Demonstration of Surf Zone Crawlers: Results from AUV Fest 01

Chuck Bernstein, Mark Connolly, Mitch Gavrilash,
Dan Kucik and Stan Threatt

Surf Zone Crawler Group
Naval Surface Warfare Center
Coastal Systems Station
Panama City, Florida 32407

Abstract

A key element in minimizing the risks of an amphibious assault is the ability to search and map the surf zone for mines and obstacles. The Office of Naval Research is sponsoring the development of an autonomous, bottom-crawling vehicle to investigate its applications in searching and clearing potential landing zones. In October 2001, AUV Fest 01 was held in Gulfport, Mississippi, where the current state of development of these vehicles was demonstrated.

Two types of missions have been identified as objectives for the vehicles. One is known as Search-Classify-Map (SCM) and the other as Reacquire-Identify-Neutralize (RIN). For the SCM mission the vehicle is equipped with a suite of sensors, used to characterize any objects encountered. The vehicle proceeds to a given starting point and performs a raster (lawnmower) search over a specified area. When a sensor indicates a potential target, the location is noted and the vehicle performs a number of behaviors designed to optimize data collection. The vehicle then returns to the search pattern and continues with this process. The RIN mission calls for a vehicle that has been equipped to identify and neutralize a threat object. Its' sensor suite includes a camera and an acoustic modem for transmitting the images back to an operator. In this scenario a potential target has been detected by another vehicle. The neutralization vehicle navigates to the reported location and performs an outward-spiral search pattern until the target is located. Positive identification of the target is accomplished by the operator, who would then either direct the vehicle to leave a neutralization charge by the object or move on to another potential target.

Results from AUV Fest show that the crawlers are capable of demonstrating the RIN mission in the near future. The search-and-map mission is more challenging, primarily due to the short detection ranges of the sensors. From the standpoint of vehicle operations, the key issue is one of mobility. In silt or mud the vehicles tend to dig themselves in and get stuck. Current investigations are now concentrating on the selection and integration of alternate sensors and the means by which vehicle mobility can be enhanced. This paper will discuss the current state of vehicle design, the sensors that are being used and the results that have been achieved.

I. Introduction

The ability to search and map a potential assault lane is critical to the success of an amphibious landing. Swimming autonomous underwater vehicles (AUVs) show a

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14. ABSTRACT

A key element in minimizing the risks of an amphibious assault is the ability to search and map the surf zone for mines and obstacles. The Office of Naval Research is sponsoring the development of an autonomous, bottom-crawling vehicle to investigate its applications in searching and clearing potential landing zones. In October 2001, AUV Fest 01 was held in Gulfport, Mississippi, where the current state of development of these vehicles was demonstrated. Two types of missions have been identified as objectives for the vehicles. One is known as Search-Classify-Map (SCM) and the other as Reacquire-Identify-Neutralize (RIN). For the SCM mission the vehicle is equipped with a suite of sensors, used to characterize any objects encountered. The vehicle proceeds to a given starting point and performs a raster (lawnmower) search over a specified area. When a sensor indicates a potential target, the location is noted and the vehicle performs a number of behaviors designed to optimize data collection. The vehicle then returns to the search pattern and continues with this process. The RIN mission calls for a vehicle that has been equipped to identify and neutralize a threat object. Its' sensor suite includes a camera and an acoustic modem for transmitting the images back to an operator. In this scenario a potential target has been detected by another vehicle. The neutralization vehicle navigates to the reported location and performs an outward-spiral search pattern until the target is located. Positive identification of the target is accomplished by the operator, who would then either direct the vehicle to leave a neutralization charge by the object or move on to another potential target. Results from AUV Fest show that the crawlers are capable of demonstrating the RIN mission in the near future. The search-and-map mission is more challenging, primarily due to the short detection ranges of the sensors. From the standpoint of vehicle operations, the key issue is one of mobility. In silt or mud the vehicles tend to dig themselves in and get stuck. Current investigations are now concentrating on the selection and integration of alternate sensors and the means by which vehicle mobility can be enhanced. This paper will discuss the current state of vehicle design, the sensors that are being used and the results that have been achieved.

