Acoustic Localization of an Autonomous Underwater Vehicle

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1. INTRODUCTION

The trend towards melting of arctic ice has resulted in the prospect of the creation of new shipping lanes, and arguably more important potential access to natural resources beneath the Arctic Ocean. Countries with northern regions have begun the task of collecting bathymetry data to be used in determining their sovereign arctic territory subject to the oversight of the United Nations Convention on the Law of the Sea (UNCLOS). Canada has planned missions to map portions of the Arctic Ocean floor using two Autonomous Underwater Vehicles (AUV). The AUVs will collect data along a 400 km path in the neighborhood of Lomonosov and Alpha ridges at depths between 5 and 6 km.

DRDC Atlantic is assisting with the development of the vehicles and providing support during the deployment and recovery phases of the mission. Initially, once the AUV is released through an ice hole it travels downward along a helical trajectory before arriving at operating depth. At this point it is necessary to perform a localization of the AUV in order to aid in calibration of the inertial navigation unit. In the final phase of the mission a similar localization is needed to guide the AUV to the predetermined position of the recovery hole. In this summary we shall briefly review the approach used to implement the localization and present the findings from data collected during an arctic trial based out of CFS Alert.

2. LOCALIZATION METHOD

The term, localization, refers to an estimate of the position of the AUV with respect to a coordinate system set up on the ice surface. Typically, we choose a three dimensional Cartesian coordinate system with origin corresponding to the deployment/recovery hole. Short range localization is conducted using a network of Teledyne Benthos acoustic modems where one of the modems is contained in the AUV and at least four modems are suspended through holes distributed over the ice surface. In this arrangement, one of the surface modems is placed at the deployment/recovery hole and designated the gateway modem. All network communications are controlled through the gateway modem, and using either a broadcast or polling request we can obtain the time of travel for an acoustic pulse between any two modems. By taking into consideration the sound velocity profile (SVP) we can deduce the range between modems. In particular, let us denote the range from the i^{th} surface modem to the AUV as d_i and the coordinates of the i^{th} surface modem to be (x_i, y_i, z_i). Moreover, setting $\boldsymbol{p} = (x, y, z)$ as the unknown AUV position gives the following nonlinear system of error equations

$$\varepsilon_i = d_i - \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}, \qquad (1)$$

where $i = 1, \ldots, N$ indexes the $N \geq 4$ surface modems and $\varepsilon_i = \varepsilon_i(\boldsymbol{p})$ represents the error associated with the position and range of the i^{th} modem. If the ranges and positions of the surface modems are exact then system (1) will, in general, yield a unique solution when $\varepsilon_i = 0$ for all i. Special cases exist in which degenerate surface modem configurations result in non-unique solutions to (1), these can be avoided by choosing different modem positions or increasing N. However, in practice we seek a solution to (1) that minimizes $\sum_i \varepsilon_i^2$. Let $\tilde{\boldsymbol{p}}_0 = (\tilde{x}_0, \tilde{y}_0, \tilde{z}_0)$ be an initial guess for the AUV position and denote by $\nabla\varepsilon_i$ the Jacobian matrix of ε_i with respect to $\boldsymbol{p} = (x, y, z)$. Applying Newton's method, we linearize (1) to obtain the following iterative system

$$\varepsilon_i(\tilde{\boldsymbol{p}}_{k+1}) = \varepsilon_i(\tilde{\boldsymbol{p}}_k) + \nabla\varepsilon_i(\tilde{\boldsymbol{p}}_k) \cdot \Delta\tilde{\boldsymbol{p}}_k, \quad k \geq 0. \qquad (2)$$

