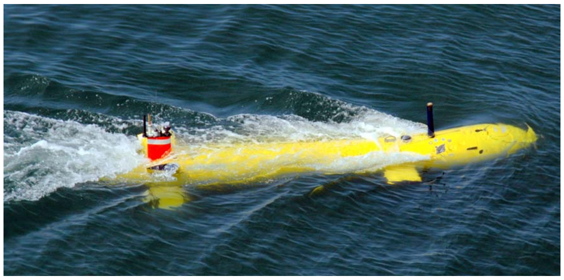

Fig. 1 Eagle Ray AUV

The Eagle Ray AUV (Fig. 1) is a torpedo shaped, 5.1 m long, 0.69 m in diameter, which weighs 882 kg in air. The Aluminum pressure hull is rated to 2200 m depth comprising approximately half of the vehicle length. The extended bullet nose and tapered tail of the vehicle are fiberglass components designed to minimize hydrodynamic drag. These sections are flooded and used for payload instrumentation and mechanical systems. The forward flooded hull section houses a bottom avoidance sonar, a pop-off buoy and recovery line, depth sensor, inertial guidance system, Doppler velocity log, acoustic modem, multi-beam sonar receiver, and conductivity-temperature-depth (CTD) instrument. Despite the number of components packed into this section, space and a bulkhead connector are reserved for modular payloads required for special missions. The aft flooded hull section houses the thruster motor, cabling to the control surfaces and an emergency drop weight system. 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 aluminum 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-1; normal survey speed is 1.75 ms-1. 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. Space is left in this section to accommodate internal payload components as well. Vehicle telemetry and real-time pilot control communications utilize hardwired or radio Ethernet while on the surface. Underwater, communication can be maintained through proprietary acoustic channels if necessary. Vehicle control and feedback are naturally much more restricted when using the acoustic modem.

B. Modifications to Eagle Ray

The vehicle configuration as delivered by International Submarine Engineering included a retractable mast. The original description and operational techniques are published by J. Williams et al. 2007[1]. During the first dives the mechanism to raise and lower the communication mast was considered to be a possible item of unreliability and an alternative in form of a fixed mast was installed. The available space inside the flooded tail section was reused to install an emergency drop weight. This 40lbs weight which can be dropped by the vehicle control computer based on a number of different scenarios in the fault response table, allowing for an additional 40lbs of positive buoyancy of the vehicle. Its position at the tail end of the AUV was argued to be the best position for additional lift to free the vehicle, in case it would get caught in an obstacle.

The new fixed communications mast was also equipped with an additional VHF radio direction beacon and a NovaTech strobe, and an ARGOS satellite transmitter. Further modifications to the AUV included the addition of a Bluefin GPS antenna, dedicated to the Kearfott SEADeVil for guidance of the Inertial Navigation System while the vehicle is at the surface. As a safety feature an Iridium satellite communication modem was installed by the manufacturer. The antenna provided with the AUV was replaced with a higher performance antenna allowing for more reliable communications with the shipboard control computer, thus providing another safety feature for a possible lost vehicle situation, where the vehicle either had to be abandoned under water for a prolonged time where the mission would time out and it would surface on its own, or it simply malfunctions and surfaces at an unexpected location. At that point the vehicle control computer would initiate an Iridium phone connection with the surface control computer and transmit its position and current status.

1. Eagle Ray AUV Mission Behavior Enhancements

Through the experience of field operations, several autonomous behaviors and enhancements were identified as valuable to mission planning and vehicle performance efficiencies. These new features were implemented through software changes to the configuration executed by the ISE Automated Control Engine runtime environment. Following shop testing, at-sea acceptance tests of all new features were successfully performed. During the most recent science cruise, these new features were proven to be useful in actual mission scenarios.

In its original configuration, the vehicle could be commanded to dive aggressively (45-degree down pitch) to a predetermined depth. Additionally, the vehicle could be commanded to attain and maintain a specified altitude. In the absence of bottom detection, the altitude acquisition logic would use a non-aggressive attitude profile for safety. Lacking was the ability to dive aggressively through the water column to a specified altitude in water of unknown (or not specifically known) depth without bottom detection.

