Multi-Band Acoustic Modem for the Communications and Navigation Aid AUV

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Abstract -**An acoustic communications system with the capability to operate at multiple data rates in two frequency bands has been designed and developed for use in 21-inch AUVs. The system is specifically designed around the 21-inch diameter Bluefin Robotics AUV, though it could be adapted to smaller vehicles (12-inch), or similar free-flooded vehicles. The system includes both high (25 kHz) and mid-frequency (3 kHz) modems and supports data rates from 80 bps to more than 5000 bps. Both of the modems utilize four-channel arrays to increase reliability. The high-frequency modem is also used to support multi-vehicle navigation via one-way travel time measurements using synchronized clocks on all of the vehicles in a work group.**

I. Introduction

The Autonomous Operations Future Naval Capability (AO-FNC) Undersea Search and Survey program seeks to demonstrate new and novel approaches to shallow-water mine countermeasure operations. One of the primary new capabilities is the use of multiple vehicles to carry out different portions of the mission. The system, which is under development by Bluefin Robotics, includes a sophisticated AUV called the Communications and Navigation Aid (CNA) which will carry an over-the-horizon HF ground wave radio for surface use, and a multi-band acoustic modem for undersea communications. The CNA vehicle will also use an accurate navigation system developed by Bluefin, and this capability will be exploited to provide navigation fixes to other vehicles operating in the group. The acoustic navigation capability is also provided by the acoustic modem using transmissions synchronized to absolute time.

The system concept is shown in Fig. 1. Two 21-inch vehicles carry sophisticated inertial navigation systems which are initialized with GPS at regular, but relatively long, intervals (hours). These CNA vehicles may carry sonar systems as well, but may also be simply devoted to communications. This is because the multi-band acoustic modem and the over-the-horizon HF ground wave radio take up most of the free payload capacity of the vehicle. The other vehicles, typically smaller 12-inch vehicles, work with the large AUVs in a coordinated fashion. Three types of vehicles may be part of the group. The first are search-classify-map vehicles that perform side-scan mapping with on-board computer-aided detection and computer aided classification (CAD/CAC) processing. This provides detailed maps of the ocean bottom and an initial list of mine-like objects for further inspection. These vehicles are followed by one or more reacquisition and identification (RI) vehicles that have forward-looking high-resolution sonar or a camera. One type of high-resolution sonar is the DIDSON, the dual-frequency identification sonar originally developed at APL/UW which provides video-like output suitable for identification of mines. The third type of vehicle is intended to perform neutralization, but that is beyond the scope of the current program.

Communications from the CNA vehicle to the other vehicles in the work group will support navigation and control. Control messages include directives to abort the current mission, perform re-acquisition and identification over targets detected by the computer-aided detection system, and so on. Navigation messages, which are synchronized to absolute time, contain the position of the CNA vehicle and the time of transmission.

Sensor data flows from the search-classify-map and reacquire and identify vehicles to the CNA for transmission back to a manned control center via HF ground-wave, Iridium or other communication link depending on the type of operation being conducted. While on-board intelligence in the form of computer-aided detection greatly reduces the amount of data that needs to be transmitted, high-rate acoustic communications is necessary so that sensor data transmission does not take all of the available bandwidth.

The acoustic communications system is based on the WHOI Micro-Modem, originally developed for use on small AUVs in shallow water. The modem can use simple low-rate frequency-hopping, frequency-shift keying (FH-FSK), or high-rate phase-shift keying (PSK). The data rate is variable and depends upon source-receiver range and acoustic propagation conditions. Data rates from 80 bps (FH-FSK) to 5000 bps and higher (PSK) are provided. The reliability of PSK is improved by use of multiple receiver channels, and thus small arrays are used for both frequency bands. The system has some similarities with a dual-frequency modem developed under a previous program [1]. That system used a

PC-based architecture with a DSP co-processor that is two generations older than the Micro-Modem. It also employed a towed array for MF reception. The new system is significantly more compact and takes a fraction of the power of the old system, and includes the navigation capability.

