A Shallow Water Acoustic Network for Mine Countermeasures Operations with Autonomous Underwater Vehicles

Lee Freitag, Matthew Grund, Chris von Alt, Roger Stokey and Thomas Austin
Woods Hole Oceanographic Institution
Woods Hole, MA 02543 USA
lfreitag@whoi.edu

***Abstract* - Autonomous Underwater Vehicles (AUVs) are an alternative to traditional mine countermeasures (MCM) operations using divers or marine mammals. REMUS AUVs can be deployed at a distance and map an area using side-scan sonar, then identify and classify bottom targets using on-board processing. A shallow water acoustic communications network has been implemented to enable cooperative MCM operations with REMUS AUVs. The network provides connectivity between an operator and multiple REMUS vehicles and also allows vehicles to exchange information. This paper describes the MCM vehicle network and the acoustic network infrastructure. Results are also presented from recent demonstrations where REMUS vehicles mapped an area and detected and classified bottom objects while being monitored and controlled by a remote operator.**

I. INTRODUCTION

The REMUS AUV was originally developed for scientific sampling applications in water up to 100 m depth [1]. After the first vehicles were built and demonstrated for civilian applications, the Navy expressed interest in equipping them with side-scan sonar and using them to map the bottom and find mines in coastal environments. As a result, WHOI built and operated several versions of the REMUS AUV, including Advanced Development Model (ADM) and Engineering Development Model (EDM) systems prior to performing a technology transfer for commercial production [2] [3].

Prior to commercialization WHOI began working to install acoustic communications systems in REMUS vehicles as part of the Office of Naval Research Very Shallow Water and the Surf Zone Mine Countermeasure program (VSW/SZ MCM). The first modem integrated into the vehicle was the WHOI Utility Acoustic Modem (UAM), operating at 15 kHz [4]. However, the UAM is relatively large for a small AUV and used payload space that was needed for additional sensors and processors. Thus the Micro-Modem, a very compact (1.75 by 7.5 in) modem developed during the MCM program was integrated as part of a pre-planned product improvement (P^{3}I) program. During the program the communications frequency was increased so that it is compatible with the on-board acoustic navigation system and an interface designed so that it can share the navigation transducer and power amplifier. The result is a highly integrated system that requires only the Micro-Modem DSP card, which is just 1.75 by 4.5 inches.

From the start the VSW/SZ MCM program included multiple vehicles navigating and communicating in the same area (Fig. 1). Thus the initial system design included time-division multiple-access (TDMA) networking with centralized control to allocate cycles to different vehicles for communications or long baseline navigation [5]. As the system has been developed and demonstrated its capabilities have continued to evolve.

The paper includes a description of the entire system, along with test results from recent exercises. The paper is organized as follows. Section II describes the communications system using the ISO 7-layer model as a guide. In Section III the operational platforms are described, and in Section IV demonstrations are described and results are presented.

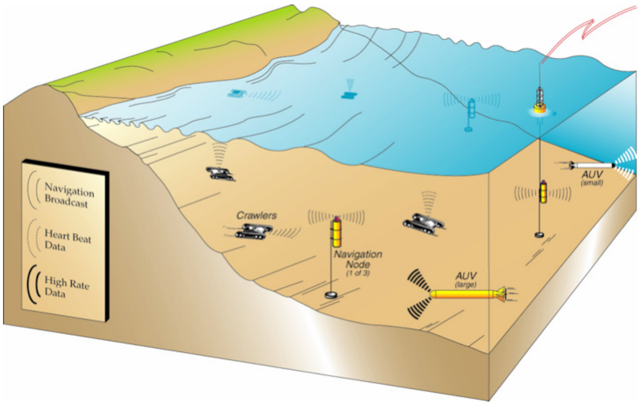


Fig. 1. Conceptual drawing of underwater acoustic network for multiple vehicle mine-countermeasures.

II. COMMUNICATIONS SYSTEM

The communications system is based on the WHOI Micro-Modem, whose electronics are shown in Fig. 2. The dry portion of the system consists of two boards, a DSP card and a power amplifier card. The transducer is a ceramic ring mounted external to the vehicle below the nose just below the hull line so that a full 360 degree field of view is available. The modem can transmit at source levels up to 190 dB through this transducer.

