Autonomous Surface Craft Provide Flexibility to Remote Adaptive Oceanographic Sampling and Modeling

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Abstract— **During field experiments conducted in Monterey Bay, CA in the summer of 2006 and Dabob Bay, WA in the summer of 2007, a team of scientists and engineers from MIT outfitted an on-board winch and CTD system onto a SCOUT autonomous surface craft (ASC). Along with allowing both teleoperated and autonomous CTD profiling capability, this system was deployed as part of a small fleet of similar ASCs equipped with acoustic modem hardware and linked via 802.11b wireless ethernet and Evolution Data, Optimized (EVDO) to the ship and the internet. Using this communications capability, the fleet of autonomous vehicles automatically uploaded oceanographic data to a remote server and remained in contact with scientists aboard the nearby research vessel. The uploaded data was nearly immediately available to the ocean modeling and prediction model maintained at MIT and Harvard University. Finally, the entire system was exercised with a completely autonomous test of sound speed using two distinct techniques: acoustic pings and a CTD cast.**

I. INTRODUCTION

Oceanographic research and discovery, like any human scientific endeavor, is limited by human and financial resources. Thus, substantial progress in the pace of discovery will likely come by new innovations in efficient use of oceanographers' time and research money. The field of marine robotics has tremendous potential to progress towards this goal by replacing many of the mundane tasks performed currently by scientists with autonomous systems. In the post Apollo era, astrophysicists have learned much through the use of robots, and as much of the ocean environment shares many similarities with the reaches beyond our planet (often treacherous, dark, and inaccessible), oceanographers will likely profit by emulating this approach.

Research in autonomous marine vehicles has largely focused on three platforms types: autonomous underwater vehicles (AUVs) (such as [1], [2], [3]), gliders (like [4] and [5]), and autonomous surface craft (ASCs). Each of these platform types has certain advantages and limitations. AUVs have high maneuverability but limited run time (on the order of a day); gliders have relatively little control over their destination but long deployment times (a month or more).

In this work, we focus on a small fleet of low cost SCOUT ASCs as the platform [6]. ASCs have several advantages over other platform types, especially for fast paced engineering research. The hardware is quickly reconfigurable and the safety of the craft does not require code freezes that are often necessary for AUV work. It is possible (and desirable) to update software while the vehicles are deployed. Simulations can be run on ship based computers and the subsequent changes pushed to the craft in minutes without retrieving the vehicles. Furthermore, a single operator can handle multiple vehicles with time left to simulate and develop new missions. They can also be used for novel purposes that transcend the traditional uses of a "marine vessel," such as the smart buoy proposed in [7].

In the present work, one of these ASCs is outfitted with a small conductivity-temperature-depth (CTD) instrument to perform the measurements for which the instrument is named. These quantities are particularly valuable to physical oceanography. (For example, temperature of the ocean studies are crucial to understanding global warming [8].) The winch used to raise and lower the CTD is mounted in the SCOUT and is controlled by the ASC's main vehicle computer. This CTD vehicle allows an oceanographer to make CTD casts while the ship is performing other tasks. Now that the vehicle can be controlled from the ship, modern communications technology enables control from almost anywhere in the world. Furthermore, since the vehicle can be commanded by a human to take casts, it is a small step to allow command by a shore based computer (running an ocean model, for example). We took these ideas and developed a multivehicle sampling system capable of being deployed remotely and automatically. In field experiments in Dabob Bay, WA in 2007, we demonstrate this system with a test that involves two of the ASCs calculating sound speed using acoustic pings while a third calculates sound speed indirectly through measurements of salinity, temperature, and depth using the CTD.

Remote sensing is hardly a new concept: sonar and other acoustic techniques fall into that category. However, many oceanographic measurements are impossible to make without the instrument in close proximity with the sample. Furthermore, it is prudent to calibrate and verify remote measurements using an independent sampling technique. The system we present here enables remote (for the oceanographer) yet immediate (for the sensor) sensing.

