Depth Adaptive Hydrographic Survey Behavior for Autonomous Surface Vessels

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Abstract—**When autonomous surface vessels conduct systematic seafloor surveying using a swath sonar system, the fixed angular coverage leads to differing horizontal coverage width with depth. Traditionally, missions have been pre-planned using fixed line spacing accounting for the minimum expected depth or with the intention of leaving gaps in some areas. A path planning algorithm and accompanying behaviors have been developed to adaptively survey a region for complete coverage with minimal gaps. Subsequent paths are planned based on measured depths in the field and this process continues until a defined area is completed or a depth threshold reached. The algorithm has been simulated in a custom environment and integrated into the MOOS-IvP marine autonomy system.**

I. Introduction

Marine vehicles were the first place to widely introduce automated navigation systems, through the use of autopilots for heading control during long transits, and had some of the first demonstrated long distance voyages in the 1920s. However, modern large ship autopilots today remain very similar in capability to these early models, being able to follow tracks and headings but not assimilate other information and react to a changing environment. Recent work in autonomous land vehicles and aircraft allow them to operate for long periods of time in complex situations without human guidance, but marine vehicles have not received as much attention.

For hydrographic surveying, autonomous underwater vehicles (AUVs) were introduced in the 1990s and became more feasible for routine surveys in the following decade. AUVs take advantage of submergence to survey closer to the seafloor and are more decoupled from surface conditions than traditional marine vessels, but still have major limitations in positioning and operational endurance and are typically very expensive as a result of the additional engineering burden for submerged vehicles. Many of these costs and concerns can be greatly reduced through the use of small autonomous surface vessels (ASVs). Global Navigation Satellite System (GNSS) reception allows for cheaper navigation systems, hull sealing only needs to withstand wave action, and absolute reliability in operation is not paramount since the vessel can still be recovered if it malfunctions or is depleted of power. Air breathing engines or generators facilitate improved operating time and batteries can be much more easily swapped than with a pressure sealed hull.

Most current hydrographic surveys employ multibeam sonar systems for depth measurement, which provide a fixed swath angle viewing of the seafloor, with a number of data points returned along the swath profile. Most multibeam hydrographic surveys require complete coverage, defined as "100% bathymetric bottom coverage with multibeam sonars [1]." The fixed angle of the sonar causes the width of the swath across the seafloor to vary with depth. Therefore, in order to achieve complete bottom coverage, neighboring survey lines must be spaced more closely in shallow water than deep water. AUVs avoid the problem of having to anticipate varying swath widths over a survey area as they can be instructed to maintain a constant altitude above the seafloor.

Obviously, maintaining a constant altitude above the seafloor is not and option for ASVs, as their height above the bottom is determined by the full water depth. However, in most existing applications, survey planning for ASVs inherits fixed or preplanned line spacing from the AUV paradigm [2]. In more complex schemes, an area can be subdivided by depth ranges and different line spacings planned [3] [4]. In order to achieve complete coverage, these parallel lines are still required to be spaced according to the minimum depths in the region, leading to inefficient extra overlap elsewhere. Any preplanned adjustments for depth also require knowledge of the area, and usually the purpose for conducting a survey is due to uncertainty in the existing data. This paper presents a method for comprehensive coverage path planning that does not require prior knowledge of the bathymetry in the survey area and adjusts survey lines dynamically based on the data acquired during the survey. This method mimics that of how human driven data is currently collected in the National Oceanic and Atmospheric Administration (NOAA), where a coxswain steers a survey launch to match and overlap realtime coverage reported from the sonar system with a graphical coverage map of previously surveyed area. It is similar to a method developed by Bourgeois [5] [6] but is intended for small autonomous platforms and uses a different algorithm to increase the probability of achieving complete coverage. The

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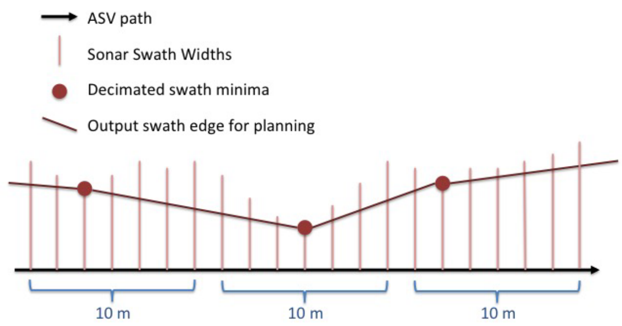


Fig. 1. Illustration of the selection of swath minima points from full raw data record, which are then used as a basis for planning the next path.

terms“line” and “path” are used interchangeably in this paper to refer to the desired survey path of the ASV.

