

Automating Seafloor Inspection Using Autonomous Underwater Vehicles

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Abstract – We present a novel method for planning and executing paths for inspection of complex structures on the ocean floor (such as seamounts or coral reefs) using autonomous underwater vehicles (AUVs). The method consists of two phases. First, a path that allows the AUV to pass its sensors over all points on the target structure is automatically planned before the mission (off-line). In the second phase, the AUV executes the planned path using its sensors to correct the path according to its perception of the target structure to account for localization error and avoid collisions. This contrasts with most existing inspection planning methods, which rely on the unrealistic assumption of an idealized path execution. We demonstrate the efficacy of our method in experiments at sea using our GIRONA 500 AUV where we obtain 3D maps of the inspected sites.

Keywords – Autonomous seafloor inspection, Coverage Path Planning, Autonomous Underwater Vehicles.

I. INTRODUCTION

Many underwater robotics applications require an autonomous underwater vehicle (AUV) to pass its sensors over all points of a target area. In a typical mission, an AUV follows a lawnmower-like path pre-planned by a human operator while. While executing the pre-planned path, the vehicle typically maintains a safe altitude from the sea bottom to avoid collisions using altitude measurements from a down-looking echosounder. However, this approach does not account for any unforeseen obstacles in the survey path-planning phase, arising a collision threat. Moreover, since only simple altitude measurements are used, the AUV must fly at a conservative distance to avoid collision with the bottom in rugged terrain. On the other hand, from the perspective of imaging applications (optical or acoustic), following the elevation profile of the terrain at a conservative altitude does not provide satisfactory results in rugged terrain. As illustrated in Fig. 1, a survey at a safe altitude from the bottom provides an askew angle of incidence with respect to the bottom normal, which results in poor imaging. In contrast, an angle of incidence parallel to the bottom normal is desired in these applications.

These limitations can be addressed in the context of coverage path planning, which is the task of passing a sensor over all points in a target surface while avoiding obstacles. Such task is integral to all the applications mentioned above. However, although coverage path planning has been studied in 2D [1], 2.5D [2], [3], [4] and 3D [5] environments and in domains such as agricultural robotics [6] and unmanned aerial vehicles (UAVs) [7], [8], little attention has been given to the coverage path planning problem in underwater environments, especially in complex, rugged terrain.

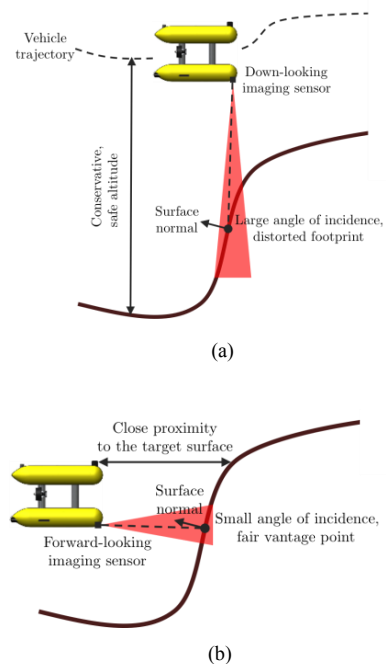


Fig. 1. Askew angle of incidence provided by constant, safe altitude survey (a) in contrast to the fair viewing point obtained by imaging the surface in parallel to its normal (b).

Exceptions are our prior work in off-line coverage path planning [9] and the method by Englot et al. for ship hull inspection [10]. Nonetheless, those coverage path planning techniques rely on an idealized execution of the path during the mission where the vehicle follows exactly the geo-referenced path without going off course. This is an unrealistic assumption, since real-world AUVs will suffer localization error due to GPS fix uncertainty while at the surface and dead-reckoning drift while under water, among other factors.

