Autonomous Bathymetric Surveying

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Abstract

This paper discusses an initial implementation of sensor performance based survey control using a multibeam bathymetric system. The goal of this work is the automation of survey navigation and sensor control utilizing actual vice predicted response of the survey system. The implemenation of the techniques discussed in this paper utilized the Naval Research Laboratory's ORCA vessel, a semi-autonomous air-breathing submersible vessel. The approaches attempted are discussed and results from the first at-sea test of these techniques are presented. During the at-sea test data from the multibeam bathymetry system was processed and gridded in real-time, and this data was then utilized to generate the next navigation trackline for the defined survey area. Sensor perfomance based control, even with a relatively simple implementation, was seen to compensate extremely well for actual data coverage.

1 Background

The Mapping, Charting and Geodesy Branch of the Naval Research Laboratory at Stennis Space Center, MS. is conducting a multi-year program for the development of unmanned, untethered sensor systems for the collection of tactical oceanographic data in littoral regions. The primary function of this program is the development of immediate survey capabilities for the collection of a variety of oceanographic data. Additional goals include the identification and demonstration of sensor systems compatible with unmanned submersibles and the guidance of future sensor developments. The long term objective of the program is to develop and transition appropriate survey system technologies to autonomous underwater vessels in use by the navy.

The prototype platform currently in use for this project is the ORCA (Oceanographic Remotely Controlled Automaton) vessel [1]. The ORCA is an actively-stabilized, untethered, air-breathing submersible vessel which travels just below the waters surface. ORCA has been fully tested with a Simrad EM-1000 multibeam bathymetry and acoustic imaging system in water up to 1000 meters depth. One of the two prototype vessels has been transitioned to the Naval Oceanographic Office to conduct world-wide bathymetric surveys. The development of a production vessel, the RMS(O), has commenced and delivery is expected in 1998. The RMS (Remote Minehunting System) will be a fleet-integral minehunting system capable of extended missions and will be deployable from naval combatants. The RMS(O) will use the same vessel and support systems but will deploy oceanographic sensors (vice minehunting) in its mid-section. As a bathymetric surveying system, the existing ORCA implementation provides the capability to collect data of the same quality and quantity as a 200+ foot survey ship, but at a fraction of the life-cycle cost. The RMS(O) will additionally provide an advance theater capability to conduct hydrographic and oceanographic surveys.

ORCA provides an interim solution to the bathymetric survey needs of the Navy until fully autonomous vessels advance sufficiently to support this mission cost-effectively. Objectives of using a fully autonomous vessel include reduction of: human operator requirements, dedication of large (high-cost) ship assets and hazard of collision with other vessels. Autonomous vehicles also provide a covert capability, but such missions would represent only a small fraction of the survey hours required for standard survey missions. Since ORCA is air-breathing, its mast allows a direct radio-link for data and control communications, as well as a DGPS system for precise platform positioning. ORCA has thus proven an excellent platform for the development and testing of the technologies required for utilization of fully autonomous systems in oceanographic surveys. A present goal of the program, which is addressed in this paper, is the development and implementation of a rudimentary 'hands-off' survey capability. Bathymetric surveys are the focus since bathymetry is the primary data requirement, and since multi-beam bathymetry systems present some of the greatest constraints on size, weight, power, computational requirements and vessel navigation.

2 Bathymetric Surveys

Multibeam bathymetric surveys offer the advantage of greatly increased area coverage and consequent cost reduction, but introduce significant complexity. The data collected by a multibeam sonar can be affected by several factors including:

- sea state/direction; affects vessel motion and the ability for the system to compensate beam pointing angles

- sound velocity structure; affects the proper location of bottom in the outer beams

- sand waves; can result in destructive interference in the acoustic signals

- bottom composition; affects return strength and subsequent system range

- bottom slope; affects the ability of the system to track the bottom and affects return strength

- bottom morphology; can result in 'blind spots' due to masking of low lying areas

Traditional survey methods typically entail utilizing predetermined tracks and line spacing based on 'best knowledge' of the area to be surveyed and nominal system performance characteristics. Additionally, pre-differential GPS surveys near-shore were usually restricted to straight lines to improve navigational accuracies. Data quality and actual coverage area would be evaluated after the survey since data could not be processed and viewed in real-time. This can result in acceptance of less than adequate data, or where data quality is imperative, in additional survey cost.

