Enhancing NIUST's SeaBED Class AUV, *Mola Mola*

M. Woolsey[1], V. L. Asper[2], A.-R. Diercks[1], K. McLetchie[1]

National Institute for Undersea Science and Technology
Undersea Vehicle Technology Center
[1]UM Field Station, 15 CR 2078, Abbeville, MS 38601 USA
[2]University of Southern Mississippi, 1020 Balch Blvd, Stennis Space Center, MS 39529 USA

***Abstract*–Mola Mola is a seafloor mapping AUV owned and operated by the National Institute for Undersea Science and Technology (NIUST). Since its initial sea trials in May of 2009, effort has been applied to enhancing the navigation and imaging systems for high-resolution surveys of specific targets in depths up to 2000 meters. These surveys require accurate positioning during the initial dive to the seafloor, and smooth navigation once the survey begins. To work toward this goal, an inertial navigation system with position and velocity aiding has been integrated with the vehicle software, and it is currently being field tested. The imaging system has also been modified by adding LED arrays to provide more consistent lighting and by merging navigation data with the images for georeferencing. The above system enhancements have forced changes in the vehicle's layout, and operational experiences have led to improvements in the vehicle's mechanical systems.**

I. Introduction

The Mola Mola AUV (Fig. 1) was acquired by the National Institute for Undersea Science and Technology (NIUST) in May of 2009. Since then, it has performed transects over coral and a shipwreck survey. It has worked independently and in tandem with NIUST's other AUV, Eagle Ray [1]. This larger and faster vehicle can complete a broad survey, which may be followed by a more focused Mola Mola survey after identifying points of interest. This two-phase survey approach was successfully carried out during a shipwreck study in October of 2009 [2].

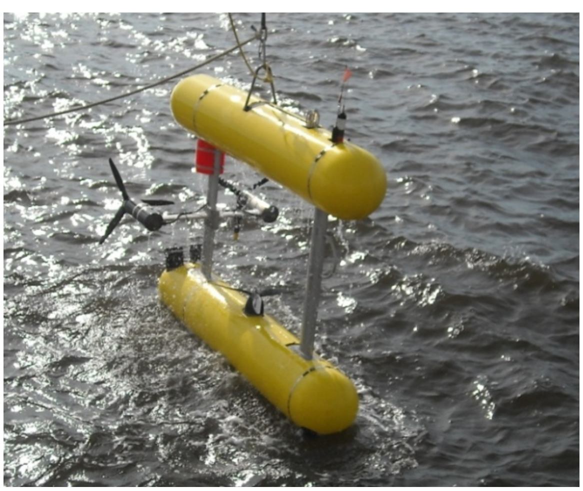

Figure 1. Mola Mola AUV during operations on October 15, 2009

Mola Mola is named for the Ocean Sunfish, with which it has a similar form factor. It is a SeaBED class AUV designed and built by Dr. Hanumant Singh and his team at WHOI [3]. It has an upper and lower torpedo shaped pod separated by two vertical struts. This multihull configuration further contributes to its double name. The upper pod is buoyant, containing the main electronics housing and syntactic foam. The lower pod provides ballast from the Li-ion battery pack and sensors. This separation of buoyancy leads to high passive stability with regard to pitch and roll. The SeaBED vehicles can operate safely at low speed near the bottom with maneuverability provided by two horizontal thrusters, port and starboard, and a vertical thruster. Typical survey parameters for Mola Mola are an altitude of 3 meters and speed of 0.15-0.25 m/s, with a maximum depth capability of 2000 meters.

Numerous institutions are currently using SeaBED class vehicles for photo, multibeam, and chemical studies. The vehicles are each customized with a suite of sensors for their particular operational tasks. Many of the surveys conducted by SeaBED vehicles are regional habitat studies in which photomosaics are created for further analysis [4], [5]. Some studies have involved deep plume detection and other water column data collection from SeaBED variants capable of operating in depths up to 6000 meters [6].

