Autonomous Bathymetry Survey System

Brian S. Bourgeois, Andrew B. Martinez, Pete J. Alleman, Jami J. Cheramie, and John M. Gravley

Abstract— **This paper discribes the Autonomous Bathymetry Survey System (AutoSurvey), a system that provides automation of swath sonar bathymetric surveys. This system enables faster surveying of an area through environmentally adaptive techniques while ensuring adequate coverage and data quality. AutoSurvey assesses data quality and coverage in real-time and generates next-trackline waypoints based on actual system performance. The need for real-time performance assessment is discussed. A primary factor considered is the effect of the environment on swath bathymetry system performance, which is difficult to predict a-priori. The system's features, design and implementation are discussed in this paper. Simulation and sea trial results are presented, as well as an analysis of the system's ability to reduce survey time.**

Keywords— **Automated surveying, environmentally adaptive, swath bathymetry.**

I. Introduction

The Autonomous Survey System (AutoSurvey) was developed to provide more efficient deployment of swath bathymetry systems through an environmentally adaptive approach. Time and cost savings are realized by minimizing total survey time while maximizing area coverage and ensuring adequate data quality. Since the environment significantly impacts system performance, it is desirable to control the survey based on analysis of the actual data collected instead of on the predicted system performance.

There are several recent examples of data dependent survey control in the literature. Tiwari et al. [1] address environment dependent navigation, utilizing a terrain-covering algorithm designed to allow gapless mosaicing of imagery. Singh et al. [2] and Burian et al. [3] address gradient following approaches to find maxima and minima of sampled scalar data fields. Aramaki and Ura [4] propose 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. The principal goal of this effort was to automate the data quality and coverage assessment processes and the generation of navigation waypoints. AutoSurvey is designed to enable *hands-off* swath bathymetry surveys. Once the operator defines the region to survey and starts the system, the remainder of the survey is executed autonomously. This is accomplished through real-time processing and analysis of the previous swath lines' data. The processing of the previous swath's data evaluates the impact of the environment on sensor system performance by assessing the quality and coverage of the collected data and adaptively determines where the next survey line should be placed to ensure quality data is collected at an operator specified percent coverage. This methodology is applicable to all swath surveying, whether executed by surface craft or underwater vessels. The system has been implemented with a simulator and validated in ORCA (Oceanographic Remotely Controlled Automaton) [5] sea trials. Simulator runs indicate that this approach to surveying can reduce surveying time by 15% or greater while maintaining desired area coverage and data quality.

The next section discusses the operational complexities that have been introduced by modern bathymetry systems which result in difficult to predict sensor performance. Section 3 discusses the overal goal of the AutoSurvey system - to achieve 100% bottom coverage with data of acceptable quality in minimum time. Section 4 outlines the system's design including data collection, error detection and georectification, data quality validation, swath edge line fit and next line waypoint generation. Section 5 presents system results from simulation studies and field tests. Finally, conclusion are given in section 6.

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II. Bathymetry Surveying

The traditional goal of bathymetric surveying has been primarily to provide the mariner with the data needed to ensure safety of ship navigation. Bottom contours and sparse selected soundings were generally sufficient to meet this need. However, with increasing demands on the accuracy of hydrographic surveys [6] and accelerating commercial exploitation of the sea floor, data is desired that will provide more than a general characterization of the seafloor. Modern requirements demand 100% coverage, i.e. coverage that produces a dense set of soundings suitable for generation of a gapless topographic representation of the seafloor. Modern hydrographic sounding systems are capable of meeting this need, but the environment significantly impacts their performance. Because of the complexity of the environmental effects, in-situ assessment of system performance is required to ensure 100% coverage.

For many decades bathymetric surveys have been primarily conducted using vertical single-beam sonar systems. Since it is impractical to achieve 100% coverage with these systems, surveys are conducted using a series of preplanned lines that are based on typically scant historical knowledge of an area's depth contours. Acoustic imaging systems are used to ensure that shallower areas do not exist between the sounding lines. These imaging systems provide wide area bottom coverage but do not yield sufficiently accurate depth soundings for charting purposes, and the generated images typically require human interpretation. When questionable areas are found in the imagery, the single-beam system is deployed over the area for accurate soundings.

In contrast, modern swath bathymetry systems use multibeam sonar technology. These systems provide multiple soundings with each sonar ping that are located within a wide swath perpendicular to the ship's track. When properly compensated, all of the soundings generated can achieve the required accuracy needed for charting and other purposes. As compared with single-beam systems, swath systems can provide 100% bottom coverage, yielding denser soundings and faster coverage of an area. Even though swath system hardware cost is much higher than single-beam, the ability to achieve rapid total bottom coverage allows these systems to be more cost effective for bathymetric charting.

Swath systems can provide superior performance, achieved through significant added complexity in the survey system and its operation. The effective seafloor coverage and accuracy of a swath system is principally affected by several factors: ocean depth, positioning errors, ray bending, and bottom type and morphology.

Swath systems are typically operated at or near the ocean surface in order to maximize bottom coverage with time. Since a swath sonar covers an angular sector (as large as 150 degrees for some commercially available systems) the actual swath width on the ocean floor varies with ocean depth – narrower in shallow water and wider in deep water.

Swath sonar systems provide range as a function of angle with respect to the sonar head. To generate soundings from this data, accurate measurements of sensor pitch, roll, heading, heave, and position (vertical and horizontal) are required. The affect of pitch, roll and heading errors are most severe in the outer beams of the system due to the greater slant range. The result of such errors is to reduce the usable system swath width.

Sea state and sea direction can adversely affect system performance. Rough seas can exceed the capability of the pitch, roll, heading, and heave sensors to correctly compensate the sonar data. Consequently, sea direction becomes significant since the vessel will handle differently depending on its heading relative to the seas. High sea states can also result in aeration of the water under the sonar head which can drastically reduce effective range and swath width, and this effect will vary with time and heading.

The sound velocity structure of the water column affects the direction sound travels through the water, resulting in ray bending. The consequence of this for a swath system is uncertainty in the proper location of the bottom, particular in the outermost beams.

