Planning Coverage Paths on Bathymetric Maps for In-Detail Inspection of the Ocean Floor

Enric Galceran and Marc Carreras

Abstract—This paper proposes a coverage path planning (CPP) method for inspection of 3D natural structures on the ocean floor charted as 2.5D bathymetric maps. This task is integral to many marine robotics applications, such as microbathymetry mapping and image photo-mosaicing, as we consider an autonomous underwater vehicle (AUV) with hovering capabilities imaging the ocean floor with an orientable sensor, such as a camera or a sonar. While standard lawn mower-type surveys at constant altitude are well-suited for covering effectively planar areas, two major problems arise when tracing such paths over high-relief terrain. First, the sudden depth changes required by such paths imply very costly motions, as moving in the vertical axis is expensive for most AUVs. Second, some time is required to adjust the vehicle depth after a sudden change in the relief, resulting in a varying distance from the target surface which deteriorates the overall quality of the collected imaging data. The method proposed in this paper accounts for these facts and generates different coverage patterns according to terrain’s relief, resulting in a well-suited coverage path for imaging tasks. The proposed CPP method is fast and easy to implement, and provides a valuable tool for planning coverage paths in marine environments. We tested the proposed method on a real-world bathymetric dataset of a lava tongue obtained during recent sea trials in the Santorini caldera in Greece and compares favorably to a standard lawn mower-type survey path.

I. INTRODUCTION

Coverage path planning (CPP) is the task of determining a path that passes a robot or a sensor over all points of a target space while avoiding obstacles. This task is integral to many robotic applications, such as vacuum cleaning robots, painter robots, lawn mowers and automated harvesters, just to name a few. A large body of research has investigated CPP in 2D [1], [2], 2.5D [3], [4], [5] and 3D [6], [7] environments. Applications of CPP in domains such as agricultural robotics [8] and unmanned aerial vehicles (UAVs) [9], [10] have been reported in the literature. However, while many underwater robotics applications, such as microbathymetry mapping, habitat monitoring or image photo-mosaicing, can benefit greatly from the complete coverage guarantees and robustness of CPP methods, their application to underwater environments up to date has been limited. Especially, research on 3D path planning for underwater vehicles so far often only deals with abstract scenarios based on very simple simulations. Examples include sets of randomly placed spheres of different sizes [11] and randomly occupied cells in a grid [12]. Notable exceptions are the recent work in CPP for ship hull inspection tasks presented in [13] and the 6 DOF 3D path planning approach presented in [14]. In general, however, few research has studied CPP in the underwater domain (see Sec. II below for further review of related work).

In this paper, we address the problem of planning a coverage path for in-detail inspection of 3D natural structures on the ocean floor charted as 2.5D bathymetric maps. This is a realistic situation arising in many marine robotics applications, such as seabed image photo-mosaicing, microbathymetry mapping or geological activity characterization. Consider, for example, an area of the ocean floor mapped navigating at a safe distance from the bottom using a bathymetry sonar. A typical task is to select a region of interest (ROI) on the mapped area and inspect it in closer detail, for instance by means of image photo-mosaicing. To accomplish this task autonomously, an automated method to plan an in-detail inspection coverage path on the selected area is required.

To this aim, we propose a 3D CPP method for coverage of bathymetric surfaces. The proposed method is particularly targeted for Autonomous Underwater Vehicles (AUVs) with hovering capabilities. The planned paths lay at a user-provided constant offset distance from the target surface, which allows for sensor imaging. Classical bottom coverage at constant altitude in high relief environments implies sudden adjustments of the AUV’s depth in order to follow the vertical profile. This results in two major problems. First, the frequent sudden depth changes imply a very inefficient motion, as moving in the vertical direction is expensive for most AUVs (due to their design characteristics, among which torpedo shapes are common). Second, some time is required to adjust the vehicle depth after a sudden change in the relief, resulting in a varying distance from the target surface which deteriorates the overall quality of the collected imaging data due to varying resolution. The proposed method accounts for these facts in the planning process and, in high relief areas, it generates a coverage path which follows constant-depth horizontal contours on the target surface. Therefore, the resulting path avoids sudden depth changes.

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∗Bathymetry is the study of underwater depth of lake or ocean floors. In other words, bathymetry is the underwater equivalent to hypsometry (the measurement of land elevation relative to sea level). A bathymetric map is an elevation map of the mapped area.
On the other hand, low-relief, effectively planar regions are covered using a classical lawnmower-type survey at constant altitude, for which the design characteristics of most AUVs available today are optimized for. Specifically, our method identifies high-slope regions and effectively planar regions in the bathymetric map. To cover the high-slope regions, we provide a slicing algorithm which plans coverage paths following constant-depth horizontal bathymetric contours at sequentially increasing depths. The resulting coverage paths provide a fair view angle on the target surface. For coverage of the effectively planar regions, we propose a cellular decomposition approach which generates standard lawnmower-type survey paths at constant altitude. By linking together the paths planned in each region, a full coverage path for the target bathymetric surface is obtained. The proposed method is fast and easy to implement.

