

AUV OPERATIONS IN THE ARCTIC

J. G. Bellingham, J. J. Leonard, J. Vaganay, C. A. Goudey, D. K. Atwood, T. R. Consi,
J. W. Bales, H. Schmidt, and C. Chrysostomidis

Massachusetts Institute of Technology, Sea Grant College Program
Cambridge, Massachusetts 02139

Abstract

This paper describes the challenges of designing an autonomous underwater vehicle system for surveying the underside of the Arctic ice canopy and results of initial tests. The objective was to launch and recover an autonomous underwater vehicle through the ice to make measurements of the topography of the underside of the ice canopy. Ultimately, transits of up to ten kilometers and mapping operations over an area of one square kilometer are desired, however the tests described here were limited to the immediate vicinity of the launch/recovery ice hole.

Introduction

The requirement for a cost effective under-ice survey capability was high-lighted by the Arctic Sea Ice Mechanics Initiative, sponsored by the Office of Naval Research. For this initiative, a capability to rapidly characterize the under-side of the ice in a region of ice activity was desired. Rapid response is necessary since ice activity lasts on the order of a day. In the past, data concerning the topography of the ice have been obtained by a variety of means, including sidescan sonar mounted on submarines [Sear and Wadhams, 1992] and mechanically-scanned sonars inserted through holes drilled in the ice [Connors et al., 1989]. AUVs offer a complement to these methods of data acquisition, providing a larger area of coverage via a single ice hole, at a much lower expense than a nuclear submarine.

There is ample precedent for employing AUVs for Arctic operations. The UARS (Unmanned Arctic Research Submersible) was used to obtain under-ice topography in the early 1970s [Francoise and Nodland, 1972]. More recently, the Seashuttle vehicles [Light and Morrison, 1989] have been demonstrated in the Arctic as a very small, economical platforms. The International Submarine Engineering ARCS vehicle was designed to operate under ice [Brooke, 1981], as is the Marconi Test Bed AUV currently under development [Tonge, 1992].

Prior to vehicle operations, a number of preparatory activities are required. First, a hydro-hole measuring at least 1 x 2.5 meters in size must be formed for launch and recovery. The hydro-hole will be maintained in a heated tent, and will provide a base for vehicle operations. Second, an array of acoustic beacons must be deployed from the ice sheet. The acoustic beacons will be used as elements of a long-baseline array for AUV navigation.

The mission chronology is:

- 1) Mission parameters downloaded to vehicle, including position of ice-mounted navigation beacons.
- 2) Vehicle deployed through a hydro-hole in base camp.
- 3) Navigation to the active region to perform its mapping mission.
- 4) Perform under-ice mapping.
- 5) Return to base camp for recovery and data retrieval.

Recovery was achieved by an arrangement similar to that used for the UARS vehicle [Francoise and Nodland, 1972]. An ultrashort-baseline (USBL) navigation system was employed for homing

the vehicle on a net suspended under the ice. The vehicle carried a set of barbs on its nose with which it entangled itself in the net.