Bottom composition affects the return strength of the sonar pulse and thus the effective range and swath width of the system.

Bottom morphology can have several affects on swath system performance. Sand waves can result in destructive interference of the acoustic signals. Proud bottom features can mask low-lying areas. Excessive slope can affect the ability of the system to track the bottom and affects return signal strength.

The significant consequence of these combined factors is that it is difficult to predict a-priori the effective swath width of a multibeam sonar, making it impractical to pre-plan survey lines to achieve minimum survey time while ensuring complete bottom coverage. Consider a particularly simple case, where a series of parallel lines are to be run over an area with a slope, and the lines are oriented perpendicular to the contour of the slope. This might be necessary due to weather or sea state. If planned line spacing is computed using the average depth and the nominal swath width, the result will be excessive overlap between swaths in the deep areas (wasted survey time) and gaps between swaths in the shallow areas (missing data). This is illustrated in Figure 2 where the black areas are missing data (holidays), the light gray indicates 100% coverage, and dark gray indicates overlap between adjacent swaths.

It is evident from the preceding discussion that in order to effectively optimize bathymetric surveys using swath systems that data quality and coverage must be assessed in-situ since system performance cannot be adequately predicted. However, while multi-beam technology has dramatically improved data quality and quantity, the state-of-the-art in bathymetric surveying is still very much *human-in-the-loop*. Prior to the implementation of AutoSurvey, the ORCA required a full-time pilot for vessel navigation and an experienced surveyor with extensive sensor system specific training for the operation of the systems and the manual generation of optimized navigation waypoints. In recent years, processing systems technology has advanced sufficiently to enable real-time processing and generation of georectified area coverage maps from wide-swath system data. This area coverage provides the opportunity to perform inter-swath as well as intra-swath data quality checks by direct comparison of multiple soundings within the same grid cells. This real-time processing capability enables on-scene quality control of the data collected, assessment of actual bottom coverage and altering of survey parameters to compensate for actual, vice predicted system performance.

III. AutoSurvey Objectives

The primary goal for the AutoSurvey system is to achieve 100% bottom coverage with data of acceptable quality in minimum time, resulting in a more cost-effective survey operation. This goal can be achieved by evaluating the effects of the environment and system performance on the collected data. No more than 100% coverage is desired in order to minimize survey time, but in practice this is not realizable. Greater than 100% is required to ensure no gapping occurs between swaths since swath edges are typically not smooth. An important point here is that the 100% criteria applies to quality data – actual data coverage will naturally exceed 100% because there will typically be data that does not meet the quality criteria, particularly in the outer beams of a swath bathymetry system. To further qualify this goal, 100% coverage is desired on the first pass of the survey vessel. In practice this approach will necessarily result in gaps. But, assuming we have used all the information available to us, this will be the best that can be accomplished. A second pass might be required to fill in any gaps, because the knowledge that the gaps will occur does not exist before the data is collected. Execution of a second pass will necessarily require a higher level decision process, and likely human interpretation, to fill the resulting gaps in an optimal manner.

It is important to note that the best information we have for surveying the next line is from the previous line's data. This is an entropological approach to surveying wherein each new line provides innovations and represents the *best* knowledge that we have of the area and the present system performance. This applies to swath width, bottom depth, bottom slope, bottom reflectivity, etc. For example, the best estimate we have of swath width over an area is the swath width from the preceding line, given that this line is spatially and temporally *close* to the next line. This estimate can be further improved, utilizing data from the previous line, by projecting factors such as bottom slope into the next swath. This approach applies to predictive estimations of data quality as well. Significant boundaries, where the parameter being measured has a change approaching a discontinuity (or the sensor system performance results in a discontinuity even if the process being measured doesn't have one), cannot be adequately handled by this approach. It the discontinuity is known a-priori, then that knowledge should be used to setup the survey plan initially. If it is not known a-priori then the feature must first be detected and then handled by a second pass. Bathymetry discontinuities can manifest themselves in cliffs, abrupt changes in bottom reflectivity, or a significant change in the sound velocity profile as examples.

A second goal for the AutoSurvey system is reduced human operator requirements, particularly tedious tasks such as driving the survey vessel, evaluating data coverage and quality by eye, and next line waypoint generation. The system should handle these functions autonomously, but alert a human operator as needed when adverse conditions are encountered. Ideally, the operator should be able to define the boundary of a region to survey and the system would handle the entire survey without intervention. Automation of the entire process is a necessary step towards implementing the system on an AUV, where a human operator may not be available. This means that AutoSurvey must evaluate data quality and coverage numerically vice empirically. This should be done continuously throughout the survey, to enable alerting the operator when data degradation occurs.

Finally, a simulation capability is desired that will allow prediction of system performance over an area given preexisting data. This should include an estimation of total survey time, a measure of the area actually covered, and identification of areas that may cause system difficulties.

IV. System Design

The AutoSurvey system is composed of the following significant modules: 1) data collection and error detection, 2) data georectification, 3) data quality validation, 4) swath-edge line fit, 5) next-line waypoint generation, and 6) the autopilot. All of these processes are implemented in near real-time, allowing unfettered survey vessel progress. The data is piped directly between processes, providing operator independent system operation; the AutoSurvey system directly controls the survey vessel via the autopilot.

A. Data Collection, Error Detection, and Georectification

The data collection, georectification and quality modules are part of Hydromap, developed by C&C Technologies, Inc. located in Lafayette, LA. Hydromap is a software system for multibeam bathymetric surveying that provides functions of sensor control, data logging, real-time data processing and georectification, geographic display of processed data, raw data and vessel position, and manual waypoint generation and line following. The data collection, error detection and georectification modules within Hydromap perform the following functions:

- Acquisition and storage of raw sensor data from the bathymetric sonar, position (vertical and horizontal), heading, attitude and surface sound velocity systems,
- Low-level rejection of invalid data due to detected errors in any of the individual sensors,
- Georectification of the sonar data using the supporting sensor systems, sound velocity profile and tides, and
- Gridding of the data into uniform cells.

