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# 3D Reconstruction of seabed surface through sonar data of AUVs

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Autonomous underwater vehicles (AUVs) are widely used to explore the mysterious underwater world. Following along predefined spatial paths, AUVs are able to gather valuable seabed information in a designated area by recruiting sonar suites. The acoustic data collected by AUVs are usually in the type of point cloud with range information. Hence, how to reconstruct the topography of seabed via 3D point cloud data is the key to build the 3D seabed map. In order to address the problem, the paper presents a practical mesh method to achieve an accurate reconstruction of seabed surface from raw sonar records. Sonar data processing consists of three stages: point clearing, point normal and 3D surface reconstruction. Simulation results show the effectiveness of the proposed approach.

**[Keywords:** AUVs, sonar data, Delaunay triangulation, triangular mesh, 3D seabed reconstruction**]**

## Introduction

3D Seabed Mapping through Autonomous underwater vehicles (AUVs) with acoustic sensors has been more and more widely studied these years in order to explore the underwater environment[1,2]. In order to design and achieve a robust implementation of 3D Seabed Mapping, 3D surface reconstruction approaches are studied in this paper. Existing methods to reconstruct surface can be broadly categorized into three groups: (1) through the use of computational geometry techniques[3,4,5,6,7], (2) by directly fitting a surface to the point samples[8,9], and (3) by fitting a 3D function to the point samples and then extracting the reconstructed surface as an iso-surface of the implicit function[10,11,12,13,14]. The computational geometry based methods proceed by computing either the Delaunay triangulation or the dual Voronoi diagram of the point samples. However these methods work less satisfactorily when the point samples are not uniformly distributed over the surface of the model. Surface fitting methods deform a base model to optimally fit the input sample points, but these methods tend to be restrictive as the topology of the reconstructed surface is required to be the same as the topology of the base shape, limiting the kind of models reconstructed by using this method. The third class of approaches use the point samples to define an implicit function in 3D and then extracts the reconstructed surface as an iso-surface of the function. The advantages of these approaches are in two-folds. First, the extracted surface is always guaranteed to be water-tight, returning a model with a well-defined interior and exterior, and second, the use of an implicit function does not place any restriction on the topological complexity of the extracted iso-surface, providing a reconstruction algorithm that can be applied to many different 3D models[14].

In this paper, a mesh method is proposed to reconstruct the seabed map. Data collection of seabed is firstly presented, and then 3D reconstruction in a three-step process is adopted to analyze these data and reconstruct the seabed map. Experiment result are given to validate the proposed method, and the final part offers some concluding remarks.

## Materials and Methods

### Data Collection

Acoustic sonar systems (e.g. side-scan sonar, mechanically scanned pencil beam, and sub-bottom profiler) provide a remarkable sensing extension in the dark and murky underwater environment. The sonar data enable the new challenges and possibilities within the field of underwater visualization. The marine robots, including ROV and

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AUVs, now heavily depend on sonar data to reconstruct the images in the unknown underwater world. By mounting the acoustic sonar on the AUVs, the seabed mapping raw data can be collected while the AUVs cruise along planned path in the interested underwater area. If the path is predefined in the interested area, the AUVs can trace the spatial path with high accuracy even in the presence of unknown ocean currents, wave action and modeling uncertainty, by adopting the path following control algorithm[15]. Moreover, multiple AUVs under specific geometric formation can augment the underwater view fields and improve the efficiency of data collection. As illustrated in Fig. 1, by requesting a specifically geometric formation of three AUVs to cooperatively traverse parallel paths and make the overlap of acoustic coverage on the seabed, large areas can be covered and no piece will be omitted. Simultaneously, the team of cooperative multiple AUVs could accomplish the task of acoustic coverage more rapidly and economically than a single AUV in a wide-range survey mission[16]. In Fig. 2, the cooperative acoustic coverage of underwater area shown in Fig. 1 is simulated by a team of three AUVs, which track the predefined paths in a triangle formation. The readers can refer to the work[17], for more details about coordinated paths following control algorithms of the AUVs. Hence, the acoustic data of the interested area can be collected, which will be processed in the next step in order to reconstruct the 3D seabed surface.