II. Adaptive Line Planning

The path planning process can be subdivided into two main steps: recording the swath data and planning the next survey line. The second step of planning the next path requires multiple sub-processes to generate the final path that will be driven by the autonomous surface vehicle. An operation region can be defined to specify limits for the survey, as is typical during human controlled acquisition.

A. Swath History Recording

Recording the data is a straightforward process, but incorporates some refinement during data collection to reduce the processing load at the end of the line. This allows the new line to be computed as quickly as possible and passed to the autonomy system so that surveying can continue without any delay. The data recorded are assumed to either come from a sonar with no errors (in simulation) or a filtered raw sonar record as discussed in Section III.

While the ASV is following a survey line, it records the swath width from the sonar system uniquely on the port and starboard sides along with the accompanying vehicle position and heading at the time of the depth measurement. This allows the edges of the swath to be positioned for later path planning. Each recorded point adds to an accumulated distance, which then triggers selection of a minimum swath when a specified interval is reached. This method is used to decimate the recorded points and therefore reduce the processing load at the end of the line as mentioned previously. The selection of the minimum along a length ensures that the next planned path will be a conservative approach to complete coverage with the previous data. However, even with this method it is possible that additional local minima within the decimation length would not be overlapped in subsequent swaths if they were planned with no overlap. The decimation process is shown in Figure 1. The subdivision of path for selection of minima can be varied depending on the resolution needed for the final path. For the simulations in this paper, a 10 meter decimation length is used.

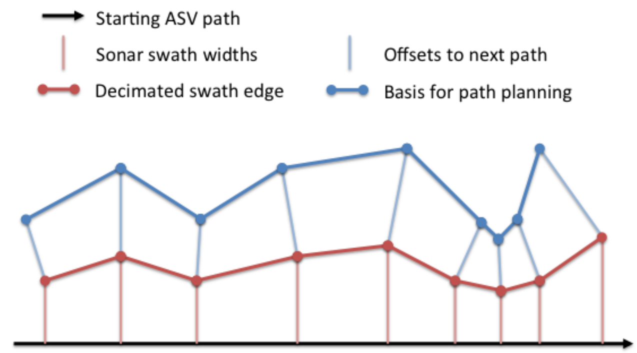


Fig. 2. Illustration of the generation of an offset line for initial input into the refinements of the path planning algorithm. This shows a straight initial line for data collection, but the same process is used for subsequent segmented lines. No additional overlap is added in this example.

In addition to maintaining the decimated swath record, the history recorder keeps a full data record for the purpose of determining what area has been covered by the sonar. This is stored as a coverage polygon which can then be displayed or used in the path planning algorithm where knowledge of the area covered by data collection is required. The data coverage from each line is unioned with previous lines to form a single polygon (possibly containing inner holes) indicating areas from which data has already been collected.

B. Planning The Next Path

When a survey line is completed, the swath recording module is signaled to output the minimum swath edge on the side of the next path to be planned (basis points) and their corresponding locations. The path planning module then uses this swath as a basis for determination of the next path. This process takes a number of steps, stating with an offset from edge of the basis points.

1) Offset from edge of swath: The basis points are used to first create an offset path that forms the first pass on path planning for the subsequent swath. If an operation region is defined, basis points outside the region are first eliminated to ensure that the vehicle is not directed to survey outside the region. The basis points on either side of each point are then used to form vectors and the perpendicular to the average heading between them is used to determine the direction of the offset vector. This translates the sequential minimum swaths to an offset direction. The offset distance is then calculated from the previous swath width at the basis point. The offset distance may also be reduced or enlarged by a factor to ensure overlap between outer beams where uncertainty is higher or create a striping pattern if full bottom coverage is not required. The first offset step is shown in Figure 2.