Real-time acquisition, low-level data validation, georectification, and gridding of the data are prerequisite to the generation of a full-area presentation of the data collected, as opposed to individual swath or waterfall displays. Waterfall displays do not georectify the data so it is difficult to assess intra-swath data consistency unless the vessel motion is small and the vessel is traveling in a straight line. Individual georectified swath displays allows intra-swath data assessment, but not inter-swath. Hydromap performs both georectification and gridding and provides a real-time coverage map that displays the collected data for the entire area being surveyed, showing previous and current line data. A human operator uses the coverage map display to empirically assess the quality of the collected data and to determine the actual, versus the predicted, coverage of the sensor system. This allows the operator to adjust the system operating parameters to compensate for ambient conditions and to determine subsequent navigation waypoints as a function of the specified survey criteria. The AutoSurvey system provides automation of the operator quality and coverage assessment tasks and also provides quantified, vice empirical, measures of these parameters. Consequently, the operator is freed from dedicated attention to system performance and waypoint generation, and is only required to infrequently evaluate survey progress. In addition to ensuring that the survey mission's goals are being adequately met, the real-time coverage map also provides the capability for the operator to observe unexpected features in real-time and to alter mission objectives accordingly.

B. Data Quality Validation

Data quality assessment is performed using both georectified and gridded data, primarily through self-consistency validation. Intra-swath validation is achieved by analyzing the variation of samples within a grid cell and by evaluation of along track and across track trends in the data. Where overlapping data exists between swaths, inter-swath data validation can also be performed. Data quality assessment is used for two specific functions, to ensure sufficient data is being collected that meets a predefined quality criterion, and to extract from the trimmed data the swath leading edge that will be used to generate the next trackline.

The design approach of the AutoSurvey system is such that sufficient quality data must be collected in each swath for the automated survey to continue. Otherwise, the operator (or a supervisory program) must be alerted to evaluate and take action on the problem. In simple cases, such as moderate sized gaps within a swath, an operator alert would be issued but the survey would continue. For more extreme degradation, such as no-data collected in a line, an operator alert would be issued and the automated survey would be terminated. The no-data condition is in fact the normal termination method for an area survey, wherein the system halts the survey if no new data is collected within the defined survey boundary. This approach takes into account operator errors (such as forgetting to turn on the sonar system) and system failures that result in total loss of data. In either case, the survey vessel is put into a safe condition by terminating the survey. To determine actual coverage, data that does not meet the quality constraint is eliminated from the swath, both interior and along the edges. Given the remaining area, and correcting for interior gaps, the total swath extent and the percent coverage within the swath can be computed directly. Additionally, gaps between the current swath and the previous swath can be determined in a similar fashion. Analysis of the achieved coverage within the swath(s) is then utilized to determine if the survey will continue.

Given that the first requirement is met, a sufficient quantity of quality data within the swath, the data required for next trackline generation is then extracted. Utilizing only the trimmed data set (poor quality data removed), the points corresponding to the outer swath's edges are extracted and trimmed by the defined survey boundary. This produces a set of bathymetry points corresponding to the leading edge of the swath, considering only quality-constrained data. These points are then passed to the swath-edge line fit module.

With this processing method it is significant to note that dropouts in the data, or pings where no data is returned, will result in spatial gaps within the resulting swath-edge line. Dropouts could occur due to intermittent system faults or due to conditions where no sonar return is received, such as excessively deep water (holes, cliffs) or areas with a soft bottom. The spatial gaps in the swath edge data are preferred over filling those gaps using the edge data from the previous swath. This is because it is not desirable for the system to repeatedly drive over the same dropout areas trying to acquire data and it is assumed that the dropout occurred because system capabilities have been exceeded. By allowing spatial gaps, the line fit module will effectively generate lines across the gapped area using points on either side of the gap. It is the function of the swath coverage algorithms to determine if the gaps are large enough to require corrective actions.

C. Swath-Edge Line Fit

Numerous approaches were considered and tested for the swath-edge line fit module. Of these, four were found sufficiently robust, accurate and efficient to be effective. These are Straight Line (SL), Linear Regression (LR), Piecewise Linear (PL) and Box. Each approach offers specific advantages and complexities in terms of vessel navigation and survey efficiency. The first three methods have been fully implemented and tested, and the Box method has undergone preliminary implementation and testing but has yet to be field tested.

The Straight Line (SL) approach uses a series of straight parallel lines to cover the survey area, and adaptive spacing between adjacent survey lines is employed. The SL approach is very effective over areas that are reasonably flat and over areas with gradual slopes when the track lines are run collinear with the bottom contours. Advantages of the SL approach include a simple navigation track (particularly in areas of high traffic), staying close to the point where the last sound velocity profile was taken, and the ability to choose line orientation for minimal sea state effect on the vessel. The algorithm for the SL approach finds the best-fit line (least squares) to the previous lines' swath edge, with the constraint that the fit must be parallel to the previous track line. This method provides the least flexibility in compensation of survey tracks for actual bottom morphology and is expected to produce gaps and areas of excessive swath overlap when traversing across bathymetry contours.

The Linear Regression (LR) approach uses a series of straight lines, without the constraint that the lines must be parallel. The LR approach offers the same advantages as SL, but will typically provide more efficient coverage over areas with nominal depth variations since the tracklines are approximately parallel to the previous swath's edge. Except in areas with extreme changes in depth, the LR lines will remain nearly collinear, offering simple navigation and the ability to choose vessel orientation with respect to the seas. The algorithm for the LR approach simply finds the least squares fit to the previous lines' swath edge.

The Piecewise Linear (PL) approach uses a series of line segments that approximate the shape of the previous lines' swath edge. This method, as compared with SL and LR, provides a superior ability to improve survey efficiency in areas with rough bottoms. However, the PL approach can generate complex tracklines that complicate vessel navigation, and preferred headings (for sea state reasons) cannot be readily adhered to. Implementation of the PL approach was significantly more complicated than the SL and LR approaches which only required a least squared error fit be done to a set of points. There is a multitude of techniques for fitting curves to an arbitrary set of points (polynomial, spline, etc.) but this application requires an unsupervised algorithm that is fast and robust. Consequently, a center-of-mass technique was chosen, which finds the spatial *center* of a sequence of swath edge points. While this algorithm does not provide a least square error solution, it essentially generates the path a human operator would choose and is computationally inexpensive. Initial testing of an adaptive PL method, where line segment length is adjusted according to the spatial variance of the local swath edge, has shown promise for handling the conflicting goals of smoothing transients and following sharp swath edge changes.

