New Capabilities of the REMUS Autonomous Underwater Vehicle

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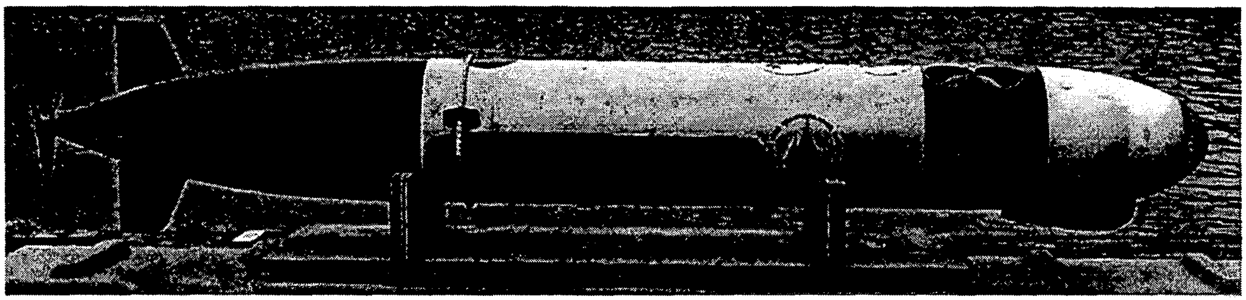

FIGURE 1. REMUS autonomous underwater vehicle, standard configuration

Abstract **- Autonomous underwater vehicle technology continues to advance at a rapid pace. REMUS (Remote Environmental Monitoring UnitS), developed by the Oceanographic Systems Laboratory at the Woods Hole Oceanographic Institution, is one of the most widely used autonomous underwater vehicles in the world. Each year REMUS vehicles participate in numerous field exercises in support of scientific and navy research objectives. Designed for coastal operations, REMUS is normally deployed with a CTD, light scattering sensor, side scan sonar and an up-and-down looking acoustic doppler current profiler (ADCP). Additional sensors are easily integrated in the vehicle and a bioluminescence instrument and a turbulence sensor package.**

Recent development efforts have improved the REMUS vehicle overall design and performance, and include integration of two new sensors. Vehicle improvements include lower drag, a new propulsion, new lithium-ion batteries and a new external interface. Maximum speed has been increased from 1.75 m/s to almost 3 m/s (6 knots) and mission length has increased to 22 hours at the 1.5 m/s (3 knots) cruising speed. REMUS has been used to demonstrate a new autonomous underwater vehicle application: plume mapping. A rhodamine fluorometer was installed to map a plume on a steep sloping sea floor. Results from the field test demonstrate the effectiveness of an AUV as a tool in this task. A second REMUS vehicle has been deployed with an optical sensor package. The instruments in the package include a chlorophyll fluorometer and up-and-down looking, seven channel radiometers. This package combined with the standard CTD and ADCP generates a significant scientific data set, which supports both physical and biological oceanographic research.

I. INTRODUCTION

Development of the first REMUS autonomous underwater vehicle (AUV) was initiated nearly six years ago [1]. Since the first pool and fresh water pond tests, technological improvements, experience from numerous field exercises and continuous engineering development have led to significant advancement in the vehicle's capabilities and reliability [2,3]. REMUS is now an effective tool for conducting scientific experiments and underwater surveys in coastal waters. As a result, REMUS is being considered for new tasks. In a recent field exercise REMUS was equipped with a sensor to detect a chemical plume. In an upcoming field exercise, REMUS will be equipped with physical, biological and optical sensors and generate data sets to study ocean optical properties and ground truth aircraft and satellite generated data sets.

II. VEHICLE DESCRIPTION AND ENHANCEMENTS

REMUS is a small AUV designed to conduct oceanographic surveys in shallow water. A standard REMUS, shown in Figure 1, is 19 cm in diameter and 160 cm long. It is equipped with side scan sonar, up-and-down looking acoustic doppler current profiler, light scattering sensor and

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conductivity, temperature and depth sensors. Vehicle operation is controlled with a PC-104, IBM compatible computer. The CPU board is mounted on a custom motherboard with eight 16-bit analog to digital converters, input/output ports, power supplies and interface circuitry. REMUS has three motors for propulsion, yaw control and pitch control. The motors are controlled by a dedicated 68HC11 micro-controller, which communicates to the main CPU via an isolated RS-232 interface. Table 1 lists many of the REMUS specifications and features.

