Semi-Autonomous Mapping System

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Abstract - There is an emerging global market for free swimming undersea robots that are reliable, increase productivity, provide high quality data, and are easy to program and operate. To gain acceptance these robots have to be inexpensive to own and versatile.

This paper describes the Semi-Autonomous Mapping System (SAMS) a UUV designed to survey the ocean from a depth of 10 m to a depth of 6 km. SAMS was developed under a cooperative program involving the Naval Oceanographic Office, the Office of Naval Research, and the Woods Hole Oceanographic Institution (WHOI). The system, including launch and recovery gear, is land, sea, and air shippable in one standard 2.4 by 6 meter ISO container. The system is operable from T-AGS-60 ships and other oceanographic vessels in sea states up to those generated by Beaufort Scale six winds. The system is operated, maintained, and repaired at sea by trained technician level personnel. SAMS is based on the REMUS UUV, which was also developed at WHOI.

During sea trials in March of 2003, SAMS completed a record dive to 4,963 m that lasted for 13 hours.

Keywords – REMUS, AUV, UUV, autonomous, launch and recovery systems, deep submergence, ship relative navigation, SAMS

I. INTRODUCTION

Currently, the majority of systems that are utilized to survey the deep sea (6 km water depths) are towed near the sea floor at the end of long cables that extend from ships on the surface. These systems are large, complex, and expensive to own and operate. The long fiber-optic cables that are used in these systems create an enormous amount of drag as they are pulled through the ocean by a vessel. The drag of the cable limits the system's productivity because it limits the average speed of the surface vessel to near 1 m/s. Surveys often require the ship to turn, which further degrades performance, limiting productivity to near 0.5 m/s. The overall quality of the data collected during these surveys is also impacted by the inability of the system to follow a desired track line and heading while operating near the seafloor. Sub sea currents and surface winds conspire to force the tow vehicle off of its desired track line and cause the tow vehicle to crab at an angle off its desired heading. These undesirable aspects complicate survey-planning and towing operation which increases manpower requirements as well as the time and cost of processing the data.

During deep operations conducted in the spring of 2003, the Semi-Autonomous Mapping System (SAMS) demonstrated a ten fold increase in area coverage rates over that which may be expected with a towed system. There was also a notable improvement in data quality, because the UUV is de-coupled from the ship's surface motions and operates closer to the seafloor. During these trials, SAMS demonstrated that it is a cost effective tool for performing precision surveys in water depths to 6 km.

Figure 1 SAMS vehicle in launch and recovery system

The SAMS system, including launch and recovery equipment, is land, sea, and air shippable in an internally customized standard ISO container. Internal modifications of the container include the addition of environmental controls and other equipment required to permit the unit to function as a shipboard operations and maintenance center. The vehicle can be operated from T-AGS-60 ships and other vessels of opportunity in sea states up to those generated by Beaufort Scale 6 winds. The vehicle's launch and recovery system is designed to function off the stern of a ship and can be set up for shipboard operations in a few hours. The launch and recovery system is based on another operational system, designed by WHOI, which has completed over 1000 launch and recovery operations at sea [1].

II. OPERATIONAL REQUIREMENTS

The Naval Oceanographic Office will operate and maintain SAMS. It will be used to acquire precisely positioned high quality environmental data in both littoral and deep oceans all over the world. SAMS will be a stand-alone self-contained system that can also be used to enhance the capabilities of the Naval Oceanographic Office's Towed Oceanographic Survey System (TOSS). The system is designed to be compatible with the TOSS operating and support systems, permitting shipboard handling and launch and recovery, while TOSS is installed on the ship. The system will be operated and maintained by the same crew that currently operates TOSS.

Figure 2 SAMS Vehicle

Sensors on board the free-swimming vehicle include a side scan sonar; pressure, temperature, conductivity, and optical backscatter sensors; and an inertial navigation system that is aided by an Acoustic Doppler Current Profiler (ADCP) with bottom lock capabilities. An optical imaging system will be added during the next fiscal year. All sensor information collected by the vehicle is marked with time, depth and latitude, and longitude as it is collected, facilitating the rapid and highly automated generation of maps and HTML based reports. The data collected by the vehicle is provided in formats that are compatible with existing TOSS data processing and analysis systems. An acoustic communication system permits the vehicle to send status messages to the surface ship containing information about the vehicle's health, its location, and some sensor data while it is performing a mission at up to 6 km below the surface. The acoustic communication system is also used to send data and redirection commands to the vehicle. SAMS utilizes electronics, control software, and the laptop based operator interface software from the already successful REMUS vehicle system [2].

A support van, based on a standard ISO container is provided with the system. Two vehicles and the launch and recovery equipment may be stored in the van. Initially, one vehicle has been provided with the system; a second vehicle will be fabricated during FY 03. Shock absorbing isolation mounts are provided in the van so that equipment is protected during shipping and transits at sea. The container is modified to support vehicle maintenance tasks and the programming and monitoring of the vehicle while deployed. A heat pump provides environmental control required for equipment maintenance and personnel comfort.

Shipboard mobilization requires a two-man crew to unload the launch and recovery system and to prepare the vehicle for operations. Some welding and/or ship preparation work is required to attach the launch and recovery system and operations van to the deck of the ship.