II. AUTONOMOUS SAMPLING SYSTEM

We demonstrate a system based on an easily deployed *sampling platform* (multiple ASCs), *autonomy software* (MOOS-IvP software architecture), and sea and air *communications* infrastructure (wireless networking, EVDO networking, acoustic communications, and the internet).

A. SCOUT ASC

The robotic platform used in this experiment is the Surface Craft for Undersea and Oceanographic Testing (SCOUT). The SCOUT (Fig. 1) is a three meter plastic-hulled craft with electric propulsion and an main vehicle computer running GNU/Linux [6].

For this work, one of the SCOUTs was outfitted with a SeaBird 49 (SBE49) CTD, a small off-the-shelf unit capable of sampling continuously at sixteen Hertz and interfacing through a RS-232 serial port. The CTD was attached to the end of the seventy meter winch cable and deployed through a penetration in the hull of the ASC (note Fig. 2 for a picture of the winch). Winch operation was accomplished using a custom fabricated controller attached to the electric reel motor, incorporating feedback from an optical encoder mounted to the spool mechanism. The winch is capable of lowering the CTD at about twenty meters per minute.

Fig. 1. CTD equipped SCOUT vehicle.

B. Autonomy Software

The vehicles in this work run an autonomy architecture comprised of the Mission Oriented Operating Suite (MOOS) and the Interval Programming (IvP) helm. (Together they are referred to as MOOS-IvP.)

1) MOOS: MOOS is an open source publish/subscribe architecture written in C++ by Paul Newman. MOOS allows individual software modules (MOOS modules) to pass data through a central database (MOOSDB). Individual modules have no knowledge of each other beyond the variables they publish and subscribe. This allows for rapid addition of software to the code base on a vehicle without intricate knowledge of existing modules. It also lowers the training time required for a new developer to begin writing useful code. All of these are valuable traits for a rapid prototyping research system. MOOS lacks some of the runtime efficiencies available in other software systems, but this negative is outweighed by the benefits for our purposes (rapid prototyping by a large group of differently skilled contributors). As MOOS is open source software, the code and documentation is freely available from P. Newman's website [9].

Fig. 2. SCOUT equipped with autonomous winch (center). The main vehicle computer is visible on the left.

2) IvP Helm: The IvP Helm (also known by its MOOS module name `pHelmIvP`) acts as the SCOUT's "captain". It is a MOOS module that publishes and subscribes to the MOOSDB. However, it also interfaces with one or more behaviors that govern different aspects of the vehicle's final actions. Each behavior produces an objective function over all speeds and headings available to the vehicle. For each speed and heading, the objective function defines a utility. The IvP Helm optimizes over the objective functions, finding compromises or, in the case of mutually exclusivity, picking the action that has a highest utility (priority weighting) [10]. Simple behaviors implement way point following or station keeping, and more complex behaviors implement true adaptive autonomy (e.g. temperature gradient following or target tracking). Uses of the IvP Helm in marine vehicle autonomy can be found in [11] and [12]. The IvP Helm is also open source and available at [13].

The following two modules (`iWinch` and `pSamplingControl`) are responsible for conducting autonomous CTD missions using the SCOUT:

3) iWinch: The winch is raised and lowered by means of the MOOS module `iWinch`, a driver that takes from the MOOSDB a desired depth for the CTD and translates it into encoder positions for the winch. The reel motor for the winch is then commanded to move the desired number of encoder positions.

4) pSamplingControl: Another MOOS module, `pSamplingControl`, is responsible for mediating the CTD sampling mission. Several types of missions are defined and `pSamplingControl` is responsible for translating CTD mission parameters into parameters for `iWinch`, turning on and off behaviors in `pHelmIvP`, and enabling CTD data logging (using `pCTDLogger`).

C. Communications

To enable remote operation and tasking of the SCOUTs, several third-party communication devices are installed on the vehicles. At the signal level, the first two use electromagnetic (EM) signals through air (802.11 wireless and EVDO), and the third (WHOI MicroModem) uses acoustic transmissions through water. The presences of both air and water links allows the SCOUTs to receive commands from either above the ocean (anywhere with access to the internet) or below the ocean (buoys, AUVs, or gliders).