In recent years, bathymetric systems technology has advanced sufficiently to allow real-time processing and generation of geo-rectified area coverages with wide-swath multibeam systems. The area coverage allows inter-swath as well as intra-swath quality checks by direct comparison of multiple soundings within the same grid cells. This real-time processing enables on-scene quality control of the data collected and altering of survey parameters to compensate for actual, vice predicted, system performance. This capability has clearly demonstrated a reduction in survey-hours with dramatic improvement in data quality.

While technology has dramatically improved survey efficiency and data quality, the state-of-the-art in bathymetric surveying is still very much 'human-in-the-loop'. The ORCA requires a full-time pilot for vessel navigation, and an experienced hydrographer with extensive sensor system specific training for the operation of the systems and the generation of navigation waypoints. Successful deployment of autonomous survey systems, without retreating to driving pre-determined track lines, will require an abundance of data processing and analysis to be performed on-board the vessel. Real-time quality control of the data is perhaps even more critical for a fully autonomous system since a future system would be expected to operate independently for days without human operator intervention.

3 Survey Automation

An autonomous bathymetric survey requires the following elements to be performed in real-time:

- acquisition and storage of raw sensor data from the bathymetric sonar, position, heading, attitude and surface sound velocity systems.
- low-level rejection of invalid data due to errors in any of the individual sensors.
- geo-rectification of the sonar data using the supporting sensor systems.
- gridding of the data including intra-swath quality assessment and bad data rejection using multiple points within a grid cell.

- generation of a full 2 dimensional area coverage allowing inter-swath data quality assessment by comparing overlapping grid cells.
- data quality assessment for the adjustment of sensor system parameters.
- data coverage assessment for the generation of next-line navigation waypoints.
- acoustic telemetry of compressed gridded data to a human operator for data quality validation.

Real-time acquisition, low-level data validation, geo-rectification, and gridding of the data are prerequisite to the generation of a full-area (vice individual swath or waterfall display) presentation of the data collected. The ORCA system presently performs these steps and utilizes a real-time coverage map that displays the collected data for the entire area being surveyed. This display is used by the hydrographer to visually assess the quality of the collected data and to determine actual, vice predicted, coverage of the sensor system. This allows the operator to adjust system operating parameters to compensate for ambient conditions and to determine subsequent navigation waypoints as a function of a specified survey criteria. In addition to ensuring that the survey mission's goals are being adequately met, the real-time coverage map provides the capability for the operator to observe unexpected features in real-time and to alter mission objectives based on the observed data.

The immediate goal of this effort is to automate the data quality and coverage assessment processes, the generation of navigation waypoints, and the adjustment of sensor system operating parameters. In essence it is desired to control the survey based on analysis of the actual data collected vice on predicted system performance. Recent examples of data dependent survey control include [2] which addresses environment dependent navigation, utilizing a terrain-covering algorithm designed to allow gapless mosaicing of imagery, [3] and [4] which address gradient following approaches to find maxima and minima of sampled scalar data fields, and [5] which proposes a two pass approach consisting of first obtaining low resolution data of a region and then analyzing this data to determine the paths necessary to fill in any additional detail (or holidays) as required.

The functions of data quality and coverage assessment, generation of navigation waypoints and adjustment of sensor system operating parameters presently require near full-time attention of a human operator with extensive system specific training. Our objective is a capability to specify a geographic area to be surveyed, and to have the system automatically adjust sensor parameters and conduct vessel navigation for a specified set of survey constraints. Initial constraints will be fairly straightforward, consisting primarily of the amount of data overlap required between adjacent survey lines. More complicated constraints that are introduced in bathymetric surveys include number of pings in a grid cell, course restrictions due to sea-state, bottom contours, acoustic interference due to sand waves, surface and subsurface obstacles.