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great deal of promise at being able to do this in shallow water, but a thorough reconnaissance includes mapping the lane all the way up onto the beach. Under the sponsorship of the Office of Naval Research (Code 321OE, Very Shallow Water and Surf Zone Mine Countermeasures Program), and in cooperation with Foster-Miller, Inc., of Waltham, Massachusetts, the Surf Zone Crawler Group at the Coastal Systems Station has undertaken the design and development of an autonomous, bottom-crawling vehicle that would accomplish this task.

The concept of operations for employing these vehicles has been evolving as the capabilities and limitations of the vehicles are explored. The original idea was that 10 to 25 small, expendable vehicles would be deployed from an autonomous carrier vehicle. The current vehicles have grown in size, primarily to accommodate the sensor packages and the batteries required to allow for enough run time to perform a thorough search. The current approach is to have one or several vehicles deployed from a Rigid-Hulled Inflatable Boat (RHIB). Rather than attempt to exhaustively search and map a lane, the emphasis is in determining whether the lane is mined and what type of threat exists.

The vehicles are equipped with a suite of sensors, by which they detect and classify objects encountered during a search [1]. The sensors that have been investigated include a bumper, a tactile sensor for determining the texture of an object, a profiler for determining the shape of an object, a still camera, a video camera, and a Pulse-Eddy Induction Coil (PEIC) for detecting any metallic objects. Acoustic modems allow for bi-directional communications between the vehicle and operator. There is also a unidirectional link from the operator to the vehicle using a magneto-inductive system. The vehicles are designed to perform basic classification behaviors autonomously, and are able to screen out any objects that are obviously not threats. Communications with the operator occurs when a potential threat has been encountered, providing for optimal utilization of the relatively narrow acoustic bandwidth.

This paper describes the current state of development of the vehicles, the mission objectives, the results and lessons learned from field experience.

II. Vehicle Description

Figure 1. Vehicle configured with a still camera and a Benthos ATM-885 acoustic modem.

Figure 1 shows the vehicle with, from front to back, the bumper, a still camera mounted on a section of PVC pipe, the Sensor Processor (SP) in an aluminum housing, a Benthos ATM-885 acoustic modem and the long baseline (LBL) antenna. Vehicle construction utilizes non-magnetic materials as much as possible, to minimize interference with the compass and magnetic sensors. The tracks are made of molded polyurethane V-belts, connected by cross pieces. Power is provided by 6 lead-acid gel cell batteries. The vehicle uses two Kollmorgen series RBE brushless motors with a 145 foot-lbs peak output rating. Processing is done by two TERN A104S boards, which are

AMD 188-based single board computers. One is designated as the Control (CTRL) computer and the other as the Position Estimator (PE) computer. The software that resides on the boards is written in Borland C.

The vehicle is run at a nominal speed of 0.5 meters/sec and a turn rate of 60°/sec. Faster speeds are possible but come at the expense of battery duration and diminishing stability. The vehicle can operate for over 2 hours on fully charged batteries. The dry weight of a basic vehicle is approximately 110 lbs, which increases as different sensor packages are installed.