1) 802.11 Wireless Networking: For basic operation from the ship, a wireless IEEE 802.11b compliant network card is installed on all the SCOUTs. A compatible router is based on the ship to form a simple IP based network. Communication with the vehicle computers is largely done with UDP packets where acknowledgments are done at the application layer when needed. The GNU/Linux Secure Shell (OpenSSH) is also used to remotely administrate the vehicle computers. The router antenna is boosted with a radio frequency (RF) power amplifier to improve range. The ocean environment can cause wireless dropouts and low throughput, which is still an area for improvement. We are investigating the use of newer protocols such as IEEE 802.11n and how they perform for our system.

A summary of this link can be given by the communication layers (top to bottom is most to least abstract):

- Application Layer: Various MOOS Modules (`pHelmIvP` and other control processes)
- Transport Layer: MOOS module `MOOSBlink` (creates UDP packets from MOOS variables)
- Network Layer: Internet Protocol (IP)
- Link Layer: specified by IEEE 802.11b protocol
- Hardware: specified by IEEE 802.11b protocol ($\sim$2.4 GHz EM carrier, 20 MHz bandwidth)

2) EVDO Networking: The second air based communication device is an Evolution Data, Optimized (EVDO) modem that allows a connection to the internet directly through compatible cell phone towers. While only usable in certain near shore areas, these modems are a low cost alternative to satellite technology. In our tests in Dabob Bay, WA, these modems provided excellent connectivity and throughput.

- Application Layer: Various MOOS modules
- Transport Layer: MOOS module `iWebsite` (invokes GNU/Linux Wget and SCP to pass MOOS variables to and from a remote server)
- Network Layer: Internet Protocol (IP)
- Link Layer: specified by EVDO protocol
- Hardware: specified by EVDO protocol (EM carrier frequency depends on region)

3) WHOI MicroModems: For underwater communications, the SCOUTS use an acoustic modem called the MicroModem developed at the Woods Hole Oceanographic Institution (WHOI). The MicroModem comes in several variants, but the ones used in the SCOUTs operate at a center frequency of about twenty-five kilohertz and provide approximately eighty bits per second (bps) throughput using frequency-shift keying with frequency hopping (FH-FSK) [14]. The messages are encoded into thirty-two byte hex sentences using the Compact Control Language (CCL) set of codecs also developed at WHOI.

- Application Layer: Various MOOS modules and `pFramer` (does compression/decompression)
- Transport Layer: MOOS module `iMicroModem`
- Link Layer: MicroModem Firmware
- Hardware: MicroModem FH-FSK (25 kHz carrier)

The MicroModem protocol does not currently support routing beyond broadcast (similar to a single ethernet link). All routing must be done above the transport layer.

III. COOPERATIVE SOUND SPEED TEST

A. Background

Initial tests using the CTD vehicle were performed in Monterey Bay, CA in 2006 (MB06). Hardware issues were worked out and the CTD vehicle performed a series of temperature gradient following missions presented in [11].

The first deployment was performed with a lead weight in place of the CTD instrument in order to test and confirm

Fig. 3. Google Earth Ocean Viewer (GEOV) screenshot during the cooperative sound speed experiment.

the basic mechanical and electrical winch functionality. Once it was decided that the winch system was functioning as expected, the CTD was calibrated alongside the Research Vessel's (R/V Point Sur) CTD instrument. This was accomplished by mounting the SBE49 directly to the ship's CTD rosette and lowering both instruments simultaneously. CTD calibration runs were then performed in close proximity to the Research Vessel in order to further confirm correlation between the SCOUT based CTD and the R/V CTD prior to deploying the vehicle on its first autonomous CTD mission.