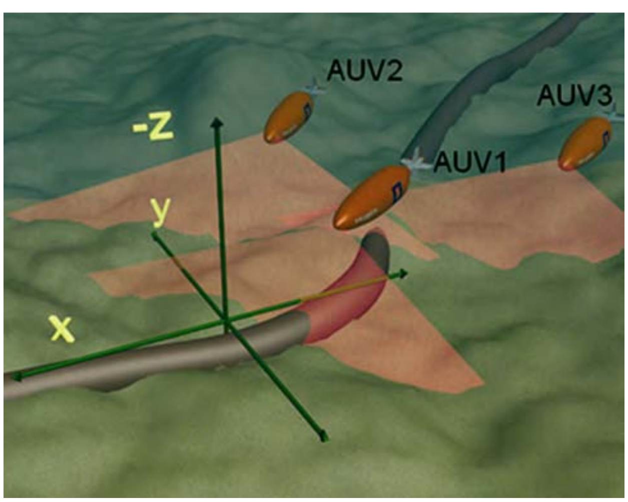


Fig. 1—3D acoustic coverage of the seabed

## Results and Discussion

### Data Processing

In order to reconstruct the topography of seabed via 3D point cloud data, the approach consists of three stages as shown in Fig. 3:

1. Point clearing via alpha shape;
2. Point normal;
3. 3D surface reconstruction.

The method proposed in this paper is designed to analyze and reconstruct unorganized or organized 3D point set. The input is an unorganized or organized 3D point set, possibly with normal attributes. The objective of the method is to reconstruct the 3D surface for these raw data acquired by acoustic sonars. We explain these three steps one by one in the following sub-sections.

### Point cleaning

In the point cleaning phase, noisy points are cleaned and deleted. It is realized by employing the alpha shape algorithm proposed by Edelsbrunner[3]. The alpha shape algorithm describes the surfaces of

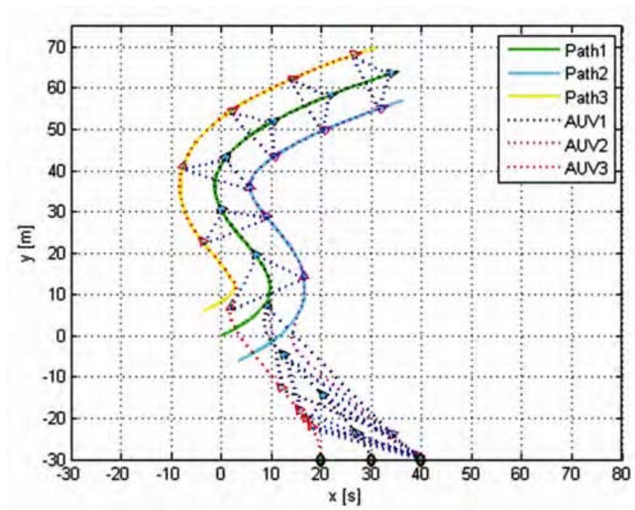


Fig. 2—Coordinated control of AUVs for acoustic data collection along predefined spatial paths

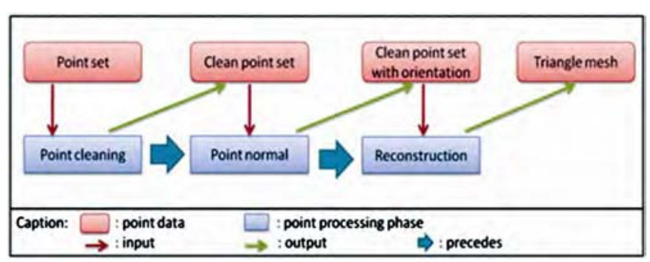


Fig. 3—Process of 3D seabed surface reconstruction

terrain as lists of adjacent triangles depending on the value of alpha, and delineates the cavity shape. Alpha shape algorithm is an effective tool for computing the "shape" of a point set. If points are affected by noise, then some points lying below the surface will not be included in the alpha shape result. Thus, the noisy points produced by sonar errors can be cleared by adopting the approach.