4 Approach

For this first attempt at survey automation a simple criteria of 'percent coverage' (PC) was used:

$$PC = 100 * [100/(100 - PO)] \tag{1}$$

where PO is ‘percent overlap’ between adjacent swaths, given by:

$$
\begin{aligned}
PO &= 100 * \mathrm{overlap/swath\text{-}width} \qquad (2)\\
&= 100 * (\mathrm{d1} - \mathrm{d2})/(\mathrm{d1} * 2)
\end{aligned}
$$

d1 and d2 are defined as follows:

- d1 - the distance from the vessel location to the (trailing) edge of the swath. This is the half-swath distance.
- d2 - the distance from the vessel location to the edge of the previous swath’s data. d2 is negative if it is in the opposite direction of d1, i.e. if the vessel location is inside the previous data.

The total swath width is thus given by (d1 $*$ 2) and the overlap is given by (d1 $-$ d2). d1 and d2 are used to compute that actual PO and PC acheived between swaths.

The position of the next trackline is determined by applying a spacing multiplier, m, to the line fit through the current swath’s edge. PO and PC are also a function of m and are given by:

$$PO = 100 * (2 - m)/2 \qquad (3)$$

$$PC = 100 * 2/m \qquad (4)$$

Equations (3) and (4) are valid for $m \geq 0$. The following examples (flat bottom assumed) are provided for clarification:

- For $m = 0$ there is no shift, the next trackline is the same as the current trackline. This gives 100% overlap and infinite coverage since all subsequent tracklines are the same.

- For $m = 1$ the next trackline is over the line fit to the current swath's edge. This gives 50% overlap and 200% coverage.

- For $m = 2$ the edges of adjacent swaths are aligned. This gives 0% overlap and 100% coverage.

- For $m = 4$ every other swath is skipped. This gives an overlap of -100% and a coverage of 50%.

Overlap of adjacent swath's is desired to allow inter-swath data consistency checks to ensure proper system operation. Overlap for the outer beams is the most critical since this is where errors typically first appear in a multibeam system. This is especially important for long track lines where time-varying conditions such as tide and sound velocity structure can change significantly. Conversely, excessive overlap results in less than optimum utilization of survey assets since more time is spent than necessary to cover a specified area.

The processing steps required to generate the next trackline based on the swath's edge of the current line are: find the points representing the leading edge of the current swath from the gridded data (the leading edge is the edge in the direction of the next survey line), crop the current swath data to remove points outside the survey area bounding polygon and perform the next line generation algorithm. Three algorithms were attempted: (1) Straight line (SL) fit, (2) Linear regression (LR) fit and (3) Piecewise Linear (PL) fit.

The edge of the current swath is detected by selecting all of the northern, southern, eastern or western most points from the gridded swath file. Once the required edge is obtained, this data is cropped to exclude irrelevant data lying outside of the survey bounds. Cropping is performed using the algorithm for convex polygons given in [6]. Once the leading edge of the swath is obtained and cropped, the next line is generated by performing one of the three fit methods indicated.

The SL approach finds the best fit (least squares) line to the current swath's edge with the restriction that the fit is parallel to the current trackline. This method provides the least flexibility in compensation of survey tracks for actual bottom morphology, but is the simplest approach with respect to navigational safety since all tracklines are parallel. It is anticipated that this approach will result in periods of excessive overlap as well as periods of insufficient overlap when traversing across bathymetry contours. Excessive overlap results in wasted survey time and insufficient overlap results can result in data holidays (gaps).

The LR approach finds the best straight line fit (least squares) to the edge of the current swath with no restrictions on its orientation. This approach allows better utilization of the survey platform's time since the next trackline will be parallel to the current swath's edge. LR also provides a simple navigation approach since all tracklines are still straight lines. The position of the next trackline is determined by applying the multiple factor to the calculated average half-swath width of the current survey line.