We tested the proposed method on a real-world bathymetric dataset of a lava tongue obtained during recent sea trials in the Santorini caldera in Greece. We execute the path in simulation using and compare it to a standard lawnmower-type survey path, showing the benefits of the proposed method. The results obtained in simulation provide valuable information, as the coverage paths generated in this work will be executed by an AUV at sea in scientific missions taking place in the near future.

The remainder of this paper is organized as follows. Sec. II briefly reviews several related CPP methods reported in the literature. The proposed CPP method for bathymetric surfaces is described in Sec. III. Sec. IV introduces the real-world bathymetric dataset obtained in recent sea trials upon which we test the proposed method. The method is then applied to the dataset and results of the simulated path execution are reported in Sec. V, comparing them to a lawnmower-type survey path. Finally, concluding remarks and directions for further research are given in Sec. VI.

II. RELATED WORK

An extensive body of research has addressed the CPP problem in planar areas (see [1] for a survey). However, there are fewer approaches in the literature which address coverage of 3D spaces.

Atkar et al. [6] presented a sensor-based coverage algorithm for 3-dimensional surfaces. This algorithm is proven complete under the assumption that the robot is equipped with a 360° range sensor. In a later work, they proposed an off-line CPP method specifically targeted for spray-painting of automotive parts [7]. The algorithm accounts for the fact that the target surface not only needs to be completely covered, but also the resulting paint deposition must meet certain uniformity requirements. To achieve uniform coverage, their proposed method takes a CAD model of the target automotive parts segments it into topologically simple regions of similar curvature. Then, individual coverage paths are generated for each region.

Cheng et al. presented an off-line approach for planning time-optimal trajectories for UAVs performing 3D coverage of urban structures presenting 2.5D features [4]. First, they simplify the structures to be covered, namely buildings, into hemispheres and cylinders. Then, trajectories are planned to cover these simpler surfaces. Their proposal is validated in hardware-in-the-loop simulations using a fixed-wing aircraft.

In the underwater domain, CPP research on planar environments has addressed mainly in the context of mine countermeasure applications [15], [16]. Regarding 3D environments, Hert et al. presented an AUV-targeted algorithm which allows for coverage of 2.5D environments [3]. The paths generated by the algorithm cover completely the water column, which is not desired in most applications. In this sense, Lee et al. proposed an extension of this algorithm for covering only areas close to the seabed (that is, avoiding coverage of the water column) [5]. However, motion constraints of the vehicle were not taken into account in these works. Recently, Englot et al. introduced an off-line, sampling-based algorithm to achieve probabilistically complete coverage of complex, 3-dimensional structures [13]. Their target application is autonomous ship hull inspection. While this algorithm can handle surfaces of unprecedented complexity, it requires an accurate 3D model of the target surface and time in the order of several minutes to plan the coverage path.

III. COVERAGE PATH PLANNING ON BATHYMETRIC MAPS

Our proposed CPP method operates on a bathymetric map, \( B(x, y) \), provided as input. For every point \((x, y)\) on the mapped area, \( B(x, y) \) returns its depth. The proposed CPP method is a three-step process. First, high-slope regions are identified on the bathymetric map. Next, a constant-depth horizontal-pattern coverage path is generated in the identified high-slope regions using a slicing algorithm. Finally, a coverage path is planned for the remaining effectively planar regions of the target surface. This later coverage path is generated using a cellular decomposition approach where the already processed high-slope regions are treated as obstacles.

A. Identifying High-Slope Regions

First, we identify high-slope regions where a horizontal coverage pattern is desired. To that aim, a “slope map”, \( S(x, y) \), is calculated for the mapped area as the norm of the gradient of \( B \), that is:

\[
S(x, y) = ||\nabla B|| = \left\| \frac{\partial B}{\partial x} \hat{i} + \frac{\partial B}{\partial y} \hat{j} \right\|.
\]

where \( \hat{i}, \hat{j} \) are the standard unit vectors in the \( X \) and \( Y \) axis, respectively.