A. Command and Control

Elementary	**ROV/Diagnostics/Primitives**	
	Command	*Reply*
A(djust relative timer) # (seconds)	a(ccelerate)	a # (nominal speed)
B(ack-up) # meters	b(ack-up)	b
C(orrection) # RTCM String (bytes)	c(oordinates)	c GPS String
D(estination) sets global X#,Y#, Z#	d(ecelerate)	d # (nominal speed)
E(XECUTE CONVENTION) #	e(nergy)	e # (percent)
F(orward) # meters	f(orward)	f
G(roup) # (assign)	g(roup)	g # (currently assigned to)
H(eading) # adjust vehicle orientation	h(eading)	h # (degrees)
I(mage) # (bytes)	i(motor currents)	i # # (left, right Amperes)
J(og) # diagnostic maneuver type	j(og)	j #
K # set heartbeat interval in seconds	k(eep heartbeat going)	k # (stop timer setting)
L(eft) # (relative degrees)	l(eft)	l
M(OVE) V #, X #, Y#, Z #	m(achine)	m # (id)
N(avigation bounds) e.g., Z<aX+b	n(avigation boundary)	n # nav. bound or obstacle
O(rigin) #,#,# sets origin coordinates	o(rientation)	roll, pitch, yaw
P(osition) X#, Y#, Z# (relative)	p(osition) rel.	x, y, z
Q(uery) # report type	q(uiet) mode	q # toggle verbose flag
R(ight) # (relative degrees)	r(ight)	r
S(top) all stop	s(top motors)	s
T(RANSIT) range #, bearing #	t(ime)	t # (seconds)
U(nit) # access subsystem	u(nknown object type)	u # (object type)
V(elocity) # # set	v(elocity)	Vx, Vy, Vz, V
W(aypoint) index #, X #, Y#, Z #	w(heel counts)	w # # (left, right count)
X # pos. in North latitude direction	x	x # (relative meters North)
Y # depth/altitude, zero at sea level	y	y # (depth)
Z # pos. in the East longitude	z	z # (realtive meters East)

Table 1: CSS Command Set (Draft 2.0)

An Applications Programming Interface (API), known as ROBO, has been developed by the Surf Zone Crawler Group, which provides the means for programming and interacting with the vehicles. ROBO consists of a command set that resides in a dictionary on the Control Computer (Table 1), an interpreter based on the FORTH programming language and an asynchronous communications scheme. The vehicle can be driven in ROV mode by entering these commands individually. Alternately, a script consisting of a series of commands can be written and loaded onto the Control Computer, allowing for autonomous operation. The scripts define microbehaviors, such as search patterns, obstacle avoidance and target investigation, and can be invoked based on sensor triggers.

The Operator Control Station (OCS) is a laptop computer with an RS-232 port connected to a Freewave DGR-115R modem. A command window allows the operator to pass commands and scripts to the vehicle. The OCS also provides data acquisition and storage capabilities, and has other windows in which the data can be plotted and displayed. OCS software is written in Java, making it compatible with a number of platforms and operating systems. This approach was chosen with the idea of making the OCS a server, allowing vehicle data to be accessed by multiple clients using Internet browsers. Figure 2 shows several of the available OCS windows.