In equation (2) we have defined $\Delta\tilde{\boldsymbol{p}}_k = \tilde{\boldsymbol{p}}_{k+1} - \tilde{\boldsymbol{p}}_k$, thus for each fixed k we impose constraints, $\varepsilon_i(\tilde{\boldsymbol{p}}_{k+1}) = 0$, resulting in an overdetermined linear system for the unknown vector $\Delta\tilde{\boldsymbol{p}}_k$. Since this $N \times 3$ system will generally have no solution we use a singular value decomposition of the matrix $\nabla\varepsilon_i$ to determine a solution with the property that the magnitude of the residual vector, $\varepsilon_i(\tilde{\boldsymbol{p}}_{k+1})$, is minimized. Solving for $\Delta\tilde{\boldsymbol{p}}_k$ then gives $\tilde{\boldsymbol{p}}_{k+1}$. Iterations continue until $\|\varepsilon_i(\tilde{\boldsymbol{p}}_{k+1}) - \varepsilon_i(\tilde{\boldsymbol{p}}_k)\| < \delta\|\varepsilon_i(\tilde{\boldsymbol{p}}_k)\|$ where δ is a sufficiently small positive number. In the applications below we chose to set $\delta = 1 \times 10^{-4}$ and singular values with absolute value less than 1×10^{-2} were set to zero.

Various surface modem configurations were considered in order to simulate deployment and recovery of the AUV. Here we provide two examples from the recovery phase assuming a normal distribution of range noise that is 0.1% of the actual range. Using six surface modems all at the same depth, a coordinate system is chosen such that $z_i = 0$. In addition, one of the modems is always located at the origin. The simulated AUV travels in the $x - z$ plane beginning at $x = 1 \times 10^4$ and $z = -5 \times 10^3$ with subsequent positions having decreasing x and increasing z. In the first configuration, the remaining five modems are positioned on a circle of radius 1000 about the origin starting with $x_1 = 0, y_1 = 1000$ and then placed at $2\pi/5$ angular increments. The second configuration is identical to the first except the circle has radius 100. Graphs in Figure 1 show the results of this simulation, they are arranged so that the first (second) column corresponds to $x, y,$ and z coordinates of the first (second) configuration. The horizontal axis represents samples of AUV positions.

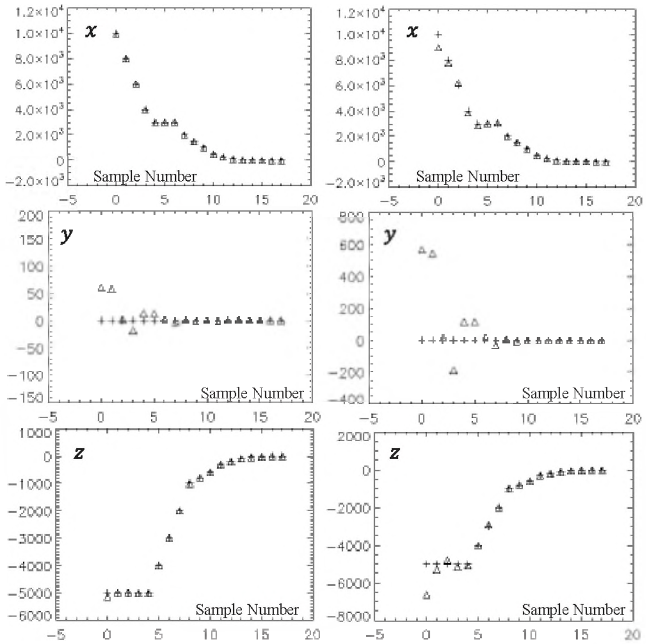

Figure 1. Surface modems at radius 1000 (100) in left (right) column. Actual AUV positions given by + and estimates by Δ

As expected, accuracy in position estimation generally increases as the AUV approaches the field of surface modems. Furthermore, it is evident from Figure 1 that larger configurations result in better accuracy than equivalent smaller configurations. Comparing x and z graphs for each configuration we note that deviations in z are typically larger than in x. This may be attributed to the fact that all modems were placed at the same depth whereas the x coordinates were distributed over a circle.

3. RESULTS OF ARCTIC TRIAL

In the spring of 2009 an arctic trial was conducted on the ice near CFS Alert. One of the objectives was to prove the efficacy of the short range localization method and to reveal any potential problems with its implementation.