Diameter	19 cm
Length	160 cm
Air Weight	37 kg
Displaced Volume	35.7 liters
Trim Weight	1 kg
Max. Oper. Depth	100 m
Power	Hotel load – 30 W total power @ 1.5 m/s is 45 W
Energy	1 kW-hr internally rechargeable lithium ion battery
Endurance	22 hours at optimum speed of 1.5 m/s
Propulsion	Direct drive DC brushless motor with open three blade propeller
Velocity Range	0.25 to 2.8 m/s
Control	2 coupled yaw and pitch fins
On/Off	Magnetic switch
External Hook-Up	2-pin combined ethernet, power and battery charging; 4-pin serial connection
Casualty Circuits	Ground fault, leak and low voltage detection, go/no go indicator
Navigation	Long baseline, ultra-short baseline, dead reckoning with doppler velocity log and compass, dead reckoning with compass and propeller turns
Transponders	10-15 kHz and 20-30 kHz systems
Tracking	REMUS Ranger, Mission abort, emerg. transponder, ORE Trackpoint compatible
Sensors	CTD, ADCP, side scan sonar, light scattering, digital compass, yaw rate gyro
Software	GUI based laptop interface for programming, training, maintenance, documentation and trouble shooting

Table 1. REMUS specifications and features

Recent design changes have significantly improved vehicle speed, endurance and reliability. Endurance has been improved through a combination of drag reduction, improved propulsion system and new battery technology. Drag improvements resulted from rounding the blunt nose and fairing the navigation transducer. The propulsion system design changes include replacing the existing DC brush motor, shaft seal and model airplane propeller with a DC brushless motor (potted and installed in a flooded cavity) and matched open three-blade propeller. Maximum speed has increased from less than 2 m/s to nearly 3 m/s. New rechargeable lithium-ion battery packs with a total capacity of 1 kW-hr are being integrated into the vehicle. Prior to this installation the vehicle was generally powered with lead acid batteries with a capacity of less than 300 W-hours. At the optimum cruising speed of 1.5 m/s the vehicle endurance has been increased to 22 hours. The previous longest mission, achieved with primary lithium batteries was 15 hours.

Installation of the lithium ion batteries and implementation of the new ethernet interface have increased system reliability. The lithium ion batteries are sealed and do not release gas during charging like the lead acid batteries. The serial link provides a connection to the main CPU, but not both the main CPU and side scan sonar CPU, as is possible with the ethernet. Thus, all battery charging and data downloading may be accomplished without opening the vehicle between missions. This eliminates many potential failures.

Other improvements include the automatic selection of optimum navigation technique, automated mission programming, simplified layout and half-size ADCP. Areas of ongoing research include implementation of acoustic communication and a GPS capability.

III. PLUME SENSING EXPERIMENT

A REMUS vehicle was deployed during the Chemical Sensing in Marine Environments test at San Clemente Island, CA in March, 1999 with the purpose of determining whether it was an effective tool for locating and defining a plume.

A. Sensor Integration

One of the REMUS standard instruments, the light scattering sensor, was replaced with Seapoint Sensors' rhodamine fluorometer for this test. The integration required an extended nose cap, 2.5 cmlonger than the standard, to accommodate the slightly larger sensor. The rhodamine fluorometer was mounted with its' open measurement chamber protruding from the port side of the nose as shown in Figure 2. Although controllable gain is an option with this fluorometer, the gain was fixed to measure concentrations ranging from 0-15 ppb. At this setting and with the open chamber, the fluorometer did register an ambient light signal at very shallow depths, but this decreased below detectable levels at depths greater than a meter.

B. Plume Generation

In this experiment plumes were generated with a 2% solution of Rhodamine WT dye mixed with seawater. The mixture was pumped to one of three outlets located on the sea floor at a depth of approximately 15 meters. Each outlet consisted of a soaker hose wrapped around a 55-gallon drum. The outlets were spaced approximately 200 meters apart in a direction parallel to the adjacent shoreline. Currents at the site generally run alongshore. Depending on their direction and magnitude an outlet was selected to position the plume within the area bounded by the outer sources. The currents, bathymetry and source spacing defined a survey area roughly 400 meters by 150 meters.

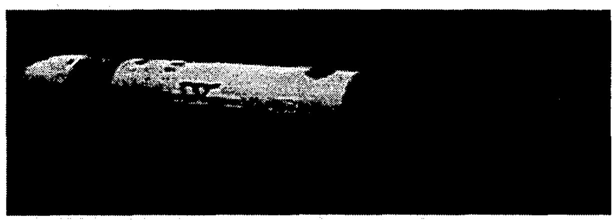

Figure 2. REMUS AUV with rhodamine fluorometer protruding from nose and kelp on fin

C. Mission Plan

Two transponder moorings, spaced 500 m apart, were deployed offshore of the survey area in approximately 30 meters of water. The transponders were position at a depth of 15 meters In addition to supporting long baseline navigation the transponders served as launch and recovery positions. After launch the vehicle implemented dead reckoning navigation to reach the survey area. While swimming the parallel tracks the vehicle used long baseline navigation. At the end of the survey the vehicle used ultra-short baseline navigation to home in on a transponder position for recovery. The survey tracks were 150 meters long. Track spacing was 10 or 20 meters. Depth over the track length ranged from 10 to 25 meters, and the vehicle was programmed to swim at 2, 4 and 6 meters above the bottom.

