A Second Generation Survey AUV

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Abstract – Odyssey class autonomous underwater vehicles (AUVs) are designed to be small, high performance survey platforms. The logistical complexities of operating off of oceanographic vessels or in hostile environments such as the Arctic make a small vehicle with minimal support requirements extremely attractive. Although built for great depths and endurances of up to two days, Odyssey class vehicles are small by the standards of existing AUVs. This paper describes Odyssey II, the second generation of Odyssey class AUV, and presents the results of under-ice field trials in New Hampshire and the Arctic.

INTRODUCTION

Small AUVs have the potential to provide economic access to the ocean. The primary advantage of small size is the potential for low cost fabrication and operation. In particular, small vehicles can be operated with minimal logistical support from remote sites (e.g. from Arctic ice camps), off ships of opportunity, or in rough seas. Small vehicles can be constructed using a variety of low-cost manufacturing techniques that are not available for larger vehicles. A major consideration in the design of a small size AUV is the trade-off between range and payload capacity. For applications with low-power (10-20 W) payloads, the state-of-the-art is an operational range in excess of 1000 kilometers. Achieving such performance requires a low drag vehicle with efficient propulsion and electronics which consume minimum power. The power constraint is a particular problem for sensor systems. At present relatively few commercial systems are suitable for incorporation in a small AUV, and even fewer are small and low power. Consequently many of the systems on board Odyssey II are custom built at MIT Sea Grant.

One exciting operational scheme for the vehicles described above is afforded by the Autonomous Ocean Sampling Network (AOSN) concept [Curtin, et al. 1994], in which groups of cooperative AUVs operate from network stations to provide a long term, reactive ocean presence. In an AOSN, moored buoys act as power and communication nodes for the vehicles. Reliable AUVs are at the heart of the AOSN, providing the building block for synoptic survey operations as well as the servicing of bottom instrumentation. For use in an AOSN, an AUV must have long-range, high endurance and the ability to carry out autonomous rendezvous and docking with a fixed platform. The last capability is closely related to the rendezvous and recovery problem faced in under ice operations.

There are numerous intermediate applications that act as "stepping-stones" to an AOSN. One such application is to increase the effective search rate of an oceanographic vessel by replacing a single "deep-tow" platform with several AUVs operating simultaneously. Another intermediate application is the semi-independent operation of AUV(s) from an oceanographic vessel. Here the vehicle would be launched and recovered by the ship, but not attended during the mission. We envision this mode of operation as complementary to operations by manned submersible or by ROVs.

Two years ago MIT Sea Grant launched the Odyssey AUV with the primary goal of demonstrating the potential of small, high performance AUVs for survey operations. Only 2.2 meters long, and weighing approximately 120 kilograms, Odyssey was used for grid survey and bottom following video operations. In 1992 and 1993 the vehicle was operated in Nahant Bay, Massachusetts and in the Antarctic [Bellingham, et al., 1993a; Bellingham, et al., 1993b]. The AUV was deployed from surface craft ranging in size from a 22-foot sports-fishing boat to a 208 foot oceanographic vessel. Since then, our laboratory has designed, built, and deployed a successor, Odyssey II, which incorporated the lessons from our experiences with the original Odyssey.

Odyssey II has been configured to satisfy two specific scientific missions: under-ice mapping, and rapid response to volcanic events at mid-ocean ridges. Because the requirements of these two missions are sufficiently similar, the same vehicle can be used for both with only minor changes. Improvements over the original Odyssey include a new structural design, an acoustically transparent fairing, an ultrashort baseline navigation system, increased battery capacity, an upgraded computer, improved software

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development environment, and a variety of new mission sensors. During 1994 Odyssey II has been operated under ice in both Lake Winnipesaukee, New Hampshire and in the Arctic's Beaufort Sea .