The Box approach entails *driving* the boundary. With this technique the first survey trackline would be the survey area boundary. Subsequent tracklines would then be generated by doing a best-fit to the interior swath's edge of the resulting data. The Box method offers the potential of a more time-efficient approach in that all turns are executed within the survey boundary so data collection is not interrupted. To utilize the Box approach the sound velocity profile must be valid over the entire survey area, instead of just in the local area of the current line. Also, sea-state must be low enough so that vessel track orientation is not a factor in survey system performance since multiple headings will be taken. The Box method algorithm also employs the center-of-mass technique. The box algorithm has undergone initial testing but is not fully tested in field trials.

D. Next-Line Waypoint Generation and Autopilot

The first survey trackline is defined to be a survey boundary edge, or the whole boundary for the Box approach. For the second and subsequent tracklines, the next trackline is generated by doing a fit to the previous lines' swath edge data and by performing a shift. The shift is required to properly position the fitted line (or line segments) to ensure a specified percent data coverage.

It is useful to relate the coverage to the shift factor, but doing this requires formal definition of percent coverage. Let d_1 be the distance from the vessel location to the (trailing) edge of the swath. This is the half-swath distance. d_2 is the distance from the vessel location to the edge of the previous swath's data. The value of d_2 is negative if it is in the opposite direction of d_1, that is if the vessel location is inside the previous data. Since we are concerned at this point only in coverage at the trailing edge, a fictitious swath of width $2d_1$ is used in computations. The overlap between adjacent swaths at the leading edge is $(d_1 - d_2)$. Using these quantities, the percent overlap between adjacent swaths, V, is defined as the overlap divided by the effective swath width,

$$V = (d_1 - d_2)/(2d_1),$$

and the percent coverage (C) is defined as:

$$C = 1/(1 - V).$$

The shift factor (S) is a function of C and is given by:

$$S = 2/C.$$

The shift factor is applied to the distance between the previous trackline and its leading swath edge to determine the proper position of the next trackline. This approach effectively shifts the resulting fit line or line segments by the average (or local average) width of the previous swath. Typically, the specification would be for 100% percent coverage with data meeting the quality constraint. In this case, the edges of each adjacent swath, after bad data is trimmed, would butt up against each other seamlessly. Greater than 100% percent coverage is often specified since some swath-to-swath overlap is desired to allow for inter-swath data validation, and gaps could occur where the swath edge fits are poor. The AutoSurvey system provides for operator specified desired coverage up to 200%, where the next trackline would be the current tracklines' swath edge. Less than 100% coverage can also be specified for situations where it is determined that gaps between swaths are allowable, such as a *quick-look* survey of a region. In the case of a *quick-look* survey it is likely that either the SL or LR fit approaches would be used.

In the simplest implementation, the shifted lines are clipped by the survey boundary and a series of evenly spaced waypoints are generated along the line using the equation for the line. For PL and Box, where a segmented line is used, the segmented line is clipped by the survey boundary and the set of vertices that connect the line segments are used as the waypoints. These waypoints are then passed to the vessel autopilot for execution. With the current implementation, AutoSurvey processes the previous tracklines' data and generates the next tracklines' waypoints within a few seconds after crossing the survey boundaries' edge. The autopilot is designed to halt the vessel in the event that insufficient valid data is collected and next-line waypoints cannot be generated.

For all of the line fit approaches, the root-mean-squared (RMS) error for the fit is computed. The RMS error has a direct relationship to the actual percent coverage that will be achieved assuming the vessel steers the generated trackline and that the next lines' swath width is the same as the previous line.

Assuming Gaussian errors in the line fit, it is straightforward to compute the expected area missed between swaths. The overlap $d_1 - d_2$ is a random variable; let its mean be d, the expected overlap between swaths. If the line fit to the swath edges are assumed to have Gaussian errors with standard deviation, σ, equal to the RMS error of the fit, then the overlap is also Gaussian with mean d and variance $2\sigma^2$. There is a potential for missed data along the scan line for each ping. The quantity of data missed at the outer edge of each ping is represented by its length δ which is zero when the overlap is greater than zero and equal to the negative of the overlap otherwise.

$$\delta = \begin{cases} 0 & d_1 - d_2 > 0 \\ d_2 - d_1 & \text{else} \end{cases}$$

When adjacent swaths overlap, $\delta = 0$. When gaps occur, $\delta > 0$ and it is distributed as the tail of a Gaussian with mean $-d$ and variance $2\sigma^2$. The expected distance missed per ping is thus

$$\begin{aligned} E\delta &= \int_0^\infty \frac{\delta}{2\sigma\sqrt{\pi}} \exp\left(\frac{(\delta+d)^2}{4\sigma^2}\right) d\,\delta \\ &= \frac{\sigma}{\sqrt{\pi}} \exp\left(\frac{-d^2}{4\sigma^2}\right) - d\Phi\left(\frac{-d}{\sqrt{2}\sigma}\right) \end{aligned} \quad (1)$$

where $\Phi(\cdot)$ is the standard normal cdf. The expected area missed is the distance traveled times the expected length missed per ping. For example, for a shift factor of $S = 2$ (resulting in a nominal coverage of 100% and a value of $d = 0$), the area missed is $\sigma/\sqrt{\pi}$ times the distance traveled.

Using Equation 1, the shift factor can thus be scaled to compensate for a lower percent coverage resulting from a poor line fit. The RMS error can also be used to execute a tiered approach to the type of line fit used. With a tiered approach, the line fit process would start with the SL algorithm for every line. If the RMS error were too great, indicating possible gaps or excessive overlap, then the LR and PL algorithms in turn would be attempted until a satisfactory error is obtained.