Initially, the vehicle may be equipped with either a Benthos 200 kHz chirp sonar or a Marine Sonic Ltd. 300 kHz sidescan sonar. Adequate reserve payload and housing space has been provided to support the future addition of a high resolution optical imaging system. Table 1 at the end of the paper contains the system's specifications.

III. VEHICLE SYSTEM

A. Mechanical Layout

The SAMS vehicle is fabricated from low maintenance materials. Main structural elements, junction boxes, and pressure housings are all fabricated from 6AL-4V alloy titanium. Emerson and Cuming El-34A syntactic foam is used to obtain buoyancy. This foam structure forms the main body of the vehicle and is therefore reinforced with a titanium backbone and covered with a gel coated layer of fiberglass. This design minimizes the use of removable outer skins and permits the vehicle to remain small and relatively light- weight.

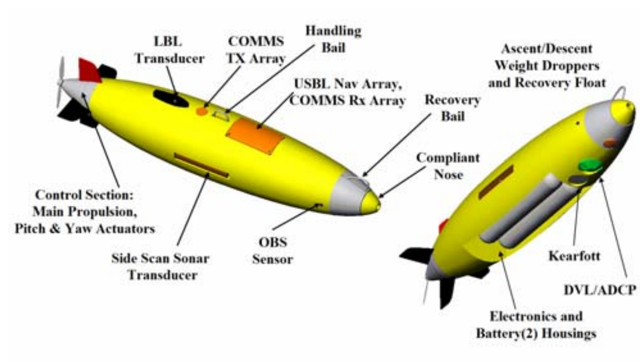

Figure 3 Layout of SAMS vehicle

A rectangular compartment in the center of the vehicle contains three pressure housings and an oil-filled junction box. Two pressure housings each contain one 4.3 kWh lithium-ion battery pack. The third pressure housing contains the vehicle and sidescan sonar electronics. The vehicle's inertial measurement unit and acoustic Doppler current profiler are housed in two other independent housings that are mounted forward of the 3 main pressure housings. Wiring from each independent subsystem is connected to the main electronics pressure housing via a feed thru connector which is mounted in the end of the junction box/end cap assembly. Oil-filled tubing and conventional cabling methods are used to interconnect subsystems. A smart pressure compensator is used to pressurize the oil-filled tubes and junction boxes and to monitor reserve fluid levels.

The propulsion system is mounted on the rear of the main foam structure. It consists of an oil-filled direct drive DC brushless motor that is coupled to an open two bladed commercially available propeller. Two coupled pitch and yaw fins are driven by two independent motors with position feed back. Motor controllers and noise suppression electronics are contained in a one atmosphere housing which is an integral part of the propulsion system. The entire propulsion system is an independent module that can be unbolted from the vehicle and replaced with a spare, if required. An oil-filled tube and mechanical connector provide power and control linkage to the vehicle electronics via the oil-filled junction box.

The nose of the vehicle contains subsystems that are required to launch and recover the vehicle. Solenoid fired release mechanisms are provided for descent weight drop, ascent weight drop, and pop off float release. These mechanisms provide considerable flexibility in how to launch and recover the vehicle in both shallow and deep water.

B. Electrical Layout

Despite the differences in size, shape and mission, the system architecture of SAMS is modeled after the much smaller REMUS vehicle. In this design, each sensor is connected to a central motherboard/CPU where it is supplied with power and RS-232 communications. Even sub-systems such as the two external batteries and motor controllers are connected to the motherboard through this method. This forces a common interface for all the sensors, which simplifies device testing and troubleshooting. Time tagged data gathered from the sensors and sub-systems are stored by the CPU in a few files, which together represent an entire mission. Instruments that generate a high volume of data, such as the side scan sonar, store data locally, but their status information is still returned to the SAMS CPU where it is included in the mission data file.

Molded into a fin mounted on the back of SAMS are antennas for GPS, Freewave radio and Argos PTT. Two long baseline navigation transducers are included, one on the top of the hull and one on the bottom, in a redundant configuration that guarantees acoustic communication whether the vehicle is surveying close to the ocean bottom or floating on the surface waiting for recovery.

An emergency board plays an important role in helping to insure the vehicle has a safe return to the surface in the event of catastrophic system failure. This board contains the electronic circuits that control the ascent weight, descent weight and pickup float solenoids and continuously monitored them for open and short circuit conditions. The board also controls the Argos PTT and listens to communications from the LBL navigation receivers. While this board is normally powered through the vehicle's 28-volt battery bus, it will continue to operate on a separate emergency battery in the event of total power loss from the main battery. Thus, if the main batteries were to become exhausted, or if a failure occurred anywhere on the motherboard or CPU, the vehicle can still be commanded to drop the recovery weight and return to the surface via a coded acoustic command through the LBL transceiver.

An Ethernet hub in the vehicle provides a 100-megabit/second connection between the vehicle computer, the side scan sonar and the deck cable plug. A low speed connection can also be established with the vehicle via the Freewave radio. This is especially useful for last minute checks prior to launch while the vehicle is in the water.

