NAVIGATION, CONTROL, AND RECOVERY OF THE ENDURANCE UNDER-ICE HOVERING AUV

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August 25, 2009

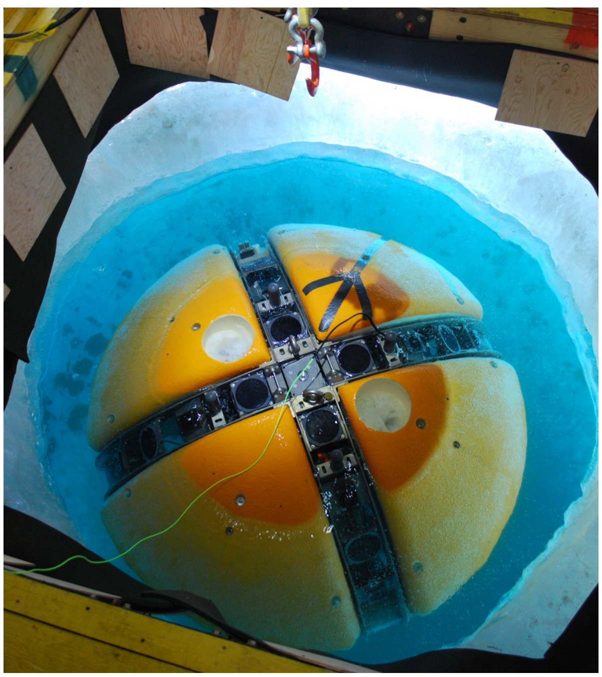


Figure 1: ENDURANCE underwater vehicle being deployed through the ice melt hole in West Lake Bonney, Antarctica.

Abstract

The AUV ENDURANCE was designed to operate in a unique environment: the waters of Lake Bonney in Taylor Valley, one of the Dry Valleys of Antarctica. This lake represents an extreme environment for AUV deployment and operation. The lake waters are permanently covered with an ice layer 3-4 m thick, and exhibit a relatively striking change in composition from the ice roof to the lake bottom, with salinity varying from that of fresh water in contact with the roof down to a sharp halocline at ∼12 m depth, then increasing to 4 times that of seawater at the maximum bottom depth of almost 40 m. ENDURANCE was successfully deployed in the West Lobe of Lake Bonney in the 2008-2009 austral summer, and will return to re-sample the same location in the 2009-2010 season. The ENDURANCE mission goals include traversing the entire ∼1 km × ∼2 km lobe of the lake to obtain a full 3-D synoptic chemical profile, high-resolution mapping of the lake bottom with a multibeam sonar, and close approach for visual and high-resolution sonar examination of the face of the Taylor Glacier at one end of the lake. Thus, to accomplish the science tasks, the vehicle is required to perform larger scale navigation over several kilometers and find its way back home, as well as being capable of fine positioning and control to deploy instruments at points throughout the lake and near the glacier face.

Environmental and logistical constraints at Lake Bonney place demands on the vehicle navigation and control. First, in order to avoid disturbing the deeper water layers, vehicle navigation is confined to the 8 m freshwater lens underneath the ice roof. Second, under-ice operation means that ENDURANCE has to be deployed and recovered through a melt hole only a few tens of centimeters larger in diameter than itself.

Operation in this stratified environment, close to the solid ice surface, presents some difficulties for sonar sensors, including the vehicle DVL and iUSBL. In addition, in order to be able to profile the entire water column while remaining near the ice roof, ENDURANCE incorporates a spooling profiler system. Profiling is performed by deploying an instrument sonde from a cable spool inside the vehicle at nodes on a pre-determined sampling grid. Accurate profiling requires even deploy-

ment of the sonde, without jerking or swaying the cable. In pre-deployment tests, vehicle stationkeeping was refined to be sufficiently smooth and disturbance-free to allow accurate sonde profiling. In the field, an ice-picking technique was developed to maximize the portion of the water column sampled, and to minimize disturbances on the instrument sonde even further.

In order to ensure successful recovery through the melt hole, ENDURANCE has a three-stage return-to-hole strategy. Normal navigation proceeds using a conventional down-looking DVL and an IMU to obtain dead-reckoned position. For recovery, as the vehicle approaches the melt hole, an on-board iUSBL and a transponder hanging under the hole provide relative position updates which are fused with the dead-reckoned navigation. The final approach and up-hole recovery are performed using a visual homing system.

Navigation and control results from vehicle trials in temperate lakes and laboratory tests are presented, along with field results from the 2008 campaign.

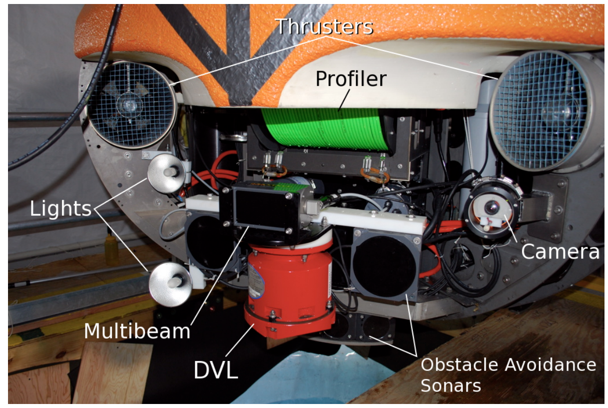


Figure 2: ENDURANCE instruments mounted in the glacier face configuration.

1 Introduction

The ENDURANCE (Environmentally Non-Disturbing Under-ice Robotic ANtarctic Explorer) vehicle is a hovering AUV designed and deployed to map the under-ice environment of West Lake Bonney (WLB) in the McMurdo Dry Valleys of Antarctica [1]. Data of interest gathered by ENDURANCE include sonar bathymetry; the temperature, electrical conductivity, ambient light, turbidity, chlorophyll-a, Dissolved Organic Matter (DOM), pH and redox of the water column throughout the lake; and visible imagery of the lake bottom and the underwater glacier face of Taylor Glacier. ENDURANCE underwent a series of lab and field tests throughout 2008, and was successfully deployed for a 4-week campaign at Lake Bonney in November-December of 2008. The vehicle will be re-deployed at Lake Bonney at the end of 2009 to finish its exploration mission there.