With more advanced implementations, the shift factor can be used to compensate for predicted environmental effects such as bottom slope and signal strength. If a consistent across-swath slope is observed, then the shift factor can be adjusted to compensate for the projected swath width by altering the position of the next trackline. This would be utilized only where an up-slope is observed, since the swath will become narrower and gapping could occur. On a down-slope the swath would broaden and will not result in gapping. Since the slope is a prediction based on the data in the previous swath, a conservative approach is taken to ensure data is not missed due to an erroneously predicted down-slope. If the return signal strength is observed to be decreasing to a critical point (particularly in the outer beams) the shift factor can likewise be used to bring the next trackline closer, compensating for the predicted reduction in next-line swath width.

V. Implementation

The AutoSurvey system has been implemented in a simulator and on the ORCA vessel. In both instances, the AutoSurvey algorithms have been embedded within Hydromap. Both the simulator and ORCA implementations use a Sun Sparc20 workstation. The simulator is designed to provide full closed-loop functionality within Hydromap allowing end-to-end testing of the software, thus providing validation of the whole system's operation. In the simulator the normal real-time sonar data input into Hydromap is replaced with a data generation module. This module uses pre-existing processed bathymetry data archives and moves a simulated vessel through it on defined survey lines. Given the simulator's vessel position and heading over the data, swath bathymetry soundings are generated ping-by-ping and these soundings are passed to Hydromap's data processing functions. AutoSurvey modules within Hydromap receive the processed data and perform the necessary data analysis and next-line waypoint generation functions. The generated waypoints are then passed to the data generation module for subsequent control of the simulated vessel. The simulator has provided an efficient method for testing and developing the AutoSurvey system, and for rapid comparison of the performance of different algorithms. The simulator also provides a convenient method to estimate the system's performance prior to an actual survey. Given historical data, the simulator can be used to provide initial estimates (assuming ideal system performance) of the time required for the survey, the best line orientation for maximum efficiency, and nominal identification of areas where over-coverage or holidays may occur.

The ORCA is an actively stabilized, untethered, air-breathing submersible vessel which travels just below the water surface. ORCA has been fully tested with a Simrad EM-1000 multibeam bathymetry system in water up to 1000 meters depth. Since the ORCA travels beneath the waves, it is a very stable platform. Consequently it 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.

AutoSurvey has been implemented in the ORCA and tested at various stages of development during three separate sea trials. The Simrad bathymetry data is collected and processed in real-time by Hydromap and the AutoSurvey system, and the generated next-line waypoints are passed to the ORCA's control system autopilot. During the last sea trial, conducted August 1998 at Pensacola Florida, the ORCA successfully demonstrated full *hands-off* AutoSurvey capability. Using the Hydromap geographic display, the operator simply uses the mouse to draw a polygon that defines the survey boundary, and selects one edge of the boundary as the first survey line. Once the system was initialized, the ORCA conducted the entire survey without the need for operator intervention.

VI. Results

Figures 1, 3, and 5 show the bathymetry generated by the AutoSurvey simulator using the SL, LR and PL approaches respectively. The varying shades of gray indicate depth contours at 5 meter intervals. Data from the East Flower Gardens, near Corpus Christi Texas, was used for these simulations. The area shown is very complex and has depth variations from 18 to 140 meters, with several sea mounds. In these figures, the broad white lines indicate the survey bounding box and the survey tracklines. The top right edge of the bounding box was executed by the simulator as the first survey line. Figures 2, 4 and 6 show the respective percent coverage of the bathymetry data within the survey region. In these figures black represents a holiday area (no data), light gray represents 100% coverage (single swath), and dark gray represents 200% coverage (2 or more overlapping swaths). Observing these figures it is evident that the PL approach provided the best coverage with minimal holidays and overages (areas with excessive coverage.) LR performed nearly as well and has only a few holiday and overage areas. SL performed poorest, with very large holiday and overage areas. For this simulation, the SL approach was implemented using the average swath width of the previous line to determine how far to shift the subsequent survey line. While this minimized the overages, it generated significant holidays. In the lower corner of Figures 3 and 5, the end-of-game problem is observed. The end-of-game problem occurs when the automated survey works itself into a corner of the survey area. This can result in a sequence of short survey lines, where more time is spent in the vessel turns than on the survey line, and the generation of a small gapped area at the end of the survey.

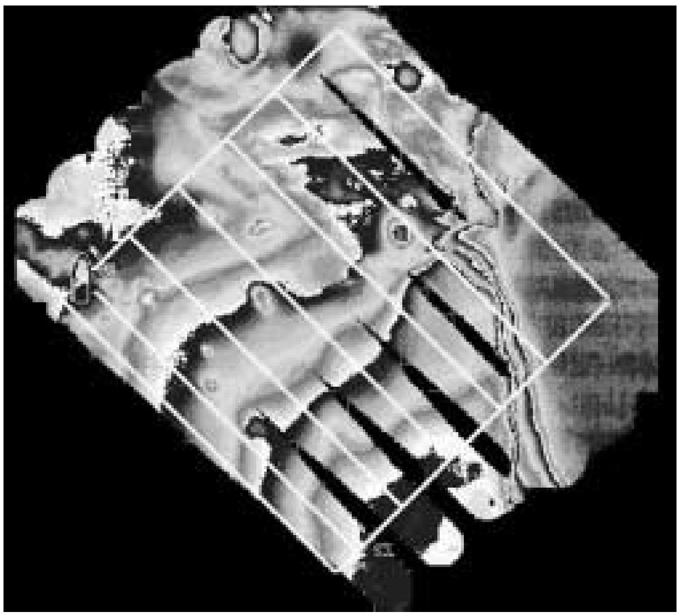

Fig. 1. Bathymetry generated by the AutoSurvey Simulator using the Straight Line (SL) swath edge fitting method. The data used for this simulation is from the East Flower Gardens, near Corpus Christi Texas. The area shown is very complex and has depth variations from 18 to 140 meters, with several sea mounds. The broad white lines designate the survey boundary and the track-lines that were automatically generated and driven. The top right edge of the bounding box was executed by the simulator as the first survey line. The simulator generated bathymetry is shown in grayscale at 5-meter intervals.