The PL approach provides a computationally inexpensive way to approximately follow the "curves" along the edge of a swath. It applies a least squares linear regression to a portion of the data, anchors one end of the linear regression line to be generated for the next portion, and then repeats the process. It uses one of the survey boundaries as a starting point and proceeds until it reaches the other survey boundary. This algorithm is tunable on the parameters of the look ahead distance and distance to keep. It utilizes a look ahead to reduce drastic changes in direction from one step to the next. For example, we might generate the linear regression line over a distance of 300 meters and keep only the first 200 meters of the linear regression line. The endpoint of the kept 200 meters becomes the anchor for the next linear regression line to be generated. This algorithm provides a way to model the general curve of the data while damping out small variations in the data. For sufficiently short segments this approach provides optimum use of the platform by allowing close adherence to the specified percent coverage. However, short segments can result in frequent changes of survey vessel heading which poses a safety of navigation problem.

5 Results

Figure 1 illustrates the survey area for the first at-sea testing. The mesh interval is 25 meters, the vertical exaggeration is 18, and the coordinates are UTM. This area, about 20 nautical miles south of Pensacola Beach, Florida, is an outcropping of pleistocene beach rock and carboniate cemented sandstone [7] with notable features providing outstanding morphology for these tests. Near the northern edge of the region is a nearly vertical 5 meter cliff, and in the center of the region is a steep grade that drops 30 meters over a 750 meter span. Both of these features extend nearly linearly for several nautical miles.

Initial tests during the 19-25MAY97 sea trial were executed with the SL and LR approaches and survey lines were executed with two different trackline orientations: along the contours and across the contours. For trackline orientations along the contours (which were nearly

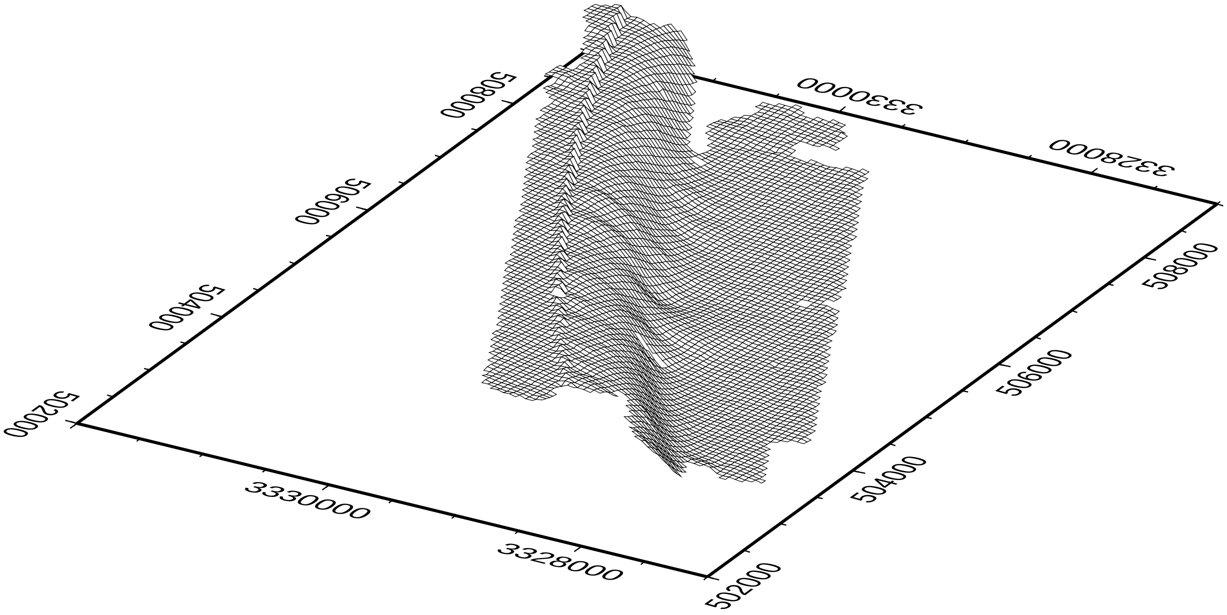

Figure 1: Santa Rosa Ridge Bathymetery

linear in this region) both the SL and LR algorithms performed as expected; the resulting next tracklines were all nearly parallel. Figure 2 shows the results of LR along the contours. The figure shows the swath edges that resulted from running the LR generated tracklines and their respective next tracklines. The trackline spacing was specified as $m = 1.2$ times the half-width of the current swath's leading edge. A problem that could occur with a contour following approach, particularly in high slope areas, is that the results are orientation (down-slope or up-slope) dependent. If the survey is progressing downslope, then the next swaths will tend to be wider than the current swath. Since the line spacing estimation is based on the current swath, a down slope progression will necessarily result in lines that are more closely spaced than the specified percent coverage would dictate. Conversely, an up-slope progression will result in line spacing that is greater than specified. This bias is reduced by making the current swath width estimation based upon the distance between the current track line and the swath edge (half-width) towards the direction of the survey