West Lake Bonney presents a unique environment for exploration. The lake has a permanent ice cover that varies in thickness from 2.5 m to 4.5 m. This cover prevents extensive exploration without the use of an underwater vehicle. The lake dimensions are approximately 1 km $\times$ 2 km, with a maximum depth of about 40 m. Under the ice cover lies a freshwater lens which extends down to a sharp halocline at a depth of about 12 m. This halocline marks the top of an ancient, salty body of water which reaches a salinity of about 4 times seawater at its greatest depths. To avoid disturbing the saltwater layers, ENDURANCE is restricted to operating in the thin freshwater layer. Deployment is effected by melting a vertical shaft into the ice cover and lowering the vehicle through the shaft. Recovery must be effected through the same hole. ENDURANCE uses a visual homing system to "dock" with the melt hole once it has navigated back underneath it [2].

1.1 Vehicle description

ENDURANCE is derived from the DepthX vehicle [3], which was designed for subterranean underwater exploration. The basic vehicle geometry is an oblate spheroid of approximately 1.8 m maximum diameter, with four blocks of syntactic foam forming a hemispherical floatation pack to stabilize pitch and roll, and six electric thrusters for direct control of the remaining four degrees of freedom. The vehicle structure and propulsion are symmetric about the vertical axis, providing simple, decoupled horizontal and vertical motion dynamics. Directionality in the vehicle horizontal plane is imposed only by the placement of sensors. For vehicle control purposes, a logical forward direction can be defined, depending on the operation mode and scientific sensor requirements.

Exploration of Lake Bonney presented special challenges requiring changes to the navigation and control systems from the DepthX configuration. In particular, while DepthX relied on a 4π-steradian array of 32 pencil-beam sonar sensors to perform simultaneous localization and mapping (SLAM) in the confines of flooded shafts [4], the Lake Bonney environment was deemed unsuitable for this type of navigation. The lack of physical relief throughout much of the lake, the significant multipath and beam bending issues due to the ice roof and water density profile, and the need for very precise navigation to ensure return to the 2 m diameter deployment melt hole all spoke against using the DepthX sonar-based SLAM for navigation. Instead, ENDURANCE uses DVL/Inertial dead-reckoning augmented with an iUSBL whose transponder is hung underneath the melt hole (see Section 2). The wrap-around sonar array is used for local obstacle avoidance, and a high-resolution multibeam sonar is used for mapping.

Another significant change from the DepthX configuration is the removal of the variable-buoyancy system. The small range of depths available for exploration in Lake Bonney, and the disadvantageous size and complexity of the variable buoyancy system overrode any control advantages that could be realized for ENDURANCE. Removal of this system required improving the depth control of the vehicle to deal with steady-state buoyant forces using the vertical thrusters instead.

1.2 Vehicle operations

Exploration of Lake Bonney with ENDURANCE is divided into three types of missions: water profiling, benthic mapping and glacier face mapping. Water profiling involves transiting between pre-defined points spaced on a 100 m grid, holding station at the points while deploying the water biochemistry instrument package (drop sonde) [5], and returning to the melt hole. Bathymetric and sonde data are also acquired on the transit legs. Benthic mapping requires following a lawnmower pattern at a constant speed, constant heading relative to the vehicle trajectory, and constant depth, while ensuring sufficient overlap of the multibeam sonar swaths. Glacier face mapping requires transiting along constant-depth contours of the glacier wall, while maintaining a standoff distance and illuminating and ensonifying the ice face.

To accomplish these exploration missions, three primary modes of operation were developed corresponding to the mission types: a transit and bathymetric mapping mode, a water profiling mode and a wall mapping mode. In the transit/mapping mode, the vehicle uses a cross-track controller to follow constant-depth, straight-line trajectories and the logical forward direction is controlled to point along the desired trajectory. This mode optimizes vehicle transit stability and allows sensors such as the multibeam sonar and sonde to operate with a constant vehicle heading relative to the vehicle path. In profiling mode, the vehicle holds position and pays out the drop sonde on a line to penetrate the halocline and obtain a profile of the entire water column. In the wall mapping mode, the multibeam sonar is remounted, rotating 90° to face the glacier wall along with a camera and lights. The vehicle then operates using a wall-following controller, orienting the logical forward direction towards the wall and following the wall contour at a constant standoff (see Section 3.3).

Figure 3: GPS fixes of the ENDURANCE profiling locations are obtained by a surface team tracking a magnetic beacon on the vehicle using loop antennas.

2 Navigation

The navigation system of ENDURANCE has been designed to deal with the conditions of the Lake Bonney environment and the requirements of the science missions.

2.1 System requirements

The primary objective of the ENDURANCE navigation system is to enable a sufficiently accurate return to the deployment melt hole that visual homing [2] can reliably find the melt hole egress light. This requires an error of less than 2 m after returning from a 6-hour mission, or approximately 0.1% of distance traveled.

The secondary goal is to provide positioning data for all mapping and profiling sensors accurate enough to form a basis for post-mission mapping and data processing. For this purpose errors on the order of 1 m are ideal, though larger errors could be tolerated at the cost of more post-processing.

The tertiary goal is to guarantee sufficiently precise positioning to avoid known obstacles (cabled instruments hanging from the ice in Lake Bonney approximately 250 m from the melt hole) which could not be reliably sensed by the sonar obstacle avoidance system. For these, errors of less than 5 m are desired. Larger errors can be accommodated by increasing the safety radius around the known obstacles.

2.2 System components

The ENDURANCE navigation system is composed of several standard underwater navigation sensors which together provide measurements of the full 6-DOF pose and velocity vehicle state.

