A Compact Control Language for AUV Acoustic Communication

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Abstract - **Acoustic communication with autonomous underwater vehicles (AUVs) implies low data rates and potentially high latency, depending on the range and the number of vehicles operating in one area. To efficiently use this limited resource the Compact Control Language (CCL) was developed for use with the WHOI REMUS AUV. CCL is a set of messages that includes commands for AUVs and data messages for typical sensors. Almost all of the messages are less than 32 bytes long. CCL commands include simple operations such as Abort Now and Abort to Mission End, but also complex commands such as re-direction with side scan sonar over areas of interest. When this simple command set is used with a telemetry system that includes network addressing (such as the WHOI Micro-Modem), sophisticated multi-vehicle operations may be carried out. The open nature of the specification allows vehicles developed at different research institutions or commercial companies to work together, thus promoting interoperability. CCL has been adopted by others working in the Office of Naval Research Very Shallow Water mine-countermeasure (VSW-MCM) program which includes multiple vehicles with different types of sensors.**

I. Introduction

This paper describes a communications protocol, the Compact Control Language, designed to allow multiple autonomous underwater vehicles (AUVs) to communicate with a central node and each other efficiently. The protocol was developed specifically for low-bandwidth acoustic communication links and thus is extremely compact. All messages are designed to fit into 32 byte packets by using the minimum number of bits necessary to denote each value. CCL data messages fall into a number of different categories:

- Vehicle information such as position, heading, speed, and subsystem fault status
- Standard data such as CTD and bathymetry,
- Special messages such as those generated when a computer-aided detection system finds an object of interest in a side-scan sonar record.
- File transfer with acknowledgement. The format of the message is such that it can be interleaved with other types of messages (and with multiple vehicles).

The compact control language is currently in use by multiple underwater vehicles from the Woods Hole Oceanographic Institution (REMUS [1], REMUS 600, REMUS 6000 [2], Seabed [3]); crawling vehicles developed by Foster Miller and NSWC, Panama City; CETUS II developed by Lockheed-Martin-Perry Technologies [4], as well as vehicles built by Bluefin Robotics. In addition, other organizations, such as the Naval Undersea Warfare Center (NUWC), Keyport have developed systems that display information transmitted from vehicles using CCL.

The paper is structured as follows. Section II provides an overview of the message structure and an explanation of how it is used with the WHOI Micro-Modem and the REMUS control system. Section III contains several example messages. Section IV includes results from several tests, including multi-vehicle operations. Section V introduces the CCL Server, a TCP-based way to interface to multiple underwater acoustic communications networks.

II. Description

The CCL protocol does not describe the communication transport layer, however it is designed around the capabilities of the WHOI Utility Acoustic Modem (UAM) and the WHOI Micro-Modem acoustic communication systems [5]. Thus it uses 32 byte packets, the smallest packet type available in those modems. All control, sensor, and status messages described here are sized to fit into 32 bytes. Messages consist of an indicator byte, followed by 31 bytes of message content. The precise format of the individual messages is described in the documentation for the Compact Control Language [6].

While CCL is independent of the acoustic modem, AUV, and control system, it is useful to describe how it is employed with the Micro-Modem and the REMUS AUV.

A. Use with the Micro-Modem

The Micro-Modem provides the user with the tools necessary to create a simple time-division, multiple-access (TDMA) network for master-slave polled systems, or a random-access peer-to-peer network. In practice both may be used at the same time if desired and if network traffic is light. All of the data packets that are received by a Micro-Modem are passed to the modem host regardless of destination. This information can be used to judge the level of network traffic and it also allows all AUVs access to any information available in the net. At present 16 addresses are available, more than the typical number of vehicles operated in one area at a time.

Each communications transaction includes a short network packet called a *cycle-initialization*, or cycle-init. The cycle-init specifies the source, destination and data rate of the packet to follow. Typical cycles include:

Data Uplink. The central node, for example a buoy with RF line-of-sight radio or satellite link and modem, polls one or more vehicles in sequential fashion.

Command Downlink. The central node sends commands to individual vehicles upon demand by a system operator.

Peer-to-Peer. Any vehicle transmits to any other system without network access control.

Acknowledgement. The transmitter of a message can specify if an acknowledgement is requested by setting the ACK flag when providing data to the modem. This can be in response to a poll (an uplink), or used on a downlink. When the message arrives at the receiving modem that is addressed, and if the message CRC (cyclic redundancy check) is good, a short ACK message is automatically sent back to the originator. While the ACK capability is not typically used for data such as state information that is repeated on a regular basis, it is essential for vehicle commands to confirm that they were received.