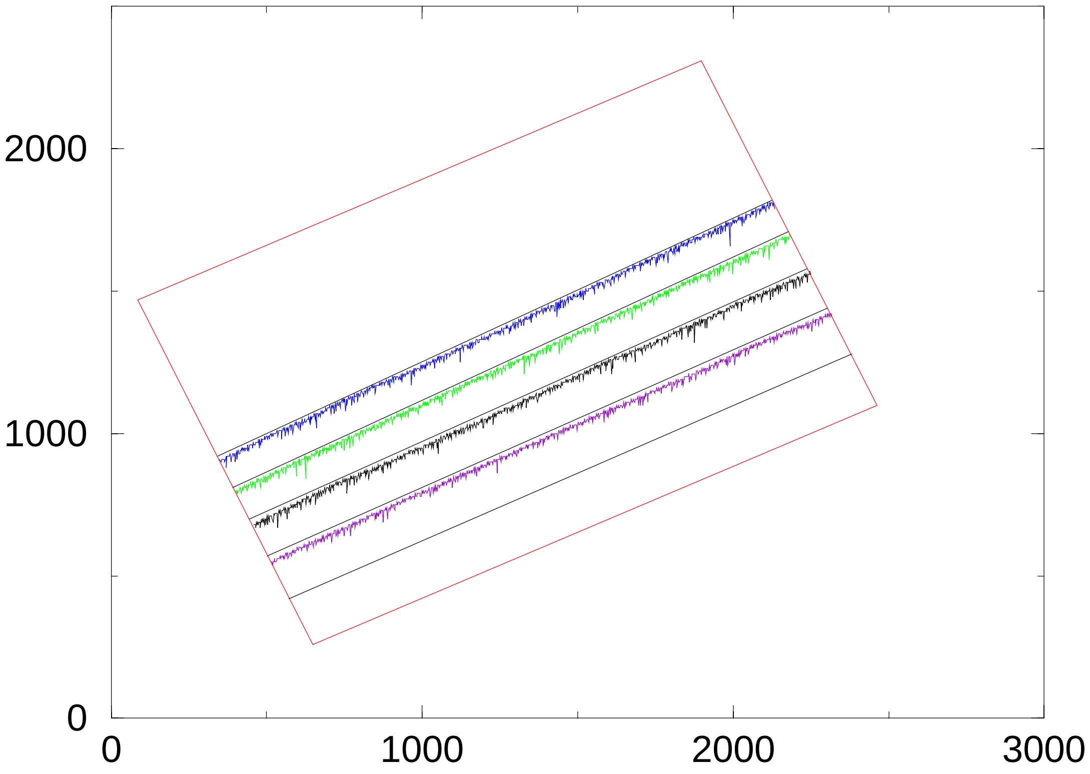

Figure 2: Linear Regression Method, Along Contours

progression vice using the entire swath width of the current line.

Figure 3 shows the results for the SL approach going across the contours with a spacing of $m = 1.2$ times the swath half-width. The figure shows the swath edges that resulted from running the SL generated tracklines, and shows the line fit to each swath edge. As anticipated, gaps and excessive overlaps occured between swaths since the next trackline is forced to be parallel to the current line. With the rapid change in depth along the trackline and subsequent change in swath width, the best fit line results in inadequate coverage at the shallow end and excessive coverage at the deep end. In contrast with Fig. 2 it is observed that the swath's edge is much more ragged going across the contours than along the contours. This is an expected outcome, particularly for the outer beams, since the bathymetry system will have difficulty tracking bottom with a rapid change in depth along track. The line fit