The primary task of Mola Mola is to survey specific targets at depths up to 2000 meters. These targets include areas of gas hydrate concentration, shipwrecks, and anomalies spotted during broad-scale habitat studies carried out by Eagle Ray. The Mola Mola was ordered essentially as a "base model" SeaBED, with the intent of enhancing this base design to fit the needs of its primary uses. Its suite of navigation sensors included an RDI doppler velocity log (DVL), Paroscientific depth sensor, and long baseline (LBL) navigation capability provided by a WHOI Micromodem. Attitude and heading were measured using the tilt sensors and magnetic compass internal to the DVL. An IXSEA Phins configured as a gyrocompass was added at WHOI after the first cruise to improve the quality of attitude and heading measurement. The vehicle was equipped with a down-facing camera in the forward end of the lower pod and flash unit in the rear of the pod. Software for adding an Imagenex multibeam sonar was provided.

II. Navigation System

The majority of engineering time devoted to Mola Mola was spent enhancing the navigation system. The original system used dead reckoning from the DVL and gyrocompass inputs to calculate vehicle position. The navigation routine integrated horizontal velocities to obtain position, requiring that the vehicle was within DVL bottom-lock range, about 30 meters from the seafloor. Above that altitude velocity estimates can be made using RPM feedback from the horizontal thrusters. This is ineffective during an initial dive, during which the vehicle drifts with currents and spirals to depth using only its vertical thruster.

Vehicle x-y positions are computed as meters east and north of an origin. When LBL navigation is used, the origin is defined relative to the beacon positions before launching the vehicle. If LBL is not used, the origin is an arbitrary point defined by zeroing the vehicle position upon reaching bottom lock. The downfall of operating in LBL mode is that whenever a new LBL solution is obtained, it simply replaces the previously computed position. This introduces jitter in the navigation that is large compared to the scale of the data products. During all operations, the navigation error can never drop below the error of an isolated LBL position calculation.

In order to set up Mola Mola for spatially-critical multibeam and photo surveys requiring smooth navigation, the Phins was reconfigured to serve as the position source for the vehicle rather than just a gyrocompass. The Phins contains an inertial measurement unit (IMU) and a signal processor. The heart of the signal processor is an extended Kalman filter which merges data from the IMU and external aiding sensors, while considering their respective error models. Fig. 2 summarizes the current configuration of the navigation system.

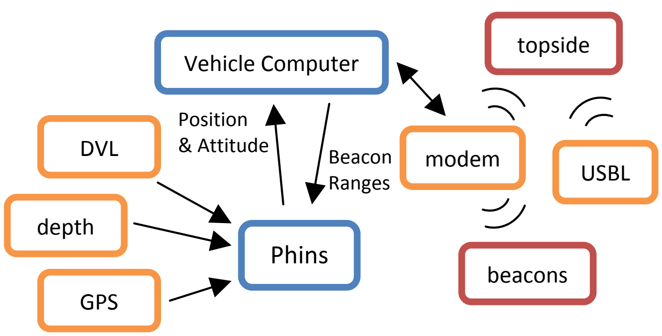

Figure 2. Block diagram of data flow within the navigation system.

The Phins, when used as a gyrocompass, was interfaced serially. This serial connection carried the attitude and heading sentences from one of five output channels of the Phins to the main electronics housing. The Phins accepts each aiding source on a different channel, which maps to either a serial connection or TCP/UDP port. Because multiple channels were needed to send aiding information and receive navigation and raw sensor data, the serial interface was dropped in favor of an ethernet connection using UDP. Overall, this required development of several new and modified sensor drivers as well as minor fundamental changes in the vehicle's I/O libraries.

The DVL was given a direct serial connection to the Phins to minimize data latency and network traffic. The DVL has no water-track capability, but sends bottom track velocity aiding at 5 Hz. This serves as the most important aiding source during a seafloor-focused survey.

During descent, the Phins receives position updates from Benthos acoustic beacons with known positions on the seafloor. The vehicle was delivered with LBL capability built into the integrated WHOI acoustic modem. Whenever the beacons are interrogated by emitting a 10.5 kHz pulse, the vehicle software logs travel times to as many as four different beacons and a position is computed. The software was modified to calculate slant range to each beacon and send these ranges (along with surveyed beacon positions) independently to the Phins, as per its input data format.

A GPS unit was added to the vehicle to provide initial alignment of the Phins at startup and position aiding while on the surface before and after a mission. The data from the GPS, LBL software, and the depth sensor are sent through the vehicle computer to the Phins over its ethernet connection. Position, velocities, attitude, and statistical data thereof, are transmitted by the Phins to the vehicle computer over the same connection.