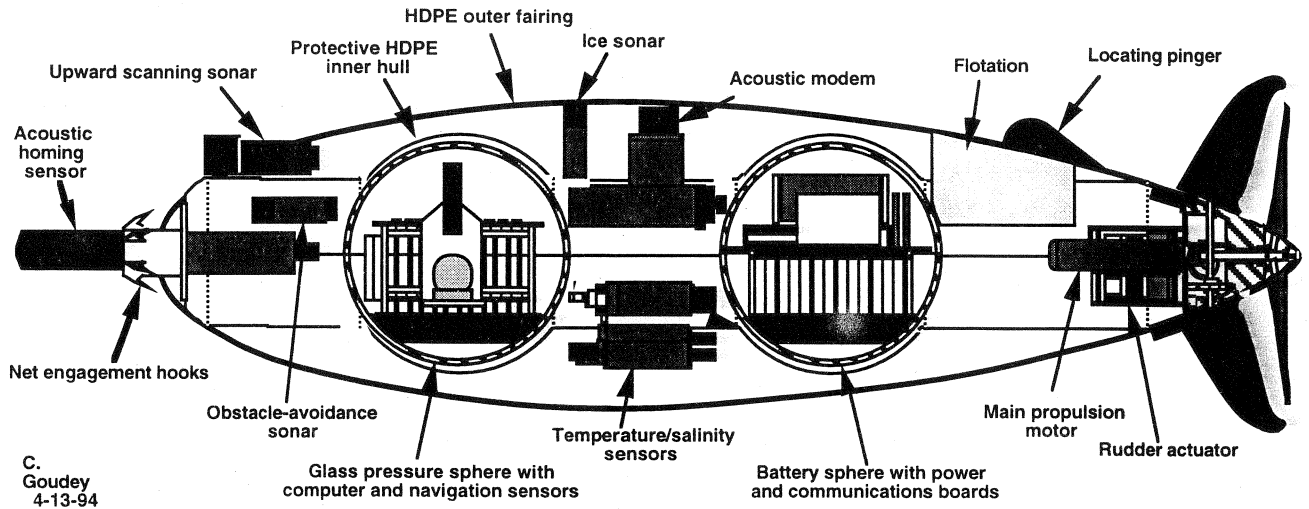


Figure 1: Arctic configuration of Odyssey II. Mission sensors are the scanning sonar at the nose, and the temperature and conductivity sensors located in the center of the vehicle.

Vehicle Description

The logistical complexities of operating in the Arctic are such that a small vehicle with a minimum support requirement is extremely attractive. Odyssey II is second generation survey class autonomous underwater vehicle, designed as an intelligent mobile instrument platform [Bellingham et. al, 1992]. Comprised of a low-drag fairing with a single ducted propeller and cruciform control surfaces, Odyssey II is 2.2 meters long, and has a maximum diameter of 0.6 meters (see Figure 1). The fairing is free-flooded, and contains the main pressure housings, which are two glass spheres. In the present configuration, the vehicle has an endurance of eight to twelve hours, depending on the operating speed and the duty cycle of subsystems such as the acoustic modem.

The primary onboard computer is built around a Motorola 68030 microprocessor [OR Industrial Computers]. In addition to the main computer, a network of small microcontrollers (Motorola M68HC11) is used to distribute "intelligence" to sensors and actuators. The present vehicle state sensor complement includes a three-axis fluxgate magnetometer [EMDS], three-axis accelerometer and angular rate sensors [Systron-Donner], a pressure transducer [Paroscientific], and a water speed sensor. Two ST500 obstacle avoidance sonar and an ST200 altimeter sonar [Tritech] are also integrated into the vehicle. An acoustic modem [Datasonics] has undergone preliminary testing on Odyssey II, and will become a standard device.

For Arctic operations, Odyssey II had no drop weights. However, two drop weights are attached for deep-water operations. The first is used to speed descent of the vehicle to its operating depth, while the second is used to speed ascent in a normal mission, or to force ascent in an emergency. The drop weights can be released either by command from the main vehicle computer, or on the initiative of a second "watchdog" computer which monitors the main vehicle computer and the progress of the mission. The watchdog operates as a backup to the main computer, to ensure vehicle recovery when all else fails.

A transponder, a radio beacon, and a strobe are used to provide a means of locating the vehicle. All three location aids operate off of power sources independent from each other and the rest of the vehicle electronics to ensure operation even if vehicle batteries run low. The radio beacon and strobe are used for locating the vehicle on the surface. An ultrashort-baseline (USBL) system is used on the surface to track the transponder. Both LXT and Trackpoint II systems [ORE] have

been used to track Odyssey II from the surface.

Attitude Heading Reference System

For operations in the Arctic, Odyssey II measures its orientation with a sensor package which measures magnetic intensity, angular rate and acceleration for all three axes. The vehicle attitude and heading are taken from the angular rate and acceleration sensors only. Drift in the heading of the inertial system is corrected by the magnetic measurement. Periods of high magnetic activity could compromise accuracy, however this was not encountered during our operations. The earth's field was monitored at the camp throughout the mission, so that post-mission correction of heading errors could have been made. While significant heading errors can degrade vehicle performance, they generally do not jeopardize recovery chances, as in the terminal phase of the mission the vehicle uses the acoustic homing beacon as the directional reference.