The DSP is a power-efficient 16-bit fixed-point processor that takes only 200 mW in receive mode. All of the modulation and user interface functions are provided by on-board firmware and user-selectable parameters such as the modem address are stored in non-volatile RAM.

The data flow for the system can be described using the OSI 7-layer network model, as shown in Table 1. While most communications systems do not actually map directly onto the ISO model, it provides a standardized way of describing the different parts of a communications system. Layers 1-4, from Physical to Transport, are incorporated in the modem, while 5-7 are done by the user and the vehicle or external control console software.

	Layer	*Micro-Modem MCM Network Component*
7	Application	Control Interface and AUV Controller
6	Presentation	*Compact Control Language* Messages
5	Session	Operator initiated via Control Interface
4	Transport	16 bit CRC and Selective ACK
3	Network	Operator configured polled TDMA
2	Data Link	32 byte data packets
1	Physical	80 bps frequency hopped FSK at 25KHz

Table 1. REMUS acoustic communications system mapping to the OSI 7-layer network model.

A. Layer 1: Physical

The physical layer for the Micro-Modem is based on frequency-shift keying with frequency-hopping (FH-FSK). Frequency-shift keying is a simple and relatively robust underwater acoustic communication technique, which when combined with frequency hopping, allows operation in a shallow-water environment with multi-path. The default data rate is 80 bps after the overhead from error-correction is applied. The system operates at approximately 25 kHz and uses 4 kHz of bandwidth.

A new development for the Micro-Modem is the addition of multi-rate phase-shift keying (PSK). All Micro-Modems can transmit PSK at data rates of 300-5000 bps (after overhead and error-correction). Modems equipped with an optional floating-point co-processor can receive the PSK transmissions, which are processed using a sophisticated decision-feedback equalizer (DFE). Multiple hydrophones can be used by the DFE, which increases reliability in horizontal shallow-water channels. In a master-slave network where most data flows from the vehicles to the surface only the gateway buoy requires the high-rate receiver, though it is desirable in all if the sensor data can be used on the other platforms.

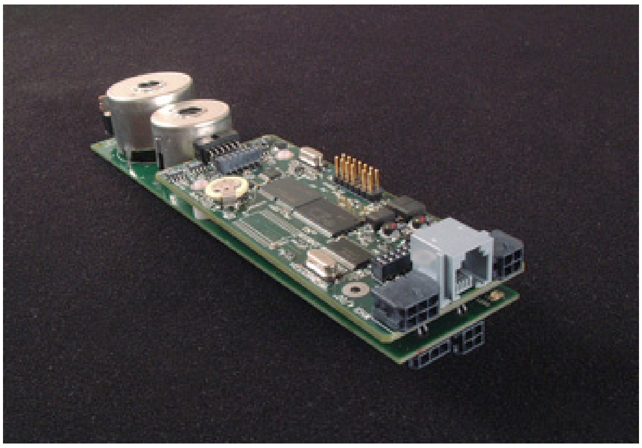


Figure 2. WHOI Micromodem electronics board set.

B. Layer 2: Data Link

The data link layer maps user data to fixed-length data frames to be transmitted by the physical layer. Two types of packets are available, normal data packets which are approximately 3-4 seconds long, and mini-packets, which are less than one second long. Mini packets hold 24 bits of data, while data packets hold 32 bytes at the lowest data rate, and 2 kBytes at the highest data rate. Mini-packets are used for ranging (ping command), low-level control of a remote modem (sleep command), and for network control (cycle-init command) as described next. Classically in the ISO model the Data Link Layer also includes the medium access method, but here that is handled at a higher level.

C. Layer 3: Network

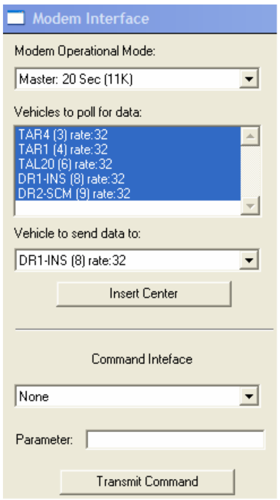
The Micro-Modem uses a packet-by-packet time-division multiple-access scheme for network control. Each unit of time is called a cycle, and cycles can include polls for data (uplink request), or data downlink. To begin a cycle, any modem can transmit a short cycle-init packet. This mini-packet designates the transmitting node, primary receiving node, and the data rate for the next cycle. This simple protocol allows symmetric peer-to-peer communication or master-slave configurations, allowing users flexibility when building applications.