This initial offset path is processed to filter track points that would lead to undesired operation of a vessel or incorrect survey methodology. Specifically, sharp turns and loops are not desired during data acquisition because they decrease data density on the outer side of the turn and can increase uncertainty in attitude measurements.

2) Removal of self intersects: The first step to refine the path is to remove areas where the path crosses over itself, which would not only cause unnecessary turns, but also duplicate coverage in some areas. These crossings can occur where the ASV executes a turn with a radius less than twice the width of the sonar swath at that point. Each segment is tested against following segments to see if it intersects them. If there are intersections, the portion of the path between the first and last intersect is removed. This process is repeated along the path until all self intersections are removed.

3) Removal of sharp bends: The processing algorithm next eliminates bends in the path that exceed a defined angle. Large angle turns are undesired because they cause increased spacing between sonar detections along the outside of the turn and force the ASV to turn in a smaller space than its physically possible turning radius which could lead to undesired operation from the line following control system. For the simulation and testing discussed in this paper, the maximum bend angle is 60°. To eliminate bends, the path is checked along the direction of travel. When an angle between segments larger than the threshold is encountered, test segments are formed by eliminating subsequent points until an angle with the first segment less than the maximum is found. Elimination of the end point of the first segment of the bend is also tested to see if it results in less points being removed from the planned path.

Even checking both these scenarios and selecting the minimum point removal strategy can sometimes result in large amounts of waypoints being removed. As a result, some alternative evaluations are built into the algorithm. If less than twice as many points as the minimum method are removed by the other method and the resulting path bend angle is smaller, then the smaller bend angle is chosen despite the fact that it will eliminate more points from the planned path. If testing to eliminate a bend reaches the end of the path, the beginning of the segment is assumed to be the problem, and the algorithm is run recursively on a path with this point removed. With these additional factors, this method of bend removal is found to give more desirable results than that of other methods, such as calculating gradients along the path.

An example of removal of both self intersection segments and sharp bends is shown in Figure 3. The resulting line is much smoother and able to be driven by the autonomous waypoint navigation behavior without difficulty.

4) Fitting of path to operation region: With drastic bends and self intersections removed, the path is now ready to be fit to the defined operational region. Since the region can be irregularly shaped and turns near the ends create swath edges that lie outside the regions, it is necessary to fit the path to the operation region. The path is first clipped to the region by eliminating any points which do no intersect the operation region polygon. The ends of the resulting path are then extended along the direction of the last segment of either end until it reaches the nearest edge of the polygon. Typically this results in a logical intersection, but turns at the end of the line can result in the nearest edge by extension being further

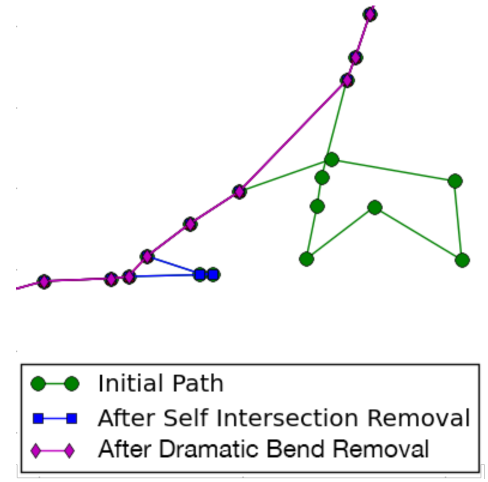


Fig. 3. Example of path refinement from a simulated path, with removal of intersecting segments (green) and areas with sharp bends

than would be desired for operation, so the extension length can be limited. For the simulations in this paper (Section IV), the length is limited to 150 meters for the small generated areas and 300 meters for the larger, real data based survey areas.