ENDURANCE uses a navigation-grade Honeywell HG2001 ring laser inertial measurement unit (IMU) with orientation drift rates of around 0.05 °/hour. This system goes through a five minute re-alignment at the beginning of every mission to ensure any accumulated drift is zeroed out. The drift and noise on the IMU orientation measurement is small enough over the course of a mission that it is considered negligible in the remainder of the system. This eliminates the need to do non-linear pose estimation.

The orientation and acceleration measurements from the IMU are fused with bottom-relative velocities from a bottom-lock RDI Teledyne Workhorse Navigator 600 Doppler velocity log (DVL). The bottom-relative DVL velocity is rotated into world coordinates using the IMU orientation measurements and combined with IMU accelerations in a linear Kalman filter. This has the advantage of allowing the vehicle to operate for several seconds without DVL lock, relying solely on accelerometer readings. The fused, world-frame velocity is then integrated to arrive at the horizontal components of vehicle position. The vertical component is taken from measurements by two Paroscientific Digiquartz 60 m rated, 6 mm resolution pressure-depth sensors.

The dead-reckoned IMU/DVL position estimate is then aided by measurements from an ultra-short baseline (USBL) acoustic positioning system. ENDURANCE uses a Sonardyne 8094 inverted USBL system to track a transponder hanging from a line at one side of the melt hole. The USBL returns the range and bearing measurements at a low update rate (every 2-5 s). This position measurement is combined in a linear Kalman filter with the dead-reckoned pose estimate to knock out accumulated dead-reckoning drift. Range-only USBL returns are ignored. The error in the USBL measurement is range-proportional, so that this system guarantees progressively better position updates as the vehicle approaches the melt hole during egress.

This on-board navigation is augmented with surface GPS fixes by a team following the vehicle via a magnetic beacon on board the vehicle (see Figure 3). The vehicle can be localized in global coordinates to within ~0.2 m using this system. GPS position measurements are not available in real time and are used for navigation system calibration and as a precise, independent record of the water column profile locations.

2.3 Special considerations

As mentioned in Section 1.1, the Lake Bonney environment posed several challenges to the navigation system. Particular consideration was given to the optimal mounting of the DVL. In an upward-looking orientation, DVL lock on the ice roof would be possible. However, the pre-established vehicle geometry and the need to approach and rest on the ice roof (see Section 4.4.1)—potentially violating the DVL minimum range—both precluded using this orientation. With a downward-looking orientation, however, DVL beams have to traverse the halocline and the significant density changes below it. Analysis of downward-looking orientations showed that DVL navigation should be unaffected by beam bending and speed-of-sound variations as long as the DVL central axis remained vertical so that density variations would be symmetric for all beams. Thus, the DVL was mounted in a straight-down configuration on the vehicle (see Figure 2).

Consideration was also given to the USBL system behavior in Lake Bonney. Reflections of the sonar pings off of the halocline and the ice roof affect the accuracy of the measured position. Fortunately, both surfaces are nearly flat and horizontal, so that horizontal deflection of the USBL beam paths is minimal, and the horizontal position measurement is unaffected. Vertical position measurements are strongly affected (see Figure 9), but are ignored in favor of the pressure-depth measurements.

Placement of the transponder beacon in this environment is also important. The transponder field of view is a full hemisphere. In Lake Bonney, it was found that the optimal USBL configuration is one in which the transponder hangs from the melt hole at a depth just above the halocline, with the hemisphere central axis pointing up. This configuration gives full 360° horizontal coverage of the operational volume and maintains a good view of the vehicle near the ice roof. When the vehicle nears to within 5 m of the melt hole, the transponder and line are retrieved to prevent snagging.

3 Vehicle Control

ENDURANCE is required to perform both long-distance transit and precision hovering and proximity maneuvers. Control modalities were developed to deal with the differing requirements of these operations.

3.1 Control Requirements

The primary objective of vehicle control is to ensure smooth, accurate control in all four controlled degrees of freedom (3D position and yaw). Steady-state errors with respect to measured positions should be less than

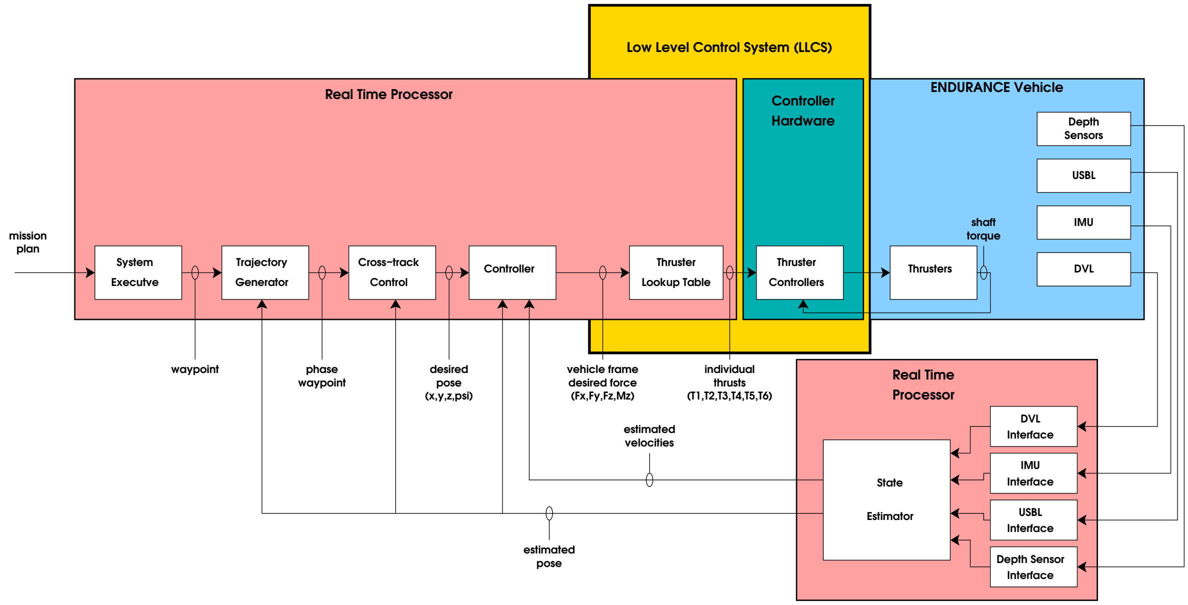


Figure 4: ENDURANCE control system for open-water transit and stationkeeping.