D. Layer 4: Transport

Transport layer features that are included in the modem are a cyclic-redundancy check (CRC) that is used to ensure that only data decoded correctly is passed to the user, and a built-in acknowledgement capability. While retransmissions are left to higher layers, acknowledgement packets (which are mini packets) are automatically transmitted by a receiving modem when a packet with the ACK bit set is received and the CRC for the data payload shows that the data is correct. All data that is received and decoded correctly is provided to the local user, even if it is not addressed to the local user. The upper layers can decide how to use this data, which can be useful not only for the information itself, but to assess the level of network traffic. The information is discarded if it is not relevant or if it is in a format that is not understood locally.

E. Layer 5: Session

The Session, Presentation and Application layers are taken care of inside the REMUS control computer. The interface between the modem and the control computer uses NMEA messages over RS-232. The session layer, which is concerned with the management of connections, includes configuration of the surface control system to poll a particular group of vehicles (Fig. 3).



Modem Operational Mode: Master: 20 Sec (11K)

Vehicles to poll for data:
TAR4 (3) rate:32
TAR1 (4) rate:32
TAL20 (6) rate:32
DR1-INS (8) rate:32
DR2-SCM (9) rate:32

Vehicle to send data to: DR1-INS (8) rate:32

Command Inteface

None

Parameter:

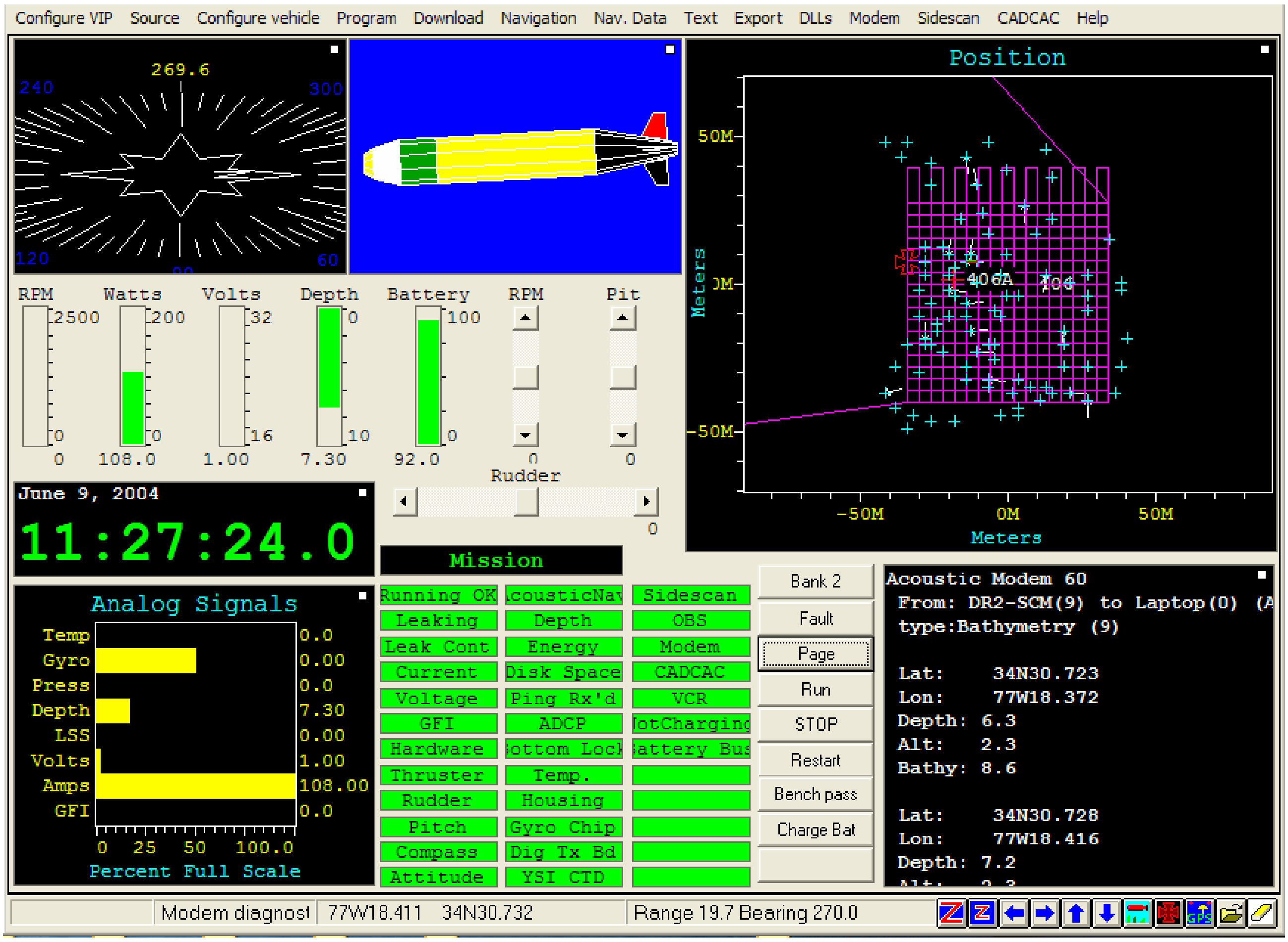
Figure 3. Modem control interface representing the transport layer (OSI layer 4). A table includes all vehicles to be polled from the surface.