Figure 7 shows the results of multiple simulation runs over the East Flower Gardens data. For this test, simulation runs were performed with the same survey bounding box rotated at angles of 0, 45, 90, 135, 180, 225, 270, and 315 degrees. This approach surveys nearly the same area which each rotation, and allows observation of the AutoSurvey system's performance based on the initial survey line's orientation. It also provides a data set for making some generalized comparisons regarding the survey time required for each approach. In order to provide a basis for comparison of survey execution time, the SL algorithm was modified to use the minimum width of the previous swath as the criteria for shifting of the next survey line. This approach ensures no holidays (100% coverage) but generates significant overages. Thus, the comparison criteria are the amount of time to survey the region while maintaining adequate area percent coverage. Note in Figure 7 that the

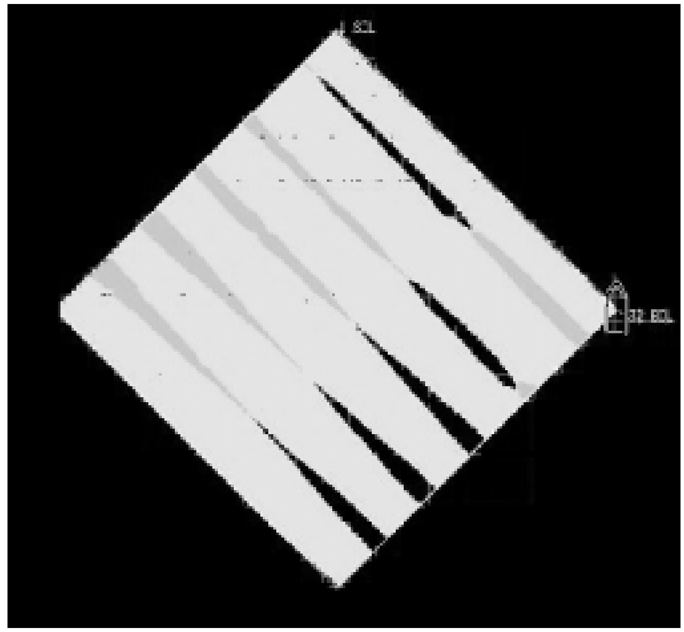

Fig. 2. Bathymetry coverage generated by the AutoSurvey Simulator using the Straight Line (SL) swath edge fitting method. Solid black designates areas where no data is collected. The light gray areas are where the desired 100% coverage has been achieved, and the dark gray areas are where 200% or more coverage has occurred (overlapping swaths).

SL results are 99.5% and not 100%; this is due to missing data in the original data set. The cluster of the five SL points was arbitrarily chosen as the nominal survey time.

The SL approach can achieve full coverage, but at the cost of significantly longer survey times as compared with LR and PL. Overages for the SL approach (ensuring 100% coverage) are on the order of 38% of the total survey area, as compared to 4.6% for LR and 4.4% for PL. Note that uniform spacing of the parallel lines, based on the minimum depth in the entire survey area, would be even less efficient than the adaptively spaced parallel lines used. Since SL was implemented here using minimum spacing, all simulation runs achieved full coverage. The three data points at 110% survey time were a result of survey boundary orientations that left a narrow region of unsurveyed area and thus required an additional survey line to complete the region.

The LR approach achieved from 10% to 35% less survey time than nominal. However, it is also apparent that the coverage achieved by LR is highly dependent upon the orientation of the survey lines with respect to the bottom contours. Holidays for this approach tended to cluster into large areas. Closing these gaps would require closer line spacing and could result in significantly poorer survey time performance.

The PL approach provided the best overall performance, achieving from 10% to 30% time savings while ensuring very nearly 100% coverage. The majority of the holidays for the PL approach were a result of unconstrained turns and the end-of-game problem. Unlike the LR results, the holidays for the PL simulations tended to be small and dispersed throughout the survey region. Also, the PL ap-

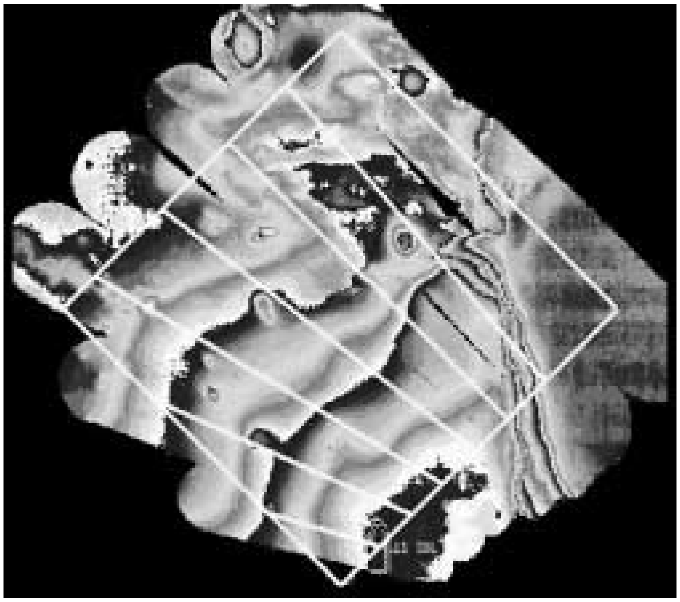

Fig. 3. Bathymetry generated by the AutoSurvey Simulator using the Linear Regression (LR) swath edge fitting method.

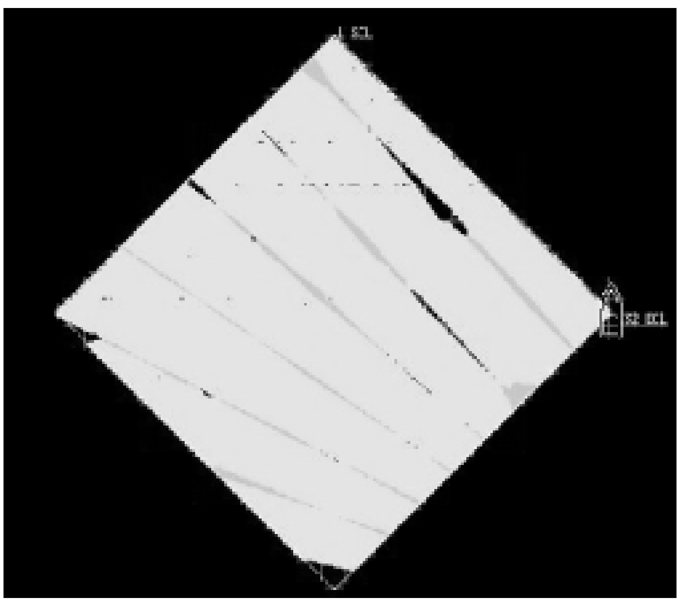

Fig. 4. Bathymetry coverage generated by the AutoSurvey Simulator using the Linear Regression (LR) swath edge fitting method.