All signals from the external sensors and sub-systems pass through an oil-filled junction box that is attached directly to the rear end cap of the main housing. A multi-pin Kemlon feed-through provides the electrical pathway between terminal strips in the junction box and the electronic circuit boards inside the main housing. An oil-filled section of the thruster assembly connects directly to the junction box, and a bladder assembly maintains positive oil pressure to the complete system. Pressure within the bladder is monitored and reported to the vehicle computer.

Leaks and water intrusion are a constant concern for all deep ocean vehicles, as even a minor leak in a connector can cause serious damage to its pins if not caught in time. SAMS monitors the integrity of its seals and connectors by testing for water leaks in each housing and junction box, and by a ground fault system that continuously monitors for the presence of an electrical pathway between the vehicle electronics and seawater. Detection of a leak causes termination of the mission and immediate release of the ascent weight. An additional safety feature is the presence of partial vacuums in the main housing and the two battery housings that are continuously monitored by the computer. Launch of the SAMS vehicle is prohibited if any vacuum is not at the correct pressure.

C. Battery System

The SAMS vehicle is powered by rechargeable Lithium-Ion (Li-Ion) batteries produced by Saft. Li-Ion batteries offer several advantages for SAMS: high energy density in terms of weight and volume; long shelf life with low self-discharge rate; high cycle life; and no gas emission. The lack of gassing permits charge and discharge in a sealed pressure housing. Along with these advantages comes the disadvantage that large Li-Ion batteries must be packaged, handled and transported as hazardous material. While safe in normal operation, the high energy density and the use of a flammable electrolyte can lead to fire if the batteries are abused mechanically, electrically or thermally.

The batteries are assembled from modules, each containing seven series-connected 40 Ah, 3.6 V, cells for a total nominal voltage of 25.2 V and energy of approximately 1 kWh. Figure 4 shows a battery module. Each individual cell in a module has independent over-charge and over-discharge protection. Each module has an on-board 30 A fuse and blocking diodes to prevent charge through the discharge terminal or discharge through the charge terminal. The module electronics provide a circuit to keep the cell voltages in balance over time. Each battery module also contains a TI BQ2040 smart battery device connected to an I^2C bus. This device is used to calculate and track the performance of the battery over time, and provides readings of voltage, current, state of charge, temperature, and full charge capacity for each module.

Figure 4 Battery module

These modules are arranged in groups of four, as shown in Figure 5, within a 7 inch I.D. titanium pressure vessel with hemi-spherical end caps. The vehicle carries two pressure housings for a total of 8 kWh of energy. Two additional battery housings are provided with the system to allow an exchange of batteries for continued vehicle operation during battery charging.

Under full load, the batteries supply 1000 W, or about 40 A at 25 V. When discharged at 550 W, corresponding to a vehicle speed of 4 knots including the hotel load of 125 W, the battery system will provide over 14 hours endurance. In normal operation, the battery voltage varies from 28 V at full charge to the vehicle's under-voltage cutoff at about 22 V. After cutoff, only the transponders and the Argos transmitter remain powered; therefore, these may draw the battery voltage down to the internal module cutoff voltage after many days.

Charge is provided by an external charger that is connected to the battery housing in place of the vehicle. The charge is controlled and logged by a computer that enables or disables the chargers. The charge computer can also enable battery discharge load resistors to provide battery conditioning or cycle testing. Full charge requires about 8 hours.

D. Radio Communication

SAMS carries three radio devices: a radio modem, an Argos transmitter and a GPS receiver. The three devices use separate antenna elements that are all contained in a single antenna fin assembly.

Normal communications with the vehicle during launch or on the surface of the water is provided by a Freewave modem operating at 900 MHz. The modem provides serial communications at 56 kbaud.

An Argos PTT is installed on SAMS to aid in emergency location if all other methods fail. It is configured to transmit every 60 seconds to improve the chances of getting a location during any satellite pass. The PTT transmits three bytes of vehicle status data: the main and emergency battery voltages, and the state of the release devices. The Argos account for SAMS is configured to send the maximum information about receptions from the vehicle, even when good positions cannot be computed. The Argos PTT remains powered by the main batteries even after the vehicle has shut down due to low battery voltage, and it is also powered by an emergency battery (10 alkaline D-cells) located in the main electronics housing.

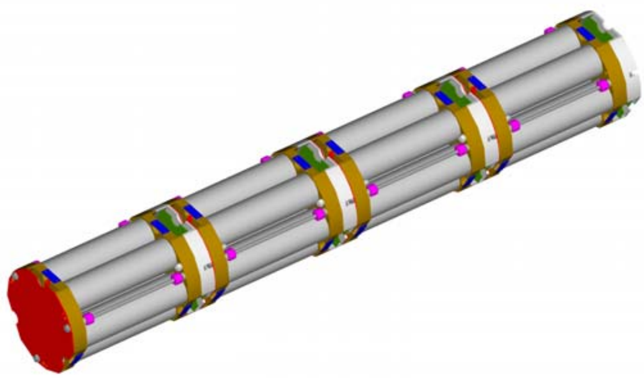

Figure 5 Four module battery pack

The GPS receiver provides the initial launch position to the vehicle and provides a recovery position to the ship via the RF modem. The GPS receiver is not powered after the battery voltage drops below the vehicle cutoff voltage, and thus the GPS position is not transmitted as Argos data.