F. Layer 6: Presentation Layer

The presentation layer typically describes the syntax of the data to be transferred. In this system the data is formatted using a standard specifically developed for the acoustic communications link called the Compact Control Language (CCL) [6]. CCL is an extensible set of messages that includes typical AUV commands to start or abort missions plus status messages that include position, depth, heading, battery voltage, mission progress, fault information and other data. CCL defines data structures with bit packing to minimize overhead and it also takes into account the dynamic range of specific sensors and the resolution needed to support the application layer.

G. Layer 7: Application

The application layer is the REMUS Vehicle Interface Program (VIP), which is used to program the vehicle before a mission and which also provides a graphical user interface where status information and mission progress are displayed for the user as shown in Figure 4.



June 9, 2004

11:27:24.0

Acoustic Modem 60
From: DR2-SCM(9) to Laptop(0) (A
type:Bathymetry (9)

Lat: 34N30.723
Lon: 77W18.372
Depth: 6.3
Alt: 2.3
Bathy: 8.6

Lat: 34N30.728
Lon: 77W18.416
Depth: 7.2

Modem diagnost | 77W18.411 34N30.732 | Range 19.7 Bearing 270.0

Figure 4. REMUS VIP showing screen shot showing operator interface with real-time data display via the modem and gateway.

III. PLATFORMS

The network includes gateway buoys, REMUS vehicles and other types of underwater vehicles, both swimming and crawling. All platforms in the operational area use the same communications network.

A. Gateway Buoy

The RF-acoustic gateway allows operation of the MCM network from a remote location. Gateway buoys consist of a Micro-Modem and FreeWave radio in a submersible housing with foam floatation as shown in Fig. 5. The transducer is located on the anchor line below. An optional four channel array that can be used with the high-rate receiver to increase reliability in shallow water is also suspended below the buoy. The acoustic communications gateway buoy design is based on the design of the PARADIGM buoys, which were originally developed to track the position of a REMUS in real time by round-trip ranging from the buoy to the vehicle.

Figure 5. RF to acoustic gateway buoy.

B. REMUS AUV

All of the different REMUS (Fig. 6) configurations include LBL navigation using broad-band coded transponders, a Doppler velocity log (DVL) for bottom lock, and an acoustic modem. Recent versions of the vehicle can optionally include a ring laser gyro inertial navigation subsystem and a GPS. The vehicle can be configured with different sensor packages for different missions. For the mine countermeasures mission, two configurations are used: *Search-Classify-Map* (SCM) and *Reacquire-Identify* (RI).