Homing

A commercial USBL system, the LXT [ORE], was integrated into the vehicle to provide a homing capability for under-ice operations. The LXT measures both direction and range to up to two acoustic beacons. Detection of beacons at ranges on the order of two kilometers was obtained in the Arctic. While power consumption of the system is high (40 watts), the USBL need only be turned on for the recovery phase of the mission (cf Figure 2). While vehicle position can be determined from range and bearing to one beacon, the ability of the vehicle to track two beacons at a time also allows for a range-range solution for the vehicle position (i.e. spherical navigation, cf Figure 4).

Algorithms

The layered control work previously developed on Odyssey I and on Sea Squirt has been substantially improved and implemented on Odyssey II. A full description is omitted for lack of space, however achievements include:

- creation and demonstration of simulation-to-vehicle software path in which code run in Macintosh simulation is transferred directly to vehicle, tested in a vehicle-in-the-loop simulation, and then used for vehicle field operations.
- extensive testing of vehicle dynamic and mission level control in field operations, including demonstration of nine new behaviors designed for Arctic vehicle operations.
- communication with the vehicle via a commercial acoustic communication system, including interrogating individual subsystems and examining mission data files.

The elementary unit of layered control is the behavior. A behavior receives sensory input and generates commands. Each behavior is responsible for a specific mission objective. For example, the objective of an obstacle avoidance behavior is to prevent the vehicle from hitting objects. A layered control command structure consists of a number of behaviors with different objectives. The command outputs of the behaviors are resolved into the final command that is sent to the vehicle. At present, a total of 18 behaviors have been written for Odyssey II, with a little more than half those behaviors employed in the field. These include:

depth_envelope: ensures that the vehicle does not exceed a maximum depth or climb above a minimum depth, and prevents the vehicle from approaching too close to the bottom.

arctic_depth_envelope: the same as *depth_envelope*, except that instead of preventing the vehicle from approaching the bottom, it keeps the vehicle from colliding with the ice canopy.

detect_collision: monitors the output of the accelerometers to detect a jerk (i.e. the time

derivative of total acceleration) which indicates a collision.

mission_timer: ensures that the vehicle shuts down after expiration of a set time.

acquire_heading: causes the vehicle to turn to a desired heading.

modem_communicate: loads messages for the modem to send indicating the progression of the mission and detection of any failures.

setpoint: commands the vehicle to attain a given heading, depth, and speed for a given length of time.

setvector: commands the vehicle to attain a given heading, pitch, and speed for a given length of time.

waypoint_2d: commands the vehicle to attain a given location in space using long-baseline navigation.

set_rudder: causes the vehicle to set its rudder to a given deflection for a period of time.

survey_dead_reckon: commands the vehicle through a grid survey using dead-reckoning navigation.

survey_with_nav: commands the vehicle through a grid survey using long-base-line navigation.

homing: commands the vehicle to home on an acoustic beacon using the ultrashort-baseline navigation system.

homing_directed: commands the vehicle to home on an acoustic beacon from a particular direction, and to try again if an approach is missed.

deep_homing_directed: the same as *homing_directed*, but also causes the vehicle to approach the beacon on a climbing path, to ensure the vehicle stays deep as long as possible.

race_track: commands the vehicle to alternately home on first one then another acoustic beacon for a given number of cycles.

An important feature of the Odyssey II vehicle control software is the vehicle state structure. This structure contains descriptions and values for sensors and behaviors. It also contains the configuration of the active layered control structure (i.e. the priority and argument values for active behaviors) and the output command structure. The state structure serves a number of important functions: it provides a single global structure which once accessed provides the entire vehicle state to a function or process. It also provides the template for both data logging and data analysis.