Using these simple network modes CCL messages can be broadcast from a command center, or sent from vehicle to vehicle. The random access mode is useful for event-driven messages that are time-critical and cannot wait for a polled uplink. However, collisions may occur, and the use of the acknowledgement capability is necessary to ensure that the data was delivered.

B. Use with the REMUS Vehicle Interface Program

CCL was originally designed specifically for use with the REMUS vehicle which has a graphical user interface that includes a plot of the vehicle's mission, position, course, attitude, depth, battery voltage and other important information. This interface was designed for use in mission planning and for play-back after the mission. With the addition of the acoustic modem some information can now be displayed in near real-time, and thus the data in the CCL state message was designed to provide updates to this user interface.

To enable use of the acoustic modem as a source for data the user simply selects it as the communications method. The interface program then performs data requests from one or more vehicles in turn. If the modem receives unsolicited data (random access mode) it is sent to the interface program, and if it is a valid CCL message, the interface program displays the data.

Commands to start or stop a mission or modify the vehicle's behavior are done by the user with pull-down menus and dialogue boxes with parameters as required by the specific command. Note that control commands may be generated by one system (for example the REMUS control laptop), and sent to a completely different type of vehicle (for example, a bottom-crawler) that is normally operated with a different user interface.

C. Gateways Buoys and Over-the-Side Modems

The surface or shore-side system connects via a modem deployed from a surface vessel, or a modem on a buoy with an RF link. The REMUS vehicle is controlled either way, though the buoy offers the best approach for remote control and avoids having a small boat in the water during a long mission. Some operations require multiple vehicles operating in multiple areas with control and monitoring from a central station. While each area may use a REMUS vehicle interface, they can be connected together through the Internet using the CCL Server capability described in Section V.

III. CCL MESSAGES

An important by-product of the introduction of the standard is that different control and display systems will be able to talk to different types of AUVs during cooperative exercises. The current scope of the protocol includes the following status and sensor messages:

- Vehicle status (position, heading, velocity, etc.)
- Environmental sensor information (depth, temperature, salinity, etc.)
- Target information
- Redirection and mission modification
- Control commands
- Error messages

A. Bathymetry Message

The bathymetry message is an example of a sensor message that includes several data values plus their location as shown in Table 1. A single 32 byte message can be used to transmit 3 bathymetry points.

Table 1: Bathymetry Message Fields

Bytes	Description
1	Message type indicator
1	Spare byte
6	Depth[3]
6	Altitude[3]
9	Latitude[3]
9	Longitude[3]
32	Total bytes used

Altitude and depth are compressed using a simple sliding scale so that there is 10 cm resolution for depths less than 100 m, 20 cm for depths between 100 and 200 m, 50 cm for depths up to 1000 m, and 1 m resolution for depths deeper than 1000 m. Altitude is encoded so that there is 10 cm resolution for altitudes up to 655 meters.

Latitude and longitude are each encoded into 3 byte values by converting the +/-180 and +/-90 degree ranges to a signed integer in the range $+/-2^{23}$. This gives resolution to several meters, sufficient for real time monitoring purposes. This encoding for position is used in many of the CCL messages.

B. Redirect Message

A more complex message example is one used to redirect a vehicle to perform a new survey as shown in Table 2 below. This message is used with the REMUS family of vehicles to perform high-resolution survey missions over small areas.

Table 2: Redirect Message Fields

Bytes	Description
1	Message type indicator
1	Spare byte
3	Latitude of center of search area
3	Longitude of center of search area
1	Speed/Depth Flags
2	Depth goal encoded transit
1	Speed encoded transit
1	Device command transit
2	Depth goal encoded transit
1	Speed encoded transit
1	Device command transit
1	Number of rows
2	Row length (meters)
1	Row spacing (odd rows)

1	Row spacing (even rows)
1	Heading
3	Latitude of start (in acknowledgement)
3	Longitude of start (in acknowledgement)
3	Spare bytes
32	Total bytes used

The redirect message (Fig. 1) tells a vehicle to perform a lawn-mower type survey over a specified area. This survey is divided into two parts. The first is a transit to the start of the survey start, the second is the actual survey. Speed and depth and/or altitude can be specified separately for the two parts since the optimum transit parameters may be different than what is optimum for a high resolution sensor survey. The search itself can have the row length, spacing, and orientation defined. Even and odd rows can have a different spacing specified because some sensors, such as a sidescan sonar, obtain faster and better coverage using unequal line spacing. A byte is reserved for control of an arbitrary sensor. In the case of a sidescan is used to set the range. The vehicle acknowledges with the same message, filling in the latitude and longitude of the beginning point of the transit to the survey area. At the conclusion of the survey, the vehicle will either return to the start initial point using the transit parameters and then continue its mission or, if additional redirect commands have been received, start immediately on the next one.