The SCM configuration allows the vehicle to make relatively fast surveys with side scan sonar, reporting CADCAC scores to the operator during the mission. SCM missions can be approximately eight hours long at 5 knots.

The RI mission requires the addition of a high resolution sensor. Sensors include 1800 kHz side scan sonar, a low-light video camera, or a DIDSON forward-looking sonar. These sensors are used to acquire high-resolution images of targets detected during the SCM phase. These images are then used by an operator for final identification.

Both SCM and RI vehicles can be equipped with an on-board computer aided detection and computer aided classification system (CADCAC). The system processes side-scan sonar data in near real time, and scores targets using several classification algorithms [7]. The target scores are reported acoustically in real time to an operator or other underwater vehicle.

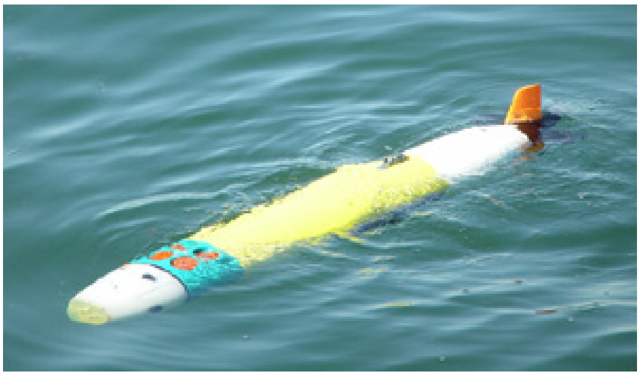


Figure 6. REMUS AUV at the surface.

IV. RESULTS

The system was recently deployed in May 2004 in Camp LeJeune, as part of a Combined Joint Task Force Exercise. It was operated for several weeks, and successfully detected mine and mine-like objects using multiple vehicles operating simultaneously. Several prototypical MCM missions that were performed are described below.

A. Target Detection Survey

The first phase of work is the Search-Classify-Map with side-scan sonar. The AUV reports CAD/CAC scores to the operator in real time through the gateway buoy, as shown in Figure 7. The operator watches the scores as the mission progresses and is able to get a feel for how many mine-like objects are present in the survey area while it is still on-going. In Fig. 7 the purple lines represent the vehicle's planned track, and the yellow and white crosses show the position where real-time data was sampled, transmitted acoustically, received by the gateway buoy, then displayed for the user on shore.