An unorganized 3D point set (Fig. 4a) is treated compared by regular Delaunay triangulation and alpha shape algorithm. As shown here, the regular Delaunay triangulation connects all the points including inner points (Fig. 4b). However, alpha shape just connects the points on the surface (Fig. 4c). After eliminating unconnected points, the contour of the object becomes visible (Fig. 4d). Note that the figures in this paper are mainly to demonstrate the result of 3D reconstruction. Some information like angular parameters are ignored, as they do not affect the 3D reconstruction results.

The algorithm is achieved by using Hull programming[***http://www.netlib.org/voronoi/hull.html***], which is designed to compute the convex hull of a point set.

**Point normal**

After clearing noisy points, the point set is oriented in this phase. The principle idea is to orient the normals of a set of points by using the method proposed by Hoppe[18]. The advantage of this method is that it constructs a Riemannian graph (the graph of the $K$ nearest neighbor points) over the input points and propagates a seed normal orientation within a minimum spanning tree computed over this graph. The result is an oriented normal vector for each unoriented normal input, except for the normals which could not be successfully oriented. Thus, the normal can be calculated according to different given $K$ attribute.

The algorithm defines a function which estimates the signed geometric distance to an unknown surface.

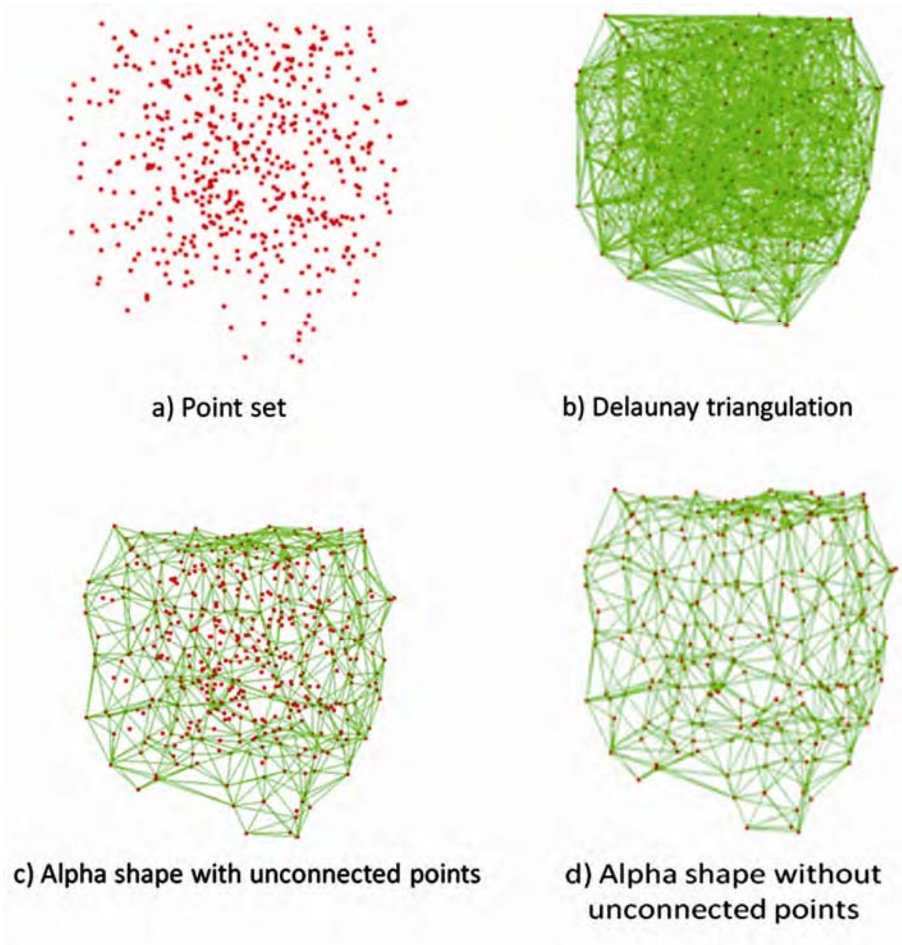


Fig. 4—Comparison of regular Delaunay triangulation and alpha shape for an unorganized 3D point set

The zero set of this function can approximate the surface. The function is based largely on computing tangent planes which locally approximate each experimental data point. This algorithm is split into two steps: calculating tangent planes locally approximate to data points, and orienting the planes (i.e., normal vectors) so as to define a globally consistent surface orientation.