III. Camera System

The Mola Mola imaging system has been modified from its original design in an effort to create a more useful data product with even and consistent lighting. During a research cruise described in [2], images were acquired over a shipwreck. The footprint of each image at 3 meters altitude is roughly 2.6 meters along-track and 3.2 meters across track with approximately 775 pixels per meter. Although the high-resolution imagery, such as that of Fig. 3, met the goals of the mission, changes were needed to generate a smoothly lit georeferenced photomosaic of the site.

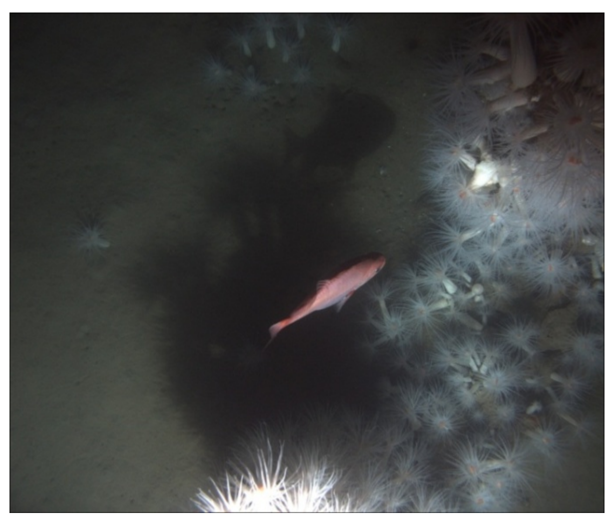

Figure 3. Fish photographed above an anemone-covered hull section.

Faults present in the survey included uneven lighting and dropped frames, which placed gaps in the lines of images. The mosaic generation was initially attempted using a graphical technique, which stretched and deformed each subsequent image to fit onto the previously placed images. The distortion prevented the output from being georeferenced with adequate quality, and since the technique required image overlap, a unified mosaic could not be generated. Only small, independent fragments of the mosaic could be assembled due to gaps present in the survey.

The cause of the numerous dropped frames is believed to be bandwidth related. The sensor itself is a Prosilica (now Allied Vision Technology) industrial color video camera with a resolution of 2448x2050 pixels that is configured to transfer single, uncompressed frames to the vehicle computer over ethernet. Since it is intended to communicate over gigabit ethernet, problems seem to arise when it must share bandwidth with other clients on a slower 100baseT network. During sea trials, the vehicle used a stereo pair of 1360x1024 cameras from the same manufacturer without any noticeable problems.

To produce a clear mosaic from the data, which has gaps with up to 30 seconds of dropped frames at a time, photos were aligned by hand to create strip of imagery from a particular transect over the shipwreck with minimal breaks. Due to inconsistent lighting, the image boundaries formed a rough transition between brightness and shadow. An example of this lighting discontinuity is shown in Fig. 4 from a different survey area around 300 meters depth in the Bahamas.

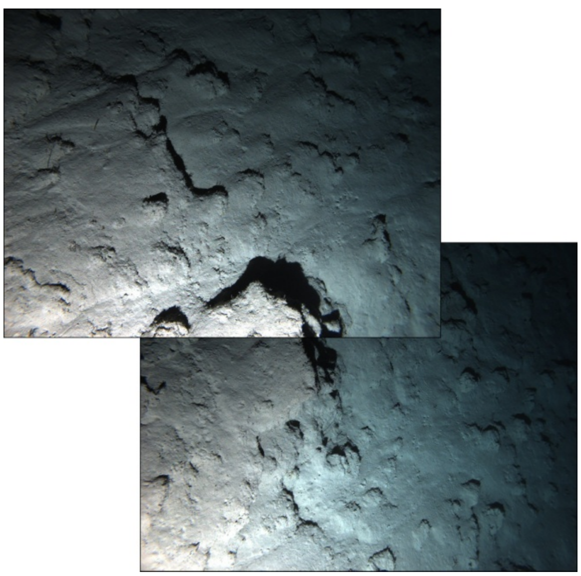

Figure 4. Neighboring images showing the bright spot of one image bordering shadows of the other.