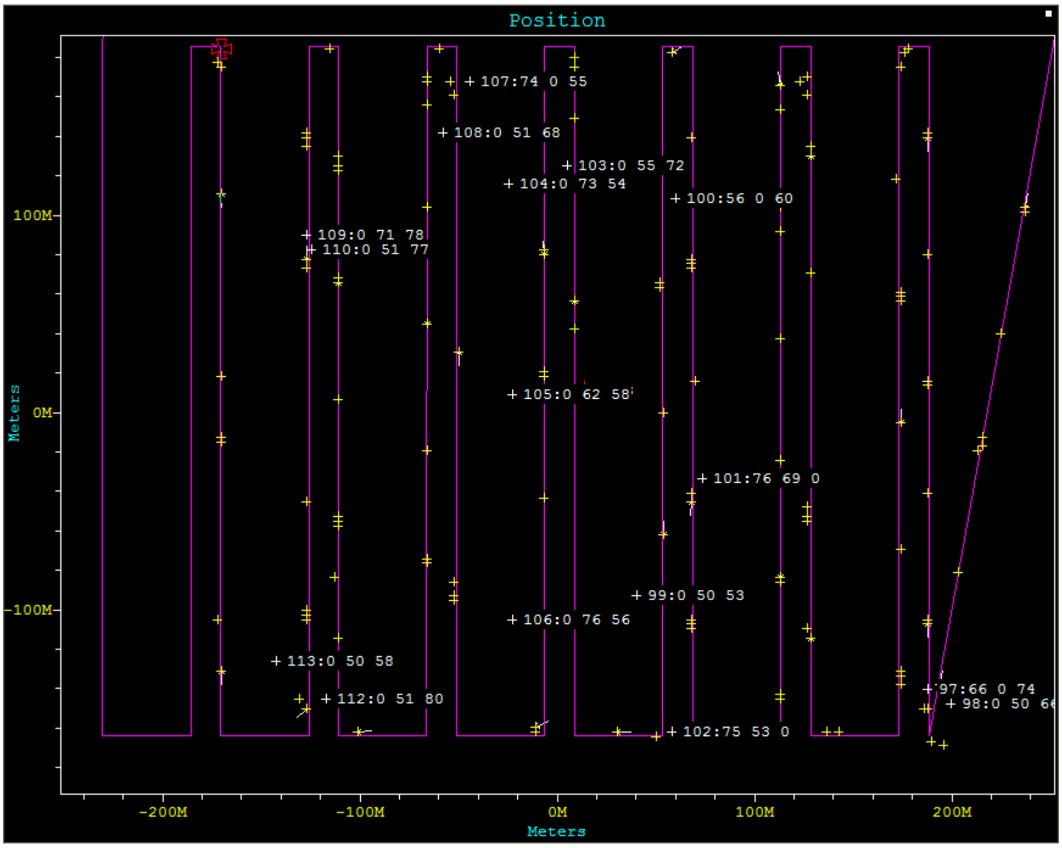


Figure 7. REMUS real-time telemetry data showing CADCAC scores for bottom targets. Each target that is identified by the CAD/CAC system includes an identifier, then three scores, which are 0-100, one for each algorithm. If any of the algorithms reports a low score, then the target has a low probability of being a mine-like object [7].

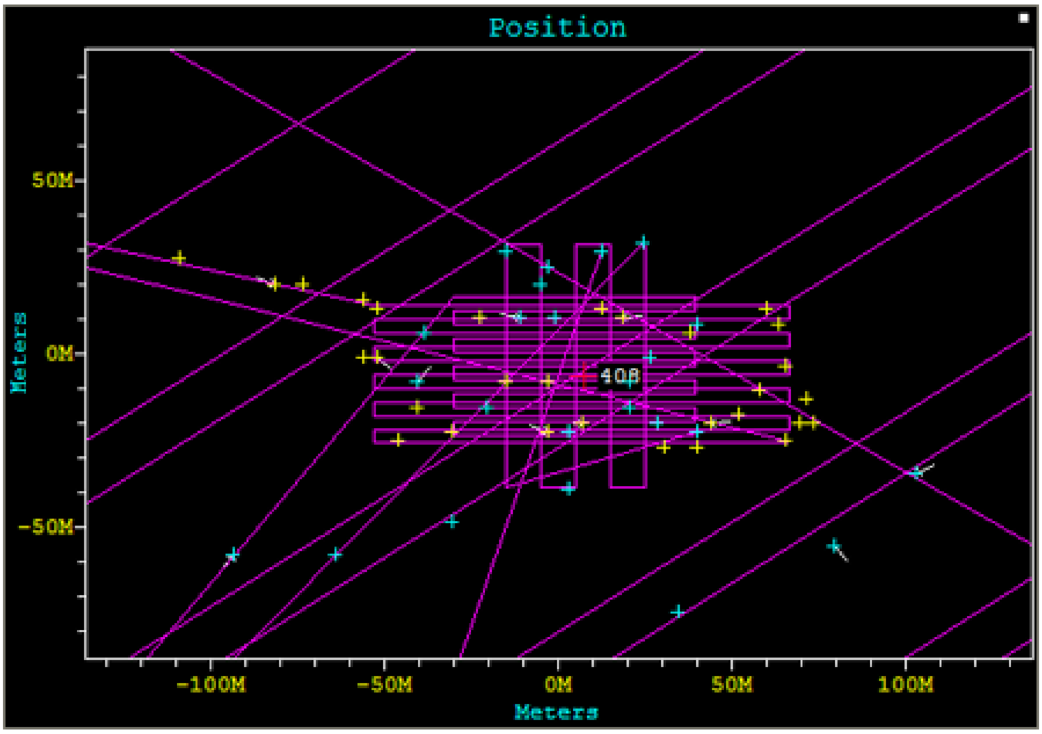


Figure 8. REMUS real-time telemetry plot showing planned tracks of two vehicles performing a two-phase mine countermeasure mission. Blue crosses (+) show position reports from an SCM vehicle which has been re-directed for a closer look over a target, while the yellow crosses (+) are from a RI vehicle with dual frequency sonar and a low-light video camera. Both missions are operator-initiated in this case.