E. Vehicle Interface Program (VIP)

SAMS uses the same Vehicle Interface Program (VIP) as the well known REMUS AUV. This simplifies logistics and training thus lowering operational costs. A person trained on the 80 lb. REMUS vehicle can easily adapt to operating the much larger SAMS vehicle. Similarly, operations manuals for SAMS duplicate much of what is in the existing REMUS manuals. The VIP is designed to assist the operator in all phases of the mission, including planning, launch, the mission itself, data download, and analysis. A single tool, a single common interface, gives operators the confidence they need to successfully deploy SAMS with the knowledge that it will execute its mission and return safely.

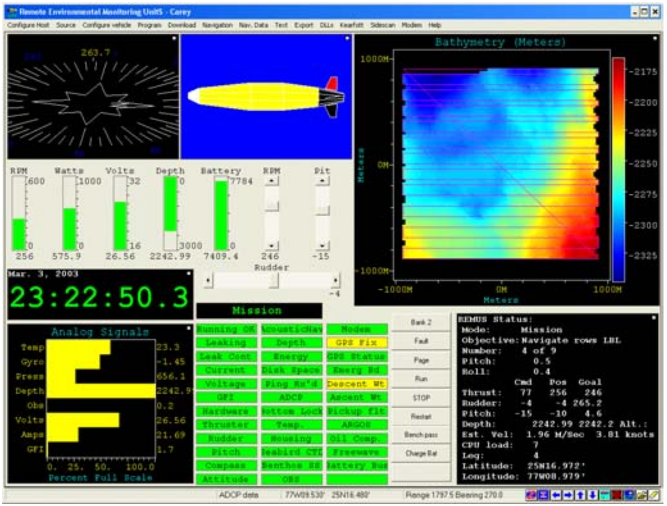

Figure 6 SAMS VIP screen

F. Acoustic Communication

The WHOI Utility Acoustic Modem (UAM) is used as a telemetry and control system. The system includes 3 modems: 1 for the vehicle; 1 for the ship; and 1 in the operations van, for pre-launch checkout. Each modem has two serial ports for control and data. In general, the first port (the "Console" port) is used for engineering tests and programming of the modem, while the second port (the "User" port) is used to send and receive data. A system block diagram, including installed locations of the three modems is shown in Figure 7.

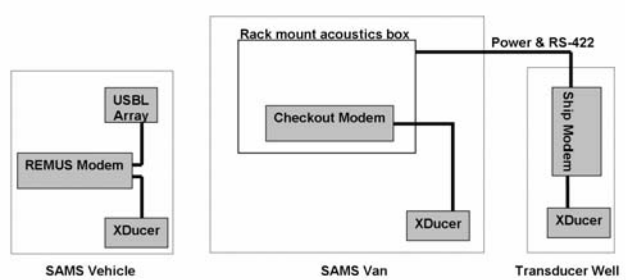

Figure 7 Block diagram showing modem locations

All SAMS Utility Acoustic Modems communicate acoustically using frequencies from 12.5 KHz to 17.5 KHz. Packets consist of an FM Sweep synchronization pulse followed by direct sequence spread spectrum (DSSS) phase shift keyed (PSK) data with duration of 3.4 seconds. The data payload consists of 3 32-byte data frames, yielding a net burst data rate of 226 bits per second (bps).

In most mission situations, the acoustic link is used to transmit vehicle status information to the surface and to assist in vehicle navigation. In addition to this mode of operation, the SAMS system also supports acoustic control of the vehicle during a mission. The Vehicle Interface Program (VIP) provides the user with an interface for sending commands to the vehicle. Both one-time commands and mission redirection commands can be sent. Examples of one time commands include start mission, abort mission, release descent or ascent weights, or pick up float, etc. Mission redirection commands the vehicle to do something new, as perform a sidescan survey at a new location. After the redirect objective is complete, the vehicle will return to its previously programmed mission. The vehicle maintains a list of redirect commands, so that they may be executed serially. Redirect commands are entered using the VIP.

IV. LAUNCH AND RECOVERY SYSTEM

The SAMS vehicle Launch And Recovery System (LARS) is a modified a-frame design, which is similar in concept to the High Resolution Profiler LARS [1] developed at WHOI. The major components include the a-frame structure, docking head, launch/recovery line winch, hydraulic power unit and vehicle cart assembly. No LARS component other than launch/recovery line enters the water. Vehicle size, vertical launch orientation, high freeboard of the T-AGS-60 Class vessels (nominally 10 feet) and sea state requirements were important factors in determining the extended pre-launch/post recovery position of the vehicle in the docking head. In this position the vehicle centerline is 10 feet aft of the stern and the vehicle tail is 4 feet above mean water level. Shipment of the LARS inside an ISO container also set limits on overall system dimensions.

The key components in positioning the vehicle for launch and recovery are the a-frame structure and the vehicle cart assembly. In switching the vehicle from horizontal storage position to the vertical launch position and providing adequate clearance from the stern the a-frame rotates 130º. Since this exceeds the a-frame rotation permissible with a single set of cylinders, two sets of cylinders hydraulically connected with sequence valves are used. The vehicle cart assembly has a multiple functions. It is used to transport the vehicle in and out of the maintenance van, it supports the vehicle during maintenance and it is critical in controlling the vehicle when the a-frame rotates between the horizontal and vertical positions. Figure 8 shows the retracted cylinders and the vehicle in the cart on the LARS skid. The vehicle cart assembly is secured in the LARS with two aluminum pins.