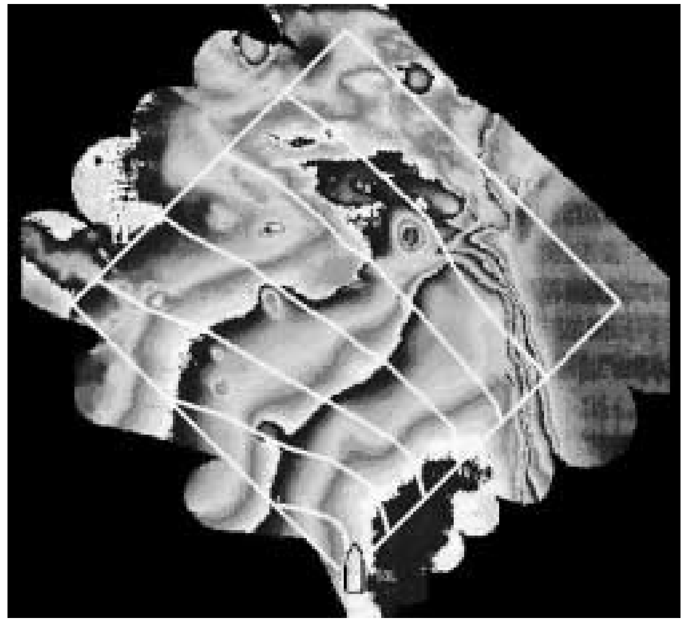

Fig. 5. Bathymetry generated by the AutoSurvey Simulator using the Piecewise Linear (PL) swath edge fitting method.

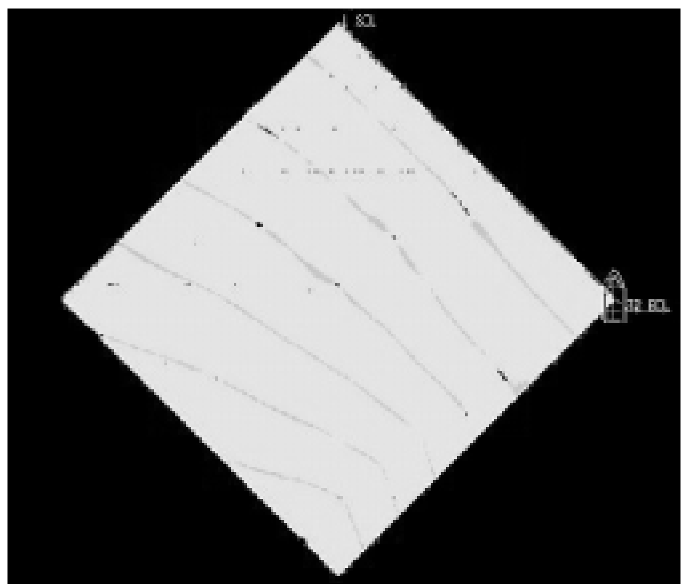

Fig. 6. Bathymetry coverage generated by the AutoSurvey Simulator using the Piecewise Linear (PL) swath edge fitting method.

proach appears to be fairly independent of the survey orientation.

For regions with complex morphology, these simulation results indicate that simulation runs should be utilized prior to a survey to choose the optimum survey orientation and algorithmic approach. From Figure 7 it is evident that a time savings of 25% can be realized, while still achieving full bottom coverage, if care is taken to properly select the best approach and orientation.

The mesh plot in Figure 8 illustrates the Santa Rosa Ridge survey area visited during the first and second sea trial tests of the AutoSurvey system. 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 carbonate cemented sandstone [7] with notable features providing outstanding morphology for these tests. Near the northern edge of the region (on the left in the figure) 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. Figure 9 shows the tracklines and swath edges for lines run across the contours using the LR method. The jaggedness of the swath edges clearly demonstrates the effect of the environment on system performance.

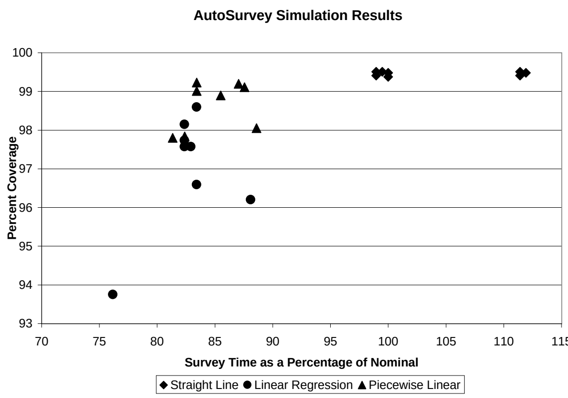

Fig. 7. AutoSurvey simulation results comparing the effectiveness of the three different swath edge fitting methods. For each fitting method, eight different runs were conducted over the same area by rotating the survey orientation in 45 degree increments.

Figure 10 shows the bathymetry, PL generated tracklines and region boundary for a survey conducted during the third sea trial over Calamity Canyon. Calamity Canyon is located southwest of Santa Rosa Ridge and is part of the extension of the outcropping at Santa Rosa Ridge. This survey was conducted completely autonomously by the ORCA using the AutoSurvey system.