The SCOUT was commanded upon deployment to transit to a predetermined way point and hold station upon arrival. Once on station, the CTD was lowered and retrieved several times in order to assure full mechanical and electrical functionality. The initial shake out tests proved satisfactory and the vehicle was then sent on its initial survey run. This mission consisted of providing the SCOUT vehicle with two way points that represented the diagonal corners of a rectangle. The SCOUT software used these two points to generate a set of ten way points arranged in a simple rectangular grid formation within the rectangle prescribed. The vehicle successfully cast the CTD at each node and completed the full transit in approximately one and one half hours. It was discovered that the addition of the winch into the otherwise stable SCOUT vehicle raised the vehicles center of gravity sufficiently enough to cause the vehicle to become unstable in roll. During operations in sea state three (wind approximately fifteen knots, wave height approximately three feet) The SCOUT vehicle inverted, but remained stable at the surface and was easily recovered and re-launched. Additional ballast was added to the vehicle which improved the stability significantly and proved to be a satisfactory solution used throughout the remainder of the experiments. The SCOUT outfitted with the CTD winch system was deployed for approximately eight hours over the course of ten days during the MB06 trials.

The following year, the EVDO modems and supporting software were integrated by the following year and further tests were performed in Dabob Bay, WA in 2007 as part of the Persistent Littoral Undersea Network (PLUSNet07) exercises. This new infrastructure allowed the SCOUTs to be commanded in Washington by a mission set by parameters in a text file at modelseas.mit.edu (based in Massachusetts). The modelseas.mit.edu server hosts the Harvard Ocean Prediction System (HOPS) ocean model. While during the PLUSNet07 exercises human oceanographers set the missions parameters on modelseas.mit.edu, the infrastructure is there to have the HOPS model produce the desired mission.

Over twenty remotely commanded CTD missions were made over the course of PLUSNet07 to perform different tests such as finding changes in the thermocline, detecting internal waves, and calibrating glider and ship CTDs.

A final experiment, the cooperative sound speed test, is presented here and demonstrates all the aspects of this system at once.

B. Setup

The cooperative sound speed test involves three SCOUTs, two outfitted with MicroModems and one with the CTD previously mentioned. One of the MicroModem-equipped SCOUTs acts as commander. The goal of the experiment is for the three vehicles to collaborate to measure the sound speed of a section of water using two independent techniques. (See Fig. 3 for a screenshot of the vehicle position viewer during the actual experiment.) Sound speed in water is a useful quantity for many acoustics techniques such as underwater communications, navigation, and tracking.

The experiment is carried out by the following events (illustrated in Fig. 4):

1) The commander vehicle ("Dee") receives an acoustic "prosecute" message from Network and Field Control (NaFCon). The prosecute message was normally used