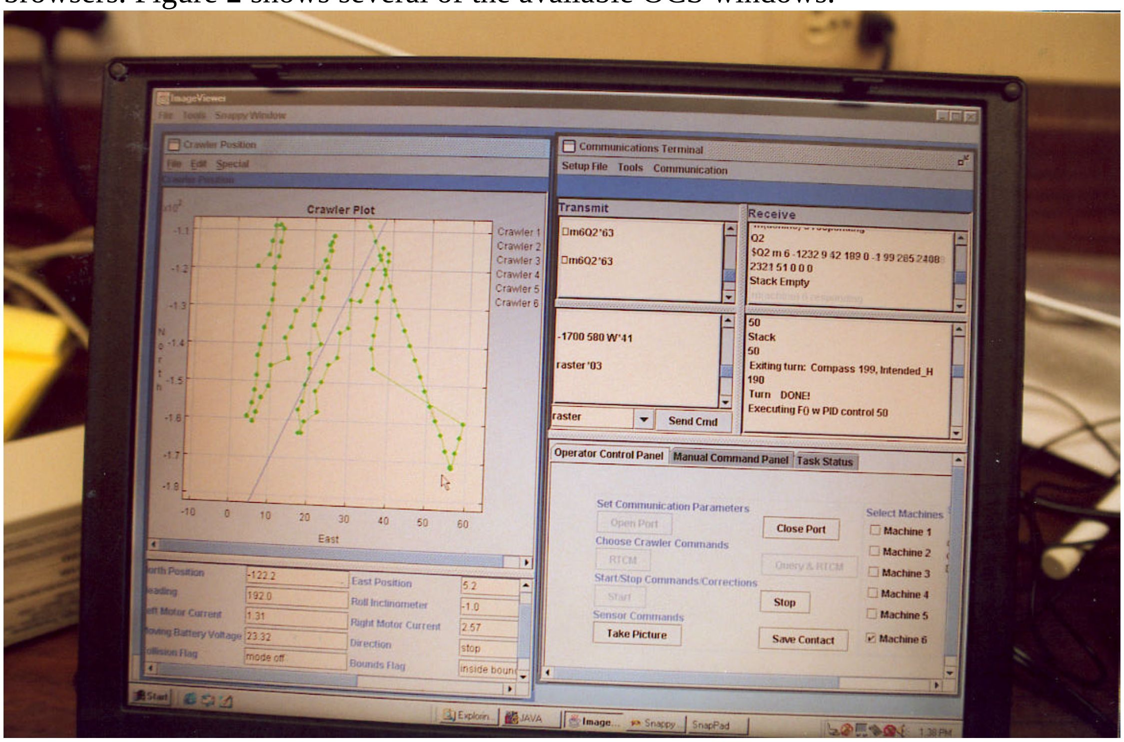

Figure 2. OCS display.

B. Communications

All commands are transmitted as simple ASCII strings. This is not a particularly efficient use of bandwidth, and care must be taken to avoid exceeding the bit rate allowed by any device. The advantage is in the ease of implementation. All devices can communicate with one another simply by plugging into an RS-232 port. All communications utilize a checksum error detection scheme to identify corrupted data transmissions. This is done in accordance with the National Marine Electronics Association (NMEA) 0183 Standard.

Acoustic communications are accomplished using a Benthos modem set [2]. This consists of an ATM-885 modem mounted on the vehicle, which communicates with a Benthos gateway buoy. The buoy then relays the communications to the OCS via an RF modem. Acoustic communications take place in the 9-14 kHz bandwidth, with a selectable bit rate of either 600 or 1200 bps. Ranges of up to 1000 meters have been achieved, dependant on water conditions.

Direct RF communications between the vehicles and the OCS is possible through the use of a tethered float on which the vehicle's modem resides. This is a developmental tool, taking advantage of the bandwidth to stream back large amounts of data. As the vehicles mature, and less data is needed to analyze vehicle and sensor performance, the floats will be discarded.

A magneto-inductive (MI) communications system has been developed by Magneto-Inductive Systems, Limited, of Halifax, Canada, under scientific authority of CSS [3]. MI systems utilize a quasi-static AC magnetic dipole field as a channel for communications and navigation applications. MISL has designed an efficient direct injection drive antenna and a high gain, narrow bandwidth, superheterodyne receiver with sub-picotesla sensitivity. This is a one-way system, from the OCS to the vehicle, as the current transmitter is too heavy to be fitted to the vehicle. The system has a range of approximately 500 meters and a bit rate of 150 bps. The primary advantage of the MI system is that it operates in any medium and across all medium boundaries. It is impervious to the obstructions that degrade the acoustic channel and provides the capability of uninterrupted command as the vehicle moves from the surf zone up onto the beach.

C. Navigation

To simplify navigation, it was decided to have the vehicles travel in straight lines and turn by pivoting rather than have them take curved paths. The difficulty is that each motor drives a separate track and it is difficult to synchronize the speed of each motor. This results in the vehicle tending to arc rather than drive in a straight line. To solve this issue a PID controller was implemented. It utilizes the compass output to maintain a constant heading by adjusting motor power levels.

Navigation relies on a long baseline (LBL) system, supplemented by an on-board system. The LBL is an acoustic system developed at Coastal Systems Station. The system consists of two transmitters and a receiver on the vehicle. It is assumed that the transmitters are at known locations, or can be surveyed with reasonable accuracy. For surf zone reconnaissance the transmitters are typically seaward of the vehicles, which are searching the shallow waters. The effect of transmitting shoreward, into the wedge, commonly results in multipath problems. Additionally, obstacles such as bubble clouds, generated by waves, and sand bars can disrupt the acoustic channel. For these reasons, an on-board navigation system is required.