The implementation of this aggressive altitude dive was two-fold: first, the forward-looking collision-avoidance sonar had to be utilized as a height sensor, and second, the mission action verbs had to be modified to invoke the new dive behavior and to detect the requisite completion condition. The vehicle contains two sonars capable of height sensing: a doppler velocity log as an intimate part of an inertial navigation system and a narrow-beam single-frequency sonar used primarily for collision avoidance. Pitch-sensing crossover logic was added to select between the sonars (and their status conditions) and the appropriate pitch-angle calculations for determining height were implemented. The “sounding” dive mode was added as an analogue to the existing “depth” and “altitude” modes to all of the mission action verbs along with completion detection logic. The mission syntax was expanded to incorporate the new mode and the mission planning software enhanced as required. In recent field operations, the sounding mode was used successfully to dive to depths in excess of 900 meters.

In practice, a deep dive is usually performed as a sequence of two or more “dive here” actions. Surface navigation may be difficult and/or costly in stored energy due to wave conditions and/or surface currents. It is preferable to dive the vehicle at a random location close to the geographic starting point of the survey mission. As originally configured, the vehicle could “dive here” by circling around a sensed (current) location. The resulting downward spiral is suboptimal for inertial navigation systems.

A new mission behavior was implemented in which the vehicle swims a square pattern starting from a sensed location. The new action verb executes a series of straight line elements followed by 90-degree turns, using waypoints calculated from the original position. All of the existing completion modes, including “depth”, “altitude”, and “sounding” were implemented. The mission syntax was expanded to include the new action verb and the mission planning software enhanced accordingly. In recent field operations, dives to 200 meters and to 900 meters were performed using the new box action.

The original mission planning syntax required the specification of a predetermined geographic location, and depth or altitude with each action verb. This design prevented the re-use of mission files at different locations.

New capabilities were added to the existing mission actions to allow a “relative” location and/or depth to be specified. Logic was implemented to capture the present geographic location as a reference and to permit the reference location to be programmatically set. Similarly, logic was implemented to capture the current depth as a reference and to be programmatically set. The mission action verbs were then modified to accommodate the reference setpoints and to calculate the actual target points based on these references and the mission-specified offsets. In recent field operations, both geographic- and depth-relative features were used to plan and execute a multibeam patch test. It is envisioned that this patch test mission plan can be incorporated into future missions with minimal (or no) modification.

From the experience of field operations, shortcomings were recognized in the original suite of AUV mission execution behaviors. New behaviors were identified to improve the efficiencies of mission planning and *in situ* vehicle performance. These behaviors were designed to complement the existing capabilities and implemented in the vehicle configuration and the mission planning tools. Subsequent tests and science operations have proven the utility of these features.

2. *Mission Statistics*

TABLE 1: OPERATIONAL STATISTICS

	Eagle Ray	Mola Mola
First year of Operation	2006	2009
Number of Cruises:	11	1
Number of Dives	45	11
Distance traveled (km) under water	1394	5.9
Max depth (m)	945	713
Total Hours of Dive time	289	19
Total Images	NA	10387

Since its delivery in 2005 to NIUST the Eagle Ray AUV has participated on 11 cruises, with 2 more planned for the remainder of 2009 (*Table 1*). A total of 45 dives for 289 hours and 1394 kilometers length provided a wealth of data to the participating scientists and the AUV team for their research and development efforts.

During the most recent cruise the ER was deployed over the MC118 Methane Hydrates Research site in the Northern Gulf of Mexico. Two main dives were performed producing an overview bathymetry map of most of the research site and a subset of the site to provide a spatial chemical analysis. The first dive was a multibeam survey run at 35m m above bottom at a speed of 1.75m/s. The second dive was at 6m above the seafloor and a speed of 1.5m/s to collect data with a mass spectrometer provided by Rich Camilli from Woods Hole Oceanographic Institution.

3. *New Sensors Integration*

NIUST AUVs are part of the vehicles used at the Hydrates Research site at the Mississippi Canyon Block MC 118 in the Northern Gulf of Mexico. The Hydrates Consortium, with its headquarters based at the Mississippi Minerals Research Institute (MMRI), expressed the need for a spatial survey of Methane and other trace gases in the water column at MC118. Utilizing the state of the art Tethys compact mass spectrometer, Eagle Ray was modified to be used as the platform for its operation at the site. The Tethys, a solid state mass spectrometer (Fig. 2) owned by Dr. Rich Camilli at WHOI, was successfully integrated and operated over the Hydrates Research Site MC118 in the northern Gulf of Mexico. The cruise aboard the R/V Pelican was a joined effort of the Undersea Vehicle Technology Center (UVTC), the Seabed Technology Research Center (STRC), both part of the National Institute of Undersea Science and Technology (NIUST) and the Woods Hole Oceanographic Institution (WHOI). Future technology development plans involve integration of two acoustic instrument systems, a chirp sonar for sub-bottom investigations and an external Hydrophone array for a Shallow Source Deep Receiver (SSDR) type deployment for investigation of deep geologic structures.