Arctic Mission

The development of an Arctic vehicle was driven by the need to measure the topography of the Arctic under-ice canopy [Bellingham et al. 1993c]. This work is in support of an Arctic Sea-Ice Mechanics research program. The AUV provides researchers with a unique capability to respond rapidly to ice events occurring as much as 10 kilometers from a base camp. The vehicle is designed to navigate to the region of interest using a long-baseline navigation system, and to survey the ice topography with a bathymetric side-scan sonar. Once the survey is completed, the AUV will then return to the base camp for retrieval. The AUV uses an acoustic homing system to return to the ice hole, a technique that has been employed previously in the Arctic by other groups [Brooke, 1981; Light and Morrison, 1989].

Deep Survey

The deep survey operations are driven by the desire to use the AUV to respond rapidly to episodic events. Here, the scientific need is to locate and make initial measurements of volcanic eruptions on the Juan de Fuca Ridge, site of the Ridge Observatory Experiment. The scenario envisioned is as follows: First detection of the event is made acoustically with the SOSUS array and the eruption is localized to within approximately a 100 km^2 area (the NOAA Pacific Marine Engineering Laboratory [Embley, 1993] has demonstrated this capability). An AUV is then deployed on a ship of opportunity and delivered to the suspect region for surveys of the water column. As the AUV surveys the region of interest, it telemeters conductivity, temperature, depth (CTD) and water clarity data to the scientists on the surface via an acoustic communications link. Upon the identification of an anomalous region in the water column, the vehicle is commanded over the acoustic link to obtain video or still images of the bottom in the region of potential eruption. This technology allows scientists to respond in an economic manner to eruptions in progress at active spreading centers. In fact, this mission was selected because the scientific needs cannot be satisfied in any other way, as it is not economically feasible to maintain in reserve one of the costly research vessels capable of responding to such events.

BASE VEHICLE

Mechanical Structure

The fairing and internal mechanical structure of Odyssey II are integral, and constructed entirely of polyethylene. This replaces the fiberglass fairing and polyethylene chassis of Odyssey I [Bellingham, et al. 1992]. This modification was made for a number of reasons:

- Fiberglass fairings are relatively expensive to fabricate, and offer minimal economy of scale,
- Fiberglass is rigid and more easily damaged by impacts than plastics,
- The difference in bulk moduli of fiberglass and polyethylene could lead to undue local stresses on the mechanical structure at abyssal pressures,
- Significant weight savings can be achieved using a buoyant plastic.

Criteria for selecting a plastic included the cost of fabrication, as well as its low temperature properties and acoustic transparency. High density polyethylene (HDPE) was chosen as having the best properties, as its glass transition is well below the -40°C encountered in the Arctic. Polyethylene in sea water is also nearly transparent to sound at frequencies up to over 35 kHz which would allow most of the vehicle's six acoustic systems to reside within the hydrodynamic fairing. HDPE has a density of 0.90 allowing conservative design practices with no undue underwater weight penalties. Its properties at full ocean depths are known [Middaugh and Goudey, 1993] and it is easily worked with hand tools.

The mechanical design of the Odyssey II is shown in Figure 1 where the arrangement of upper and lower fairing and the internal "egg carton" pieces are shown. These pieces are identical top and bottom and were vacuum-formed from a 1/4" thick sheet. The four pieces are fastened together to form a rigid structure while allowing full access to the internal pressure spheres, wet wiring, actuators, and the suite of sensors.

The internal arrangement of vehicle subsystems is shown in Figure 2. As with Odyssey I [Bellingham et al., 1992], two 17" glass spheres have been used as the primary pressure housings, the forward one containing the computer and sensor electronics and the rear containing the silver-zinc batteries, the thruster controller, and additional sensor electronics. The spheres nest securely in the egg-carton depressions which serve as the "hard-hat" protection commonly employed when glass buoyancy spheres are used in oceanographic arrays. The sensor and actuator mounts, the tail cone, and propeller hub were all machined from HDPE plate. Added buoyancy aft and fixed lead ballast forward provides even trim for the vehicle. The relative vertical position of these, together with the low center of mass of the batteries, provides passive roll stability.