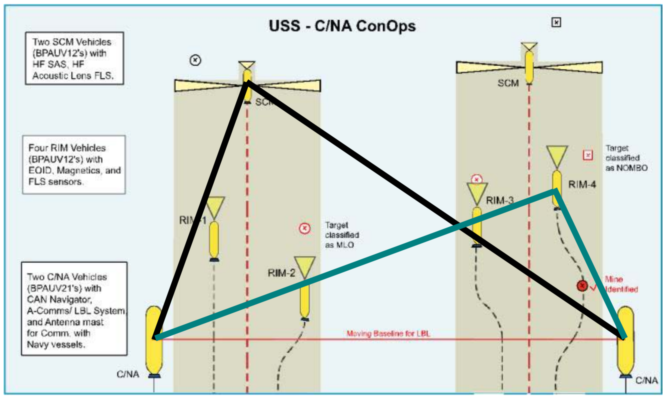

Figure 1. The Bluefin concept for multi-vehicle undersea search and survey.

The paper is organized as follows. Section II contains the communications system overview. Section III describes the synchronous navigation system. Section IV includes the current status of the system and future work.

II. The Communications System

The modem operates in two frequency bands, one in the 3-5 kHz range for long range communication with Navy vessels equipped with compatible sonar systems, and the other in the 20-30 kHz band for communication with nearby AUVs.

A. Micro-Modem

The Micro-Modem is a modular communications and navigation system that consists of several small circuit boards. The Micro-Modem DSP card is the core of the system. It contains a fixed-point Texas Instruments processor (5416), serial interface and single-channel analog IO. Additional details on the design are included in [2], but the main points are summarized here. A block diagram of the Micro-Modem is shown in Fig. 2.

The modem DSP card connects directly to the power amplifier card, which functions as a motherboard. The amplifier card includes the FET driver circuitry, step-up transformer, matching inductor, transmit-receive network and receiver pre-amplifier. Several different versions have been designed; two are used in the CNA system: a long form-factor board suitable for use in a small pressure housing equipped with magnetics for 10-30 kHz, and a larger board with room for a larger transformer and inductor to support frequencies less than 10 kHz.

High-rate multi-channel PSK reception requires the use of a sophisticated adaptive algorithm, the decision-feedback equalizer (DFE). The DFE algorithm has been implemented on the previous generation WHOI modem, the Utility Acoustic Modem, which has a floating-point processor. To add the PSK receiver capability to the Micro-Modem a floating-point co-processor card was designed in collaboration with engineers at the Naval Undersea Warfare Center, Newport. The co-processor also uses a Texas Instruments DSP, the 6713. The card stacks onto the Micro-Modem and it communicates via a memory-mapped interface. It has a separate power connector and a switch that is controlled by the Micro-Modem. It is only turned on when an incoming PSK packet is detected.

Multi-channel analog input is done with yet another small card that stacks with the main DSP card and the co-processor cards. It communicates with the main DSP card over a high-speed serial bus. The card has two banks of four channels, but just four are used at one time. The data flows from the multi-channel A/D to the Micro-Modem main board where it is converted from passband (at 80 kHz) to baseband (10 kHz) before transfer to the floating-point coprocessor.

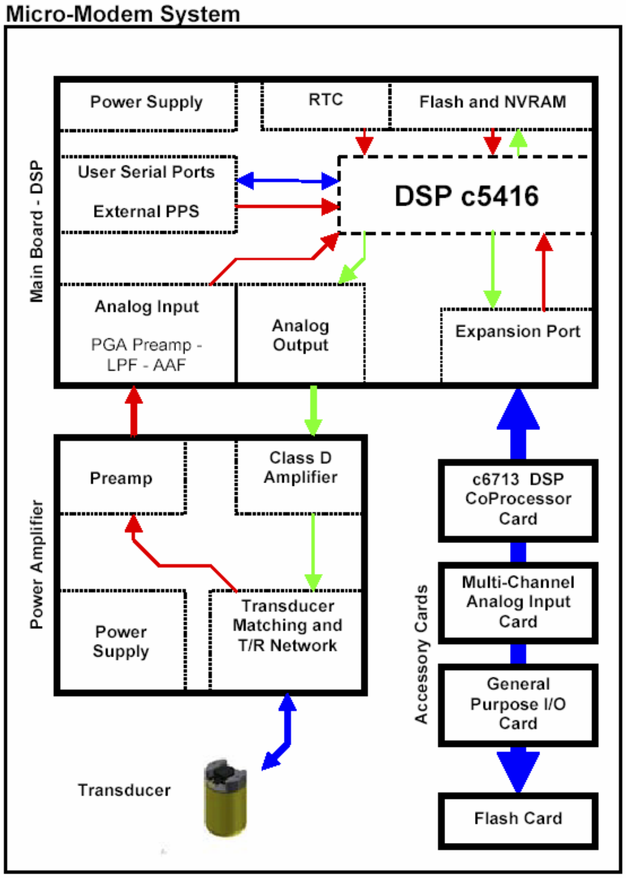

Fig. 2. Micro-Modem system block diagram showing major components.