5) Elimination of points in existing coverage: A final step is taken that eliminates planned points that fall within existing coverage to try to prevent unnecessary duplication in data collection. Points can fall in existing coverage after turns in areas of rapidly changing depth, as a result of elimination of intermediate waypoints from the removal of intersections and bends or from the extension process of the previous step. While elimination of waypoints within existing coverage does not guarantee that the planned path will not overlap previous data (an example of this is seen in Figure 8b), it helps reduce the amount of unnecessary data collection.

C. Completion Metric and Holiday Detection

The operating region is considered completed when the next planned path has all waypoints eliminated, either because they are outside the operating region or because they go through an area with existing coverage as described in the previous paragraphs. At this point the vessel can be instructed to either hold its last position, return to the deployment location (or another specified meeting point) or continue to another operating region.

Within the operating region that has just been completed, the coverage record kept by the swath recorder can be used to identify where there are gaps in the data such that it would not meet complete coverage requirements. These gaps are known as *holidays* and are required to be filled before a survey area is deemed complete. The holidays can then be targeted for completion. The current algorithm only addresses holidays as point locations, but larger ones could be addressed as a separate set of operation regions.

III. Auxiliary Functionality

In addition to the core path planning routine, some functionality has been implemented to facilitate integration of the in situ path planning with physical systems and autonomy environments.

In order to ensure safety of the ASV and not waste time surveying areas that are not significant to navigation, the ASV can be set to avoid shallow areas of a certain threshold. A combination of current depth and the depth trend (for example if the bottom rises rapidly) are used to determine if the ASV needs to divert from a planned survey line and avoid a shallow area. Since the data coverage area is known and the sonar is continually monitored, it can be assumed that the previously surveyed area is safe for transit by the ASV. Therefore, upon detection of a shoal, it will divert in the direction of the prior survey line and follow the edge of the previous swath. This is the same procedure currently followed by human coxswains. If the edge of the data recorded during these lines is still shallower than the threshold, the vessel will follow the threshold depth contour at those locations. Likewise, if the depths increase, such as for an isolated shoal, the ASV will resume normal path planning operation. If all other areas in the operation region are completed but a shoal remains, the region is determined to be completed.

Between survey lines, an ASV must be directed to properly reach the next survey line. The ASV must turn from one line to the next in a logical fashion, which depends on the spacing between the lines and the possible turning radius of the vessel. For a typical turn, a single point is placed outside the survey operation region, along a line leading from the last segment of the survey path. For the simulations in this paper, it is placed 50 meters from the edge of the survey area. This point is planned along with the line, so that the vessel can immediately begin transiting to the point while the next line is planned. After the path planning algorithm determines the next line, if the spacing is smaller than the turning radius of the ASV, two additional points are placed to create a modified Williamson turn pattern that directs the vessel onto the next line as shown in Figure 4.

On the end of the turn, an alignment line is planned that extends the first segment of the survey path beyond the operation region. This line forces the ASV which is operating a line following behavior to align its heading with the upcoming survey line so that it is not oscillating when entering the survey region, which increases data quality due to the decreased yaw motion. This line is also shown in Figure 4.

As mentioned in Section II-A, the swath recording component of path planning assumes that the data are correct, but actual sonar systems report incorrect depths occasionally as a result of bubble sweepdown under the transducer or incorrect bottom detections on objects in the water column such as fish. Multibeam sonars are also susceptible to interference from the specular reflection of the main lobe at nadir being detected in sidelobes. All of these processes reduce the depth detected as compared to the actual depth and therefore would