In this paper, we present a 3D coverage path planning approach for inspection of complex seafloor structures that addresses the aforementioned issues. Our method initially plans a coverage path using a chart of the target region. The resulting path completely covers the target structure by following its contours at uniformly spaced depths maintaining a fixed offset distance from the structure. Furthermore, unlike previous approaches, our method does not rely on an idealized execution of the path. To handle the vehicle's position uncertainty, we present a novel on-line re-planning technique based on stochastic trajectory optimization to adapt the initially planned coverage path in real-time using range sensor measurements. The resulting path is smooth and provides successful coverage under

bounded position error. We validate our method in experiments at sea with GIRONA 500, a reconfigurable AUV equipped with pencil-beam sonar for obstacle detection and side-looking bathymetry sonar and a stereo camera as payload sensors. Our experiments comprise coverage of a concrete block of a breakwater structure in a harbor and coverage of a seamount rising from 40 m depth to 27 m depth. Results show that our method successfully adapts the planned paths in agreement with real-time perception on site. Additionally, we present 3D surface reconstructions and optical maps resulting from the data collected in the coverage tasks that demonstrate the high quality of the data products enabled by our coverage path planning method.

II. OFF-LINE PLANNING PHASE

The first phase of our coverage method consists in planning a coverage path off-line using prior knowledge of the target environment. We build upon our previous work [9] to plan a coverage path for our target surface. While in our previous work we presented a method for covering both effectively planar and high-relief regions, here we focus on planning coverage paths for high-relief regions only. Given an *a priori* bathymetric map of the target region our algorithm plans a coverage path by intersecting a horizontal plane with the map at uniformly spaced depths. The procedure is illustrated in Fig. 2.

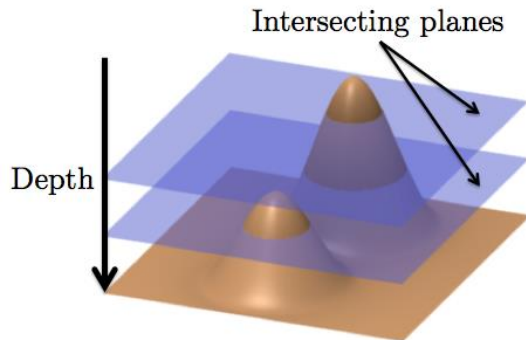


Fig 2. The off-line coverage path planning procedure generates a coverage path by intersecting horizontal planes with an *a priori* bathymetric map at uniformly spaced depths.

The inter-plane spacing is determined by the robot's sensor footprint. The intersections are finally offset by a desired distance Ω from the target surface and linked together to form a coverage path. We refer the reader to [X] for further details on the algorithm.

III. REAL-TIME RE-PLANNING PHASE

Once a coverage path has been planned off-line, we propose an iterative re-planning method to adapt the path in real-time using range sensor information. Our re-planning method incrementally constructs and maintains a 3D map of the environment onboard the vehicle using range data. In each iteration, our algorithm operates on the piece of the off-line path yet to be processed within a given

range from the robot. That piece of the off-line path is then optimized using a trajectory optimization algorithm that, given an appropriate cost function, produces a smooth path at the desired offset distance from the target structure. The vehicle then executes the optimized trajectory. The process repeats until the end of the off-line path is reached. The algorithm is detailed in Table 1.

Input:

- Initial coverage path as a list of K waypoints $w_0 \dots w_K$
- Current environment's map, M
- Re-planning step radius, R

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1  Navigate to initial waypoint  $w_0$ 
2   $i := 0$ 
3  while  $i < K$  do
4     $x := \text{GetRobotPosition}()$ 
5     $\text{stepPath} := \emptyset$ 
6    while  $\text{Distance}(x, w_i) < R$  and  $i < K$  do
7       $\text{stepPath.append}(w_i)$ 
8       $i := i + 1$ 
9     $\text{adjustedWaypoint} := \text{AdjustWaypoint}(\text{stepPath.GetLast}())$ 
10    $\text{stepPath.SetLast}(\text{adjustedWaypoint})$ 
11    $\text{optimizedPath} := \text{STOMP}(\text{stepPath}, M)$ 
12    $\text{ExecutePath}(\text{optimizedPath})$ 

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Table 1. Real-time coverage path re-planning algorithm.