D. Challenges

Although REMUS is robustly designed, a concern prior to the test was the relatively steep slope of the bottom. Since the currents generally force the plume in the alongshore direction and the goal was to swim across the plume, it was necessary for the vehicle to swim perpendicular to the shoreline. REMUS would also have to swim at low altitude to detect the plume. REMUS generally swims at two meters when conducting side scan surveys, but not up and down the slope that was present at the test site. When operating in the altitude mode, REMUS is programmed to respond very quickly to decreases in altitude as compared to increases in the altitude. This is evident in the altitude plot shown in Figure 3. On offshore tracks the vehicle generally swam at 3-4 meters and on the inshore tracks the vehicle swam at 1-2 meters. The altitude plot also indicates the different response of the vehicle in port and starboard turns. This is most likely caused by the non-symmetric fluorometer installation.

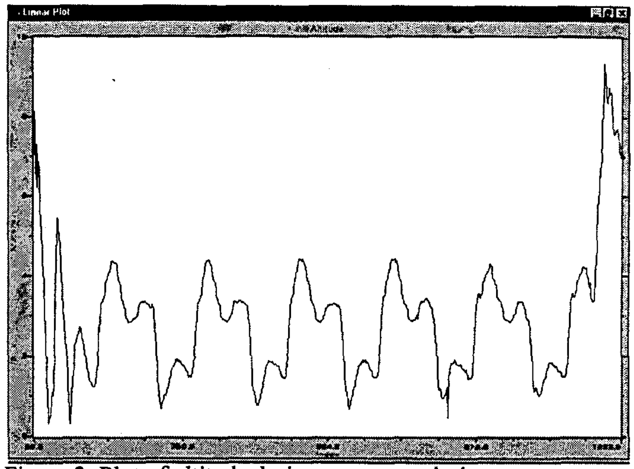

Figure 3. Plot of altitude during a survey mission

A second concern particular to the test site was the kelp. Seaweed has been a rare problem during the many years of REMUS operations. On the first day higher altitude (nominally 7 meters) side scan surveys were conducted without problems. On the second day kelp disrupted four plume survey missions (altitude goal of 4 meters). Review of position, attitude and power data indicates that the vehicle became entangled in kelp numerous times. On other occasions the vehicle dragged kelp (Figure 2). The vehicle aborted the first two missions because it did not reach mission objectives within the required time. The third mission was completed and the fourth was terminated early because the battery voltage dropped too low. On the final day the vehicle was programmed to swim at an altitude of 2 meters. The mission was completed, but the vehicle did drag kelp during parts of the mission.

The vehicle performance in the kelp was surprisingly good. This is primarily attributed to the new, more powerful propulsion system. Each time the vehicle became entangled it was able to break free. Even when kelp was caught on the vehicle body or fins the vehicle continued to swim and navigate effectively. No kelp was attached to the vehicle at the end of a survey mission whether it was aborted or completed. This suggests that operational strategies are available for the vehicle to shed kelp.

E. Plume Detection

Despite the kelp, the vehicle successfully detected the plume. The best performance was achieved on the final day when the vehicle, programmed to swim tracks with 10 m spacing, crossed through the plume twelve times. Figure 4 shows a linear plot of the fluorometer measurement during this mission. The initial high concentration (approximately 15 ppb) measurements were for tracks very close to the source. The plume was located near the inshore end of the track. The lower readings occurring on offshore bound tracks are attributed to the higher altitude of the vehicle.

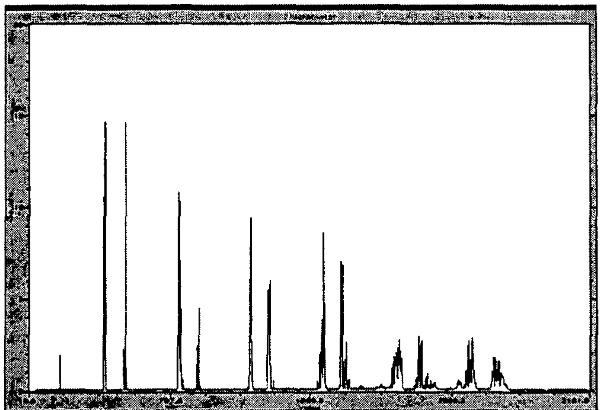

Figure 4. Linear plot of fluorometer output (ppb)

Fluorometer readings are averaged and correlated with actual vehicle position in Figure 5. The track shown on the plot represents the programmed track. The source location is marked on the plot. This data is typically available within one hour of vehicle recovery.