When the a-frame is rotated past vertical the vehicle is captured in the docking head and supported by the launch recovery line. The docking head components include the launch/recovery winch, cylinders and the vehicle capture ring. Figure 9 shows the docking head unit. The winch stores the multi-component launch/recovery lines. The primary component is a 10.5 m section of 12.7 mm diameter nylon braid, which supports the vehicle between the waterline and the docking head. Maximum winch torque is set to a value slightly higher than required to recover the vehicle to minimize snap loading. The cylinders are used to dampen motion of the vehicle in the docking head and can be used to position the docking head. Normally the cylinders are in the dampening mode, unless the docking head cylinder control stick is engaged. The amount of dampening is controlled with an adjustable valve. The capture ring is supported with four air springs pressurized to 69 kilopascal. The capture ring splits to allow installation on and removal from the vehicle.

Figure 8 Vehicle on cart assembly prior to launch

The LARS has an integral hydraulic power unit and oil tank mounted on the deck skid. The hydraulic unit is powered by a 3 phase, 480 VAC, 15-horsepower electric motor running a axial piston hydraulic pump. There are three separate hydraulic circuits to rotate the a-frame, dampen/position the docking head and rotate the launch/recovery line winch.

Both a-frame rotation and the winch are proportionally controlled. Docking head rotation is on-off controlled and docking head dampening is a passive. The oil tank has a capacity of 1,34.5 liters and is outfitted with a heater for cold weather operations. The system is controlled from a remote control box positioned for good viewing of launch/recovery operations.

Except for the remote control box, all components of the LARS are mounted on the deck skid. On the T-AGS-60 ships, simultaneous installation of the TOSS system determined the position of the LARS. The deck skid is mounted to the deck with a set of deck plates that align with the ships deck bolt configuration, and position the LARS directly aft of the vehicle maintenance van with the aft skid edge at the vehicle stern. The deck skid is 2 m wide and 3.4 m long. In the retracted position the a-frame extends .762 m forward of the forward edge of the deck skid.

An important component in deployment of the vehicle is the descent weight. The launch is conducted with the ship moving forward at roughly 1 m/s. The vehicle and two sections of the launch line, approximately 23 kg , are deployed. The a-frame is retracted and the line is secured to a cleat on the a-frame leg. The knot connecting the second section of launch line to the permanent line on the winch is untied and the launch line is connected to the descent weight assembly. The descent weight assembly includes a small section of line, a corrosive link and 23 kg of steel chain. The line is released from the cleat and the descent weight is pushed off the stern when ready. With the 23 kg descent weight and vehicle fins at maximum rotation, the vehicle descends at about 0.83 m/s. The descent weight is released as the vehicle nears the seafloor.

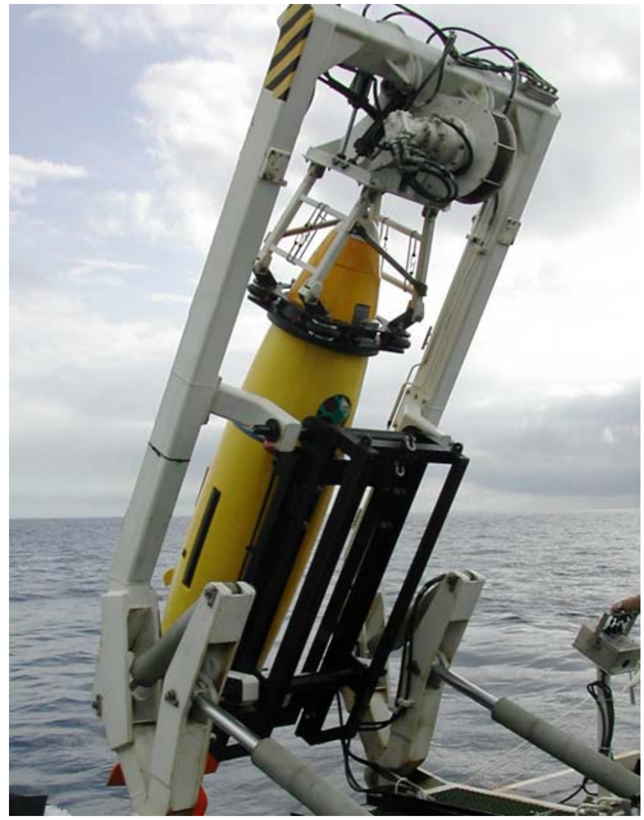

Figure 9 Vehicle captured by docking head and cart

When the vehicle returns to the surface and the ship positions itself based on the sea and wind conditions, the final phase of recovery is initiated with release of the recovery float from the vehicle. The float pulls a 36.6 m long, three-section line out of the body of the vehicle. The line is captured with a grapple fired from a pneumatic gun. The recovery float line is then recovered and tied to the end of the permanent line on the LARS winch. After the ship gains forward motion (similar to the launch speed), all of the line and the vehicle are recovered.