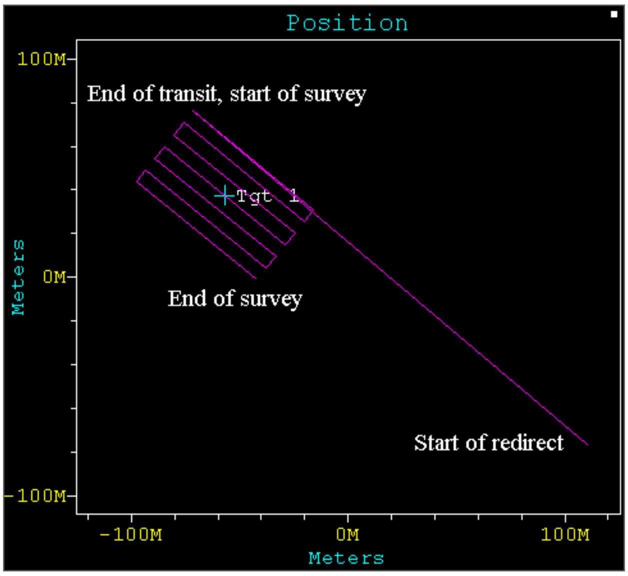

Figure 1. Redirect mission as carried out by a REMUS vehicle.

C. REMUS STATE Message

A third example is a message transmitted by REMUS vehicles to provide a user with regular updates. This message includes position, heading, speed, depth, subsystem status, time since last navigation fix, leg number, current goal, power and percent of battery capacity used. This message is the one most often used for interoperability when working with the REMUS vehicle interface program, but because it was designed around the sensors and capabilities of the REMUS it may not be well suited for use by other AUVs. Variations of this message, which will require assignment of a new message type number, should be considered for other vehicles.

IV. RESULTS

CCL has been used with the REMUS class of vehicles for more than five years and was first demonstrated during a Navy-sponsored AUV Fest held in Gulfport, MI in 1999 [7]. These early tests used the Utility Acoustic Modem operating at 15 kHz on the vehicle and a ship-based over-the-side receiver. In Fig. 2, the vehicle position with respect to the receiver (R/V Gyre) is shown. This test demonstrated 4 km modem range in very shallow water.

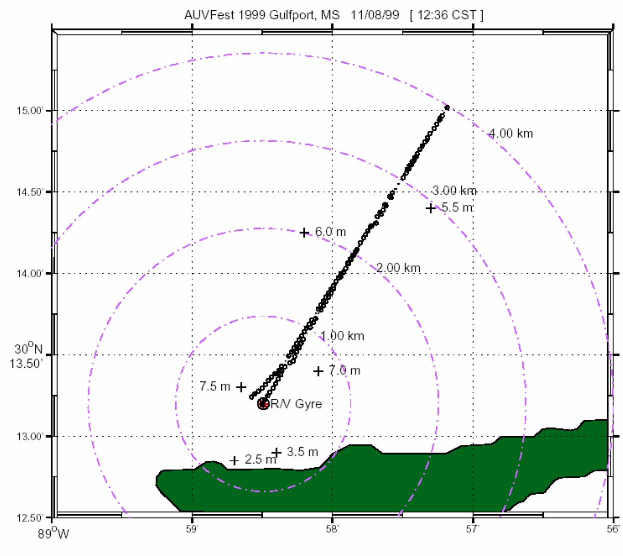

Figure 2. Plot of position data sent from a REMUS.

In cooperative exercises sponsored by the Office of Naval Research and the United States Navy, vehicle to vehicle communication has been demonstrated. An example is a mission where a Search-Classify-Map (SCM) REMUS with sidescan and on-board CAD/CAC (computer aided detection, computer aided classification) is used to detect the location of mine-like objects (MLOs). The positions of MLOs are broadcast using the CCL CAD/CAC message and are received by other vehicles, including crawlers, REMUS vehicles equipped with video, very high frequency sidescan, or a forward-looking sonar such as the DIDSON (Dual frequency Identification SONar). These other vehicles then modify their missions to perform high-resolution identification surveys with search parameters (altitude or depth and lane spacing) appropriate for their particular sensor.

Note that the CAD/CAC message is not a command, simply information. It is up the recipient to take appropriate action based on the information. REMUS reacquisition missions are only undertaken when the score is above a threshold set by the user prior to the mission.