Summary of Runs (Winnepesaukee & Arctic)

Lake Winnepesaukee, New Hampshire

Odyssey II was tested extensively under-ice in lake Winnepesaukee in New Hampshire. During five weeks of operations of the vehicle under 18 inches of ice, the following was accomplished:

- The basic vehicle subsystems - power, propulsion, steering, communication, and control - were tested.
- Handling techniques were developed for launching and recovering Odyssey II through the ice.
- The ultra-short baseline navigation system used for acoustic homing behaviors was characterized.
- Several trajectory-generation algorithms for homing the vehicle into the recovery net were

tested. The most promising was implemented in a "missed-approach retry" mode.

- Lost-vehicle strategies for locating and recovering a vehicle away from the ice hole were successfully tested. Acoustic and radio beacons were used to locate the AUV.
- The attitude heading reference system was characterized to evaluate its performance in high-magnetic-inclination environment found in the Arctic.

Beaufort Sea, Arctic

In the Arctic, Odyssey II was repeatedly deployed and recovered through 6' of ice. The AUV performed a series of "out-and-back" missions to demonstrate its ability to home into the recovery net using an ultrashort baseline navigation system. Several trajectory generation algorithms for homing the vehicle into the recovery net were tested and the most promising implemented in a "missed approach-retry" mode. The ultra-short baseline navigation system used for homing was also employed for long-baseline navigation, thus providing a backup navigation system. An ROV was used to observe and document AUV operations under ice. Other activities during Arctic operations included making preliminary maps of the ice canopy along the vehicle track, demonstrating lost-vehicle location and recovery strategies, and demonstrating an attitude heading reference for high magnetic inclination environments. Acoustic communication was demonstrated from the AUV to receivers as far as 10 km away (WHOI collaborators).

Figure 2 shows a 3D vehicle track for one of the Arctic runs. Figure 3 shows the measured profile of the under-ice canopy along that track. The AUV was traveling at approximately 3 knots. The vehicle begins at the origin, and travels out by dead reckoning. When the vehicle turns, the USBL system picks up the transponder in the recovery net and the position is updated (causing the jumps visible in the vehicle track). The portion of the vehicle track extending to the northeast is an artifact of dead-reckoning being continued despite capture of the vehicle in the recovery net.

In addition to the AUV, we deployed a small ROV (a Benthos Mini-Rover) from our ice-tent. Our experience showed the benefits and difficulties of tethered vehicles in the Arctic. We found that the ROV provided an ability to see what was going on beneath six feet of ice which was quite helpful in several stages of the experiment. In addition, we used the ROV to scout the around the ice hole and located ice keels that extended as much as 15 meters below the ice surface. In the process of carrying out this reconnaissance, the tether lodged on a protrusion from the ice keel, clearly demonstrating the hazards of operating tethered vehicles underneath ice. Finally, we note that the limited length of an ROV tether prevents it from providing the 10-km lateral excursion required for the ice mechanics experiment.

Conclusions

The capability described here is the first stage of a larger effort to develop a cost effective means to monitor the Arctic ocean. By addressing the issues fundamental to operation of unmanned underwater vehicles in the Arctic, our intent is to set the groundwork for longer term vehicle operations. Future work will focus on addressing difficulties encountered in the two scheduled tests, and on the development and incorporation of more sophisticated sensor packages for under-ice mapping and water column characterization.