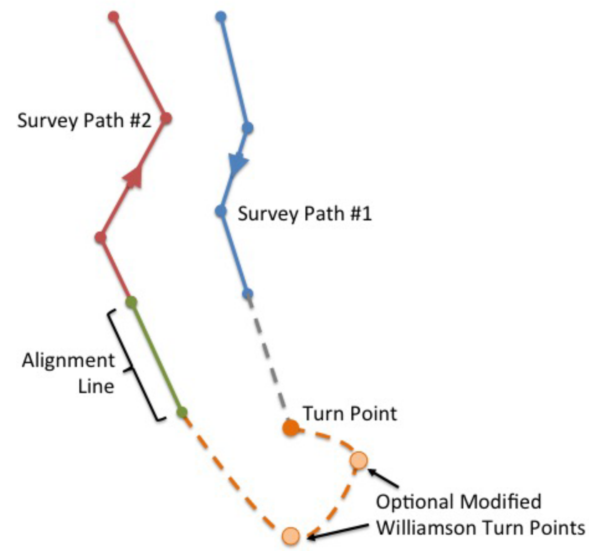


Fig. 4. Example of a planned turn between subsequent survey lines showing the turn point extended from the end of the first line and alignment line extending from the beginning of the second line.

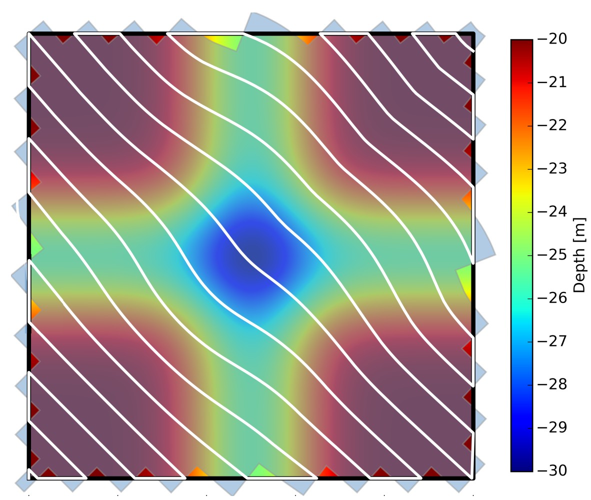


Fig. 5. Custom simulation with generated terrain. Survey paths shown in white, coverage in transparent blue.

affect the minimum swath based decimation. To avoid this, some filtering of the raw data is necessary. For the system implemented, a standard deviation filter is used that maintains a history of the previous swath widths and rejects those that are above a set number of standard deviations from the mean. Since the processing system has not been tested in the field, the length of averaging and standard deviation limits have not yet been optimized, but this is an easily customizable parameter of the system.

IV. Simulation Results

The path planning algorithm is developed and tested using a custom simulation program created for this purpose. After the algorithm was determined to perform suitably, it was