The SAMS LARS system was delivered with a dummy vehicle. The dummy vehicle permits the ship's crew and captain to become familiar with launch and recovery operations before the actual vehicle is used. We attribute the fact that the vehicle received only minor damaged during one launch and recovery operation to the decision to include a dummy vehicle in the system for training purposes.

V. OPERATIONAL EXPERIENCE

Field testing and personnel training with the SAMS system was conducted aboard two NAVOCEANO T-AGS-60 class ships: the USNS Heezen in April 2002; and the USNS Pathfinder in February-March of 2003. The 2002 tests were conducted in the Strait of Juan De Fuca, and off the coast of Washington. The 2003 tests were conducted in the vicinity of the Grand Bahamas Islands.

During the initial testing period in 2002, the vehicle was operated in shallow water (30 m inside the harbor of Port Angles and in Fresh Water Bay in the Strait of Juan De Fuca) and in 500 m of water off the coast of Washington. During these tests, over 18 hours of in water time was logged with numerous vehicle launch and recovery operations completed. During the 500 meter mission, the vehicle mapped a 1 square nautical mile area in 6 hours at 0.25 m resolution. This achievement represents at least a six fold increase in productivity over conventional towed systems. Figure 10 is an image of the bathymetry of and the vehicle track in the area surveyed by the vehicle.

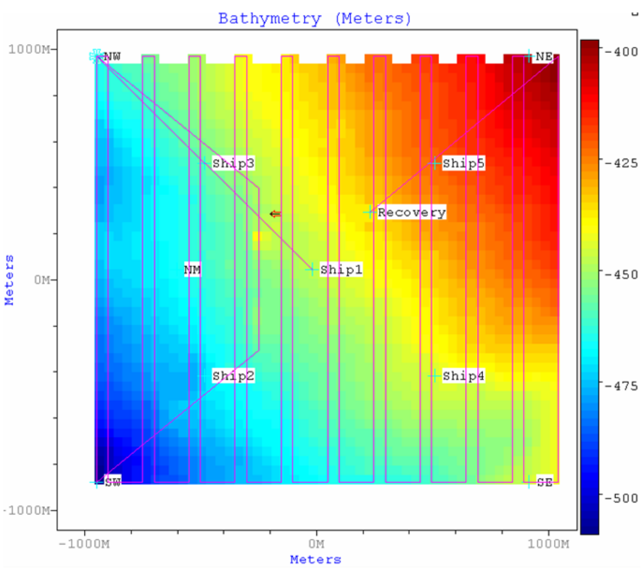

Figure 10 SAMS bathymetry from the 500 m test site

Testing during the spring of 2003 was conducted in two locations. Figure 11 presents the location and a bathymetry plot of the 2,500 m test area. It was created with a shipboard multi-beam sonar system develop by Kongsberg Simrad. The detailed bathymetry plot of this test area shows extremely rugged terrain which is very similar to the topography of the Grand Canyon; a 4.6 degree slope falling from -2.25 km to -3.99 km in 20 km. , the SAMS vehicle was sent on a 20 km transit down the side of this steep wall to the valley floor, after completing a survey of a portion of the upper area depicted in Figure 11. Vehicle status data that was up-linked to the ship over the acoustic link during the descent provided enough information about the terrain to convince us to abort the mission rather than redirect the vehicle back up slope. On descent, a number of cliffs over 150 m high were detected. The purpose of this test was to demonstrate that the vehicle was capable of performing long linear transects. The transit portion of the mission took about three hours.

A. Deep Water Testing

Deep water testing of the SAMS vehicle was conducted in an area about 185 km northeast of the island of Abaco, on a flat abyssal plain. The south end of Abaco Island can be seen above the 2,500 m test area in Figure 11. At this point in the cruise, the training program had been completed, so NAVOCEANO personnel programmed the vehicle for this mission. The vehicle was programmed to survey a 3.7 km^2 area in 10 hours. The sidescan sonar was operated with the range set to 200 m. The vehicle was launched with a 22 kg descent weight and a 23 kg ascent weight, providing a spiraling descent rate of 0.83 m/s at an angle of 40 degrees; the dive to 4,660 m took about an hour and forty-eight minutes. At this depth, which was about 300 m above the seafloor, the vehicle automatically released the descent weight, and started to drive itself the rest of the distance to the seafloor. Two minutes after the vehicle released the descent weight, the emergency board indicated a fault (an open circuit) in the wiring to one of the two unused release mechanism solenoids. The acoustic uplink of vehicle status provided the information indicating the fault.