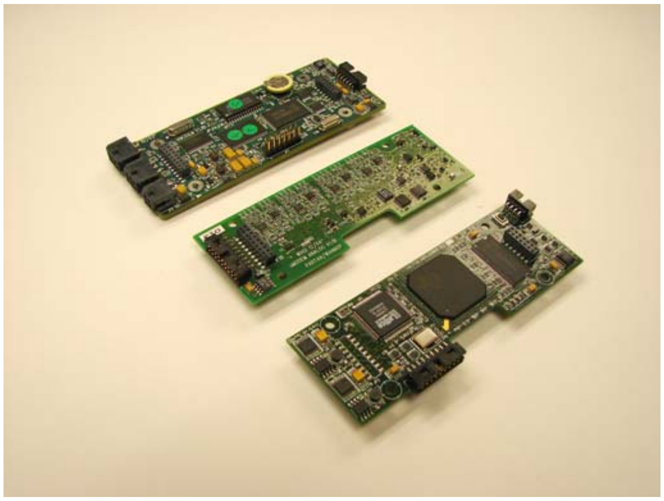

Fig. 3. Micro-Modem main board (top), Multi-channel analog board (middle) and floating-point co-processor card (bottom).

B. Architecture and Packaging

The system was developed as a module that will fit in a free-flooding vehicle, specifically the payload section of the 21-inch diameter battle-space preparation (BP) class of Bluefin AUVs. Thus it is contained in a small diameter pressure housing that fits into the center of the payload section which allows syntactic foam flotation to be placed above, and batteries to fit on either side. For compatibility with an existing payload the pressure case is sized to be the same as a sidescan sonar system used on the same vehicle. The system has a simple interface to the vehicle: power and communications to the tail section are on one connector on the aft end cap, while acoustic signals, both transmit and receive, are on the forward endcap. A block diagram of the major system components is shown in Fig. 4.

The power to the modem is unregulated and is provided directly from the vehicle battery via power switching in the tail section. A regulator and switching card in the modem housing generates appropriate voltages for the DSP cards. The unregulated power is used by the modem power amplifiers for maximum efficiency.

There are four processors in the CNA modem module, the primary transmit-receive HF system, two four-channel HF receive-only systems, and one MF system with transmitter and four-channel receiver. The interface to the Micro-Modems is RS-232. The primary HF modem is directly connected via its serial port back to the vehicle controller. The rest are connected to a serial port server which converts serial to ethernet for communication with the processor in the tail section.

An Iridium modem and connector to an external antenna is also included in the CNA system. The integration of the Iridium modem into the acoustic modem housing avoids the need for an additional, separate housing for satellite communications in the payload or tail sections and takes advantage of the power regulation in the CNA modem and the serial to ethernet converter.