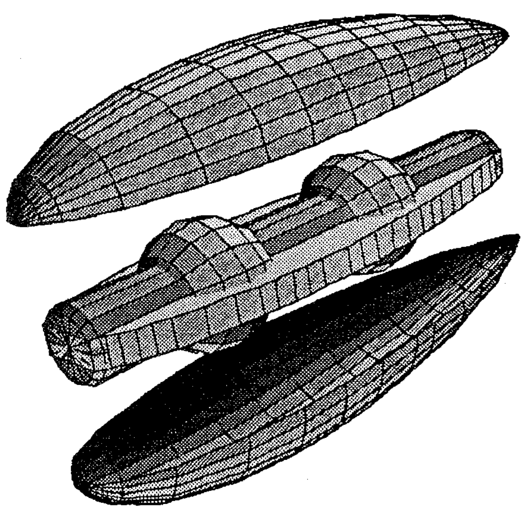

Figure 1: Exploded View of the Odyssey II Mechanical Structure

Electronics

The main vehicle computer is a VME-bus system based on a Motorola 40 MHz 68030 CPU. It includes a math co-processor, 8 MB of RAM, and a 120 MB hard-disk drive. As with previous MIT Sea Grant AUVs, the real-time, multitasking, operating system OS-9 is used. There is an Ethernet link for high-speed data transfer, 10 serial I/O lines, and a multiplexed 100 kHz, 16-bit A/D converter. A number of subsystems (thruster, actuators, CTD, video, etc.) are controlled by dedicated 8-bit microcontrollers (Motorola 68HC11). These smart subsystems communicate with the main computer via a serial network utilizing the SAIL protocol [Bradley and Terry, 1983].

As with Odyssey I, the fin actuators are based on a Woods Hole Oceanographic Institution (WHOI) design [Bradley, 1991], while the thruster was purchased from Benthos [Benthos, Inc.]. A significant change from the original vehicle is the removal of the propeller duct to improve efficiency. The propeller design was optimized using the PLL software package [Goudey, 1991; Coney, 1989] and a commercial product was located that closely matched the optimum design. Another major change from Odyssey I to Odyssey II is the replacement of the oil-filled junction box with a dedicated wet-wiring harness. This was done to increase the overall reliability of the system.

The energy source for Odyssey II is 64 silver-zinc cells [Whittaker-Yardney, model LR-12] arranged in two parallel banks of nominally 48 V each. The total capacity of the battery (at zero Celsius) is approximately 1.1 kW-hr. It weighs 8 kg and is located in the bottom half of the aft sphere. This configuration gives Odyssey II a typical endurance of 6-10 hours at 2-3 knots, depending upon the mission sensors used.

In collaboration with researchers from WHOI, an experimental acoustic modem was mounted in Odyssey II during the Arctic tests. Data was transmitted from the AUV to an array of receivers over distances of up to 10 km. For the Juan de Fuca mission a commercial acoustic modem [Datasonics, model ATM-850] will be used.

VEHICLE SENSORS AND NAVIGATION

Sonar Systems

Obstacle avoidance poses a special problem for torpedo-like vehicles. With only a single thruster, and steering provided by hydrodynamic surfaces, such vehicles can only maintain dynamic control under motion. Odyssey's minimum stable speed is about 0.5 m/sec. Maneuverability of the vehicle is limited, with a turning radius of approximately five meters. Thus the objective of obstacle avoidance is not to stop the vehicle from hitting objects, rather it is to ensure that the vehicle never enters a circumstance which will result in a collision.

The primary threat of collision for a scientific survey vehicle comes from the bottom, or in the case of under ice mapping, from the ice canopy. The vertical extent of typical bottom or ice features would require relatively large horizontal excursions for vehicles to maintain depth. Since typical survey requirements call for vehicle trajectories following a horizontally constrained path (e.g. a grid or a straight line) horizontal maneuvering as a means of obstacle avoidance is both inefficient and counterproductive. Thus a vertical sensor configuration and avoidance strategy has been adopted for Odyssey II, a strategy that is very similar to that described for PTEROA [Suto and Ura, 1993].