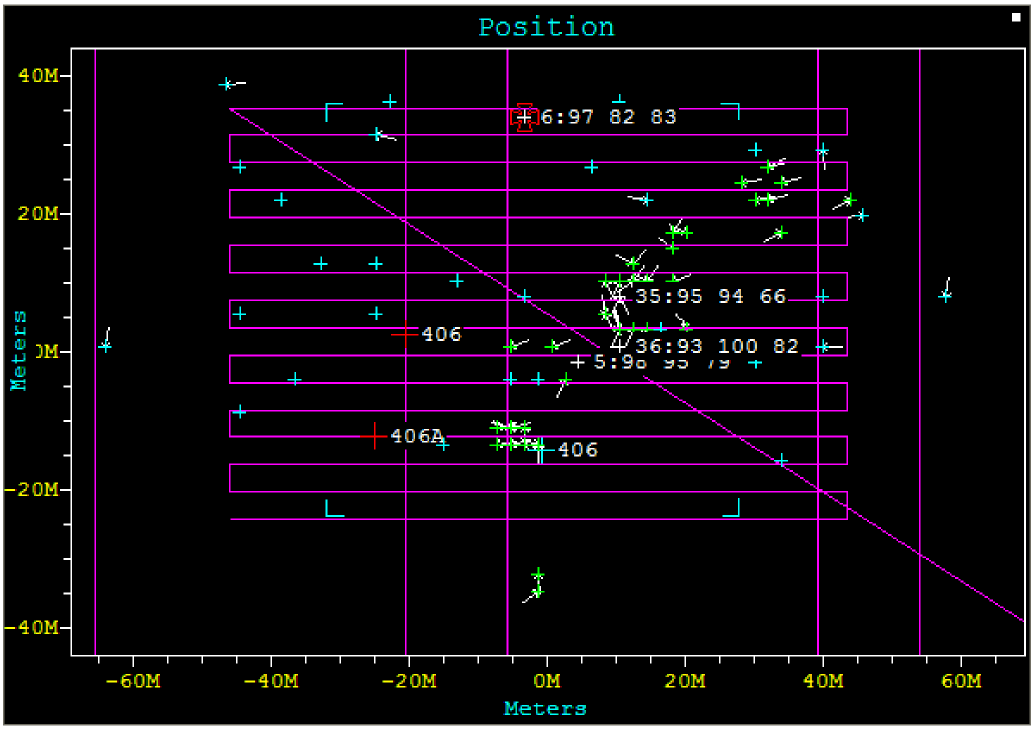

Figure 3. Vertical lines show the original REMUS mission and the close horizontal line is an operator-initiated redirect mission. The blue dots show REMUS positions. Green dots show the position of a crawler searching for a target detected by the REMUS CAD/CAC subsystem.