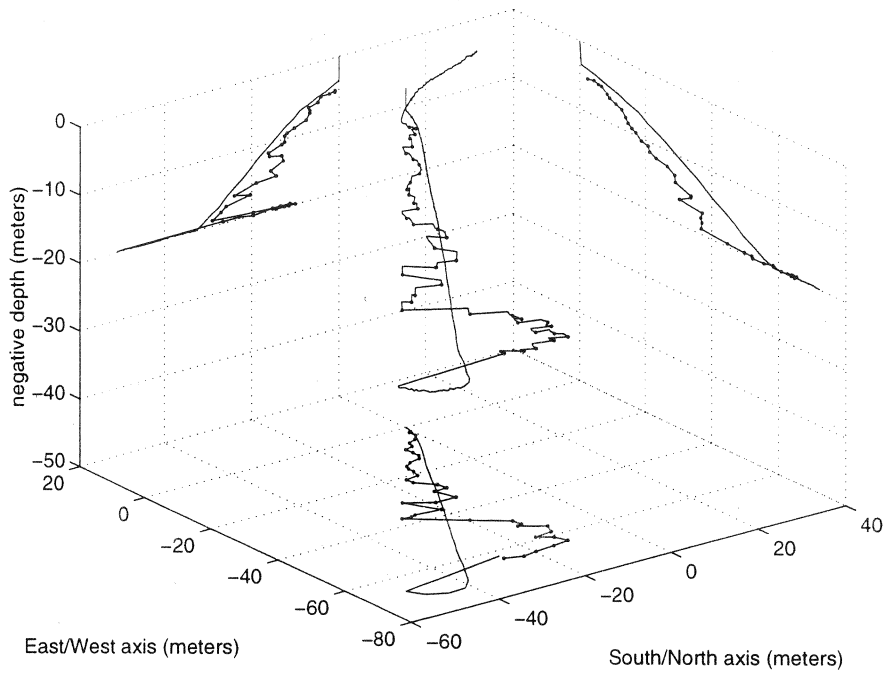


Figure 2: This plot shows Odyssey's trajectory during one of the Arctic runs. The vehicle starts at position (0,0), and proceeds to the southwest while diving down to 20m. On turning, the vehicle acquires the homing beacon, and resets its dead reckoned position. The successive updates cause the jumps visible in the vehicle track. The portion of the vehicle track extending to the northeast is an artifact of dead-reckoning being continued despite capture of the vehicle in the recovery net. The 3D trajectory is also projected on three orthogonal planes to clearly show the extent of the motion along each reference axis.

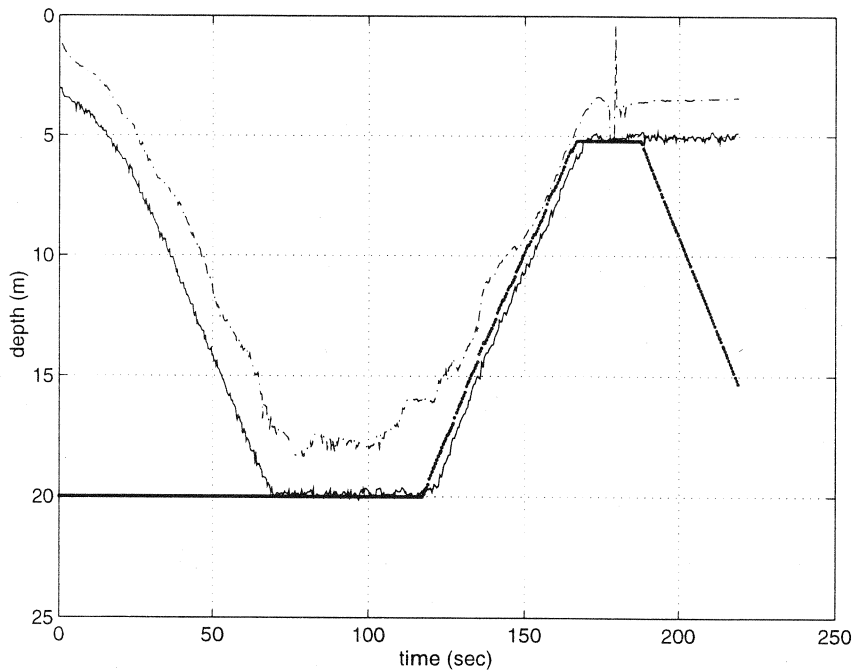


Figure 3. This figure shows a plot of the depth of the Odyssey II vs. time for one of the Arctic runs. The measured depth of the vehicle is shown as a solid line and the commanded depth is shown as a dotted line. The output of the vehicle's upward-looking 200 kHz sonar is shown as a dashed line, giving an indication of variations in the under-ice topography.