**Step 1** Tangent plane estimation:

In this step, the tangent plane for a point *x* is defined by a center point and a unit normal vector. The center is defined as the centroid of the *k*-neighborhood of *x*, or the k points geometrically nearest to *x*.

**Step 2** Tangent plane orientation:

In this step, a method for reliably orienting the normal vectors is used, in order to sufficiently close tangent planes to point in the approximately same direction. During this phase, the unoriented point set can be treated which is more generally produced by ordinary sensors.

To achieve this functionality, related algorithms of CGAL[*http://www.cgal.org/*] is adopted.

#### Reconstruction

The reconstruction phase addresses the problem of reconstruction 3D surface via the oriented point set obtained in the previous stage. Some algorithms are proposed for 3D reconstruction[10,11,12,13], while the meshing algorithm[14] is adopted in this paper which is a method for reconstructing water-tight surfaces from an input of oriented points. The advantage of this algorithm approach is that it provides an automatic, simple, and efficient method for computing the solid model represented by a point set without requiring the establishment of adjacency relations between samples or iteratively solving large systems of linear equations. Secondly, it can be directly applied to models with holes and cracks, providing a method for hole-filling and zippering of disconnected polygonal models. Furthermore, the additive nature of the reconstruction makes it stable in the presence of noise and a simple heuristic technique works well when the points are non-uniformly distributed[14]. In a word, all these advantages are what we need to reconstruct the undersea terrain model.

Generally speaking, this method reduces the problem of surface reconstruction to convolution, and provides an efficient method for reconstruction that reduces the reconstruction process to three simple steps. It constructs the characteristic function of the solid defined by the point sampling the function, whose value is one inside of the solid and zero outside of it, and then the appropriate iso-surface is extracted.

The characteristic function $_V$ of a solid *V* is the function:

$$_V(x,y,z)=\begin{cases}1 & \text{if } (x,y,z)\in V\\ 0 & \text{otherwise}\end{cases}$$

The Fourier coefficients of the characteristic function are computed by using the divergence theorem. If ***M*** is a solid model and $\hat{}_V$ is its characteristic function, the coefficients can be calculated as:

$$\hat{}_V(l,m,n)=\int_{\mathrm{R}} {}_V(x,y,z)e^{-i(lx+my+nz)}dxdydz$$

$$=\int_{p\in M} e^{-i(lp_x+mp_y+np_z)}dp$$

Using the Divergence Theorem, if $\vec{F}_{l,m,n}(x,y,z)$ is any function whose divergence is equal to the *(l,m,n)*-the complex exponential, there is:

$$\left(\nabla\cdot\vec{F}_{l,m,n}\right)(x,y,z)=e^{-i(lx+my+nz)}$$

$\vec{F}_{l,m,n}(x,y,z)$ is defined as follows, which does not depend on the alignment of the coordinate axis.

$$\vec{F}_{l,m,n}(x,y,z)=\begin{pmatrix}\dfrac{il}{l^2+m^2+n^2}e^{-i(lx+my+nz)}\\ \dfrac{im}{l^2+m^2+n^2}e^{-i(lx+my+nz)}\\ \dfrac{in}{l^2+m^2+n^2}e^{-i(lx+my+nz)}\end{pmatrix}$$

The inverse Fourier Transform is applied to obtain the characteristic function. Since the input to our algorithm is an oriented point set, the Fourier coefficients of the characteristic function can be computed by using a Monte-Carlo approximation. Specifically, given the points $\{\vec{p}_1,\ldots,\vec{p}_n\}$ with associated normals $\{\vec{n}_1,\ldots,\vec{n}_n\}$, let set:

$$\hat{}_V(l,m,n)=\frac{1}{N}\sum_{i=1}^{N}\left\langle\vec{F}_{lmn}(p_i),n_i\right\rangle$$

To extract an iso-surface, we use marching cubes method[19], and an appropriate iso-value is required to be chosen in order to extract an iso-surface from the characteristic function.

The average value of the obtained characteristic function at the sample positions $\vec{p}_j$ is used as iso-value. It can provide a robust iso-surfacing value even in the case that input points are obtained from a not-water-tight model.