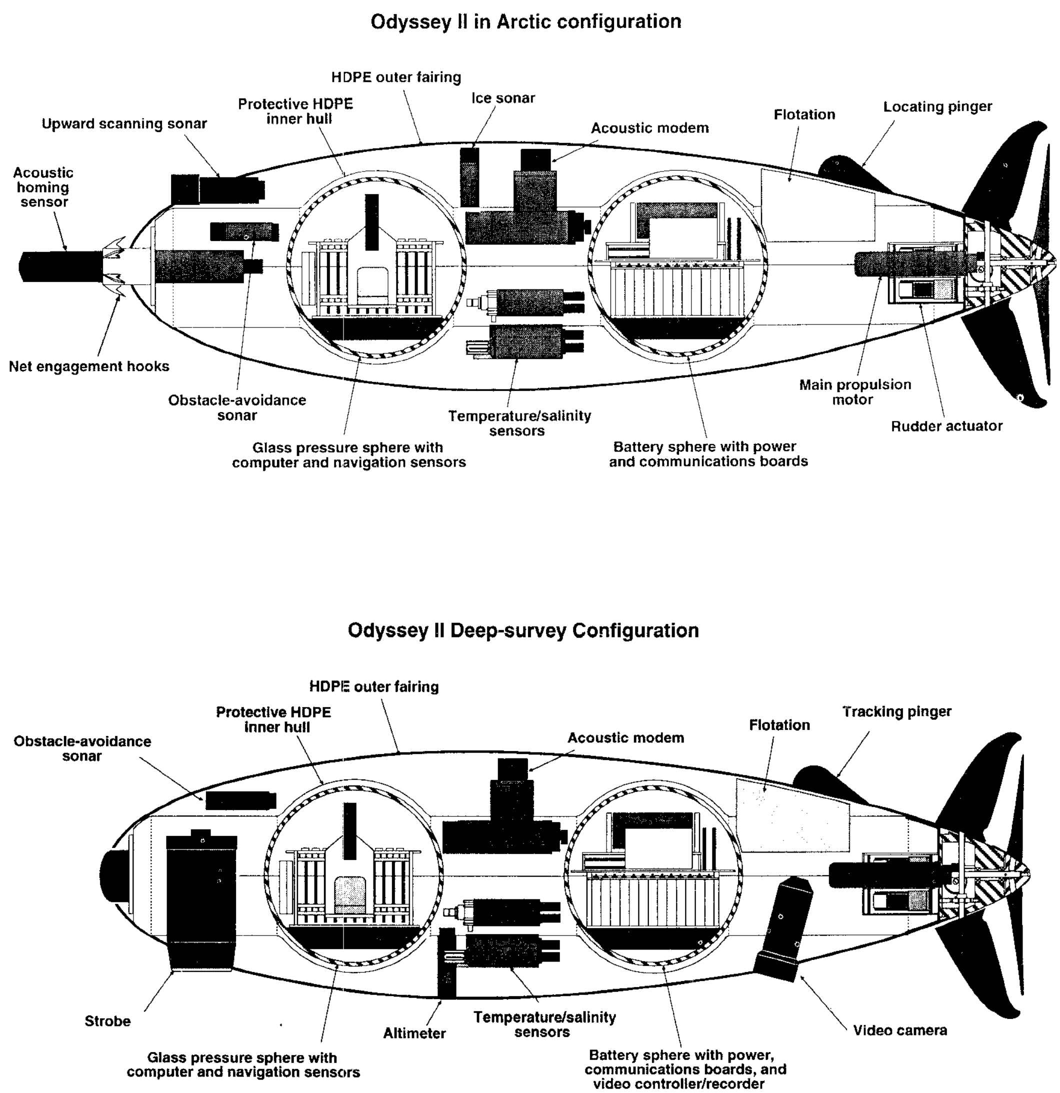

Figure 2: Top, Arctic configuration of Odyssey II. Bottom, Deep-sea configuration of Odyssey II