Then, we apply a user-defined slope threshold, \( \delta_s \), to \( S \) to obtain a binarized map

\[
T(x, y) = \begin{cases} 
1 & \text{if } S(x, y) \geq \delta_s \\
0 & \text{if } S(x, y) < \delta_s 
\end{cases}.
\]

In order to filter out small regions, we apply the dilate and erode morphological operations [17] to \( T \) using an appropriate structuring element. Finally, the bounding boxes of the connected components of \( T \) are calculated. Each bounding box will be treated as a high-slope region.
B. Covering High-Slope Regions using the Slicing Algorithm

We propose a slicing algorithm to generate an in-detail coverage path for each identified high-slope region. The proposed algorithm draws inspiration from the algorithm proposed in [6]. The main idea is to intersect a horizontal slice plane with the target surface at incremental depths, and then link these intersections.

Consider a point-mass robot equipped with a limited field-of-view (FOV) sensor. The sensor FOV is determined by an aperture angle, α, and a maximum range \( r_{\text{max}} \), as shown in Fig. 1. The sensor FOV can be oriented towards a given point in the target surface by means of a pan and tilt unit. To image the target surface with the sensor, the robot navigates at a user-defined fixed offset distance, \( \Omega < r_{\text{max}} \), from the target surface. Note that \( \Omega \) can be chosen to accommodate a robot modeled as a sphere with non-zero radius.

The sensor footprint on the target surface determines the spacing between successive slice planes, \( \Delta \lambda \) (where \( \lambda \) is the current slice plane depth), as shown in Fig. 2 (top). Note that the footprint extent depends on the curvature of the target surface on the imaged area. We approximate the footprint extent as a circle of radius \( r = \Omega \tan \frac{\alpha}{2} \), and therefore \( \Delta \lambda = 2r \).

The slicing algorithm is detailed in Algorithm 1. The algorithm is applied to each identified high-slope region of the bathymetric map. For each high-slope region, the algorithm takes as input the corresponding subset of the bathymetric map \( B(x, y) \), the offset distance, \( \Omega \), and the slice plane spacing, \( \Delta \lambda \). First, it initializes the coverage path, \( p \), as empty (line 1) and the current slice plane depth, \( \lambda \), as the minimum depth in \( B \), plus the slice plane spacing (line 2). The algorithm runs at incremental values of \( \lambda \) until \( \lambda \) surpasses the maximum depth in \( B \) (line 3). At each depth level, a horizontal plane is intersected with the bathymetric surface (line 4). The function \texttt{INTERSECT}() returns the list of closed edges composing the intersection, as illustrated in Fig. 2. Next, a coverage path for the current slice plane is generated by linking each edge in the list to the next (function \texttt{LINK_EDGES}(), line 5). The function \texttt{LINK_EDGES}() uses the function \texttt{LINK}() to generate the “link paths”. \texttt{LINK}() traces a straight line path between two given points. If the straight line intersects the bathymetric surface, it traces the projection of the line on the bathymetric surface. Finally, the path generated at the current depth level is linked and concatenated to the global path (line 6). The value of \( \lambda \) is increased (line 7) and the process continues. Notice that, when the while loop exits, the path generated so far lays exactly on the bathymetric surface. The path is then projected onto the offset surface by \texttt{OFFSET_PATH}(), which projects all points in the path along the bathymetric surface normal by an offset distance \( \Omega \). The result is a coverage path on the desired offset surface. Using this very same surface normal, the orientation of the robot and the sensor pan and tilt angles are set for the sensor to point normally to the target surface along all points in the path in order to maximize imaging quality.

Algorithm 1: Slicing Algorithm

\begin{algorithm}[h]
\begin{algorithmic}[1]
\Require \text{High-slope region of a bathymetric map, } B(x, y)\\
\Ensure \text{Slice plane spacing, } \Delta \lambda\\
\State \( p \leftarrow \emptyset \); \label{line1}
\State \( \lambda \leftarrow \min_{x,y} B(x, y) + \Delta \lambda \); \label{line2}
\While {\( \lambda < \max_{x,y} B(x, y) \)} \label{line3}
\State \( E \leftarrow \text{INTERSECT}(\lambda, B) \); \label{line4}
\State \( l \leftarrow \text{LINK_EDGES}(E) \); \label{line5}
\State \( p \leftarrow p \cup \text{LINK}(p.\text{end}, l.\text{start}) \cup l \); \label{line6}
\State \( \lambda \leftarrow \lambda + \Delta \lambda \); \label{line7}
\EndWhile
\State \( p \leftarrow \text{OFFSET_PATH}(p, \Omega) \); \label{line8}
\State \Return \( p \) \label{line9}
\end{algorithmic}
\end{algorithm}

C. Covering the Effectively Planar Regions using the Rectilinear Decomposition Algorithm

We propose a rectilinear cell decomposition algorithm to cover the remaining effectively planar areas. The idea of the algorithm is to decompose the space outside the high-slope areas into rectilinear cells. Then, individual coverage paths are generated within each cell. Each individual path within a cell consists of a lawnmower-type motion at a fixed offset distance above the target surface. This algorithm we propose bears similarity with other CPP algorithms for planar environments, such as the trapezoidal decomposition [18], the boustrophedon decomposition [19] or the \( CC_R \) algorithm [20].