In each iteration, the algorithm takes the off-line *sub-path* composed of all unprocessed waypoints within given range R from the vehicle (lines 4-8). The magnitude of R must be smaller than the maximum sensor range used to perceive the target structure since the environment is still unknown beyond that limit. Next, the last waypoint on the sub-path (the most distant from the vehicle) is projected along the mapped surface normal using the *AdjustWaypoint()* function so it lays at the desired distance from the target structure (lines 9-10). This step is necessary because the first and last waypoints of the initial sub-path do not change during the re-planning process. Then, the sub-path is "deformed" so it keeps the actual desired offset distance from the target structure (recall that, due to localization error, the position of the target structure with respect to the vehicle may vary from the map on which the off-line path has been planned). We use the Stochastic Trajectory Optimization for Motion Planning (STOMP) algorithm [11] for that matter. STOMP explores the space around an initial trajectory (in our case, the within-range- R part of the off-line path) by generating noisy trajectories, which are then combined to produce an updated trajectory with lower cost. In each iteration, STOMP optimizes a cost function based on a combination of smoothness and application-specific costs, such as constraints, obstacles or motor torques. An important characteristic of this algorithm is that it does not use gradient information, and so general costs for which derivatives are not available can be included in the cost function. To achieve our objective of keeping the path at the desired offset distance, we provide the following application cost function to STOMP:

$$q(\theta) = \sum_{t=0}^T | \|\theta_t - c_t\| - \Omega |,$$

where θ is the trajectory discretized in T time-steps, c_t is the closest point of the target structure to θ_t and Ω is the

desired offset distance. Finally, the optimized path is executed (line 12) and the process repeats until the end of the off-line path is reached.

IV. THE GIRONA 500 AUV

We tested our method using the GIRONA 500 AUV [12], a reconfigurable vehicle rated for depths up to 500 m shown in Fig. 3. GIRONA 500 is a hovering-capable AUV actuated in 4 DOFs: surge, sway, heave and yaw. The two upper hulls contain flotation foam and electronics housing and are positively buoyant. The lower hull contains the heavier components such as the batteries and the payload. Thanks to this arrangement, GIRONA 500 is passively stable in roll and pitch. The overall dimensions of the vehicle are 1 m height, 1 m width, and 1.5 m length weighing less than 200 Kg. The vehicle is equipped with a navigation sensor suite including a pressure sensor, a Doppler velocity log (DVL), an inertial measurement unit (IMU) a GPS to receive fixes while at the surface, and a horizontally-scanning SeaKing pencil-beam sonar by Tritech, whose range measurements we use to maintain the environment's map. For our coverage experiments, GIRONA 500 additionally mounts a side-looking Delta T bathymetry sonar by Imagenex.

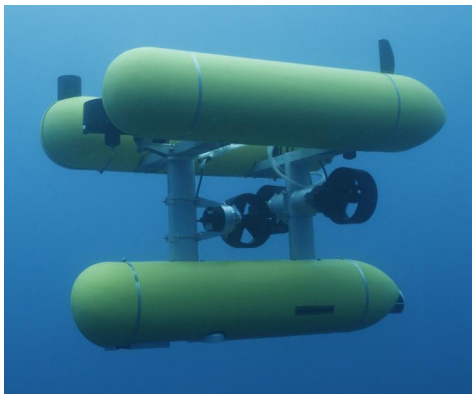


Fig. 3. The GIRONA 500 AUV.

V. RESULTS

We have tested our method by performing two coverage tasks with the GIRONA 500 AUV. In the first task we cover a concrete block of a breakwater structure in a harbor. In the second task, we cover a 13 m high seamount. In both experiments we planned an off-line path with an offset distance of 10 m, with re-planning steps given by a range $R = 5$ m. Our re-planning algorithm has been implemented in Python and integrated in the rest of GIRONA 500's software architecture using the Robot Operating System (ROS) framework. The algorithm produces an optimized path at each re-planning step in a fraction of a second.

We validate the benefits of our method for 3D mapping using range data. Our 3D mapping results show how the paths planned with our method are useful in mapping complex 3D structures, not amenable for traditional 2.5D

mapping. The unorganized range data collected by the bathymetry sonar promotes the use of 3D surface reconstruction techniques. More precisely, we apply the screened Poisson method [13] to recover a triangle mesh resembling the surface described by the range data. All the data products we show are the direct result of the 3D mapping techniques we use, without any manual tuning or refinement.