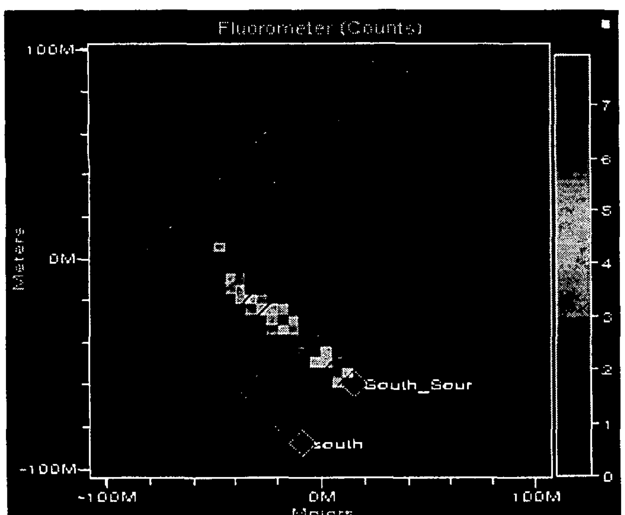

Figure 5. Plot of fluorometer readings (ppb) in the survey area

IV. "OPTICAL" REMUS

The Oceanographic Systems Laboratory has conducted REMUS field operations at the LEO-15 site off the coast of New Jersey every July since 1997. These operations have supported the Coastal Predictive Skill Experiment conducted by Rutgers University. These operations have been key in evaluating new REMUS capabilities and each year has seen a dramatic increase in the operational capabilities.

A. New Sensor Integration

During past LEO-15 operations, REMUS has been equipped with the up-and-down looking ADCP, the light scattering sensor and a CTD. For this summer, as part of the Hyperspectral Coupled Ocean Dynamic Experiment (HyCODE), the light scattering sensor has been removed, and a new sensor module has been installed aft of the nose. This module is equipped with up-and-down looking multi-channel radiometers and a chlorophyll fluorometer. Each radiometer has seven channels. They will provide measurements of downwelling irradiance and upwelling radiance at the following wavelengths: 412, 443, 490, 510, 555, 670 and 683 nanometers. Overall length of the modified "optical" REMUS is 173.5 cm. All data generated by the new sensors is logged on the vehicle main computer.

B. Mission Plan

Data collected with the new REMUS will support analysis and modeling of ocean optical properties. REMUS will swim long tracklines roughly perpendicular to the coast. Figure 6 shows a typical trackline extending from the nearshore region out to almost 25 km offshore. REMUS will undulate between 5 meters above the bottom and 5 meters below the surface as it swims the trackline. Vehicle missions will be coordinated with flights of aircraft carrying optical instrumentation to provide groundtruth data.

Each mission will consist of an offshore and onshore track. The vehicle will be launched from the inshore end and recovered at the inshore end. The trackline is defined by six buoys (indicated by the black squares in Figure 6) spaced four kilometers apart. The vehicle uses the buoys to perform long baseline navigation [4]. The buoys are also capable of determining range to the buoy and transmitting this information to the shore station. The combined navigation/tracking system is called PARADIGM [4].

V. CONCLUSIONS

Experience, continuous engineering development and improving technologies have resulted in maturation of the REMUS autonomous underwater vehicle. The system is now a critical data collection tool in many oceanographic experiments. This trend will continue for autonomous underwater vehicles in general as they gain wider acceptance within the research, commercial and military communities.

V. ACKNOWLEDGMENTS

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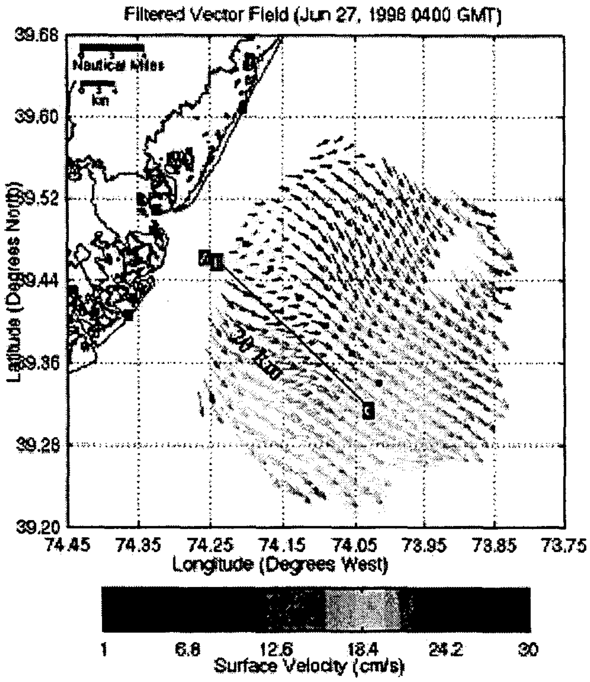

Figure 6. REMUS trackline displayed with surface current field

VI. REFERENCES

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