The on-board system utilizes a Precision Navigation TCM-2 compass and a Systron-Donner Horizon gyroscope, mounted to measure the yaw axis. Heading is determined by a fused solution of compass and gyro outputs, and displacement is measured from motor tachometer counts. In order to account for compass lag, when the vehicle is turning or it has been disturbed from its path by terrain features, the gyro is primarily responsible for providing the heading. The arcing motion as described above happens too gradually to be detected by the gyro, so when traveling in a straight line the PID controller relies on the compass to maintain a constant heading. The LBL system provides updates every 3 seconds. The navigation system uses a least-squares filter to determine when a consistent LBL trackfile has been established and then to reject any spurious readings. When an LBL update falls within the expected variance, it is taken as the true location of the vehicle. The navigation system is calibrated using a Krupp-Atlas Elektronik Type 422-00 laser tracker to provide truth data. The vehicles are run over a prescribed course, recording the data from the on-board system while stopping periodically to take measurements with the laser tracker. The discrepancies between the two readings are entered into a curve-fitting routine, which generates coefficients that are used to correct the on-board solution. The navigation system uses a North-East-Down (NED) coordinate system, relative to a given origin. Conversion to latitudes and longitudes, if desired, takes place at the OCS.

III. Sensors

Figure 3. Bumper.

The bumper, shown in Figure 3, is mounted to the front of the vehicle, and consists of a piezoelectric element inside a flexible tube. Any deflection of the tube triggers a signal. The bumper also includes an inductance sensor that can identify aluminum or ferrous material at a range of 1-2 inches. This sensor consists of a coil, an oscillator that sends a 4-5 kHz signal through the coil and a controller that receives this signal. Proximity to metallic objects changes the inductance of the coil and thus the frequency of the signal. Aluminum and iron cause different frequency shifts, so the controller is able to distinguish between them.

The profiler and tactile sensors are rods that emerge from either side of the vehicle. They are both used in determining whether an object is natural or man-made. When an object is encountered, a script is called that instructs the vehicle to swipe these sensors along the object. The tactile sensor is a flexible, grit-coated rod with a piezoelectric sensor that converts vibrations into electrical signals as the rod is scraped against the object. A spectral analysis of these emissions is done to determine the composition of the object. The profiler is a stiff, spring-loaded rod that deflects as the vehicle passes by the object. A switch at the tip triggers the sensor and a potentiometer measures the angle of deflection. By comparing the angle of deflection with the distance traveled, the shape of the object can be determined.

The PEIC, shown in Figure 4, is made from parts supplied by JW Fisher. This is a two-coil system, where one coil is used to stimulate eddy currents in an object and the other coil senses these currents. It can detect any kind of conductive material at a range of up to 1 meter. The PEIC is mounted on a sled and towed behind the vehicle, to keep the vehicle out of its detection range.

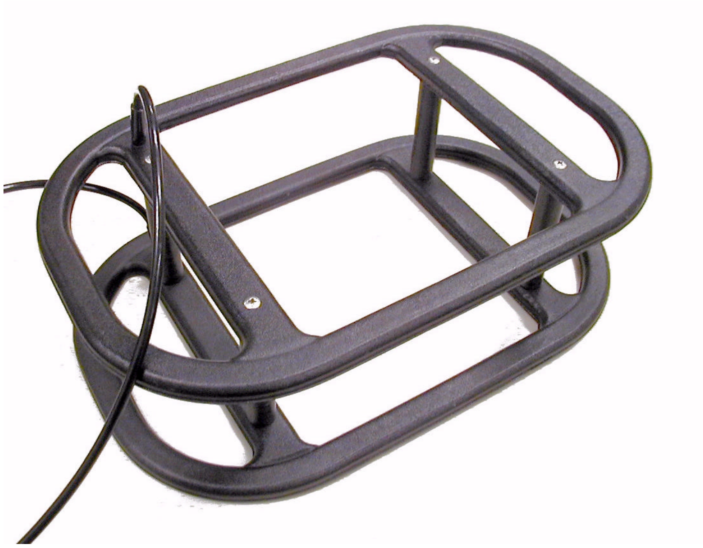

Figure 4. Pulse-Eddy Induction Coil (PEIC).