0.1 m horizontal, 0.05 m vertical and less than 2° in yaw for stationkeeping, and 0.5 m/0.25 m/10° for transit at maximum speed. This includes rejecting disturbances such as transient hydrodynamic forces and tether pull.

A secondary objective is to minimize vehicle energy usage over the course of a mission. This requires reducing the integral of the amount of actuator authority applied over time. Another secondary objective is to provide stable depth control during deployment of the drop sonde. This requires variations of less than 0.005 m depth and 0.05 m horizontally during stationkeeping for sonde deployment.

3.2 Control System

Control is applied in various modes depending on the operating conditions and motion objectives. The two primary control modes are open water transit and open water stationkeeping. Additional modes include wall following (see Section 3.3) and visual homing (see [2]).

The basic open water control scheme for ENDURANCE is shown in Figure 4. During stationkeeping, position errors in the world frame are fed directly to the PID controller block. The resulting desired force and yaw moment on the vehicle are then converted into vehicle-relative coordinates, passed through a deadband which smooths out control and reduces energy usage, and converted into individual thruster components by the thruster matrix. This matrix can be changed on the fly in response to sensed thruster outages. The vehicle can still be effectively controlled with up to three of the six thrusters disabled. All control modes include the deadband and thruster matrix components.

For transit to distant goal locations, trajectory-generation and cross-track error components are added to the basic stationkeeping control. In order to provide a consistent depth and heading to science sensors during transit, motion is divided into three phases: the vehicle first dives or ascends to the desired depth while maintaining horizontal position, then turns the logical forward to face the target position, and finally transits along a horizontal line to the target while maintaining heading. During both the descent and transit phases, the cross-track error controller balances motion towards the goal with minimizing deviation from the straight-line path. If, during transit, vertical or yaw deviation from the desired path become too large, the trajectory starts over from the descent phase.

3.3 Wall following

In order to operate in close proximity to walls in its subterranean environment, a wall-detection and wall-following capability was developed for DepthX. This capability has been extended and employed on ENDURANCE for glacier face mapping in West Lake Bonney. The wall-following capability relies on one quadrant of the obstacle-avoidance sonar array. The wall sensors (camera, lights, multibeam sonar) are mounted facing outward from the center of this quadrant, and the logical forward direction is set along the median ray of the quadrant.

In wall-following mode, sonar hit locations from the quadrant's sonars are accumulated in the vehicle local frame. As the vehicle moves, dead-reckoned position changes are used to update the local point collection. The number of points in the collection is limited, so that new sonar hits replace the oldest ones. At every time step, a vertical plane is fit to the local collection of points. The instantaneous desired velocity direction is taken along this plane. Both range and heading error to this plane are calculated, and controlled with PD controllers. Depth is controlled using the pressure depth.

4 Experimental Results

4.1 Test locations

The navigation and control components of ENDURANCE have been tested in a number of field and lab locations. Navigation and control tests were performed at the Hyde Park Quarries Lake (the quarry) in Austin, Texas; the NASA Neutral Buoyancy Lab (NBL) in Houston, Texas; and in West Lake Bonney.

The quarry is a flooded rock quarry containing terrain at a variety of depths and with varying bottom composition (muddy, vegetated and bare rock), including several submerged sheer rock faces. The quarry measures approximately 200 m $\times$ 400 m and has a maximum depth of 12 m.

The NBL is the largest indoor pool in the world, holding 23,500 m^3 of chlorinated water and containing a variety of space vehicle mock-ups used to train astronauts in extra-vehicular activities. The NBL pool has concrete floors and walls and measures 31 m $\times$ 62 m, with a depth of 12 m.

4.2 DVL navigation

DVL navigation was tested extensively during operations at both the quarry and the NBL. While return-to-hole capability was verified during these tests, extensive evaluation of DVL navigation was not possible due to the lack of precise truth measurements at these locations. For the 2008 Lake Bonney campaign, ENDURANCE relied almost entirely on dead reckoning for all navigation tasks. The dead reckoning system proved sufficiently reliable to ensure return to the melt hole in almost all cases.

The error in dead reckoning navigation divides into three primary components: random-walk drift due to noise in the DVL and IMU measurements, a rotation error in global coordinates due to misalignment between the DVL and IMU, and a scale error due primarily to speed-of-sound errors. During the dead-reckoning integration process, measurement noise must naturally also be integrated, resulting in a position drift error which increases with the path length traveled. This error is considered random, and must be accounted for in the estimation process. The scale and rotation errors are systematic and can be eliminated via system calibration. Both systematic errors are zero at the initialization location of the dead reckoning and increase as a function of distance from this point. In the case of ENDURANCE, dead reckoning is initialized at the melt hole, so that the systematic errors do not factor into the return-to-melt-hole reliability.

The vehicle navigation system was calibrated at Lake Bonney using the GPS tracking system. The vehicle was precisely localized via the magnetic beacon while ice picking (generally while performing profiles). Least-squares fitting of the dead-reckoned ice-picking locations and the corresponding GPS measurements was used to find the calibration similarity transform. Due to logistical delays in processing the GPS survey data, operations proceeded without a full calibration of the dead reckoning system. Recoverability of the vehicle was not compromised as the calibration errors do not effect the ability of the vehicle to return to the melt hole. For uncalibrated runs, rotation and scale were applied in post-processing for the purposes of localizing scientific data. Figure 5 shows the measured GPS locations along with the (calibrated) dead-reckoned trajectory.

Drift error was determined by the dead-reckoned position estimate upon egress. Since the egress location is forced to be the same as ingress/initialization by the melt hole, the final position estimate is purely composed of the drift error accumulated during a mission. At Lake Bonney, the dead-reckoning system on ENDURANCE demonstrated a 50% circular error probable (CEP) drift error of about 0.1% of distance traveled (see Figure 6).