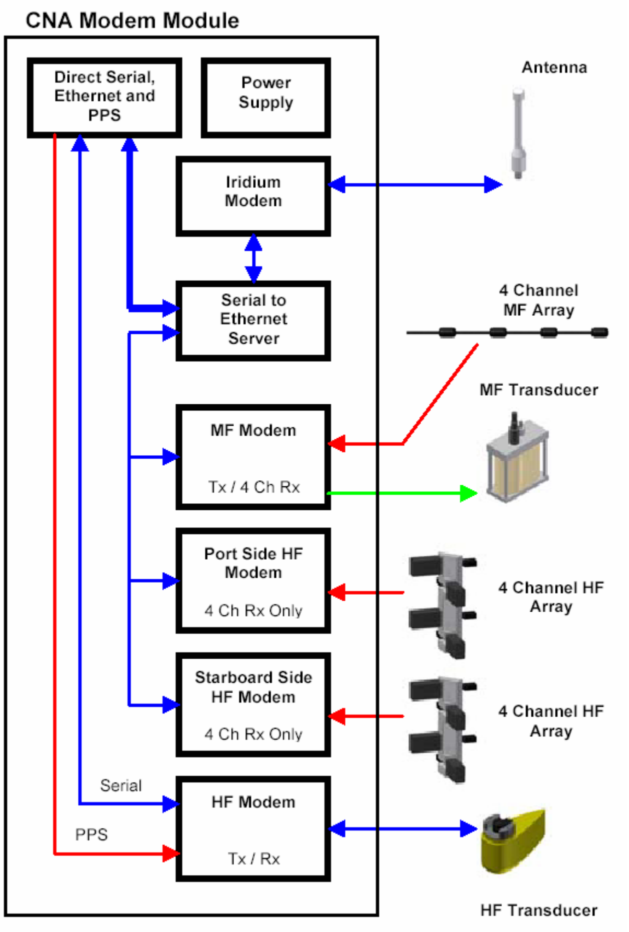

Fig. 4. CNA modem system block diagram.

C. Primary HF Modem

The primary HF modem provides the core functionality for the system. It is directly connected via RS-232 in case there is a problem with the ethernet to serial converter or with the ethernet wiring from the payload section to the tail. This modem also has the one pulse per second (PPS) input that is used for synchronous navigation. A single transducer which is omnidirectional in the horizontal and has a 60 degree vertical beamwidth is used for both transmit and receive. The design is by BTech Acoustics and uses two ceramic rings which are capped and encapsulated in polyurethane. The power used during transmit is approximately 50 W, and the source level is 188 dB re micro-Pascal.

D. Dual High-Rate Receivers

Two high-rate receivers are used, one aimed to port, the other to starboard. They are located in the nose of the vehicle, slightly offset to provide as much horizontal coverage as possible. Figure 5 shows the arrangement of the hydrophones in the nose. Directional hydrophones with backing plates are used for this application so that their beampattern stays constant and is not affected by objects behind the transducers. The transducers are produced by Materials Systems Inc., and utilize a piezo-composite design. The active element is similar to that used for a hull-mounted array on the REMUS AUV [3], but the backing is metal rather than air. Figure 6 shows the horizontal and vertical beampatterns of the hydrophones that are used in the nose cone arrays. The vertical spacing is 0.12 m, approximately 2 wavelengths at 25 kHz. In previous work [3], the advantage of a small vertical array was demonstrated for high-rate PSK reception. Figure 7 shows the frequency response for the hydrophone with built in preamp. The frequency response of the elements is approximately 10-40 kHz, thus additional receiver bands may be easily added without any new hardware.

Each of the high-rate receivers has a dedicated 4-channel input card and floating-point co-processor and they operate asynchronously from each other. In the case where the source is in front of the vehicle the same data may be received on both modems. The data is provided to the vehicle from both modems and thus the vehicle must check for duplicate receptions.

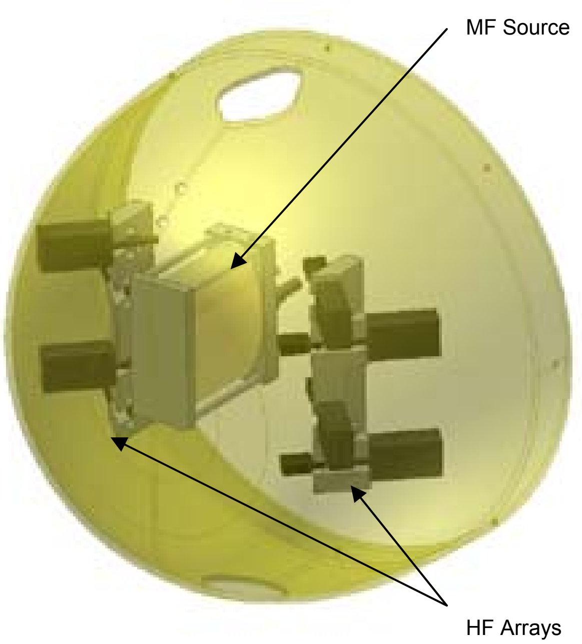

Fig. 5. Receiver hydrophones and MF source in the nose of the Bluefin 21-inch vehicle.