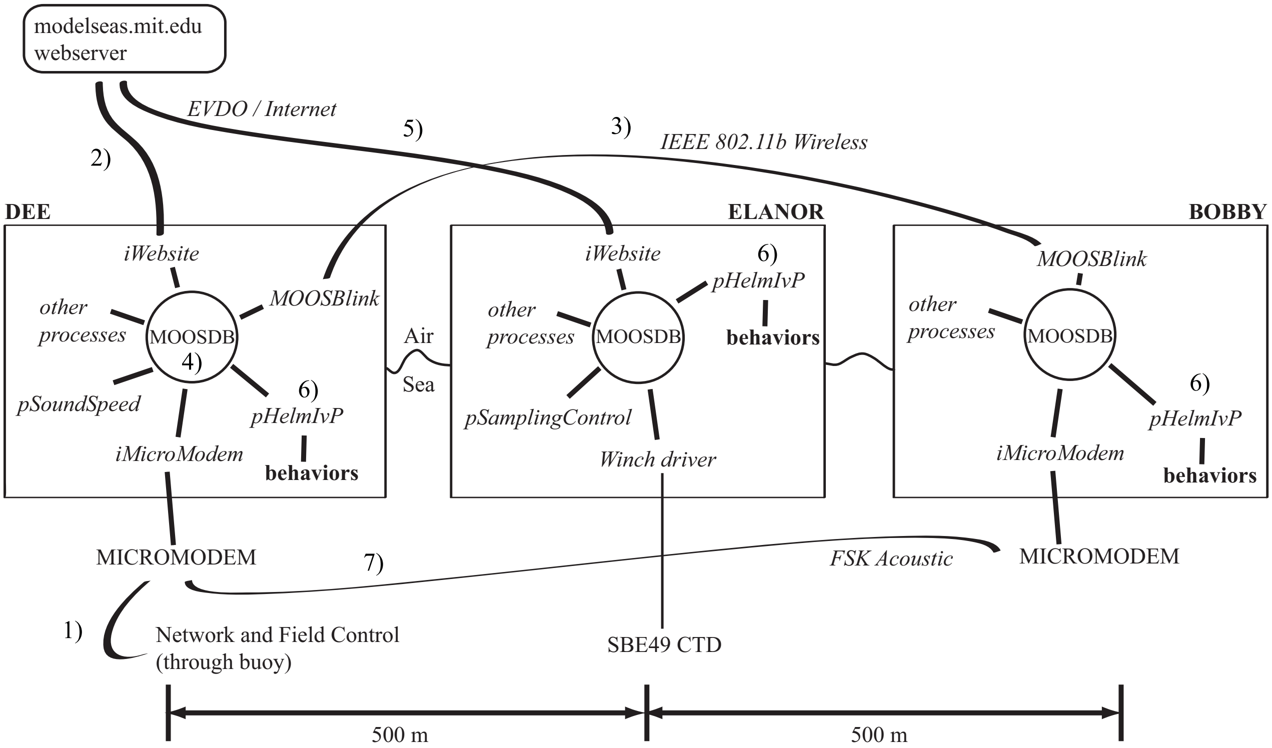

Fig. 4. Schematic demonstrating the software and communication links for the cooperative sound speed test.

for acoustic target tracking but we adapted it for our sound speed test use.

2) A MOOS Module called `pSoundSpeed` on Dee takes the message and processes. Within the prosecute message is a location in the bay that should be sampled (target point). `pSoundSpeed` emulates a remote modeling computer to test the long range EVDO/internet link by giving the target point to the CTD vehicle ("Elanor") via modelseas.mit.edu (a server based in Massachusetts).
3) `pSoundSpeed` (running on Dee) provides the target point, offset 500 meters to the *east*, to the other MicroModem-equipped vehicle ("Bobby") via wireless.
4) `pSoundSpeed` passes the target point offset 500 meters to the *west* to its own MOOSDB for consumption by the IvP Helm.
5) The CTD vehicle, Elanor, reads the mission file from the modelseas.mit.edu web server and `pSamplingControl` mediates the CTD test (per other CTD experiments). The CTD data is used to calculate sound speed (from temperature and salinity).
6) `pHelmIvP` on Dee and Bobby consumes information published locally and through MOOSBlink, respectively, and all the vehicles transit to their appropriate sample places using the *BHV_WayPoint* behavior. Once the vehicles reach their station points, the IvP helm behavior *BHV_StationKeep* ensures the vehicles stay within an acceptable radius of their deployed point even in the presence of wind or current.
7) `pSoundSpeed` initiates pinging from the Dee's MicroModem and Bobby responds. The one way travel time is recorded and the sound speed is directly computed using the known separation of the vehicles through the vehicles' GPS.

C. Results

Due to ship time constraints, this experiment was only completed (after several tests) for a thirty minute run in a single location. The positions of the vehicles throughout the experiment are given in Fig. 5 and the measured sound speeds from both techniques in Fig. 6. The sound speed calculation from the CTD is done by the Chen and Millero formula based on temperature, salinity, and pressure [15]. The direct ping sound speed was computed simply from

$$c = d/t \tag{1}$$

where d is the separation of the two vehicles, t is the direct path one way travel time after removing the modem turnaround time, and c is the speed of sound.