The still camera is a CCD image array. It produces a NTSC standard video signal that is captured using a framegrabber and stored in bit map format. A wavelet-based compression algorithm, using a 50:1 compression ratio, produces a binary file [4]. This file is transmitted to the OCS, using either RF or acoustic communications, where it is decompressed and displayed in bit map format.

All sensors interface to the Sensor Processor (SP), which is a Windows-based single board computer. The SP continuously scans the sensor signals to determine if one of them has been triggered. When a trigger event occurs, the SP opens a data file to record the sensor data and transmits a subset of the data to the OCS.

IV. Mission Objectives

Two basic mission types have been defined for the vehicles. One is known as Search-Classify-Map (SCM) and the other as Reacquire-Identify-Neutralize (RIN). For the SCM mission the vehicle performs a raster (lawnmower) search of a specified area. The starting point and dimensions of the search area are determined by the operator and passed to the vehicle using the OCS. It has been noted that the LBL provides more reliable updates in deeper water. For this reason the search patterns are run with legs perpendicular to the beach, as this ensures that the vehicle will spend part of each leg in deeper water. When a sensor is triggered the vehicle executes a script designed to optimize data collection from the different sensors. The SP opens a log that notes the location of the object and records the sensor data. The vehicle then continues on the search pattern until another trigger event occurs or the search is complete.

The RIN mission calls for a vehicle that is specifically equipped to neutralize a target. In this scenario another vehicle, either a swimmer or a crawler, has detected an object and sent the location to the OCS. The RIN vehicle then navigates to this position and performs an outward-spiral search pattern until the target is located. Using the cameras and acoustic communications, the vehicle transmits images of the target to the OCS. The operator can instruct the vehicle to maneuver around the target, taking images from a variety of angles, until a positive identification can be made. The operator can then instruct the vehicle to leave a neutralization charge by the target, loiter by the target, or move on to identify another object.

V. Results

AUV Fest 01 took place on Ship Island, offshore from Gulfport, Mississippi, from October 22 to November 2, 2001. The daily activities of the Surf Zone Crawler Group were to seed a search area with a number of targets at known locations, and see how successfully the vehicles were able to locate and gather data on the targets. A number of unforeseen challenges became readily apparent:

- The vehicles run well on sandy or rocky bottoms, but where the bottom tends towards viscousness, in mud or in silt, they are inclined to dig themselves in and get stuck. Attempts were made to limit the search areas to the high-energy zones of the beach, where wave action had removed the finer material.
- The sled carrying the PEIC contributed to the mobility problems. In addition to causing the vehicle to get stuck more regularly, it inhibited the vehicle from being able to back up and perform other investigative maneuvers when a target was located.
- The LBL navigation system produced a signal that was noisier than had been seen in previous testing. On some occasions, this signal was so noisy that the navigation filter rejected all LBL fixes received during the run. Figure 5 compares samples from navigation trackfiles recorded at AUV Fest (blue lines)