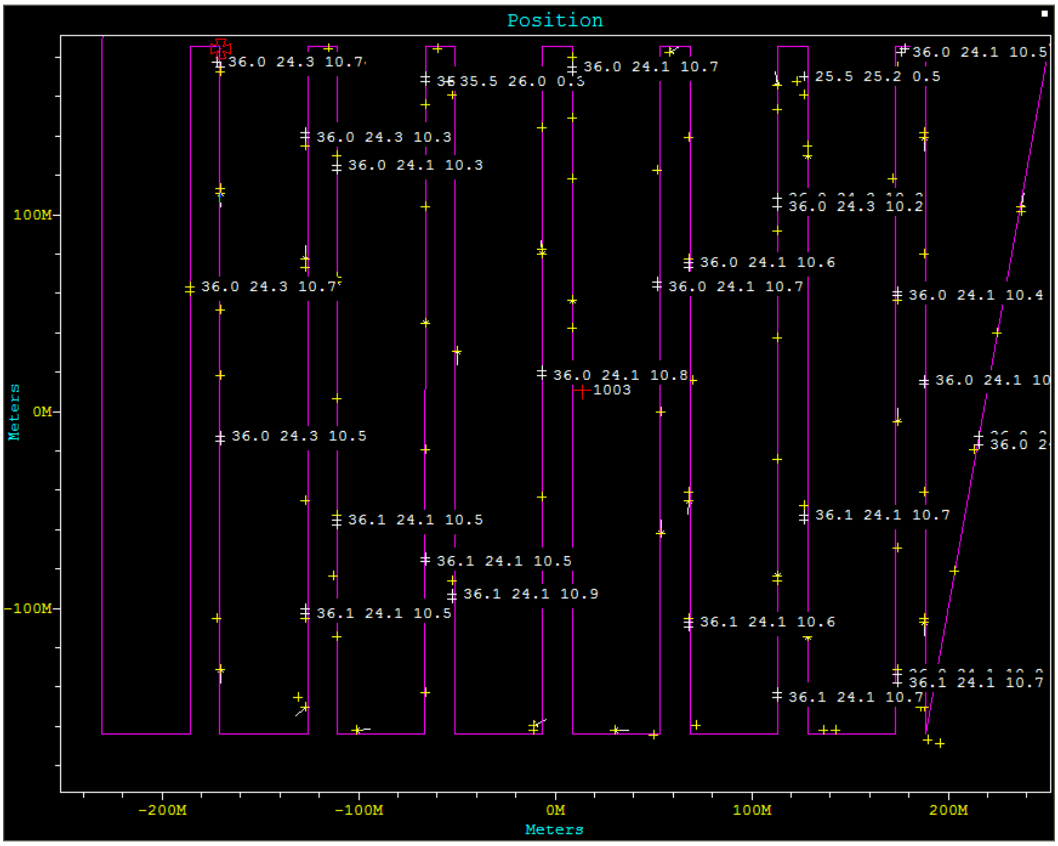

Figure 4. Data example using the CCL CTD message. The figure above is real-time salinity, temperature and depth plot from the REMUS Vehicle Interface Program. For example, 36.0 24.3 10.5 is salinity in parts per thousand, temperature in degrees C, and depth in meters.

Fig. 3 shows an example of a REMUS performing a search-classify-map mission (wide vertical tracks spaced 15 and 50 m apart), followed by a redirect mission (horizontal tracks 5 m apart) for identification. A bottom crawler is working in the same area, listening for CCL CAD/CAC messages, which it will then attempt to find and scan with a high-resolution sonar. Fig. 4 shows an example of CTD data received in near real-time on the REMUS. If multiple vehicles are operated in the same area their tracks are plotted in different colors.

In addition, during the AUV Fest in 1999, the Utility Acoustic Modem was used to send compressed snippets of MLO sidescan (Fig. 5) to a base station in real time, thus allowing a user to confirm the presence or absence of an MLO after a CAD/CAC detection.

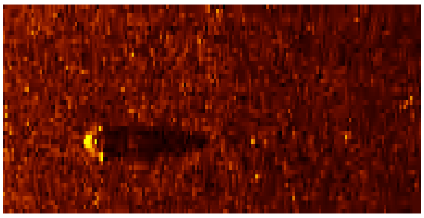

Figure 5. Compressed image of a mine-like object.

V. CCL Server

In complex networking environments it is useful for there to be a "forwarding" scheme for CCL messages so that multiple receivers may be made aware of transmitted or received data (Fig. 6). In the case of the WHOI Micro-Modem, which communicates via RS-232, it may be easier to forward messages via standard Internet protocols rather than sending serial data streams to multiple destinations. Additionally, CCL is implemented as a layer in some systems, and is simply one part of a much larger communications scheme. To minimize the need for custom parsers an approach has been defined that allows a server connected to CCL network node (i.e. an acoustic modem), to rebroadcast messages as a TCP server. Clients can connect and receive the data in a standard unified format from across the room or across the world.

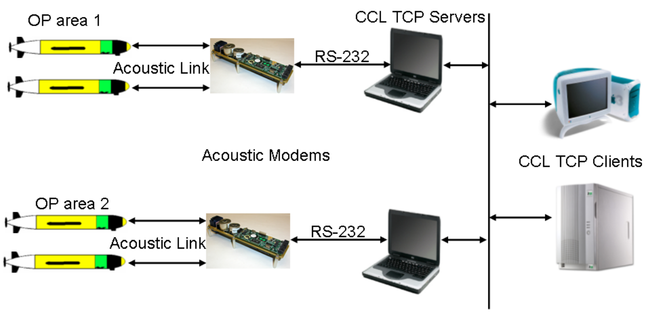

Figure 6. CCL Server architecture

This topology supports individual servers for each operational area and IP connections to higher-level systems which provide a larger tactical picture. There is nothing in the specification that prevents these TCP Clients from also acting as servers as well, thus the system can easily scale to very high levels of complexity using a layered approach.

VI. Conclusion

The publication of the Compact Control Language will allow autonomous vehicles and sensors to interoperate. Common data formats are a simple but powerful way of allowing different control and display systems to operate with different classes of AUVs from different manufacturers. Additional messages may be added by users as necessary for new missions, both Navy (for example mine countermeasures) and civilian (for example, pollution monitoring).

The specification is available on the web at [6], and submissions of new messages and requests for type numbers should be sent to ccl@whoi.edu.

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