A. Coverage of a Block of a Breakwater Structure

The first coverage task in which we test our method serves as a minimal test of our implementation. The target structure is a concrete block of a breakwater structure composed of twenty of such blocks. Each block's footprint is 5-by-5 m, spanning from 2 m above the surface down to the sea bottom at 10 m depth. This structure is located in the harbor of Sant Feliu de Guixols, in the Costa Brava in Catalonia, Spain. In this minimal validation experiment, we target the right-most block of the structure and we plan a coverage path of a single contour at 5 m depth (as shown in Fig. 4).

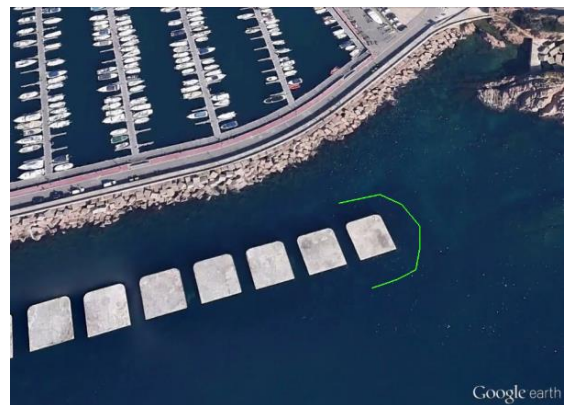


Fig. 4. Concrete block off-line coverage plan plotted using Google Earth.

Fig. 4 shows also the path resulting from the off-line planning phase plotted using Google Earth. Note that the path is not closed (it resembles a semi-circle) since there is not enough clearance between the concrete blocks for the vehicle to go through. Therefore the path provides coverage on only three of the four vertical faces of the block.

The trajectory followed by the robot during the on-line execution and re-planning phase is shown in Fig. 5 with the depth-colored raw range data acquired by the side-looking bathymetry sonar. It can be observed that the resulting trajectory provides full sensor coverage of the target structure. As a validation of the coverage trajectory executed by the AUV, Fig. 6 shows the surface reconstructed from the raw range data. Note how the point cloud depicted in Fig. 5 is far from ideal, as it contains high levels of noise and outliers coupled with registration errors. Although some undesirable roughness and artifacts show up, the overall structure of the three surveyed walls of the block is recovered successfully.

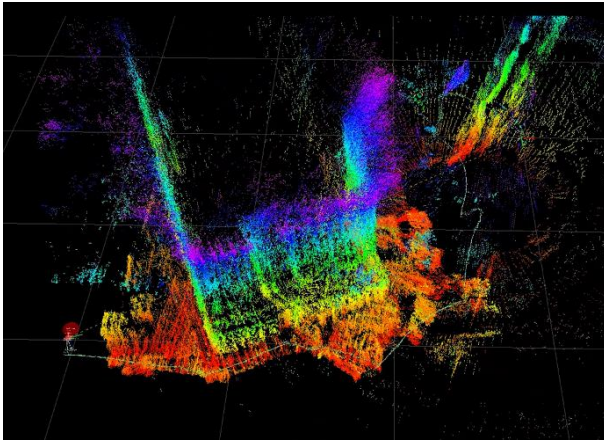
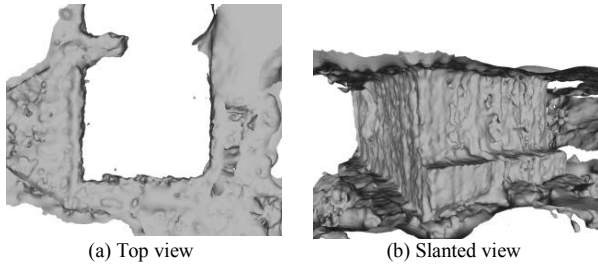


Fig. 5. Trajectory executed by GIRONA 500 during the concrete block coverage experiment using our real-time re-planning method with the depth-colored raw range data provided by the bathymetry sonar.



(a) Top view (b) Slanted view
Fig. 6. Surface reconstruction of the concrete block using range data.

B. Coverage of “l’Amarrador” Seamount

Our second coverage task targets “l’Amarrador” seamount, which rises from 40 m up to 27 m depth. It is located approximately 1 Km off the harbor of Sant Feliu de Guixols. The off-line coverage plan for this site, shown in Fig. 7, consists of 3 contours at an offset distance $\Omega = 10$ m from the seamount. The 3 contours are spaced 1 m in the vertical axis. These parameters provide redundant coverage, which is of interest to us for testing SLAM and 3D reconstruction algorithms.