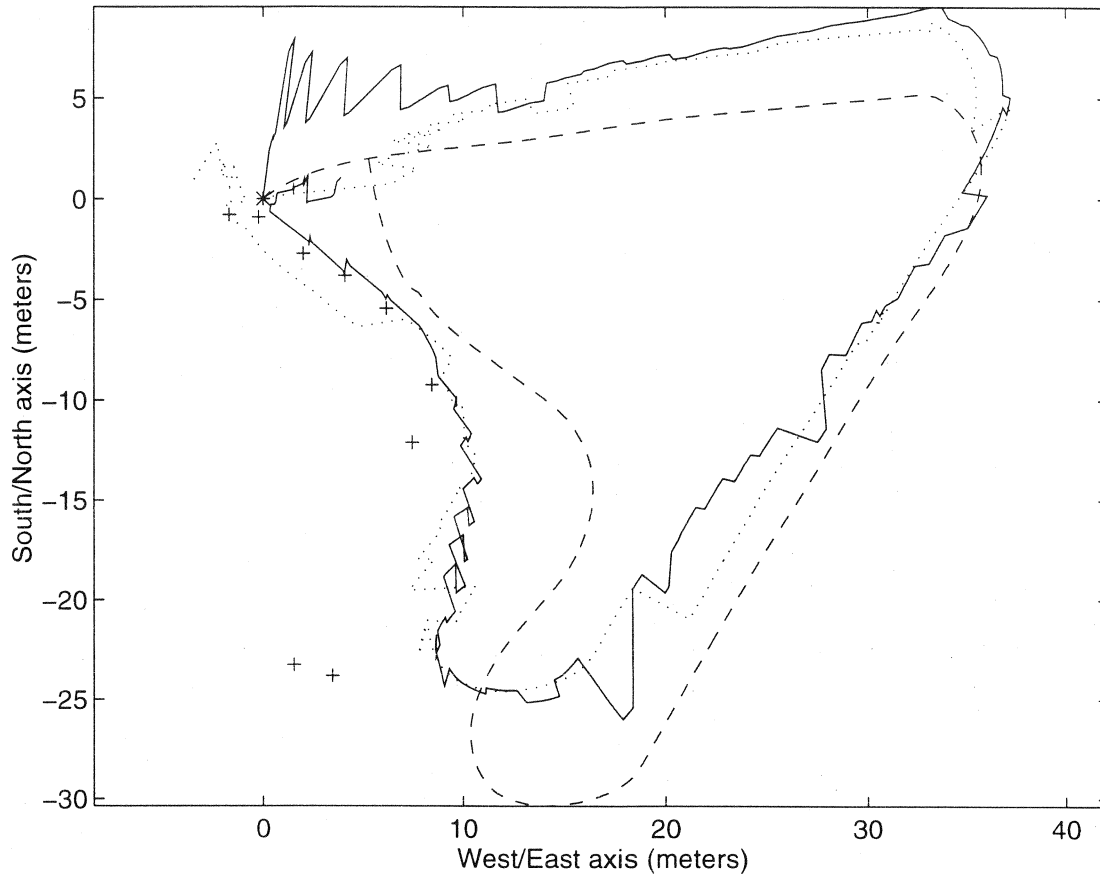


Figure 4: Odyssey is able to compute its position in many different ways thanks to its sensor suite. This plot shows the vehicle trajectory, estimated by four different methods, in one of the many runs executed at lake Winnepesaukee. 1) dashed: dead reckoning. 2) dotted: Two beacons are tracked by the USBL hydrophone located in the vehicle nose. The measured ranges have to pass a validation test before being used to compute a fix which is used to update the dead reckoned position. 3) solid: A Kalman filter uses the ranges to the two beacons, as they arrive, instead of waiting for a couple of ranges. Each new range measurement is used to correct the predicted position (dead reckoning) and improve positioning accuracy. 4) crosses: The range, azimuth and elevation of the homing beacon, measured by the USBL hydrophone, allow computation of the beacon's position in the vehicle frame. Given the orientation of the vehicle measured by its Attitude and Heading Reference System and the beacon's depth, the position of the vehicle can be computed

Acknowledgments

This work was supported by the Office of Naval Research under contract N00014-92-J-1287 and the Massachusetts Institute of Technology Sea Grant College Program under contract NA90AA-D-SG424. This description of vehicle operations was partly extracted from three papers:

- Bellingham, J. G., Goudey, C. A., Consi, T. R., Bales, J. W., Atwood, D. K., Leonard, J. J., and Chryssostomidis, C., "A Second Generation Survey AUV", Proceedings AUV 94, Boston MA, pp 148-155, 1994.
- Bellingham, J. G. and Leonard, J. J., "Task Configuration with Layered Control," Proceedings of Mobile Robots for SubSea Environments, International Advanced Robotics Programme, Monterey CA, pp 193-202, 1994.
- Bellingham, J. G., Deffenbaugh, M., Leonard, J. J., Catipovic, J., and Schmidt, H., "Arctic Under-Ice Survey Operations," 8th Int. Symp. on Unmanned, Untethered Submersible Technology, pp 50-59, 1993.