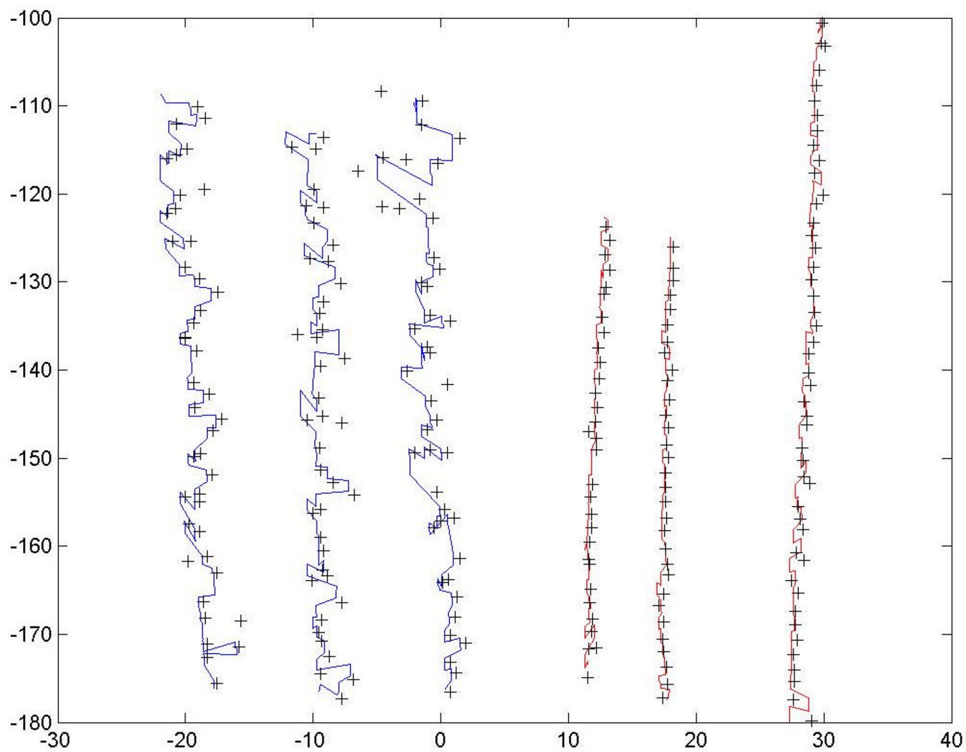

Figure 5. Comparison of samples of navigation trackfiles

and in testing at Panama City (red lines). The crosses represent LBL updates. In each case the vehicle was traveling in a straight line. Investigation is underway to determine the source of this noise.

- Field experience showed that a more efficient means of setting up the LBL system is clearly needed. The LBL receiver on the crawler must be initialized with the transmitter locations prior to the deploying vehicle. This information cannot be entered via the OCS communications link, but requires a direct link from a laptop computer. A more efficient interface would allow the transmitters and vehicles to be deployed simultaneously. It would also allow for on-the-fly modification of LBL locations, as was the case on one occasion when wind caused the transmitters to migrate. The advantages of a self-surveying system were also clearly evident. Investigation is proceeding into the possibility of utilizing DGPS receivers mounted on floats tethered to the transmitters.
- The PEIC trigger discrimination software needs to be refined. This type of system typically incurs a high false alarm rate. At AUV Fest, the PEIC was triggering so often that it wasn't able to provide any meaningful data.

Despite these challenges, the crawlers enjoyed a great deal of success at locating and imaging targets. Figures 6 and 7 are images transmitted to the OCS during an RIN mission on October 25th. The object is an overturned flower pot with a cinderblock on top of it. The vehicle was provided with the latitude and longitude of this target and navigated to that point. A terminal search was then conducted until the target was located by a bumper strike. Figure 6 was taken immediately following the bumper strike. The

Figure 6. Initial image.

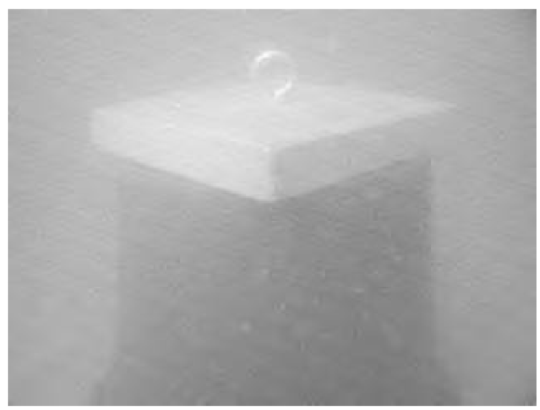

Figure 7. Image after vehicle repositioning.

vehicle was then maneuvered by the operator until the target was fully in the cameras' frame, and Figure 7 was taken. The images were compressed and transmitted by acoustic modems, as described earlier in this paper.

On October 27th a potential target was located by a swimming AUV. The location of this target was relayed from the AUV to the crawler via the OCS. The crawler successfully located and imaged the target. The image (Figure 9) allowed the operator to identify the target as a ladder (lower portion of the image). The potential for cooperative behavior among a number of autonomous vehicles was clearly demonstrated.