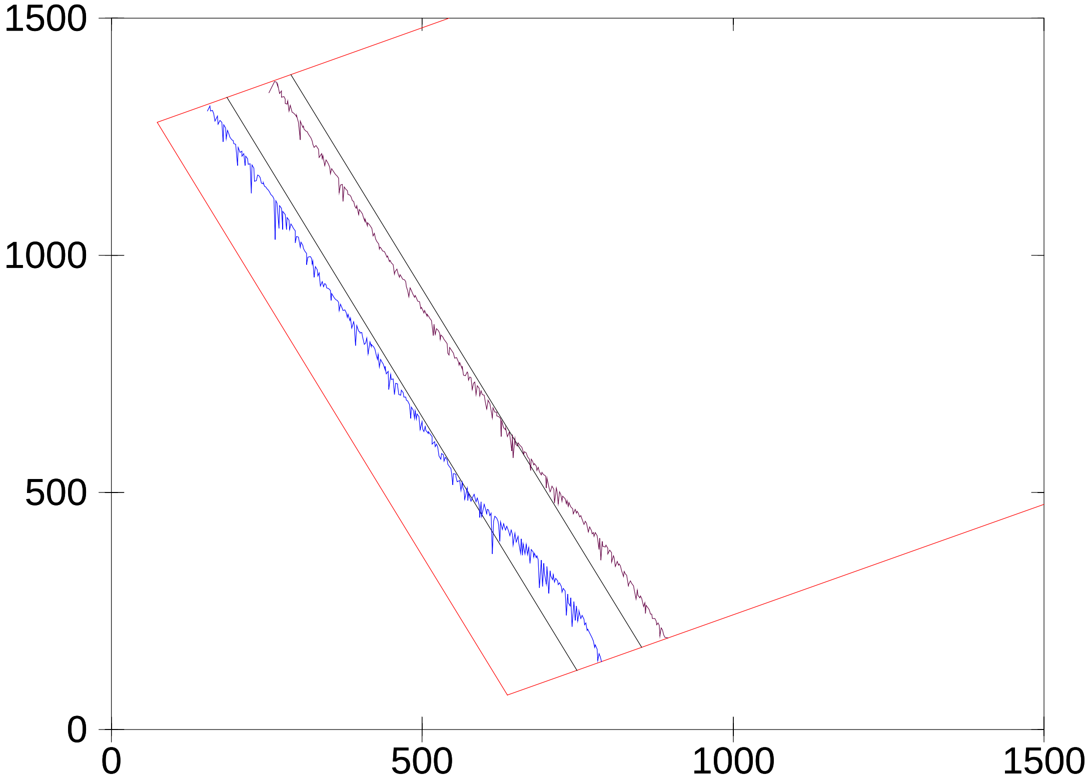

Figure 3: Straight Line Method, Across Contours

to the swath's edge data helps to compensate for this 'loss' of data since the line is biased towards the current trackline by the missing data in the outer sonar beams. For this data set the line is shifted inward by 4% of the swath's half-width (mean average width was 124 meters) due to the missing data. This case provides an excellent example where the algorithm correctly compensates for actual vice predicted system performance.

Figure 4 shows the results for the LR approach going across the contours with a spacing of 1.2 times the swath half-width. The figure shows the swath edges that resulted from running the LR generated tracklines and their respective next tracklines. The lines clearly display the tendency for this approach to skew the lines as a result of increasing depth along the track. With each consecutive trackline the orientation tends more towards the direction of the contour. The PL algorithm was not tested during this sea-trial, but post-analysis