From a technical standpoint the test was highly successful; the vehicles performed as expected with a minimal amount of debugging. While the data set here is too small to be of scientific use, it points to improvements needed to our system before a larger scale test can be performed. The accuracy of the Garmin GPS (several meters at least) on both vehicles means that the uncertainty in the sound speed over a one

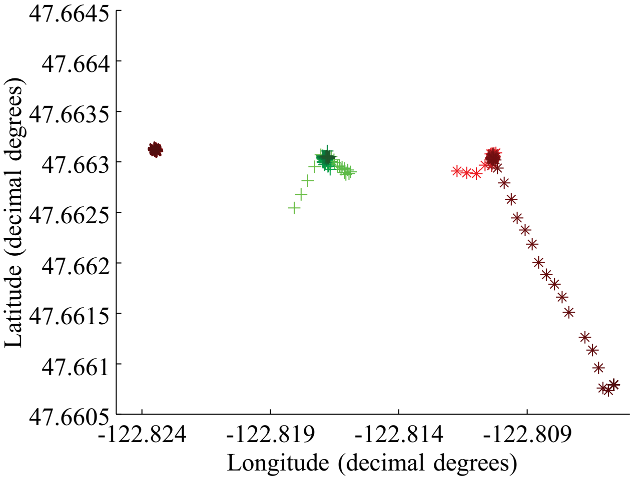

Fig. 5. Positions of vehicles during cooperative sound speed test. Bright colors indicate early time in the experiment and coloring corresponds to Fig. 6.

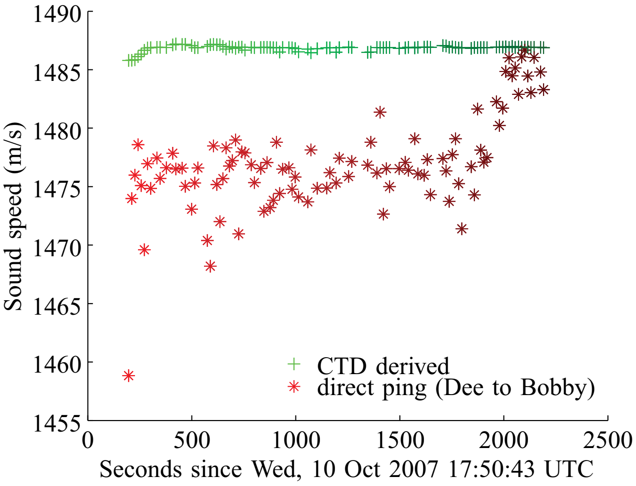

Fig. 6. Measured speed of sound during the October 10, 2007 sound speed experiment using three SCOUT ASCs performing two techniques. Note that the coloration corresponds to that of Fig. 5.

kilometer test is too high to give sufficiently precise data to be used for acoustics work. Though, since the data point that matters is the difference between the two MicroModem-equipped vehicles, the error is likely much lower (common mode rejection). However, using higher accuracy differential GPS would certainly lead to higher accuracy in the final sound speed measurement. The acoustic modem specifications state an accuracy of ± 125 microseconds in the computation of the one way travel time, after subtracting out the turnaround time in the second modem [14].

IV. CONCLUSION

Use of multiple low cost autonomous craft has shown to be a feasible tool for oceanographic sampling over long distances. It will be a simple next step to incorporate shore based computer models into our system; remaining is having the HOPS model produce a text mission file for the vehicle(s) and read in the resulting data and create a new mission. We plan to extend this remotely commanded multiple vehicle sampling structure to other sensors, such as sidescan sonar, and other platforms, including AUVs.

Within the specific sound speed experiment demonstrated here, we would like to put winches on the MicroModem SCOUTs as well so the height of the MicroModem transducers can be autonomously controlled in the same manner that the CTD is. By having this flexibility along with the mobility of the SCOUTs, the sound speed could be calculated through a number of different ray paths, creating a three dimensional (averaged) sound speed profile.

This experiment has validated the suitability and certain advantages to be gained through using an ASC in gathering oceanographic environmental data. Ship based instrumentation offers advantages including speed of transit between data points, lab space and so on. Some of these benefits may be offset by factors including complexity, cost, station keeping considerations and the potential to contaminate data through water discharge (including heat and particulates) and magnetic signature. The small, highly maneuverable ASC offers substantial cost savings and may be most suitable for applications requiring smaller scale spatial distribution of data points where the ship based system may be more suitable to sampling over larger areas and greater data point spacing. The ASC will likely offer significant advantages when applied to sampling data over very large time scales (days - years potentially) as operational costs are insignificant and robotic systems faithfully fulfill their objectives without regard to manning schedules and labor restrictions. The advantages of providing unmanned operation and more importantly autonomous adaptive capability provided by the ASC will likely prove to be very powerful utilities once all of the long term survivability and deployment duration requirements are satisfied.