Due to its dead-reckoned nature, DVL navigation is subject to large errors if outages occur. On two occasions at Lake Bonney, the DVL minimum range was violated, resulting in DVL outages of sufficient duration to cause large errors in the dead-reckoned pose estimate. In these cases, the vehicle was guided back to a pre-surveyed location using the surface magnetic beacon tracking system, and dead reckoning was re-initialized to the surveyed coordinates. These runs were not included in the navigation system evaluation.

4.3 USBL navigation

Due to a number of logistic and development delays, USBL navigation was not fully integrated into the ENDURANCE navigation and control system in time for the 2008 Lake Bonney campaign. The USBL was used primarily as a backup navigation sensor in case of failure of other systems. However, USBL navigation data

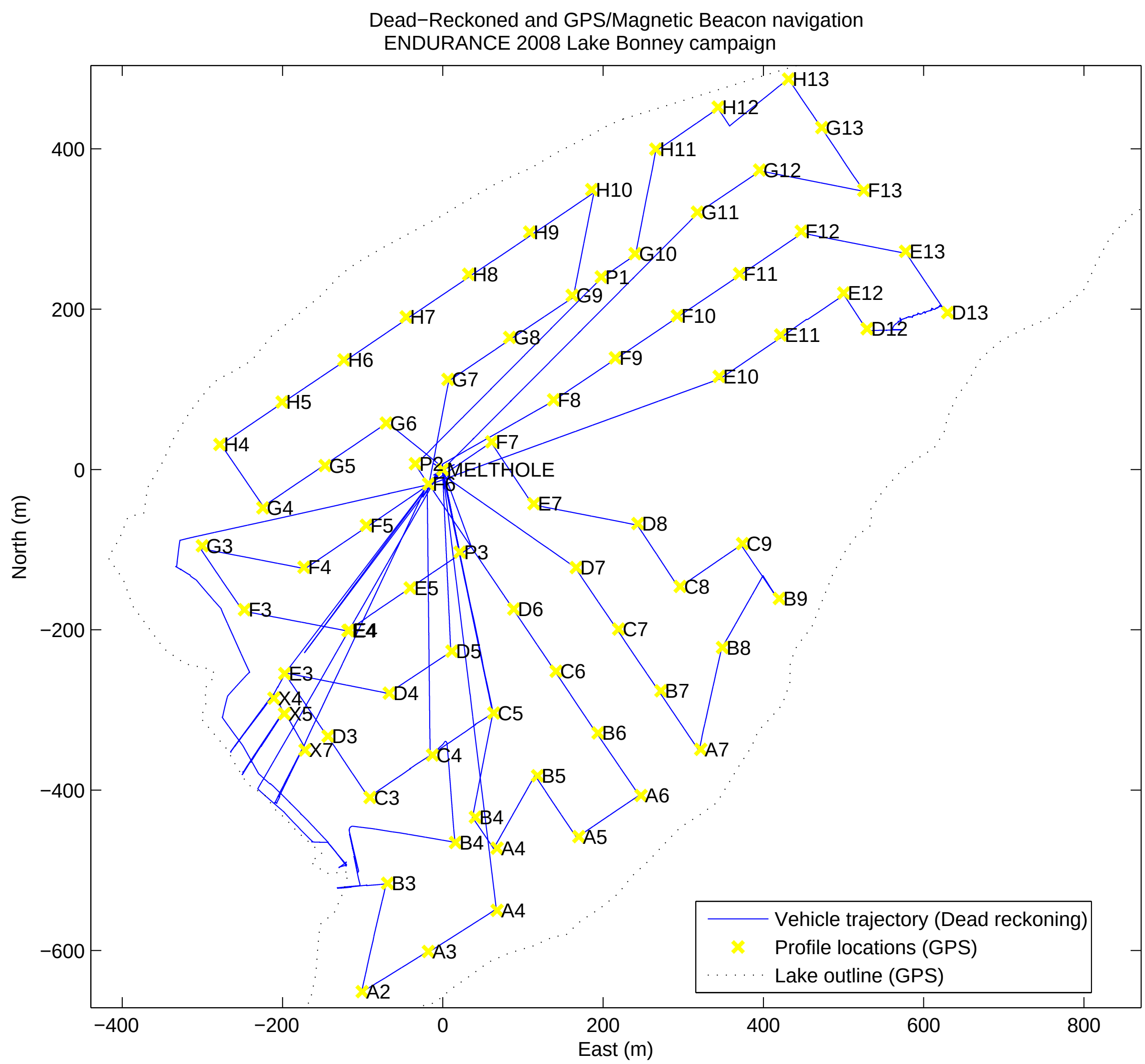


Figure 5: ENDURANCE navigation at Lake Bonney in 2008. Vehicle trajectory is given by DVL/IMU dead-reckoning (calibration applied *post hoc* for initial runs). GPS locations are established by tracking the on-board magnetic beacon from the surface.