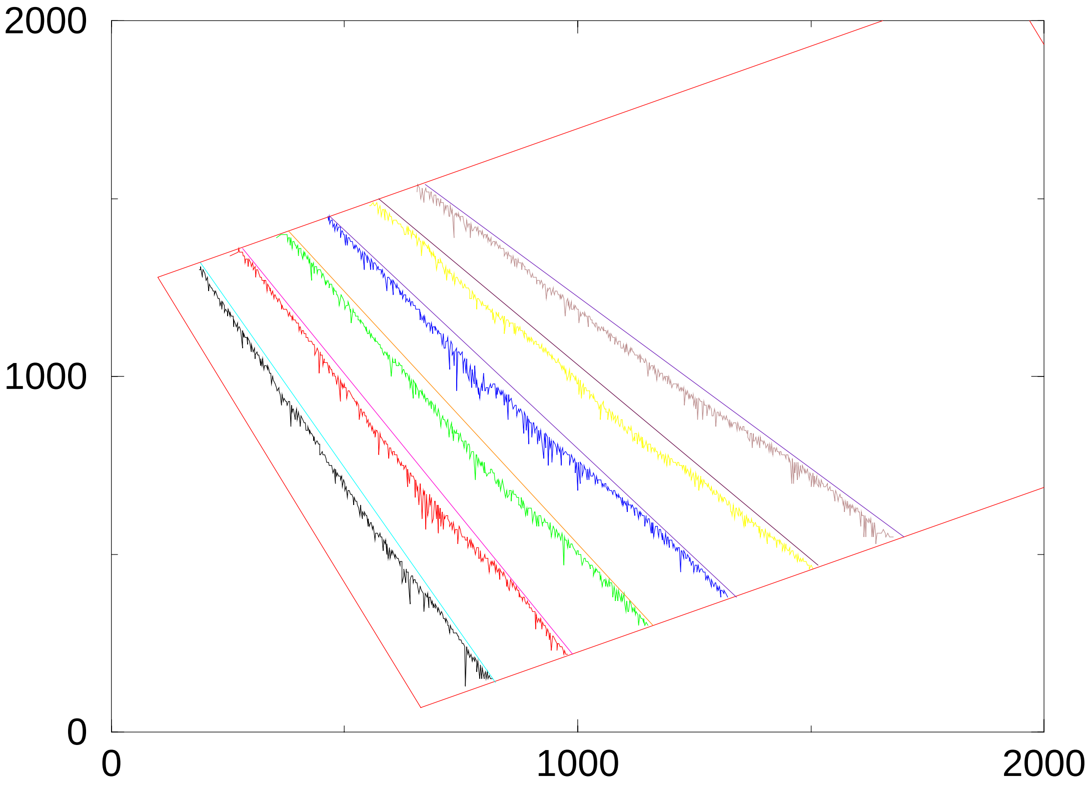

Figure 4: Linear Regression Method, Across Contours

of the collected data indicated a good fit to the swath edges. It is anticipated that the PL algorithm will behave similar to the LR (line orientation tending towards the contours) but should provide more efficient use of the survey platform at the cost of more complex navigation.

6 Conclusions

The steep grade of the Santa Rosa Ridge provided a good test area to contrast the different approaches for generating the next survey trackline based on the current lines' actual coverage. As anticipated, the straight line approach resulted in too great spacing at the shallow end and too little spacing at the deep end of the across-contour track lines since the spacing is inherently based on the mean swath width and the next trackline is forced to be parallel to the current one. The linear regression approach adjusted the spacing more effectively by fitting the next trackline to be parallel to the edge of the current swath's edge, but adjacent lines are progressively skewed towards the direction of the bathymetry contours. In both cases, the approaches exhibited an excellent ability to compensate for actual vs. predicted sonar system performance, and the spacing for the next tracklines were adjusted accordingly. Case in point, the sonar system was suffering from a power supply problem which significantly reduced its power output and thus its swath width - this problem was automatically compensated for by the survey technique; had predicted swath widths been used to generate pre-determined survey tracklines the result would have been large gaps between each swath.

The goal for the next trial is to collect sufficient data for detailed analysis of the performance of the straight line, linear regression, and piecewise linear fit methods at two different trackline spacing setpoints along and across the contours. Additionally, it is also desired to develop real-time performance metrics that would allow immediate evaluation of how well the algorithms are accomplishing the stated goals; self-evaluation of performance will be a critical component for a fully autonomous implementation of the survey system. Long term goals include the automation of sensor control functions based on data coverage/quality, transition to a criteria based on the number of soundings in a grid-cell vice percent overlap between swaths, and the transition of all of the data processing to computers on-board the vessel vice on-board the host-ship.

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