Consider a horizontal plane above the target bathymetric surface where the bounding boxes of the high-slope regions discussed above represent obstacles. The rectilinear decomposition is generated by sweeping a vertical slice segment from left to right through this plane. Whenever the slice segment encounters the boundary of high-slope region bounding box, a vertical cell division along the current slice segment is placed. The cell division extends upwards and downwards until it encounters the boundary of another obstacle region or until the boundary of the mapped area is reached. Once constructed, the decomposition is encoded as an adjacency graph. In the adjacency graph, each node represents a rectilinear cell, and an edge represents an adjacency relationship.
of Athens with the infrastructure support of Hellenic Centre for Marine Research (Greece). During the Caldera 2012 trials, the GIRONA 500 AUV [21] was used for characterization of hydrothermal activity within the caldera via optical mapping and for collection of other oceanographic data. The GIRONA 500 AUV, shown in Fig. 4, is a reconfigurable vehicle rated for depths up to 500 m. It is equipped with a complete sensor suite including cameras and bathymetry sonar.

In one of the missions carried out during the Caldera 2012 trials, the GIRONA 500 AUV gathered bathymetric data on a lava tongue in the vicinity of the caldera. The vehicle mapped the area navigating at a safe altitude of 15 m from the bottom. The mapped area is 427.5 m by 406.5 m, with depths ranging from 284 m to 363 m.

A 100 m by 250 m ROI on the mapped area was selected for further in-detail inspection. The selected ROI comprises the boundary of the lava tongue, and is therefore of high geological interest. Fig. 5 shows the bathymetric maps of the entire mapped area and of the selected ROI.

V. EXPERIMENTAL RESULTS

We apply our proposed CPP scheme to the selected ROI of the bathymetric map introduced above. The objective is to

IV. THE CALDERA 2012 DATASET AND THE GIRONA 500 AUV

We now introduce the real-world lava tongue bathymetric map and the AUV we use to test our CPP scheme. The lava tongue bathymetric map was obtained during the Caldera 2012 sea trials, which took place from July 13th to July 23rd within the caldera of Santorini (Greece). These sea trials were part of a joint project involving an international and multidisciplinary team, formed by the Institut de Physique du Globe de Paris (France), the University of Girona (Spain), the Woods Hole Oceanographic Institute (USA), the University of Athens with the infrastructure support of Hellenic Centre for Marine Research.

The generated path is then linked in the order determined by the exhaustive walk through the depicted adjacency graph. An exhaustive walk through the path is finally projected onto the target surface. At level $\lambda_1$, the intersection comprises one single closed edge, $e_{\lambda_1,1}$. Path $l_1$ links the partial path at $\lambda_1$ with the partial path at $\lambda_2$. At $\lambda_2$, the intersection comprises two closed edges, $e_{\lambda_2,1}$ and $e_{\lambda_2,2}$. Those two edges are linked by $l_2$ to form the final path.

between two cells (i.e., cells that share a common boundary). Then, an exhaustive walk through the graph (i.e., a path that visits all the nodes in the graph) is computed to determine the order in which the cells will be covered. Once the order is determined, individual lawnmower-type paths are generated within each cell. Generation of such lawnmower-type motions, also called seed spreader motions, is well documented in the literature [19], [2]. The individual paths within the cells are then linked in the order determined by the exhaustive walk using straight line paths. The generated path is then projected onto the target surface, i.e., for each point $(x, y)$ in the path, its depth value becomes $B(x, y)$. From the target surface, the path is finally projected onto the offset surface using the OFFSET_PATH() function of Algorithm 1. Fig. 3 illustrates the application of the rectilinear decomposition to an example workspace and its corresponding adjacency graph.