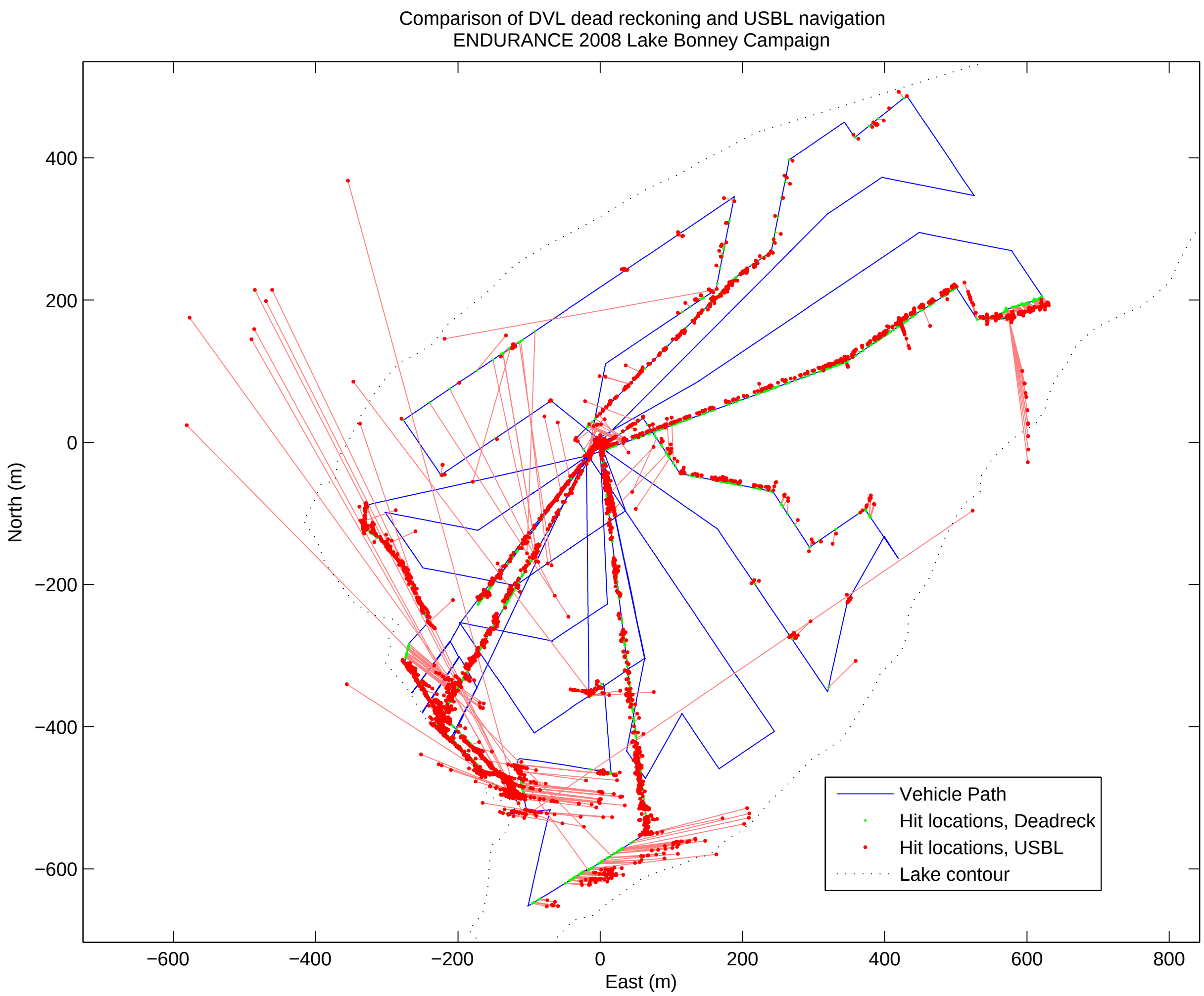


Figure 7: USBL navigation performance at Lake Bonney. Overall performance was satisfactory. USBL position measurements at the lake margins often displayed large errors, though these represent extreme acoustic environments (ice-to-bottom separation of < 7 m, close proximity to glacier ice face and moraines).

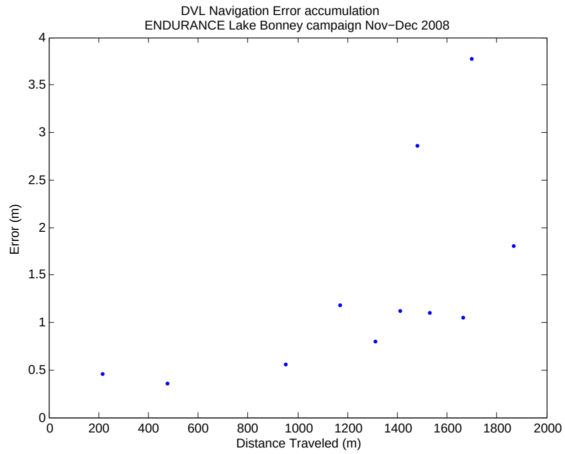


Figure 6: DVL drift errors established upon returns to the melt hole during 2008 Lake Bonney campaign. The resulting empirical 1-σ drift error is 0.13% of distance traveled.

was recorded throughout the campaign and an analysis of USBL performance in the Lake Bonney environment was completed.

USBL navigation performed well throughout the lake and the horizontal position measurement was generally reliable even at the greatest distances from the melt hole achieved in the 2008 campaign (~650 m). USBL performance degraded in shallow water at the lake edges and near the glacier face and accompanying submerged moraine. In these areas, significant offsets were observed depending on vehicle orientation (see Figure 5), most likely due to multipath effects from the nearby surfaces. By comparing USBL position measurements to the GPS-corrected dead-reckoning pose measurements, the error distribution in the USBL can be studied. During operations in Lake Bonney, the USBL achieved a horizontal 50% CEP error distribution of approximately 2.5% of range (see Figure 8).

Vertical errors in the USBL position measurements were of much greater magnitude (see Figure 9), displaying a cone-like distribution over several hundred meters as a result of reflections from the overhead ice at 3 m depth and the underlying strong halocline at about 12 m depth. As this component of USBL position is ignored, these errors do not affect navigation on ENDURANCE.