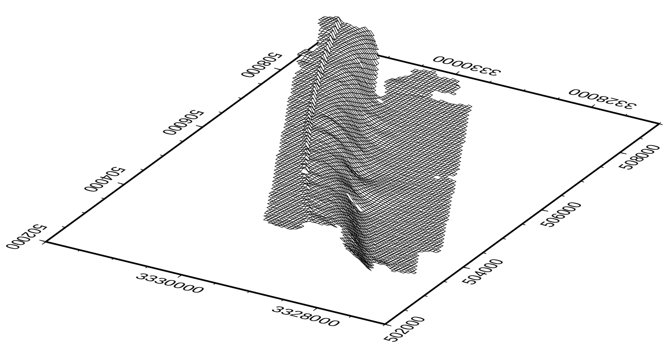

Fig. 8. Santa Rosa ridge survey area bathymetry. Depth is 60m at the northern edge (left) and 110m at the southern edge; vertical exaggeration is 18.

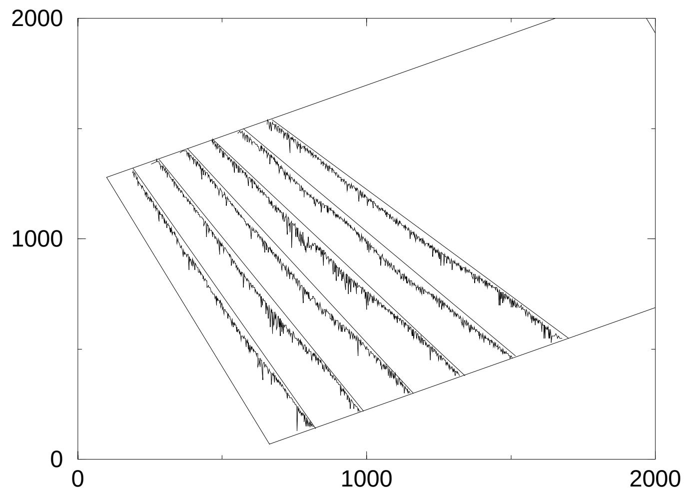

Fig. 9. Linear Regression (LR) survey of the Santa Rosa ridge. The straight lines, including the left edge of the area boundary, are the ship's track lines. The jagged lines show the position of the bathymetry points obtained along the swath's leading edge as the ship progresses along the track line.

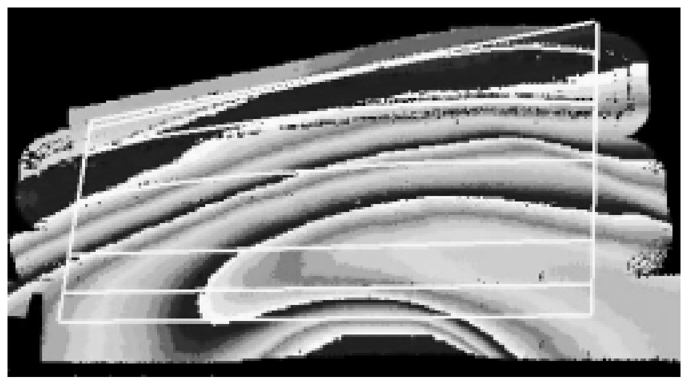

Fig. 10. AutoSurvey results over Calamity Canyon, covering an area of approximately 4000 meters by 2000 meters. The broad white lines show the survey boundary and the track lines that were automatically generated and driven by the ORCA vessel. The bottom boundary edge was used as the initial trackline, starting on the left. The depth varies from 50 meters (top left corner) to 110 meters (bottom right corner). The collected bathymetry is shown in grayscale at 2-meter intervals.

VII. Conclusions

The AutoSurvey system has been successfully implemented in a simulator and has been utilized for hydrographic surveys with the ORCA vessel. The present implementation provides a full *hands-off* capability – the operator need only define the survey area boundary and AutoSurvey autonomously conducts the entire survey, performing real-time data analysis and next-line waypoint generation. The data analysis performed by AutoSurvey enables an environmentally adaptive surveying approach, where actual (versus predicted) data quality and coverage are assessed and used to generate the next survey trackline. Simulation using data with large depth variations indicates that the AutoSurvey system can achieve 15 to 30% time-savings while ensuring complete bottom coverage and quality data. Field tests in a challenging environment demonstrated the success of the system.

Further work that should be pursued includes the following:

- development of an adaptive segment length, piecewise linear algorithm;
- utilization of line-fit error to adjust next-line positioning;
- utilization of previous swath data analysis to compensate for predicted bottom slope and signal strength effects on swath width;
- inclusion of vessel turning constraints in the waypoint generation algorithm;
- implementation of the box survey approach; and
- development of approaches to handle the end-game problem.

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References

[1] S. Tiwari, S. Hert, and V. Lumelsky, "An algorithm for covering an unknown underwater terrain," in *Proceedings of the Ninth Intl. Symposium on Unmanned Untethered Submersible Technology*, Durham, NH, Sept. 1995, pp. 307–316.

[2] H. Singh, D. Yoerger, R. Bachmayer, A. Bradley, and K. Stewart, "Sonar mapping with autonomous benthic explorer (ABE)," in *Proceedings of the Ninth Intl. Symposium on Unmanned Untethered Submersible Technology*, Durham, NH, Sept. 1995, pp. 367–375.

[3] E. Burian, D. Yoerger, A. Bradley, and H. Singh, "Gradient search with autonomous underwater vehicles using scalar measurements," in *Proceedings of the Ninth Intl. Symposium on Unmanned Untethered Submersible Technology*, Durham, NH, Sept. 1995, pp. 86–98.

[4] K. Aramaki and T. Ura, "Surveying and map-drawing by underwater vehicles based on ultrasonic range sensors," in *Proceedings of the Ninth Intl. Symposium on Unmanned Untethered Submersible Technology*, Durham, NH, Sept. 1995, pp. 416–425.

[5] B. Bourgeois, M. Kalcic, and M. Harris, "ORCA - oceanographic remotely controlled automaton," *The Hydrographic Journal*, no. 79, pp. 3–11, Jan. 1996.

[6] International Hydrographic Organization, *IHO Standards for Hydrographic Surveys*, 4th edition, Special Publication number 44, Apr. 1998.

[7] P. Fleischer of the Naval Research Laboratory, personal communication, July 1997.