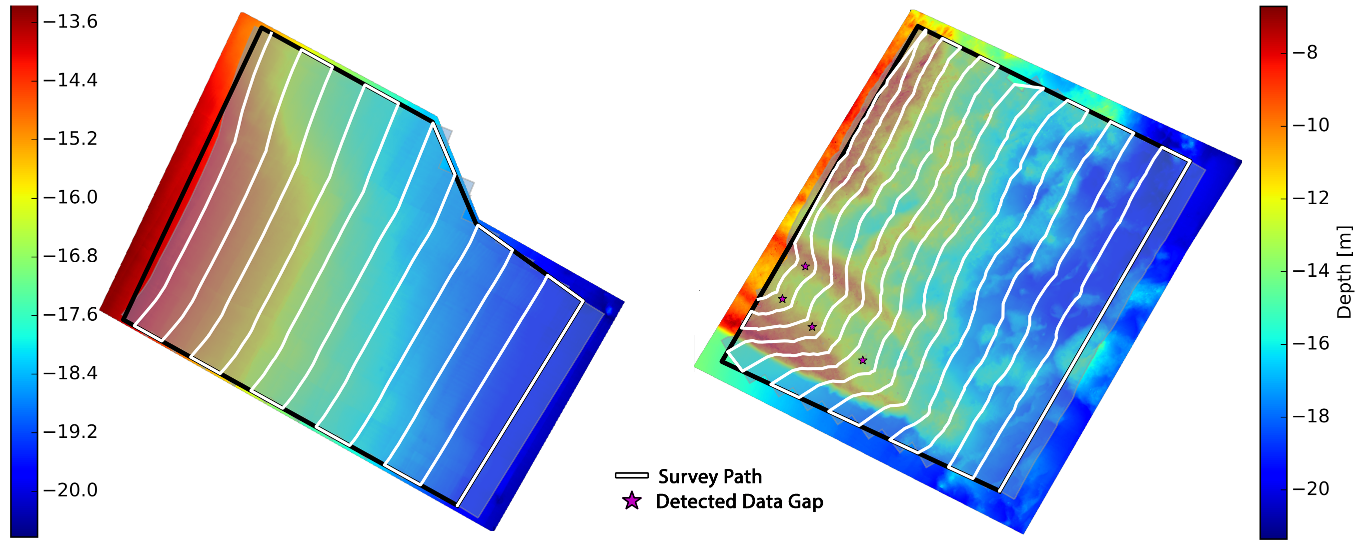


Fig. 6. Custom simulation using actual terrain. Data coverage is shown in transparent blue and holidays marked with stars.

integrated into the MOOS-IvP autonomy environment for deployment on ASVs and further testing in simulation.

A. Custom Simulation Program

The program developed for this research simulates a vessel following a trackline made up of waypoints and gives sonar depth and swath width values from either generated depth patterns or data imported from previous surveys. It implements the full sonar swath recording and path planning algorithm from Section II.

An example of a simulation run on a generated pattern of an "X" shaped depression with a hole in the middle is shown in Figure 5. The survey lines are initially planned at an angle to the edge of the operation region in this example, showing how the lines will be extended and clipped as needed. The distance between lines increases in the deeper areas (blue) causing them to bend around the about. The calculated coverage using this simulator shows gaps at the edges of the survey area, but this is because it does not include the turning points when driving the simulated vehicle. In an actual survey using the turning points and alignment lines, these planned paths would achieve full coverage of the assigned region. This issue is also discussed in more detail by Bourgeois in [6].

The simulation developed for this research can also be run with previously collected and gridded data as a background. A GeoTIFF file is used as the input along with the survey operation region and starting line. The program uses data from near the coast of New Hampshire collected by the 2014 Summer Hydrographic Field Course at UNH [7], and the results are shown in Figure 6. In the relatively flat section on the left, the swaths are spaced closer as the simulated vessel moves inshore, but the survey lines remain fairly parallel. In the more complex terrain of the right section, the paths become bent where the depths change and some holidays are left where dramatic bends were removed from the planned paths. These