One solution to the lighting problem is to use multiple light sources to illuminate the target from different angles. The Australian Center for Field Robotics at the University of Sydney operates a SeaBED class AUV, Sirius [5], [7]. This vehicle is modified to use strobes mounted in the fore and aft ends of the lower sensor pod while mounting a stereo pair of cameras between them.

To incorporate this solution into the Mola Mola, the camera and capacitive flash module were removed, and DeepSea Power and Light LED arrays were mounted at either end of the sensor pod. These lights can be pulsed like strobes or used as constant sources for video work. The camera was moved to the unused space starboard of the vertical thruster, with the port side reserved for a second camera, currently on order. The two cameras and lights will allow a variety of imaging configurations. Both cameras may be used to acquire stereo imagery, or one may take still photographs while another records lower-resolution video. Additionally, the cameras may be faced in different directions with lighting adjusted accordingly.

IV. Data Georeferencing

To produce a photomosaic without excessive distortion and without the requirement of overlapping imagery, a different approach is necessary. Instead of a graphical technique, a geographical one is used. A post processing step extracts vehicle log data for each image recorded. Vehicle altitude, attitude, heading, and position are used to derive coefficients for an affine transform that properly stretches, rotates, and translates the image in a Cartesian coordinate system. The images are then tiled using GIS software.

Positive aspects of this solution include minimal distortion to the individual images and the ability to handle gaps in the survey. The main negative attribute of the technique is that the resulting mosaic has rough boundaries due to navigation errors. An improved approach may be to perform a graphical blending and smoothing of the images after they have been tiled geographically.

Development of the multibeam system has been avoided for now due to the priority given to photomosaic capability, as dictated by cruise requirements. Currently, the multibeam system does not receive any vehicle navigation information, so navigation data must be parsed and merged during post processing. Because a program has not been written to perform this step, in-house processing of existing multibeam records is not currently possible. After thoroughly testing the newly overhauled navigation system, development will begin on properly storing position and attitude information alongside the multibeam data as it is collected, allowing subsequent multibeam records to be processed using standard software suites.

Since the photo and multibeam data are recorded simultaneously, the resulting photomosaic and bathymetry could be layered, if desired. In terms of survey line spacing, the multibeam swath encompasses the photo coverage, with the outer beams extending beyond the edges of the photos by nearly 3 meters on either side.

V. Vehicle Layout

The subsystems of Mola Mola are the following: scientific payload, navigation, control, and telemetry. As changes have been made to the hardware and software that make up these subsystems, the physical layout of the vehicle's components has been modified. Fig. 5 shows the vehicle as delivered, with additional equipment borrowed from WHOI, including a stereo camera system and LinkQuest TrackLink ultra-short baseline (USBL) transponder. This transponder is independent of all other electronics for vehicle safety.

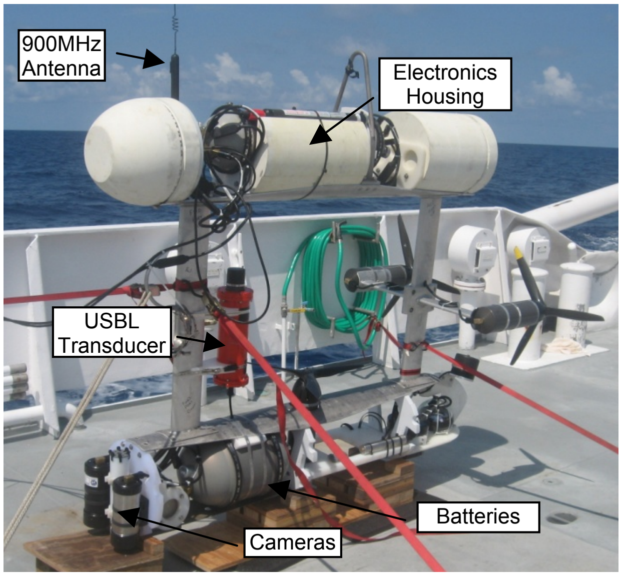

Figure 5. Mola Mola in May of 2009, on sea trials.