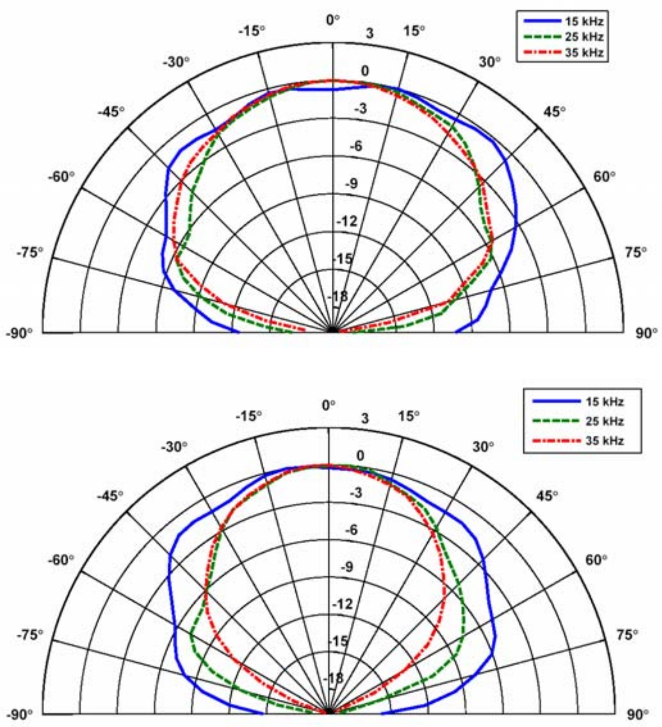

Fig. 6. Beampattern plots for MSI hydrophone. Top: Horizontal beampattern at 15, 25 and 30 kHz. Bottom: Vertical beampattern at 15, 25, and 30 kHz. Zero degrees is perpendicular to the face of the receiving element. The over all scale is 24 dB.

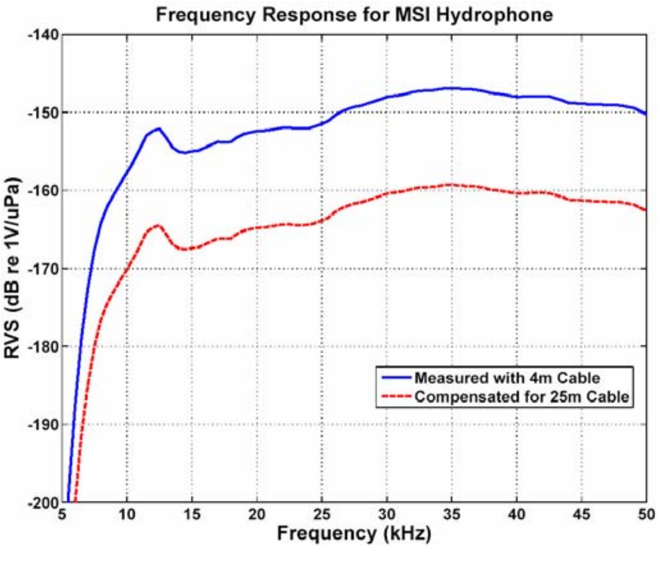

Fig. 7. Measured frequency response for MSI hydrophone. Solid: Measured response with 4m of cable. Dashed: Measured response compensated for 25m of cable. The horizontal axis is frequency in kHz. The vertical scale is in dB re 1V/uPa.

E. Medium-Frequency Modem

The medium frequency (MF) modem is designed for long-range communication and compatibility with the ARCI-based acoustic communications capability of the 688-class SSN and Arleigh-Burke class DDG. Compatibility with those platforms allows command and control from remote platforms, both on the surface and undersea. The range of the MF modem depends significantly on the propagation conditions, but previous tests [4] have demonstrated ranges well in excess of 20 km, though with very high source levels (at least 10 dB higher than that available with the AUV system). However, when transmitting to the SSN and DDG sonars, the array gain available by using their sonar domes helps to make up for the lower source level.

The acoustic source is the EDO 6969-3500, a flextensional design 2.13 by 5.75 by 5.75 inches that weighs 8.5 pounds in water. The transducer is also mounted in the nose (Fig. 5). The approximate maximum source level is 188 dB re micro-Pascal. The receiver array is a line of omni-directional broadband hydrophones mounted just inside the shell along the bottom of the vehicle. The element spacing is 0.5 m, which is 1.18 wavelengths at 3.5 kHz. Ideally a longer array would be used, but this is the largest that can be easily installed in the vehicle. Fortunately the data rate required to the vehicle is low and the source level of the Navy vessels can overcome the lack of gain on the vehicle.