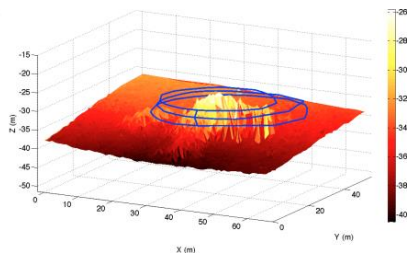


Fig. 7. Off-line coverage plan for “l’Amarrador” seamount.

Fig. 8 shows an instant of the on-line re-planning and execution phase, where GIRONA 500 is modifying the initial trajectory so it agrees with the sonar range data of the seamount perceived in real-time. The overall trajectory provides successful coverage of the seamount. Indeed, Fig. 9 shows the reconstructed surface from the raw range data in Fig. 8. Despite some small artifacts, the surface faithfully represents the seamount’s shape, increasing by far the resolution from the off-line model in Fig. 7.

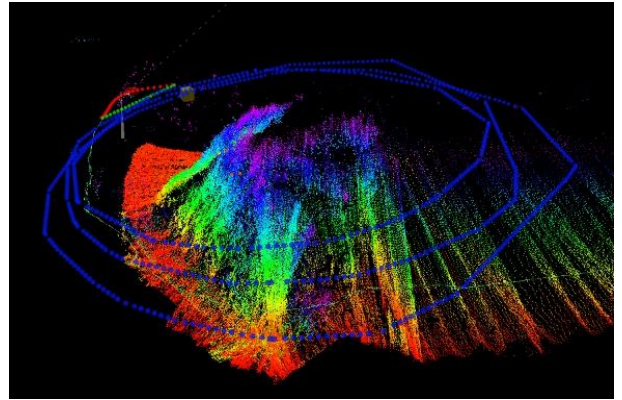
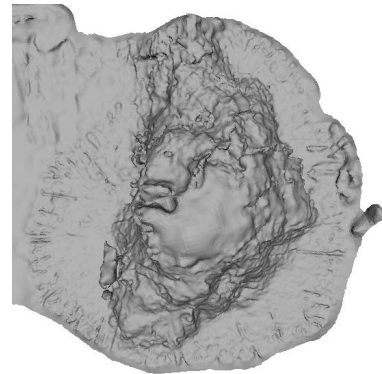
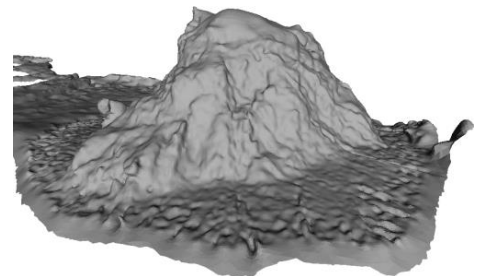


Fig. 8. On-line re-planning on “l’Amarrador” seamount. The blue-dotted line represents the off-line plan; the green-dotted line represents the initial trajectory for the current replanning step; the red-dotted line represents the optimized trajectory, which the robot is executing at that particular time instant. The depth-colored range data acquired by the bathymetry sonar is also displayed.



(a) Top view



(b) Slanted view

VI. CONCLUSION

This paper has presented a 3D coverage path planning approach for inspection of complex structures on the ocean floor. The method first plans a path off-line on a bathymetric chart of the target area. In a second phase, rather than relying on an idealized path execution, an on-line re-planning algorithm uses range data to correct the path on-line. The result is a robust inspection planning method that can deal with bounded AUV localization error. We have tested our algorithm in a harbor and in a seamount, achieving successful coverage of the target structures. Moreover, we have presented 3D maps resulting

from the data obtained during the experiments that validate the paths generated by our coverage path planning method.

At the moment, we are working in further testing the algorithm in different environments. We plan to analyze our algorithm in the future to investigate its theoretical guarantees. Finally, we would like to integrate our off-line planning method in an open AUV mission planning suite, such as MB-System, to allow users to use our technique off-the-shelf for planning inspections of complex seafloor structures.

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