For the Arctic mission, an upwards-looking altimeter sonar was employed to determine the location of the bottom of the ice-sheet immediately over the vehicle. Two additional sonars, one pointing directly forward, one pointing 30° up from forward, were used for obstacle detection. The upwards looking system operates at 200 kHz, while the other two operate at 500 kHz [Tritech, models MES200 and MES500]. Since the obstacle detection sonars are single beam systems, they will only be used to trigger dive and bank avoidance behaviors, rather than more sophisticated algorithms to plan optimal paths around obstacles. For operations near the bottom, the 500 kHz sonars are mounted to look forward and at a 30 degree depression angle, while the 200 kHz system will look down as an altimeter.

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 not jeopardize recovery chances, as in the terminal phase of the mission the vehicle uses the acoustic homing beacon as the directional reference.

Acoustic Navigation

Three acoustic navigation systems exist which have been (or will be) used on Odyssey II. There is a hyperbolic long-baseline navigation system originally built for Sea Squirt, MIT Sea Grant's first AUV, a low frequency long-baseline navigation system first tested in the Arctic this spring, and a commercial ultra-short baseline navigation system [ORE, model LXT] repackaged to fit in a glass sphere.

In the hyperbolic LBL system, the vehicle determines its position by listening passively to an array of acoustic beacons, one master and two transponders [Bellingham, et al., 1992a]. The system was constructed for the autonomous underwater vehicle, Sea Squirt [DiMassa, 1993] and has been demonstrated in Odyssey I. Using frequencies between 26 and 30 KHz, operation over areas on the order of a square kilometer are possible. A new system operating in the frequencies of 8-12 KHz and using a GPS-based time reference is being developed for operational areas as large as 10 square kilometers.

A more sophisticated multipath navigation system is in development. It is being designed for longer distances where refraction and multipath pose severe problems for range determination since different paths introduce significantly different travel times. By using all the detectable arrivals of each beacon (instead of just the first arrival) the position error can be reduced significantly. While computationally a more challenging problem, multipath navigation may result in accurate position fixes over areas as large as 100 square kilometers. [Deffenbaugh et al., 1993]

To provide the vehicle with a homing capability, a commercial ultrashort baseline (USBL) system has been employed. The components from an ORE LXT system were used to measure both direction and range to acoustic beacons over ranges on the order of two kilometers. Although power consumption of the system is high (40 watts), USBL usage can be limited to the recovery phase. This technique was used in the Arctic with great success, where the control software used the USBL updates to guide Odyssey II back to a capture net suspended below the ice hole. With this system, the vehicle typically returned to within 30 cm of the homing transponder.

Mission Sensors

Standards for conductivity, temperature and depth (CTD) measurements are set by the science requirements. To ensure the scientific utility of the data collected by Odyssey II, we have adopted the stringent standards of the NOAA VENTS program. A typical VENTS cruise uses a Sea Bird Electronics, Inc. CTD package, with one-second averaging on the sensor and an additional ten-second averaging by the top-side data acquisition system. We have mounted a Sea Bird oceanographic thermometer, a Sea Bird conductivity sensor, and a Sea Bird pump [Sea Bird Electronics, models SBE-3, 4, and 5] on Odyssey II. The Paroscientific pressure sensor used by the AUV provides oceanographic accuracy. In addition, we are obtaining a deep-ocean-rated light-scattering sensor [Sea Tech, model LS-6000] for use in the Juan de Fuca mission.