4.4 Vehicle control

4.4.1 Stationkeeping and ice picking

Water column profiling provided a particular challenge to ENDURANCE vehicle control. Providing a stable platform for the sonde involves maintaining very precise

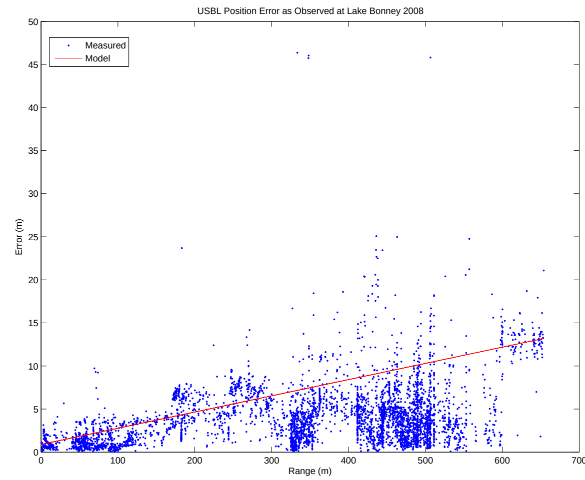


Figure 8: USBL horizontal navigation error as a function of range at Lake Bonney (excluding outliers). The empirical 1-σ error is $0.9\,\mathrm{m} + 0.019 \times \mathrm{range}$.

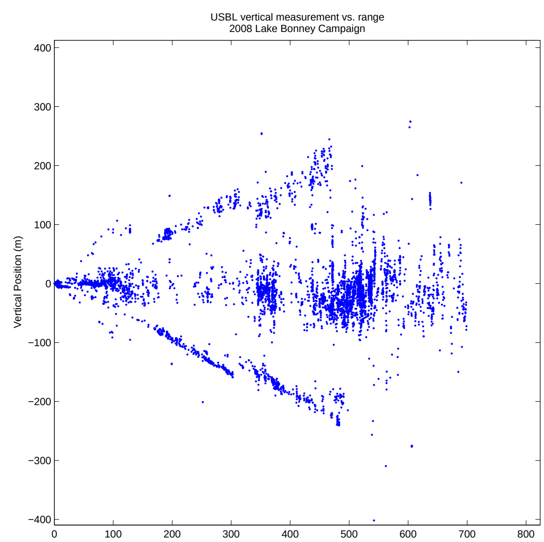
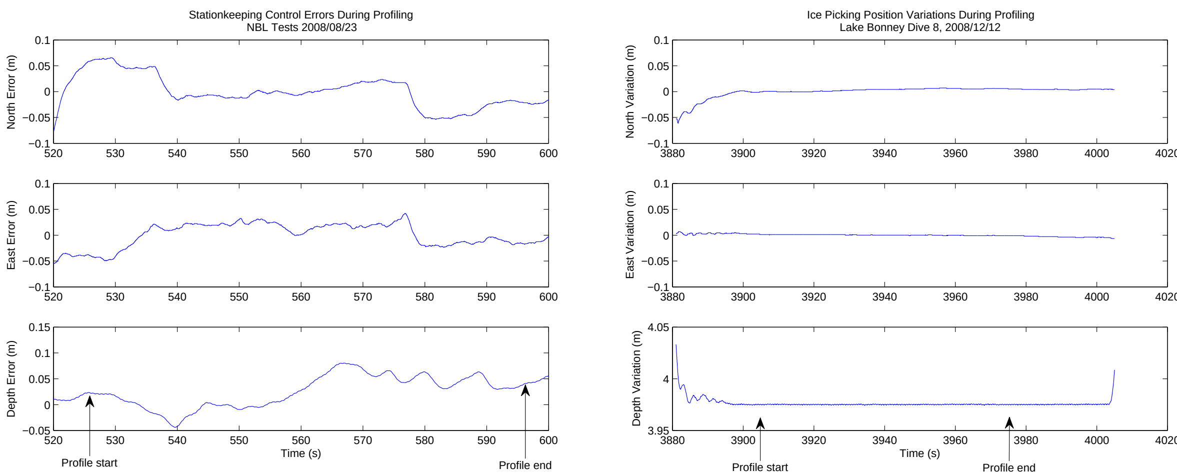


Figure 9: Vertical component of USBL position measurement as a function of range at Lake Bonney. The USBL transponder was deployed at a depth of 8 m, and the vehicle with the transceiver operated between 3.5 m and 8 m. The significantly greater vertical distribution of USBL position measurements is due to the density structure of the Lake Bonney environment.



(a) Stationkeeping

(b) Ice picking

Figure 10: To achieve a stable platform for deploying the drop sonde, an ice picking technique was developed for use at Lake Bonney.

depth (0.005 m) and minimizing horizontal oscillation to prevent swinging the sonde on its line.

During initial testing in the quarry and the NBL, the stationkeeping ability of ENDURANCE was refined (see Figure 10a), but proved unsatisfactory for sonde deployment. Instead, an ice picking technique was developed in the field, taking advantage of the smooth, stable underside of the Lake Bonney ice cover. Use of this technique provides the most stable platform for deploying the drop sonde, and has the additional advantages of minimizing energy usage and maximizing the vertical extent of water column sampling. To perform this technique, the vehicle is equipped with four rounded “feet” sticking a few centimeters above the remainder of the vehicle. The vehicle is ballasted positively buoyant, and transits at a depth approximately 0.5 m underneath the ice roof. When the vehicle reaches a location to be profiled, it stops, stabilizes its horizontal position and then turns off control, floating up until it hits the roof. Once the vehicle has stabilized in this ice picking position, profiling begins. Using this technique, disturbance-free drop sonde deployment was possible (see Figure 10b).

4.4.2 Microbubbles

Due to the presence of the permanent ice cover, the waters of Lake Bonney are supersaturated with dissolved gases. The surface of ENDURANCE moving through these waters provides excellent nucleation sites for the formation of microbubbles from these gases (see Figure 11). Extensive bubble formation on sonar transducer surfaces was mitigated through the use of proper surface

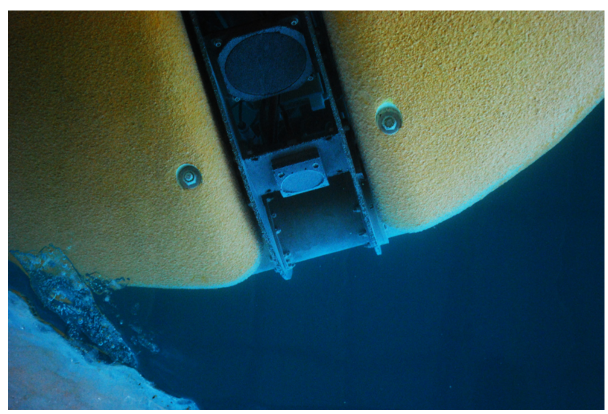


Figure 11: Microbubbles from the supersaturated dissolved gases in the waters of Lake Bonney forming on the surface of ENDURANCE. Significant microbubble formation on transducer surfaces posed challenges for sonar navigation, and buoyancy changes of several pounds throughout a mission due to accumulation of bubbles complicated the performance of ice-picking maneuvers and energy usage calculations.