The ability to relay image files among several vehicles, known as the Seaweb concept, was successfully demonstrated. As mentioned previously, the acoustic modems have ranges up to 1000 meters, under ideal conditions. The acoustic channel, however, is dependant on water conditions, and ranges can be attenuated in unfavorable situations. Relaying images provides a means of compensating for reduced transmission ranges.

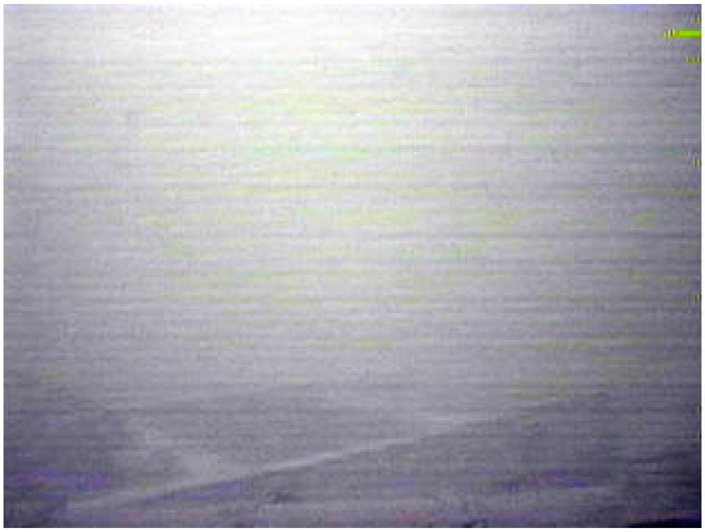

Figure 9. Image of a ladder.

The seamless transition from acoustic to magneto-inductive command and control as the vehicle drove from the water up onto the beach was also demonstrated. While on the beach, image transmission was accomplished using an RF link. This reverted to acoustic transmissions when the vehicle reentered the water.

VI. Conclusions and Future Work

The success of the RIN mission demonstrates the crawlers' effectiveness at providing information about potential threats within a sea lane. The capabilities of being able to continue a search onto the beach and to interact with other vehicles show the unique role the crawlers will play in an integrated approach to sea lane reconnaissance. The difficulties encountered at AUV Fest, primarily mobility and the overall effectiveness of the classification sensors, are currently being addressed. Work is proceeding on acquiring and integrating new sensors, as well as making modifications to those already in use. The following efforts are underway:

- A Kongsberg-Simrad rotating head sonar and a Dual Frequency ID Sonar (DIDSON) are in the process of being acquired. These are felt to be the most suitable types of sonars for this application, as the vehicle does not provide a sufficiently stable platform for a side-scan or synthetic aperture sonar. The rotating head sonar, which has a range of up to 100 meters, would be used during searches, having the vehicle stop periodically to scan the search area. The DIDSON uses an acoustic lens to produce an image, and would be used in identifying an object.
- The PEIC is being redesigned and now employs two Giant Magneto-Resistive (GMR) effect IC magnetometers, intended to null the effects of the vehicles' magnetic signature.
- Methods of using bistatic illumination are being explored. Backscattered light returning to the camera is a primary source of obscured images. With bistatic illumination, the source is physically removed from the camera. When combined with polarimetry and fluorescence techniques, the quality of the imagery will be much improved.

- A range imager is being built. This imager pans a fan-shaped laser beam across the surface of the target and captures successive images of the reflection from the beam. The range samples are then rendered into a 3-D image at the OCS. The advantage of this technique is that a laser illuminates a very small volume of water and therefore there is very little backscatter to contend with.
- A gradiometer is under development, for the detection and location of magnetic anomalies. Lab tests show a good detection range for mine-like targets. Like the PEIC, however, the vehicles' magnetic signature will degrade this sensors' performance. The gradiometer is currently undergoing modification, replacing fluxgate magnetometers with MEMS-based Triaxial Magnetometer-Accelerometers [5].

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