In the next layout, shown in Fig. 6, the Phins gyrocompass was added to the upper pod. The borrowed stereo camera was replaced with a single higher resolution camera, and the USBL transponder was replaced with a TrackLink 5000HA unit within a 2000-meter rated housing. This transponder, with a remotely mounted transducer, was located within the sensor pod. It was selected because compatible topside equipment is already in use for the Eagle Ray, and the transponder itself can be used as a spare for the Eagle Ray as well.

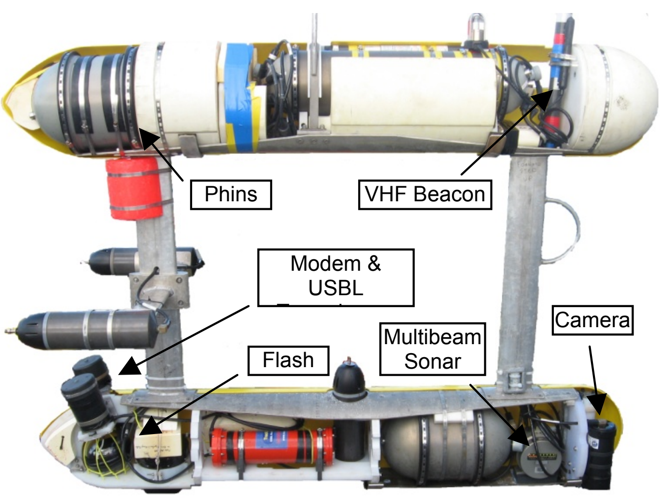

Figure 6. Mola Mola, properly ballasted in October of 2009.

Currently, the Phins has been moved to the lower housing, near the vehicle's yaw-center. There, it may eventually be properly indexed to the DVL with a lightweight bracket. Since these components are not indexed, a calibration is required when either component is moved.

Also visible are the fore and aft LED arrays and the center-mounted camera. As a result of these changes, the USBL transducer has been displaced to the exterior, where it is mounted onto the aft strut. Fig. 7 shows this new configuration.

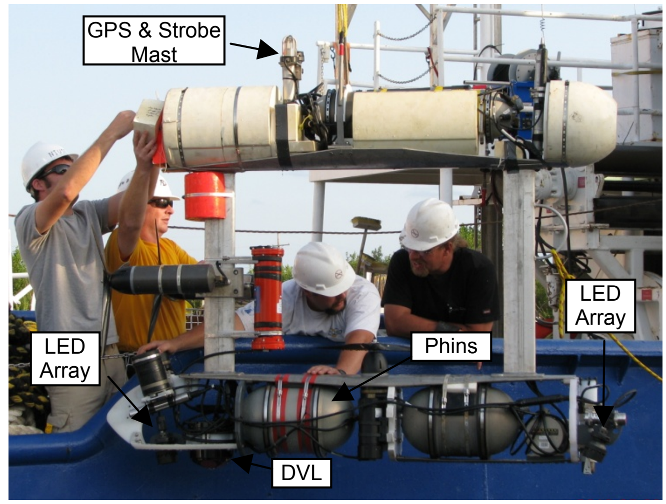

Figure 7. Configuration of the Mola Mola as of May of 2010.

VI. Additional Developments

The vehicle was delivered with a Novatech strobe which works extremely well for locating it during night operations. While surfaced during the day, Mola Mola has a very low profile, with only a few inches above the waterline. This makes the vehicle difficult to spot despite its bright yellow coloring. A VHF beacon was added as a recovery aid in case the vehicle surfaces outside of visual range. A temporary mast has been used during the last two cruises to mount the GPS antenna and elevate the recovery strobe.

The long-term mast solution, currently being fitted to the vehicle, is a fiberglass fin that will protect and elevate the ensemble of antennas and the strobe. A major function of the mast is to protect the antennas from the dangers of recovery operations. Recoveries are conducted either by bringing the ship alongside the AUV and catching its lift bail with pole-mounted hooks or by launching a small boat to attach a tow rope to the vehicle's forward bail. So far, recovery accidents have only caused bent antennas, but the addition of the glass-domed GPS antenna is a cause for concern. In addition to protecting the antennas, the mast has a foil shape to minimize its effect on vehicle dynamics, and its projection above the waterline should drastically improve both day and night visibility as well as antenna function.