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REFERENCES

[1] B. Allen, et al.,"REMUS: a small, low cost AUV; system description, field trials and performance results," OCEANS 1997. MTS/IEEE Conference Proceedings, vol. 2, pp. 994-1000, Oct. 1997.
[2] D. R. Yoerger, A. M. Bradley, and B. B. Walden. "The Autonomous Benthic Explorer (ABE): an AUV optimized for deep seafloor studies," Proceedings of the Seventh International Symposium on Unmanned Untethered Submersible Technology (UUST91), pp. 60-70, 1991.
[3] H. Singh, et al., "Seabed AUV offers new platform for high-resolution imaging," EOS, Transactions of the AGU, vol. 85, no. 31, pp. 289, 294-295, Aug. 2004.
[4] D. C. Webb, P. J. Simonetti, and C. P. Jones, "SLOCUM, an underwater glider propelled by environmental energy," IEEE J. Oceanic Eng., vol. 26, pp. 447-452, Oct. 2001.

[5] J. Sherman, R. E. Davis, W. B. Owens, and J. Valdes, “The autonomous underwater glider ’Spray’,” IEEE J. Oceanic Eng., vol. 26, pp. 437-446, Oct. 2001.

[6] J. Curcio, J. Leonard, A. Patrikalakis, “SCOUT - a low cost autonomous surface platform for research in cooperative autonomy,” OCEANS 2005. MTS/IEEE Conference Proceedings, vol. 1, pp. 725-729, 2005.

[7] J. Curcio, et al. “Self-positioning smart buoys, the “un-buoy” solution: logistic considerations using autonomous surface craft technology and improved communications infrastructure,” OCEANS 2006, MTS/IEEE Oceans Conference Proceedings, pp. 1-5, Sept. 2006.

[8] S. Levitus, J. I. Antonov, T. P. Boyer, and C. Stephens, “ Warming of the world ocean,” Science, Vol. 287. no. 5461, pp. 2225-2229, 24 March 2000.

[9] P. Newman, “TheMOOS,” Dec. 2007. [Online]. Available: http://www.robots.ox.ac.uk/∼pnewman/TheMOOS/ [Accessed July 18, 2008].

[10] M. R. Benjamin, “The Interval Programming Model for Multi-objective Decision Making,” AI Lab Technical Memo AIM-2004-021, Massachusetts Institute of Technology, Cambridge MA, September 2004. [Online]. Available: http://oceanai.mit.edu/mikerb/publications/aim-2004-021.pdf. [Accessed July 18, 2008].

[11] D. P. Eickstedt, M. R. Benjamin, J. Curcio, “Behavior Based Adaptive Control for Autonomous Oceanographic Sampling,” 2007 IEEE International Conference on Robotics and Automation, pp.4245-4250, 10-14 April 2007.

[12] M. Benjamin, D. Battle, D. Eickstedt, H. Schmidt, A. Balasuriya, “Autonomous Control of an Unmanned Underwater Vehicle Towing a Vector Sensor Array,” International Conference on Robotics and Automation (ICRA), Rome, Italy, April 2007.

[13] M. Benjamin, “MOOS-IvP Home Page,” [Online]. Available: http://www.moos-ivp.com/ [Accessed July 18, 2008].

[14] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, K. Ball, “The WHOI micro-modem: an acoustic communications and navigation system for multiple platforms,” OCEANS 2005. MTS/IEEE Conference Proceedings, vol. 2, pp. 1086-1092, 2005.

[15] C-T. Chen and F. J. Millero, ”Speed of sound in seawater at high pressures,” J. Acoust. Soc. Am., vol 62, issue 5, pp 1129-1135, Nov. 1997.