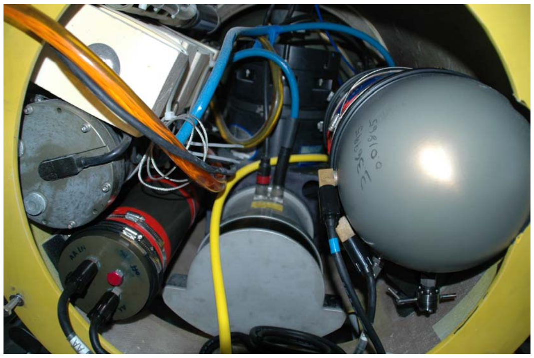

Fig. 2 Tethys Mass Spectrometer installed in Eagle Ray AUV. Image shows from left to right Syntactic Foam, Battery Housing for Acoustic Modem, External Battery Pack for Tethys, EM2000 Multibeam Receiver, and the Tethys Mass Spectrometer.

III. THE MOLA MOLA AUV

A. *Mola Mola Capabilities*

In late May 2009 NIUST took delivery of the Mola Mola (Fig. 3), a SeaBED class AUV. The Mola Mola is capable of working off of small coastal vessels or other ships of opportunity. The 200 kg AUV is constructed of an upper and lower hull connected by vertical struts. Each hull is composed of individual pressure housings attached to an aluminum frame, which is then packaged in a plastic cover. Positive buoyancy is achieved by syntactic foam pieces integrated into the vehicle. The vehicle has two main pressure housings, one for batteries and another that contains the control computer and electronics. The batteries and the payload sensors are located in the bottom hull, while the top hull contains the electronics housing and syntactic foam. This layout places most of the buoyancy in the upper hull, and most of the weight in the lower hull for pitch and roll stability. Wet cabling routed through the vertical struts provides power and communication within the vehicle.

Mola Mola is designed to precisely navigate survey tracks at altitudes as low as 2.5 m above the sea floor. Thrusters oriented in two different planes allow the AUV to maintain course and altitude while avoiding obstacles. On launch, the vehicle propels itself vertically downward until its navigation system locks onto the seabed at 30-m altitude and it can begin its programmed survey. It can acquire digital color photographs, high-resolution swath topography and current-meter data. In its present configuration, the AUV can remain submerged for as long as 8 hours and can acquire 1,200 photographs per hour, with varying degrees of overlap as determined by the vehicle speed (0.25-2 knots). Images obtained can be post-processed into larger, color corrected mosaics revealing stunning views of the sea floor.

Mola Mola is equipped with an RDI Workhorse Navigator Doppler Velocity Logger (DVL) for bottom-locked navigation, an Imagenex Delta-T imaging sonar for bathymetry capture and a custom camera system based on high dynamic range Prosilica cameras. A WHOI Micro Modem provides acoustic communication, and a SeaBird CTD sensor for measuring salinity and water temperature. The main computer is a 1.2 GHz PC104 Pentium processor, running Ubuntu Linux 8.04. The vehicle control software is a multithreaded C program linked to a mission planner written in Perl. Full source code was provided by the manufacturer.

Currently, Ultra Short Baseline (USBL) Navigation is being used to track the AUV from the surface once it is deployed and running its mission. The vehicle navigation is performed by a software position estimator integrated with the DVL. This barebones navigation package will be upgraded by adding a Phins Inertial Navigation System from IxSea. Positioning will be further enhanced by employing Long Base Line (LBL) navigation using the already present WHOI acoustic modem with Teledyne Benthos TR-6001 transponders. The WHOI modem is currently used to send position and mission status messages to the surface and receive mission abort commands if a problem is detected by the operators.

The Mola Mola is preprogrammed to perform various functions during its dive. Vehicle speed, altitude, photograph timing, and use of camera and multibeam sonar all can be varied during a single deployment. For example, the AUV can acquire photographs at low altitude along separate transects, or along overlapping transects to make a mosaic of the seabed followed by a higher altitude multibeam survey over the area.