Two vehicle developments stem from mechanical problems that occurred during missions. Both issues involved propeller shafts, which are magnetically coupled to the sealed thruster motors. One of the original ball bearings used between the propeller shaft and vertical thruster housing failed during a descent. The ceramic bearing race fractured, either due to sediment presence in the exposed bearings or by axial force caused by a loose screw that holds a magnet to the shaft. Marks on the thruster housing suggest that this screw had apparently contacted it at some time. The field repair was to apply a locking compound to the screw and replace the broken bearing with a PVC bushing machined from a boat hook shaft. This bushing is actually still in use, and works well enough that spare PVC bushings have been made in case other ceramic bearings fail.

The propellers themselves had been indexed to the round thruster shaft using pins that fit into groves milled in the propeller hubs. These pins eventually cut into the composite hubs, and in one extreme case the propeller could spin freely on the shaft, after the pin cut a groove around the entire hub. To prevent this problem from happening again, the shafts were milled lengthwise and fitted with a protruding key. A square bushing was machined to accept the key and then fitted into each propeller hub, as pictured in Fig. 8. Currently, these plastic propeller bushings are being replaced by brass ones.

Figure 8. Redesigned propeller hub and keyed shaft.

The latest addition to the vehicle is a small serially connected sensor module designed to monitor temperature, pressure, and the presence of seawater within the electronics housing. This sensor, which has been tested independently but not yet integrated into the vehicle software, will provide the operator with vehicle safety information during testing and deployments. It will be used to prevent overheating while running the vehicle electronics on deck, to monitor vacuum when closing and leak-testing the housing, and to abort missions if anomalies are detected.

VII. Summary

Modifications have been applied to the Mola Mola AUV to enhance vehicle safety and capability as well as to improve the quality of its navigation and scientific data. While Mola Mola has already been used to gather geological, biological, and archaeological data, the first science missions in its new configuration have been scheduled for the summer of 2010. Engineering trials have been conducted successfully in the lab and at sea, off the Mississippi Gulf Coast, but the definitive measure of the vehicle's performance will be the quality of its scientific data products.

Acknowledgments

NIUST gratefully acknowledges funding from NOAA's office of Ocean Exploration and Research.

References

[1] J. L. Williams, V. L. Asper, G. H. Taylor, "Experiences with the operation of a commercially-available deep-water AUV," in *Proc. 2007 Oceans Conf.*, Vancouver, BC, 2007.

[2] A.-R. Diercks, V. L. Asper, M. Woolsey, J. L. Williams, F. Cantelas, "NIUST AUVs study shipwrecks in the northern Gulf of Mexico," *Proc. AUV Conf.*, Monterey, CA, 2010, in press.

[3] H. Singh, R. Armstrong, F. Gilbes, R. Eustice, C. Roman, O. Pizarro, J. Torres. "Imaging coral I: imaging coral habitats with the SeaBED AUV," *J. for Subsurface Sensing Technologies and Applicat.*, vol. 5, no. 1, pp. 25-42, 2004.

[4] N. Tolimieri, M.E. Clarke, H. Singh, C. Goldfinger, "Evaluating the SeaBED AUV for monitoring groundfish in untrawlable habitat," in *Marine Habitat Mapping Technology for Alaska*, J. R. Reynolds, H. G. Greene, Eds. University of Alaska Fairbanks: Alaska Sea Grant College Program, 2008, pp. 129–141.

[5] S. B. Williams, O. Pizarro, M. How, D. Mercer, G. Powell, J. Marshall, R. Hanlon, "Surveying noctural cuttlefish camouflage behaviour using an AUV," in *Proc. 2009 IEEE Int. Conf. Robot. Autom.*, Kobe, Japan, 2009, pp. 4352-4357.

[6] C. Kunz, C. Murphy, R. Camilli, H. Singh, J. Bailey, R. Eustice, C. Roman, M. Jakuba, C. Willis, T. Sato, K. Nakamura, R. Sohn, "Deep sea underwater robotic exploration in the ice-covered arctic ocean with AUVs," in *Proc. 2008 Int. Conf. Intelligent Robots and Systems*, Nice, France, 2008, pp. 3654-3660.

[7] P. Rigby, O. Pizarro, S. Williams. "Improved AUV navigation through multi-sensor data fusion," *Sea Technology*, vol. 48, no. 3, pp. 15-19, March 2007.