III. Synchronous Navigation

To support their role as navigation aids, the CNA vehicles maintain high-quality navigation data, with sophisticated inertial navigation systems. The general survey client vehicles do not require expensive inertial navigation systems. All vehicles in the area, both the CNA vehicles and the client vehicles, maintain accurate, precise, and stable clocks.

In the synchronous navigation system, each CNA vehicle transmits its location and other navigation information (see Table 1 below) to the client vehicles. All transmissions are synchronized to the start of a second. With their locally-maintained accurate and precise clocks, the client vehicles can measure the arrival time of the packet, and hence the one-way travel time from each CNA vehicle. The data packets contain the locations of the CNA vehicles, and so the client vehicle can estimate its own location.

In terms of details of the implementation, each vehicle supplies its Micro-Modem with an accurate and stable pulse-per-second (PPS) signal. The Micro-Modem uses its on-board clock to make precise timing measurements between the externally-referenced PPS ticks. Combining these clocks allows accurate and precise timing measurements of the packet arrival times to be made. All vehicles supply a PPS which has an absolute accuracy of better than 20µs, the CNA vehicle's Micro-Modems transmit within 10µs of the PPS rising edge, and the packet arrival detection time is accurate to within 125µs.

The message format is below in Table 1. The 32-byte data packet follows the Compact Control Language specification [5], and contains the information required for the client vehicles to estimate their locations. Due to the finite length of the data packet, a number of fields are less than one byte, and are implemented as packed bit fields. A further note is that due to the finite mantissa of a 32-bit float, the latitude and longitude are instead represented in 32-bit integer fields in order to achieve 0.1m resolution over the entire globe.

Table 1: CNA Message Fields

Bytes	Description
1	Message type indicator
1	Fix type: GPS, Inertial, Acoustic, Dead Reckoning
1	Heading
1	Estimated speed
2	Depth
2	Circular Error Probable, error radius
4	Packed: Speed of Sound, GPS fix standard deviation
4	Latitude (integer, not float)
4	Longitude (integer, not float)
4	Time of Ping
4	Time of Fix
2	Time Since last GPS fix
2	Packed: GPS NSAT and HDOP

IV. Conclusion

A multi-band acoustic modem that fits into the Bluefin 21-inch vehicle has been designed and will undergo testing as a system in 2005 and 2006. The ability to handle multiple frequencies allows use with different Navy platforms, and the synchronous navigation capability allows the search vehicles to utilize the navigation capability of the larger vehicles.

Future work also includes a version of the system that will fit into a 12.75 inch vehicle. The exact configuration of that version remains to be determined, but it will be necessary to downsize the HF acoustic array. All of the synchronous navigation capability will be the same, but the range and rate of the high-speed link may be reduced somewhat. Field testing will be done to determine the differences.

V. Acknowledgements

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References

[1] Freitag, L., M. Grund, S. Singh, S. Smith, R. Christenson, L. Marquis, J. Catipovic, "A Bidirectional coherent acoustic communication system for underwater vehicles," Proc. Oceans 98, Nice, France, 1998.

[2] Freitag, L., M. Grund, S. Singh, J. Partan, P. Koski, K. Ball, "The WHOI Micro-Modem: An acoustic communications and navigation system for multiple platforms," Proc. Oceans 2005, Washington D.C., 2005.

[3] Freitag, L., M. Grund, J. Catipovic, D. Nagle, B. Pazol and J. Glynn, "Acoustic Communication with Small UUVs Using a Hull-Mounted Conformal Array," Proc. Oceans 2001, Honolulu, HI, pp. 2270-2275, 2001.

[4] Freitag, L., M. Johnson, M. Stojanovic, D. Nagle and J. Catipovic, "Survey and analysis of underwater acoustic channels for coherent communication in the medium-frequency band," Proc. Oceans 2000, Providence, RI, Vol. 1, pp. 123-128, 2000.

[5] Stokey, R.P, L.E. Freitag, M.D. Grund, "A Compact Control Language for AUV Acoustic Communication," Proc. Oceans Europe 2005, Nice, France, June 2005.