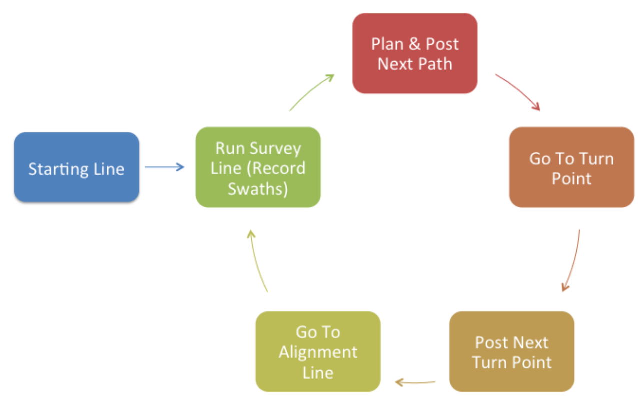


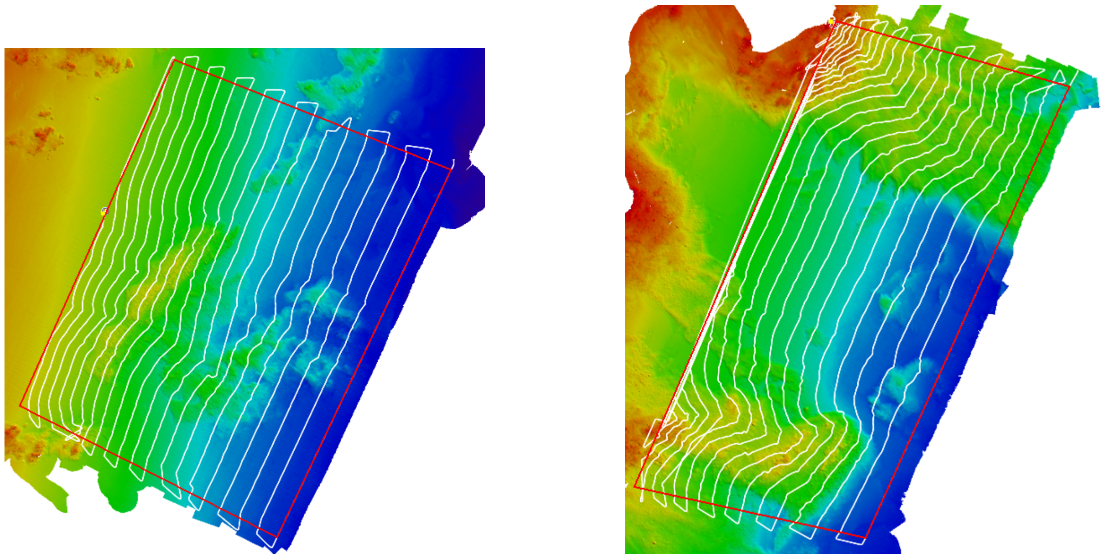
Fig. 7. MOOS behavior and application flow diagram showing states during path planning algorithm and simulation execution.

are marked with stars and can be addressed by additional data acquisition.

B. MOOS-IvP Simulation

The MOOS-IvP autonomy operation environment [8] provides a framework for marine autonomy that utilizes a centralized message passing database which coordinates communication between multiple processes. The public release includes premade autonomous behaviors and applications useful to the operation of marine vehicles. Using this environment the path planning algorithm was integrated with the full autonomy system under development at UNH. MOOS-IvP also provides simulation capabilities which simulate the movements of a boat in a more realistic method than the custom simulation by including elements such as turning and a PID feedback controller for the heading of the ASV.

The path planning algorithm and simulation is implemented into MOOS-IvP as 3 separate MOOS applications. The sonar simulator reads data from a gridded file of previously collected bathymetry, the swath recorder keeps track of both the full



(a) Southern Region

(b) Northern Region

Fig. 8. Simulation results from MOOS-IvP simulation showing larger regions and full turn behavior. A red box denotes the specified operation region and the white lines show survey paths. Bathymetry is shown as a rainbow colored background where blues represent deeper depths and reds shallower.

coverage and decimated swath records and the path planner outputs the next survey line based on the recorded swaths as well as the turn points and alignment lines. The implementation of these core and some auxiliary behaviors discussed in Section III is shown in Figure 7.

Using this more realistic MOOS-based vehicle simulation along with some recently collected data from the UNH 2015 Summer Hydrographic Field Course [9], the path planning algorithm is tested over operation regions matching those used during the human driven multibeam sonar data collection. Due to requirements of the course, lines are required to be run parallel to each other, so a direct comparison with the shape of the lines cannot be made. However, the efficiency gains realized by surveying in this adaptive manner are apparent. In one region, where the lines are run adaptively based on observed swath widths (but still parallel lines), the same number of lines are run by the depth adaptive algorithm as the ones adjusted by field operators. This validates the genrally correct application of the algorithm in simulation. However, the parallel method resulted in large holidays and less overlap in the outer beams than the method presented in this paper. The results of the depth adaptive path plan are shown in Figure 8a.

In a second region, the survey lines for the field course are adjusted only for the shallowest depths expected in the region, a common method for preplanned ASV missions. In that region, the adaptive path planning runs 17 lines along the southern side and 13 in the flatter middle. The lines in the middle end so the remaining lines are shorter on the southern side only. The fixed spacing during preplanned data collection requires 30 lines to be run in the same area. Assuming a similar survey speed, the depth adaptively planned survey would have taken half as long as the static spacing version, a considerable time and fuel savings considering the size of the region. The survey planning results are shown in Figure 8b.