There is significant scientific interest in obtaining visual images of the sea floor at the ocean spreading centers. We are using a sensitive B/W CCD camera [Deep Sea Power and Light, model SC-503] as the imager and recording onto a Hi-8mm camcorder in the aft sphere. A 150 W-s strobe [Photosea-Hydrovision, model 1500SX] provides the necessary lighting. An electronics package synchronizes the camera, camcorder, and strobe, as well as encoding onto the video tape telemetry from the main vehicle computer [Pisces Electronics, model PVP II]. Finally, we are installing two pointing lasers with optical axes parallel to the axis of the camera to provide two spots in the camera field of view for scaling objects in the image [Tusting, 1993].

SOFTWARE

Intelligent Control

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. A list of these includes:

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.

Dynamic Control

The vehicle dynamic controller commands the actuators to achieve a desired vehicle state, as specified by the layered control level. Odyssey II's dynamic controller has been augmented to accept a variety of command modes. For example, control in the vertical plane can be performed by specifying desired depth, pitch, or elevator angle. The dynamic control of the vehicle is achieved with the same algorithms as were used for Odyssey, described in [Perrier and Bellingham, 1992]. Odyssey II is substantially more maneuverable than the original vehicle, primarily because the large stabilizing duct at the stern of Odyssey has been removed. Also, the two vehicle's are commanded differently: Odyssey by voltage control, Odyssey II by current control. Consequently the control parameters for the two vehicles and some minor calculations differ.

RESULTS

Lake Winnipesaukee, New Hampshire

Odyssey II was tested extensively under-ice in lake Winnipesaukee 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.
- An ROV was used to observe and document AUV operations.

Beaufort Sea, Arctic

In March of 1994 five members of our laboratory deployed Odyssey II from an ice-camp in the Beaufort Sea. All operations were carried out in a 15' x 15' tent, enclosing a hydrohole through six feet of ice. Unfortunately, tests were cut short after nine days when the ice flow began to break up, forcing the evacuation of the camp. While at the ice camp, the following was accomplished:

- 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.
- Acoustic communication was demonstrated from the AUV to receivers as far as 10 km away.
- Preliminary maps of the ice canopy along the vehicle track were generated.
- An ROV was used to observe and document AUV operations.

Figure 3 shows a vehicle track (top) and the measured profile of the under-ice canopy along that track (bottom). The AUV was traveling at 2 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
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.

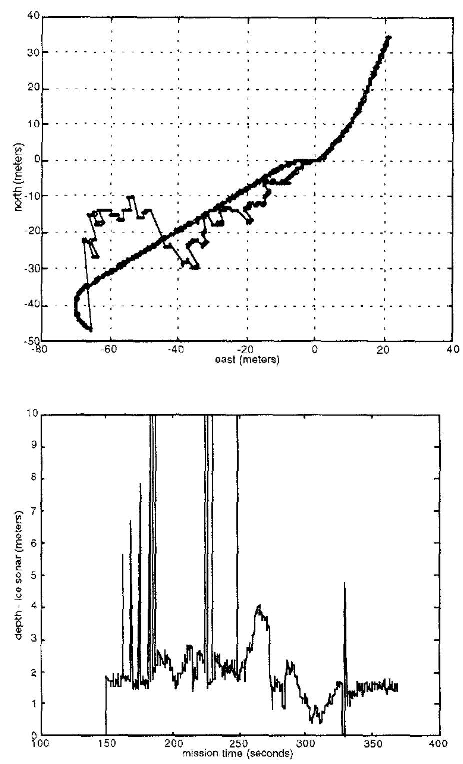

Figure 3: (top) Vehicle track with ultrashort-baseline navigation system updates for a homing mission in the Arctic. The vehicle starts at position (0,0) and proceeds to the southwest. On turning, the vehicle acquires the homing beacon, and the sucessive updates cause the jumps visible in the vehicle 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. (bottom) Difference between vehicle depth and upward-looking sonar for this mission, illustrating variations in the underice topography.