B. Operator Redirects Vehicle

The network allows multiple vehicles to be monitored and remotely controlled. Fig. 8 shows the tracks from two vehicles operating in the same area. The first vehicle has performed a SCM mission and reports CAD/CAC targets back to the operator. The operator sends the vehicle back for a second look at two different aspects from the target to get multiple views. A RI vehicle, which has been on standby waiting for tasking, is vectored into the same area to perform a close-in mission with dual-frequency side-scan and a low-light video camera.

C. Vehicle to Vehicle Redirect

All vehicles in the network monitor communications traffic. Thus when a SCM vehicle reports CAD/CAC messages to a central station, they are also received by a nearby RI vehicle. The RI vehicles can also be programmed to act on CAD/CAC messages automatically. The score and the location are used to prioritize the targets and maintain a list of redirect missions to be carried out. This capability forms the basis for a completely autonomous group of vehicles performing both SCM and RI missions without a human in the loop.

D. Vehicle Self Redirect

Vehicles that are equipped with side-scan sonar and a re-acquisition sensor such as a high-frequency side-scan, video camera, or forward-look sonar can also carry out redirect missions by themselves when a CAD/CAC target score exceeds a pre-set threshold. This has been used successfully to perform SCM plus RI missions together on one AUV. Only vehicles which have a modem are allowed to use this mode because the modem is necessary to keep track of the mission. If no modem were available it would be impossible to know what was happening.

E. System Performance

The performance of the system during actual tests has been very good. The range of the system depends heavily upon the local acoustic conditions, but is typically 2000 m or greater. In environments that are well-mixed with a hard bottom the range can be 3000 m or more, while in heavily stratified conditions with surface warming (which causes downward refraction) and an absorbing bottom, the range can be substantially less, occasionally 1000 m.

V. CONCLUSIONS

A multi-vehicle network has been developed and demonstrated with the REMUS AUV and recently with other vehicles using a common command capability [6]. The system works in a master-slave mode as well as peer-to-peer when there is no supervising authority. Additional vehicles can be added to the network to carry out other tasks such as reacquisition prior to neutralization.

Acknowledgments

The authors would like to thank the Office of Naval Research, Code 321OE (Dr. Thomas Swean) for continued support of this work under grants N00014-99-1-0280 (REMUS development), and N00014-99-1-0287 (acoustic communications).

REFERENCES

[1] C. von Alt, B. Allen, T. Austin, R. Stokey, “Remote environmental measuring units,” *Autonomous Underwater Vehicle Conference ’94*, Cambridge, MA., 1994.

[2] Von Alt, C., Allen, B., Austin, T., Forrester, N., Goldsborough, R., Purcell, M., Stokey, R., “Hunting for Mines with REMUS: A High Performance, Affordable, Free Swimming Underwater Robot”, *Proc. Oceans 2001*, Honolulu, HI, pp. 117-122, 2001.

[3] von Alt, C, “REMUS 100 Transportable Mine Countermeasure Package,” *Proc. Oceans 2003*, San Diego, CA. pp. 1925-1930. 2003.

[4] Freitag, L., M. Grund, S. Singh and M. Johnson, “Acoustic communication in very shallow water: Results from the 1999 AUV Fest,” *Proc. Oceans 2000*, Providence, RI, Vol. 3, pp. 2155-2160, 2000.

[5] Freitag, L., M. Johnson, M. Grund, S. Singh and J. Preisig, “Integrated Acoustic Communication and Navigation for Multiple UUVs,” *Proc. Oceans 2001*, Honolulu, HI, pp. 2065-2070, 2001.

[6] Stokey, R. L. Freitag, and M. Grund, “A compact control language for AUV acoustic communication,” *Proc. IEEE/OES Oceans ’05 Europe*, 2005.

[7] C. Ciany, W. Zurawski, G. Dobeck, “Real-time Performance of Fusion Algorithms for Computer Aided Detection and Classification of Bottom Mines in Very Shallow Water Environment”, *Proc. Oceans 2003*, San Diego, CA. September 2003