References

- Bellingham, J. G., Goudey, C. A., Consi, T. R., and Chryssostomidis, C., "A Small Long-Range Autonomous Vehicle for Deep Ocean Exploration," Proceedings of the Second International Offshore and Polar Conference, pp 461-467, 1992.
- Bourke, R. H., and Garrett, R. P., "Sea Ice Thickness Distribution in the Arctic Ocean," Cold Reg. Scie. Technol., Vol. 13, 259, 1987.
- Brady, D., and Catipovic, J., "Robust Multiuser Communication for Underwater Acoustic Channels," Proceedings of the 26th Asilomar Conference on Signals, Systems and Computers, 1992.
- Brooke, J., "ARCS (Autonomous Remotely Controlled Submersible)," Proceedings of the Second International Symposium of Unmanned Untethered Submersible Technology, p 28, 1981.
- Conners, D.N., Levine, E. R., and Shell, R. R., "Morphology of a Multi-year Ice Ridge in the High Arctic", Photogrammetric Engineering and Remote Sensing, Vol. 55, pp. 1123-1128, No. 8, August, 1989.
- Duckworth, G. L. "A Robust Algorithm for Tracking of Drifting Acoustic Arrays in the Arctic." 1987 Asilomar Conference Proceedings, 1987.
- Francois, R. E. and Nodland, W. E., "Unmanned Arctic Research Submersible (UARS) System Development and Test Report," Technical Report No. APL-UW 7219, Applied Physics Laboratory, University of Washington, 1972.
- Fricke, J. R., "Acoustic Scattering from Elastic Ice: A Finite Difference Solution", PhD thesis, M.I.T. Department of Ocean Engineering, 1991.
- Hurdle, B. G. "The Nordic Seas," Springer-Verlag, New York, 1986.
- Leonard, J. J., and Bellingham, J. G., "Directed Sensing Strategies for Feature-Relative Navigation", in "SPIE Sensor Fusion VI", Paul S. Schenker (editor), Boston, MA, September, 1993.
- Light, R., and Morrison, J., "The Autonomous Conductivity-Temperature Vehicle: First in the Seashuttle Family of Autonomous Underwater Vehicles for Scientific Payloads," Proceedings Oceans '89, pp 793-798, 1989.
- Scheer, E., personal communication, 1992.
- Sear, C. B., and Wadhams, P., "Statistical properties of Arctic sea ice morphology derived from sidescan sonar images", Prog. Oceanog. Vol 29, pp. 133-160, 1992.
- Stewart, W. K., personal communication, 1992.

Stojanovic, M., Catipovic, J., and Proakis, J., "Phase Coherent Digital Communications," to appear in the Journal of Oceanic Engineering.

Tonge, A., "An Incremental Approach to AUVs," Proceeding Oceanology International, 1992.

Tritech International Limited, Aberdeen, Scotland, "Commercial offer: ST1000 profiling sonar system; MES200 and MES500 mini-echosounders", 1993.

von der Heydt, K. and Scheer, E., "CEAREX 89 Sensor Localization with STS System." (In preparation).

Wadhams, P., "A Comparison of Sonar and Laser Profiles along Corresponding Tracks in the Arctic Ocean," In "Sea Ice Processes and Models", Pritchard, R. S. (editor), University of Washington Press, Seattle and London, 1980.

Zvonar, Z., Brady, D., and Catipovic, J., "Adaptive Multiuser Receiver for Shallow Water Acoustic Telemetry," submitted to the Journal of Oceanic Engineering, July 1992.