TABLE 2: SEABED VEHICLE CHARACTERISTICS

Vehicle Depth Capability	2000 m
Size	2.0m(L), 1.5m(H),
Mass	200 kg in air
Speed Range	(Typical) 0-1.0m/s (0.15m/s)
Batteries	1.8kWh rechargeable Li-ion Pack
Propulsion	3 DC thrusters
Depth	Paroscientific pressure sensor, 0.01%
Position	LBL+ 300 kHz RDI navigator, 0.1-1 m
Altitude	RDI navigator, 0.1 m
Optical Imaging	Electronic Camera Prosilica 12bit 1360x1024 color CCD
Lighting	one 200 Watt-Second strobe
Separation	1.5m from Camera to light
Acoustic Imaging	Imagenex Delta-T Multi Beam Sonar
ADCP	300 kHz RDI navigator

1. *Lee Stocking Island Operations*

The maiden voyage of the Mola Mola AUV was performed at Lee Stocking Island in the Bahamas, aboard the M/V Liberty Star out of Cape Canaveral, FL. The goal for this field operation was to collect high resolution images of deep coral habitats off of the East coast of Lee Stocking Island. For this trip, the Mola Mola was modified and outfitted with two identical cameras to obtain stereo photographic images of the bottom floor. An Imagenex Delta-T multibeam sonar was used to obtain simultaneously acoustic bottom topography data for possible future integration of both data sets to produce a 3D representation of a photo mosaic draped over the bathymetry. This work is planned to be a part of the dissertation of one of the graduate students that participated in the cruise.

During 13 dives, a total of 12000 images were collected on each camera. The terrain along the west side of the island, gradually slopes down to approximately 75 feet and then abruptly slopes down to almost 400 feet, making this a very difficult terrain to follow in simple bottom lock navigation.

During the LSI operations, the need for a forward looking avoidance sonar was made evident. The present line following behavior controls x-y position and altitude independently. In rough terrain, such as that found at LSI, the altitude handling routine can reach its limits while a constant velocity is maintained on the x-y plane. Downhill, this led to driving off slopes and missed photo coverage of the study area. Had the vehicle run uphill, this behavior would cause collision into the slope. Also, the heading control software showed signs of oscillation, which will require time spent tuning the control loop in following engineering cruises.

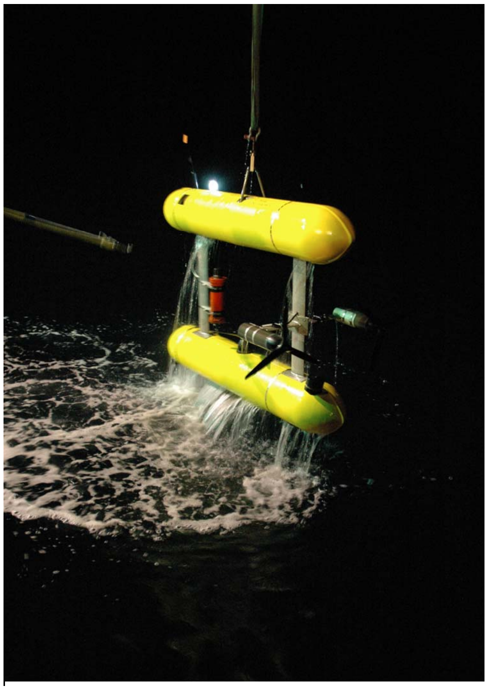

Fig. 3 Mola Mola AUV

IV. CONCLUSION

The Eagle Ray and Mola Mola represent two very different AUV designs. The features of these designs allow for an easy selection of the proper vehicle for a given task, and the available of both at the same time will provide great versatility in survey abilities. The NIUST AUV shop facilitates the further development of the two vehicles in the areas of hardware improvement, sensor addition, and software modification. Being maintained by the same personnel, both AUVs can be enhanced in parallel such that they remain compatible with many of the same support equipment and programming concepts. With each modification made to the capability of these two vehicles, the goal is always to increase their reliability and the quality of data they produce.

REFERENCE

[1] J.L. Williams, V.L. Asper, G.H. Taylor, “Experiences with the Operation of a Commercially-Available Deep-Water AUV” , Oceans 2007.