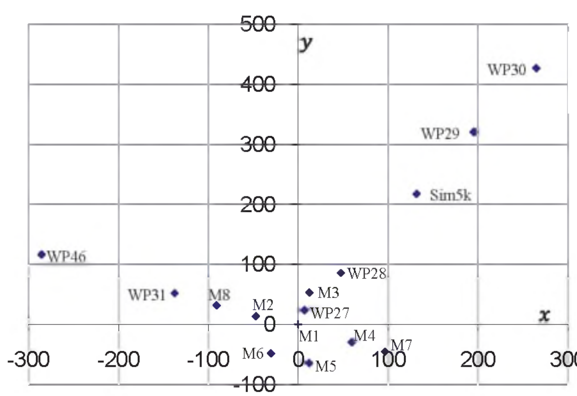

Figure 2. Modem positions labeled M1-M8 along with simulated AUV positions, in meters.

The area over which the experiment was carried out is given in Figure 2; water depth in this region was approximately 100 m. Modems M1 to M8 were used to perform the localization and the remaining waypoints (WPn, Sim5k) were used as simulated AUV positions. Coordinates of all points were measured using a geodimeter, the vertical displacements were all within 8 cm thus deviations in elevation due to ice roughness are negligible. M1 to M8 were lowered to a depth of 50 m, approximately the center of the water column. At each of the remaining seven waypoints another modem, simulating the AUV, was lowered to depths of 10, 30, 50, 70 and 90 m and the time of travel for an acoustic pulse to M1 through M8 was measured. The corresponding ranges were determined by taking a SVP in this region which gave an average sound speed of 1436 m/s with a standard deviation of 2.5 m/s, indicating that ray paths can be regarded as straight given the short distances considered.

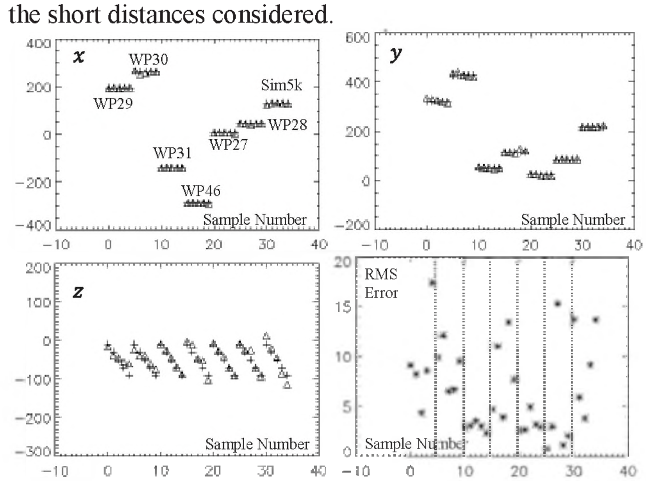

Figure 3. Estimated and actual AUV positions grouped in each graph according to their corresponding waypoints, as well as associated root mean square errors.

It is worth mentioning that at some waypoints and depths a broadcast request resulted in no response from one or two of the modems. In addition, modems that did respond displayed a 10 s delay in returning travel time data. We expect that polling individual modems will reduce this time delay and possibly the number of no responses. The root mean square errors in Figure 3 are all less than 18 m, by considering the ranges of simulated AUV positions and possible multipath effects of shallow water conditions we anticipate that a deeper water environment will give estimation errors less than 5%.

4. CONCLUSION

The singular value decomposition has been used to determine a least squares solution of a system containing errors arising from modem ranges and positions. We have shown that larger spans in x, y, and z of surface modem configurations result in greater accuracy of estimating AUV positions. Arctic trial data supports the feasibility of this method in short range localization.

REFERENCES

Press, W. H. *et al* (1992). Numerical Recipes in C, 2nd ed. Cambridge University Press. Cambridge.