Two differences in the planned paths from what a human coxswain might be expected to follow can be observed in the northern region. Near the lower left there is a path where enough points are eliminated from a bend and that the path overlaps existing coverage. However, since this line remains straight for a long distance, subsequent lines resume a more normal path planning behavior and the overall operation is not affected. Near the upper right corner, an error in the start line position is visible. This is due to a planning the start line before final elimination of points from the survey path and will be improved in future development.

C. *Implementation on Platforms*

The MOOS-IvP autonomy system and the path planning algorithms described in this paper are currently being installed and tested on multiple ASV platforms. The primary research at UNH is focused on installation on a 4 ft long gas powered ASV know as EMILY that will be capable of making single beam sonar depth measurements. From this, an estimated swath will be established assuming the depth would be the same as that detected by the single beam sonar for testing of the adaptive path planning. The algorithm also allows for fixed spacing lines to be generated within the operation region, which is standard operating procedure for actual single beam surveys. More information on the development of this ASV is available in a previous presentation by the authors [10].

V. Conclusion and Future Work

The algorithm for depth adaptive path planning explained in this paper shows promise in its ability to improve the hydrographic surveying workflow for autonomous surface vehicles. The path planning algorithm works for both simple, geometrically generated depth grids as well as complicated seafloors taken from existing survey data. While some differences exist from the paths a human driven launch would take to complete the same area, the planning process is robust enough to be able to complete unknown areas with inputs of only a starting line and a region to survey. The MOOS-IvP autonomy system provides a framework for integration of the path planning within a larger overall mission structure and an addition resource for simulation and testing.

In future work, the MOOS-IvP based autonomy system will also be tested on NOAA-owned electric powered boats with integrated single beam sonars that are currently designed for remote control or preplanned line operation. Eventually, after the acquisition of a more powerful autonomous platform capable of operating a multibeam sonar, the algorithms and behaviors can be tested under the actual conditions for which they are designed.

Also, some minor errors such as incorrect extension of the end of paths and path adaptation to avoid entering already surveyed regions will be added, along with possible improvements to the processing efficiency of the algorithm. While the current method requires human selection of a starting line, it is also desirable for the system to be able to analyze existing data and determine a starting orientation for an assigned survey area and logically subdivide the area if it covers differing aspect slopes.

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REFERENCES

[1] N. Oceanic and A. Administration, *NOS Hydrographic Surveys Specifications and Deliverables*, May 2015.

[2] I. Spatial Integrated Systems, "Demonstration of autonomous maritime navigation (amn) in support of noaa surveying missions," 2012.

[3] E. Galceran and M. Carreras, "Efficient seabed coverage path planning for asvs and auvs," in *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*. IEEE, 2012, pp. 88–93.

[4] C. Fang and S. Anstee, "Coverage path planning for harbour seabed surveys using an autonomous underwater vehicle," in *OCEANS 2010 IEEE-Sydney*. IEEE, 2010, pp. 1–8.

[5] B. S. Bourgeois, P. J. Alleman, J. J. Cheramie, J. Gravley *et al.*, "Autonomous bathymetry survey system," *Oceanic Engineering, IEEE Journal of*, vol. 24, no. 4, pp. 414–423, 1999.

[6] B. S. Bourgeois, D. L. Brandon Jr, J. J. Cheramie, and J. Gravley, "Efficient hydrographic survey planning using an environmentally adaptive approach," DTIC Document, Tech. Rep., 2006.

[7] K. Wylie and T. Ketter, "Summer hydrographic field course 2014," University of New Hampshire, Descriptive Report, July 2014.

[8] M. Benjamin, H. Schmidt, and P. Newman. (2015, May) An overview of moos-ivp and a users guide to the ivp helm - release 15.5. MIT. [Online]. Available: http://oceanai.mit.edu/ivpman/pmwiki/pmwiki.php

[9] D. Manda, O. Irish, M. Valee, A. Kimeni, M. DeStefano, and H. Kurita, "Summer hydrographic field course 2015," University of New Hampshire, Descriptive Report, July 2015.

[10] D. Manda, A. D'Amore, M.-W. Thein, and A. Armstrong, "A flexible, low-cost moos-ivp based platform for marine autonomy research," in *MOOS-DAWG 2015*, July 2015.