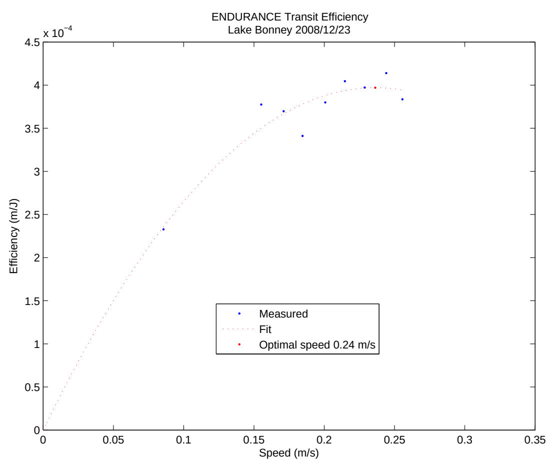


Figure 12: Vehicle transit efficiency from tests performed in Lake Bonney.

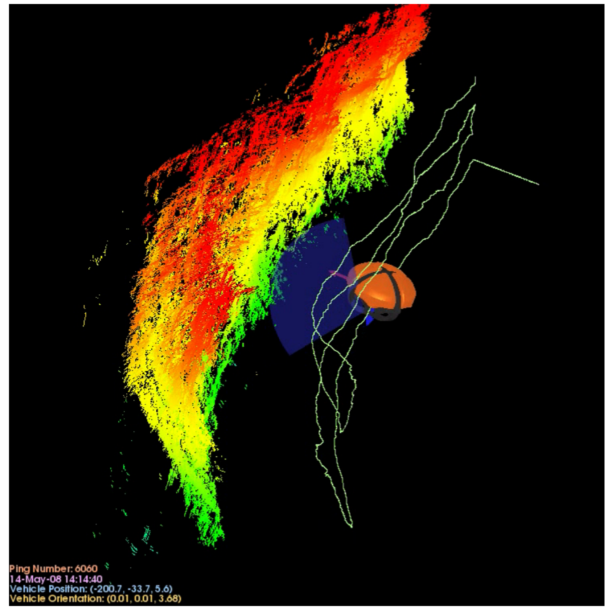


Figure 13: View of wall-following maneuver in the quarry. The vehicle performed a vertical lawnmower pattern along the wall (trajectory in white). The blue fan represents the multibeam sonar, and the sonar hit locations are plotted with color representing depth under water. Total mapped wall extent is approximately 5 m $\times$ 35 m.

treatments (a small amount of silicone grease). However, microbubble formation on all exposed surfaces of the vehicle affected vehicle buoyancy trim to the point that mission duration was compromised due to excessive energy use in the vertical thrusters.

It was found that at the transit depth of 5 m, pressures were high enough to suppress bubble formation. To avoid excessive thruster churning and bubble formation in the shallower melt hole waters during vehicle deployment, the vehicle was launched by placing a dive weight on its upper surface, letting the vehicle sink to the transit depth and then retrieving the weight via an attached line. This technique effectively mitigated bubble formation on ENDURANCE for the Lake Bonney campaign.

4.4.3 Transit efficiency

To maximize mission distance, the transit efficiency of ENDURANCE was tested in the Lake Bonney environment. The vehicle power draw was monitored over a range of velocities at the transit depth (see Figure 12). The resulting efficiency curve suggests an optimal transit speed of around 0.25 m/s for this vehicle configuration.

4.4.4 Wall following

Experimental validation of the wall-following implementation was performed in both the quarry and the NBL. ENDURANCE demonstrated wall-following and multibeam mapping of a 35 m wall in the quarry (see Figure 13).

At Lake Bonney, it was discovered that the submerged portion of the face of the Taylor Glacier contains significant relief in most places, mostly in the form of horizontal shelves several meters deep. Since the wall-following routine assumes a vertical wall, and fits an average plane to the measured wall hits, it was unable to handle the widely varying ranges presented by the shelves and intervening caverns. Only a small portion of the glacier face was navigable with the wall-following behavior, and only at a distance of > 5 m. The use of a local occupancy grid to maintain the sonar hits and a minimum distance plane, rather than an average, may permit operation in more challenging portions of the Taylor Glacier face.

5 Conclusion

The ENDURANCE AUV has demonstrated successful exploration of the unique environment of West Lake Bonney in the Dry Valleys of Antarctica. Lake Bonney presents a highly stratified underwater environment completely covered by ice, presenting unique challenges to the navigation and control of an AUV. The need for a hover-capable vehicle able to successfully explore the entire lake, provide a stable platform for deploying the drop sonde, and conduct proximity operations at the glacier face, while ensuring successful return to the melt hole and dealing with the unique acoustic and physical environment of Lake Bonney, drove the design of the vehicle navigation and control system. ENDURANCE was successfully tested and deployed in Lake Bonney in 2008 and will return for a second campaign in 2009 to finish its data-collection mission in this extreme, remote environment.

6 Acknowledgments

Support for the ENDURANCE project is provided by the NASA ASTEP program. The principal investigator is Peter Doran at the University of Illinois, Chicago. Logistical support in Antarctica is provided by the National Science Foundation through the US Antarctic Program. The authors would like to thank the Center for Limnology at the University of Wisconsin, Madison, the Hyde Park Baptist Church at the Quarries, and the Sonny Carter Training Facility Neutral Buoyancy Lab, and their respective staffs for their enthusiastic support of the ENDURANCE test program.

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