CONCLUSIONS

We have demonstrated that small AUVs such as Odyssey II can be easily deployed and recovered in difficult environments (e.g. Arctic). In addition, we have shown that Odyssey II is a robust base vehicle that can be adapted to a wide range of scientific missions. We envision this vehicle as a key element in the proposed Autonomous Oceanographic Sampling Networks.

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REFERENCES

Bellingham, J.G., Consi, T.R., Tedrow, U., and Di Massa, D., "Hyperbolic Acoustic Navigation for Underwater Vehicles: Implementation and Demonstration," *Proceedings AUV '92*, 1992.

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.

Bellingham, J. G., Bales, J. W., Atwood, D. K., Chryssostomidis, C., Consi, T. R., and Goudey, C. A. "Demonstration of a High-Performance, Low-Cost Autonomous Underwater Vehicle," *20th Annual Symposium of the Association for Unmanned Vehicle Systems*, June 28-30, 1993, Washington, D. C., pp. 1017-1031.

Bellingham, J. G., Bales, J. W., Atwood, D. K., Perrier, M., Goudey, C. A., Consi, T. R., and Chryssostomidis, C. "Performance Characteristics of the Odyssey AUV," *Proc. 8th Int. Symp. Unmanned Untethered Submersible Technology,* Autonomous Undersea Systems Inst., Portsmouth, NH, Doc. 93-9-01, pp. 37-49.

Bellingham, J. G., Deffenbaugh, M., Leonard, J. J., Schmidt, H., Catipovic, J., "Arctic Under-Ice Survey operations," *Proc. 8th Int. Symp. Unmanned Untethered Submersible Technology,* Autonomous Undersea Systems Inst., Portsmouth, NH, Doc. 93-9-01, pp. 50-59, 1993.

Bradley, A. M., and Terry, W.E. Jr. "A Coherent Approach to Instrumentation Intercommunication and Testing Using SAIL," *IEEE Proceedings of the Third Working Symposium on Oceanographic Data Systems,* IEEE, 1983.

Bradley, A., Personal Communications, 1991.

Brooke, J., "ARCS (Autonomous Remotely Controlled Submersible)," *Proceedings of the Second International Symposium of Unmanned Untethered Submersible Technology*, p 28, 1981.

Coney, W. B., "A Method for the Design of a Class of Optimum Marine Propulsors," Ph.D. Thesis, MIT Department of Ocean Engineering, Cambridge, MA, 1989

Curtin, T. B., Bellingham, J. G., Catipovic, J., Webb, D., "Autonomous Oceanographic Sampling Networks," to appear in *Oceanography*, 1994.

Deffenbaugh, M., Bellingham, J. G., and Schmidt, H. "Acoustic Navigation for Arctic Under-Ice AUV Missions," *Proceedings Oceans '93*, Victoria, British Columbia, Canada, 1993.

Di Massa, D., "Navigation of an Autonomous Underwater Vehicle for Shallow Water Operations," *Meeting of the New England Section of The Society of Naval Architects*, 4 February, 1993.

Goudey, C. A., "A Computer-Based Propeller Design Series for Human Powered Submarines," Proceedings of the Marine Technology Society Conference, New Orleans, LA, 1991.

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.

Middaugh, R., and Goudey, C. A., "The Dimensional Change of Polymers Under High Hydrostatic Pressure," *Proceedings Oceans '93*, Victoria, British Columbia, Canada, 1993.

Perrier, M., and Bellingham, J. G., "Control Software for an Autonomous Survey Vehicle," *Proceedings International Advanced Robotics Programme*, Workshop on Underwater Robotics, Genoa, Italy, 1992.

Suto, T. and Ura, T., "Unsupervised Learning System for Vehicle Guidance Constructed with Neural Network," *Proc. 8th Int. Symp. Unmanned Untethered Submersible Technology,* Autonomous Undersea Systems Inst., Portsmouth, NH, Doc. 93-9-01, pp. 222-230, 1993.

Tusting, R., Personal Communications, October, 1993.