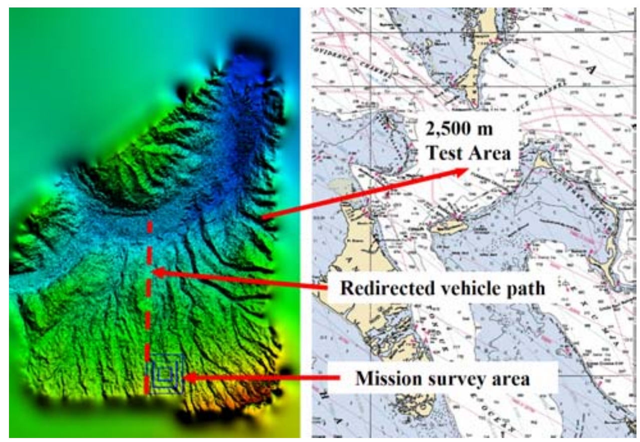

Figure 11 Detailed bathymetry and location of 2.5 km test area

Operational experience gained in the rough terrain of the 2,500 m test area led to the development of a new altitude algorithm for acquiring the bottom. This new algorithm caused the vehicle to over-react and climb each time it established initial bottom lock from the ADCP. This situation prevented the vehicle from reaching its programmed altitude above the bottom for the survey. Vehicle status information up-linked over the acoustic communication link provided enough information to diagnose the problem. A redirection command was used to take the vehicle out of altitude mode and to dive it through this window at 100 m above the seafloor. Once the vehicle passed through this transition zone, it resumed and completed its previously programmed mission in altitude mode. This problem caused the vehicle to take an additional forty-eight minutes to acquire the bottom and begin flying at 20 meters above the bottom. It also demonstrated the value of being able to redirect the vehicle's mission from the surface.

After reaching the desired altitude above the seafloor, the vehicle took about 10.2 hours to complete the survey of the 3.7 km^2 area, at which point, it tried to drop the ascent weight and return to the surface. It was at this time, as luck would have it, that we found out for sure that the detected open was to the solenoid in the ascent weight drop mechanism. The vehicle is designed to be buoyant at depths up to 6 km after dropping either the descent or ascent weight, and to drive itself to the surface whether or not the ascent weight drops. At 4,660 m, the same depth at which the open appeared, the open to the solenoid cleared itself and the ascent weight dropped from the vehicle. The vehicle continued to drive itself to the surface with this additional buoyancy, achieving a spiraling ascent rate of 2.3 m/s at an angle of 70 degrees. Figure 12 provides a profile of this historic mission.

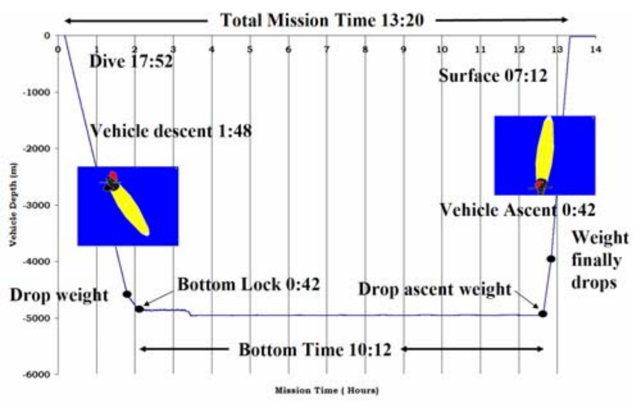

Figure 12 Plot of events during mission 9

The SAMS vehicle is designed so that the descent weight weighs less than the ascent weight, and so the vehicle is buoyant at depth when either weight is released. Limiting the weight adds about 80 minutes to a mission conducted at 6 km. While limiting the descent is not attractive if bottom time is the priority, it does offer a level of redundancy that is very attractive; as long as either the descent or ascent weight releases, the vehicle will return to the surface, despite the fact that it loses buoyancy as it rises from the deep ocean.

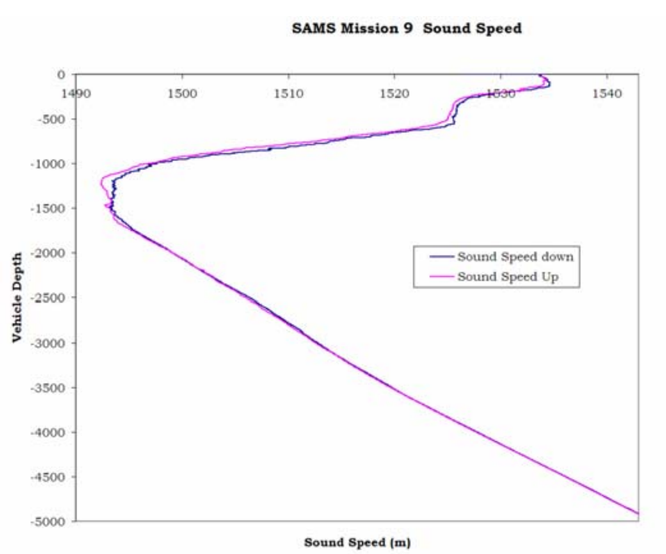

Figure 13 Descent and ascent Sound speed profiles to 4960 m

Figure 14 is a plot of the temperature of the seawater approximately 20 meters above the seafloor collected during the mission. Note the river of cold water that runs up the center of the areas surveyed (north is up). Considering the fact that it took the vehicle almost 10 hours to survey this area, this feature is very stable. The purple lines show the track lines the vehicle was programmed to follow. The area at the top of the survey without temperature data represents the portion of the survey that the vehicle took to acquire the bottom.