![Fig. 2: 3D view (top), top view (middle) and side view (bottom) of the slicing algorithm applied at two different depth levels ($\lambda_1, \lambda_2$) on an example target surface. At level $\lambda_1$, the intersection comprises one single closed edge, $e_{\lambda_1,1}$. Path $l_1$ links the partial path at $\lambda_1$ with the partial path at $\lambda_2$. At $\lambda_2$, the intersection comprises two closed edges, $e_{\lambda_2,1}$ and $e_{\lambda_2,2}$. Those two edges are linked by $l_2$ to form the final path.](image)

![Fig. 3: Rectilinear decomposition of an example workspace. Cells are labeled $C_1, \ldots, C_7$. Each curved line $e_{ij}$ represents adjacency graph edge between cells $C_i$ and $C_j$. Dashed vertical lines represent cell boundaries. An exhaustive walk through the path is finally projected onto the offset surface.](image)

![Fig. 4: The GIRONA 500 AUV during the Caldera 2012 sea trials.](image)
obtain a coverage path on the ROI at a 2 m offset distance from the target surface to collect imaging data with the GIRONA 500 AUV. A 60° aperture angle camera is used.

Values in the slope map, $S(x, y)$ of the ROI range between 0.001 and 0.622. A threshold $\delta_s = 0.5$ is applied to the slope map. Fig. 6 shows the slope map and the single identified high-slope region after applying the described morphological operations. The resulting rectilinear decomposition of the remaining space is comprised of two cells, laying to the left and above the high-slope region.

The slicing and rectilinear decomposition algorithms are then applied to the corresponding regions. The resulting path is shown in Fig. 7. The algorithms are implemented in unoptimized MATLAB and generate the full coverage path in less than 5 seconds on a standard PC.

We next simulate the execution of the planned trajectory with UWSim [22], an underwater robotics simulation package. The very same software architecture which runs on the GIRONA 500 during sea trials is used in conjunction with UWSim to carry out the simulation, thus allowing for immediate transition from simulation to real-world missions. A dynamic model of the vehicle is used in the simulation. The robot can navigate at a maximum speed of 1.5 m/s.

We compare the path obtained using our bathymetric CPP scheme and a standard constant-altitude lawnmower-type survey path in Table ??, where the path lengths and execution

Fig. 5: Bathymetric map of a lava tongue near the caldera of Santorini with the ROI approximately indicated by the rectangle (a). Bathymetric map of the selected ROI (b).

Fig. 6: Slope map of the Caldera 2012 bathymetric dataset (a) and the high-slope region thresholding (b). The bounding boxes in both subfigures indicate the single identified high-slope region.

Fig. 7: Resulting in-detail coverage path for the Caldera 2012 dataset. Point of view in (a) is the same as in Fig. 5(b). A lateral point of view is provided in (b), showing in more detail the horizontal contours on the high-slope region.
times for each region, for the full coverage path and for the 
lawnmower survey path are shown.

Note that, although the classical survey path is shorter, it 
takes almost as long to execute. This is mainly due to 
the sudden depth changes which are difficult for the 
AUV to accommodate. While we have not quantified the 
vertical/lateral energy cost ratio of our vehicle, this difficulty 
is clearly observable in the simulation. It can be qualitatively 
observed that our method better accommodates these motion 
constraints of the AUV. The method might be less beneficial 
for an AUV with a lower vertical/lateral energy cost ratio, 
such as a spherical vehicle. However, such AUV designs are 
not common nowadays.

Finally, we note that the constant-depth horizontal edges 
 traced by our method provide a fair, normal-to-target view 
angle for imaging tasks, whereas the sudden depth changes of 
the classic survey path bring about steep view angles which 
negatively affect imaging quality.

### TABLE I: Maximum, final and average uncertainty (SSE) 
and path length for a path planned using a standard 
lawnmower-type path with two arbitrarily selected cross-tracks.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Max. unc.</th>
<th>Final unc.</th>
<th>Avg. unc.</th>
<th>Path length</th>
</tr>
</thead>
</table>

VI. CONCLUSION AND FURTHER WORK

We presented a CPP method including two algorithms for 
coverage of bathymetric surfaces. The method takes into 
account the slope of the areas on the bathymetric surface 
and generates paths suiting the characteristics of effectively 
planar regions and high-slope regions. We demonstrated the feasibility of the method by planning a coverage path on 
a real world bathymetric dataset.

Execution of the planned paths will take place in sea trials 
in the near future. A map-based localization approach will 
be used together with a standard PI path following controller 
to carry out the execution. We plan to use this method intensively as a standard tool to obtain valuable scientific 
data in our future sea trials, especially in the context of the 
ongoing MORPH European research project, which includes 
mapping and inspection of structures such as coral reefs. 
A more detailed study of the benefits of the proposed CPP 
method with respect to the vehicle vertical/lateral energy 
cost ratio will be conducted in the near future. Further work 
will include incorporating localization uncertainty into the 
planning phase in order to improve path quality. Generating 
coverage paths for marine environments such as those 
addressed in this paper using only sensor information, that 
is, without an a priori bathymetric map, is also part of our 
future research roadmap.

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