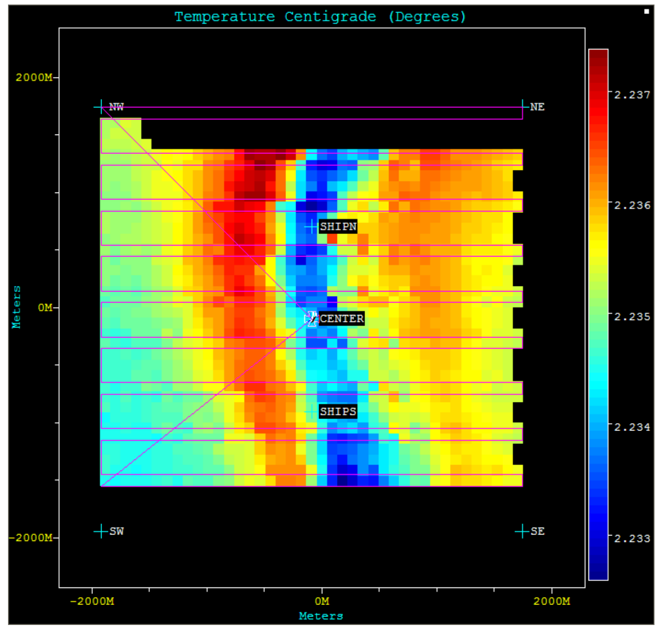

Figure 14 Temperature plots at 4943 m, altitude 20 m

VI. CONCLUSIONS

The SAMS vehicle system was accepted as initially operational at the end of the second test cruise in March 2003, after 16 days of testing and training. On March 5th, all WHOI personnel left the USNS Pathfinder, leaving NAVOCEANO personnel in charge of the system. The NAVOCEANO team completed four additional missions in the 2,500 m test area before returning to port.

Operational experience gained with the launch and recovery system indicates that it is a key component of the system. Safe and efficient launch and recovery aids in the quick turn around of the vehicle, permitting operators to maximize bottom time. The ability to conduct safe launch and recovery operations in mild gale winds extends the operating envelope of the system and thereby de-motivates the need for large costly vehicles with extended battery life for ship based operations.

VII. ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the Office of Naval Research, especially Dr. Thomas Swean, and the Naval Oceanographic Office, including the Systems Readiness Team, whose contributions, ideas, and hard work are an inherent part of this system. Their help has made this vehicle system a success. Complex ocean systems like SAMS take time to create. Cary Ingram, a great man who is no longer with us,

played a key role in the creation of this system. He had the vision to back it, because he knew ONR, NAVOCEANO, and WHOI would make it work. Here's to Cary.

VIII. REFERENCES

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[2.] C.J. von Alt, B. Allen, T. Austin, and R. Stokey "Remote Environmental Measuring Units," *Autonomous Underwater Vehicle Conference '94*, Cambridge, MA, 1994

Requirement	Specification
Maximum Diameter	71 cm (28 inch)
Maximum Length	3.72 m (12.2 ft)
Hull Shape	Turbulent flow My ring
Weight in air	884 kg (1950 lbs)
Displaced Volume	876 liters (31 cu-ft)
Buoyancy	Titanium reinforced syntactic foam with gel coated fiberglass covering
Descent Weight	22.6 kg (50 pounds)
Descent Speed	0.67 m/s (1.3 knots)
Ascent Weight	22.6 kg (50 pounds)
Ascent Speed	2.5 m/s (4.86 knots)
Maximum Operating Depth	6 km
Nominal power @ 2 m/s	Hotel load 120 w; total @ 2 m/s 600 w
Energy content of batteries	8.6 kWh rechargeable Li-ion battery pack in two pressure housings. A second 8.6 kWh set is provided with system permitting 2 hour turn around .
Battery Charging	Charge time 11 hours
Temperature range	-2 to + 30 degree C in water -10 to +45 degree C on deck operations
Number of recharges	100-300 deep cycles
Endurance	12 hours at 2 m/s; 10% of energy capacity in reserve
Propulsion	Direct drive DC brushless motor to an open 2 or 3 bladed propeller
Velocity Range	0.5 to 2 m/s variable over range
Working Velocity	2 m/s
Range @ working velocity	86.4 km (47.25 nm)
Control	2 coupled yaw and pitch fins ± 2 degree heading ±1 foot altitude
On/off	Mechanical switch
External Hook-up	Two pin combined Ether net and vehicle power
Casualty Circuits	Ground fault, leak and low voltage detection; go/no go indicator
Navigation	Long base line, 7-10 kHz; upward looking transducer Automated single beacon navigational position update Dead reckon with ADCP and compass.
Tracking	Emergency transponder, mission abort, ascent weight drop, ARGOS, GPS.
Acoustic Modem	WHOI utility modem, 7-10 kHz
Radio Modem	900 kHz Free wave Modem
Sensors	CT, OBS, Paroscientific depth, 300 kHz bottom lock ADCP, Electronic Still Camera with 200 watt-sec strobe, 300/900 kHz switchable sidescan sonar
Reserve Payload (in water)	27 kg (50 pounds)
Launch and Recovery	Over centered lifting frame; vehicle is in vertical orientation for launch and recovery operable from a T-AGS-60 ship in Beaufort Scale 6 winds
Shipping	Vehicle, LARS, and operations van on one 40 ft flatbed (2 20' ISO containers)
Software	GUI based laptop interface for programming, real time mission monitoring and redirection, training, documentation, maintenance and trouble shooting

Table 1 SAMS System Specification