The result of 3D triangular mesh for a simulated seabed map is shown in Fig. 5, where the contours of the seabed terrain are well sketched out.

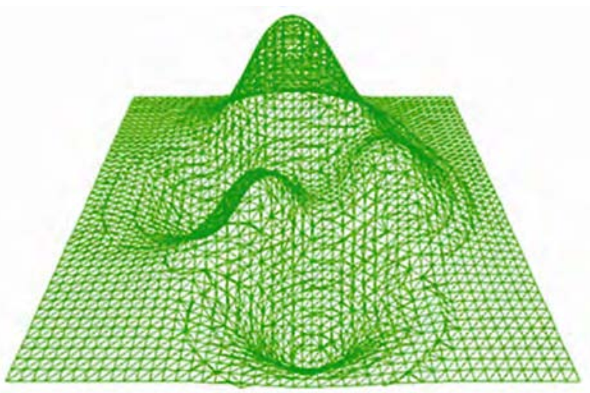

Fig. 5—Example of triangular mesh for a simulated seabed map

**Experiments**

Based on the theories and methods described above, a dedicated software is developed that can treat the real sonar data obtained from AUV as well as the data generated by the simulator. The software is developed by C++ and supported both by Windows and Linux32/64 bit.

In this paper, some representative experiments are given to illustrate the feasibility and effectiveness of proposed methodology. Behind these illustrative experiments, we have made many different experiments to valid the methodology. However, considering the size of this paper and the objective of experiments, we only demonstrate the representative cases.

Generate random points and Delaunay triangulation.

The software allows generating any number of random points and connecting these points by Delaunay triangulation, as shown in Fig.6 a-c.

### Alpha shape and mesh

In this trial, the program accepts 500 points as input and then alpha shape is computed by using automatic alpha value. After alpha shape, inner points are eliminated from the point set as shown in Fig. 7 a-c. The normals of remained surface points are calculated by calling CGAL and the object is meshed out in Fig. 7.d.

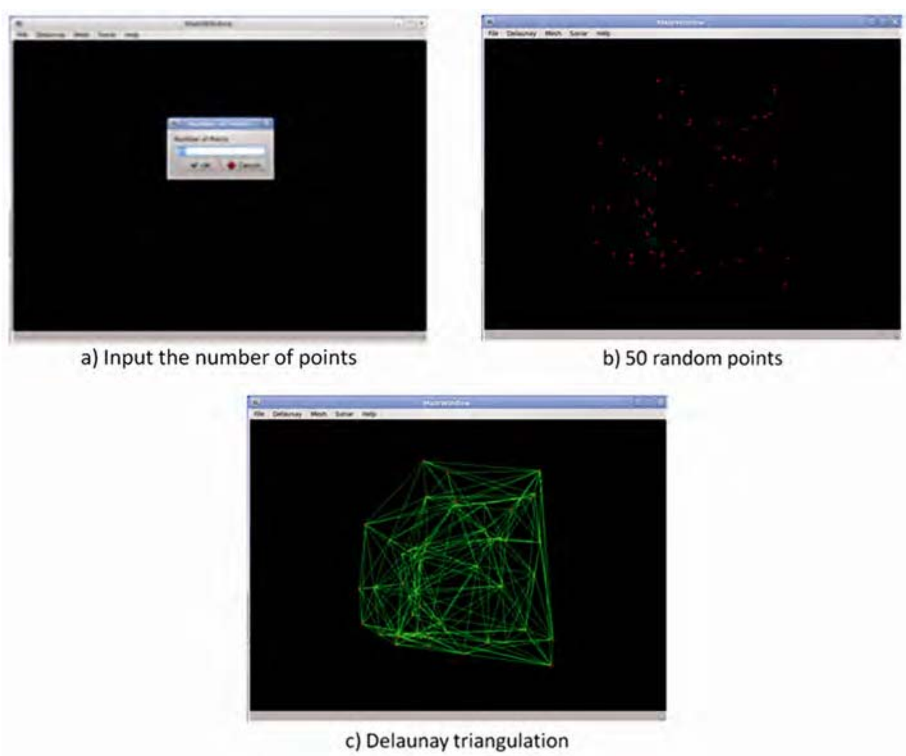


Fig. 6—Random points generation and Delaunay triangulation

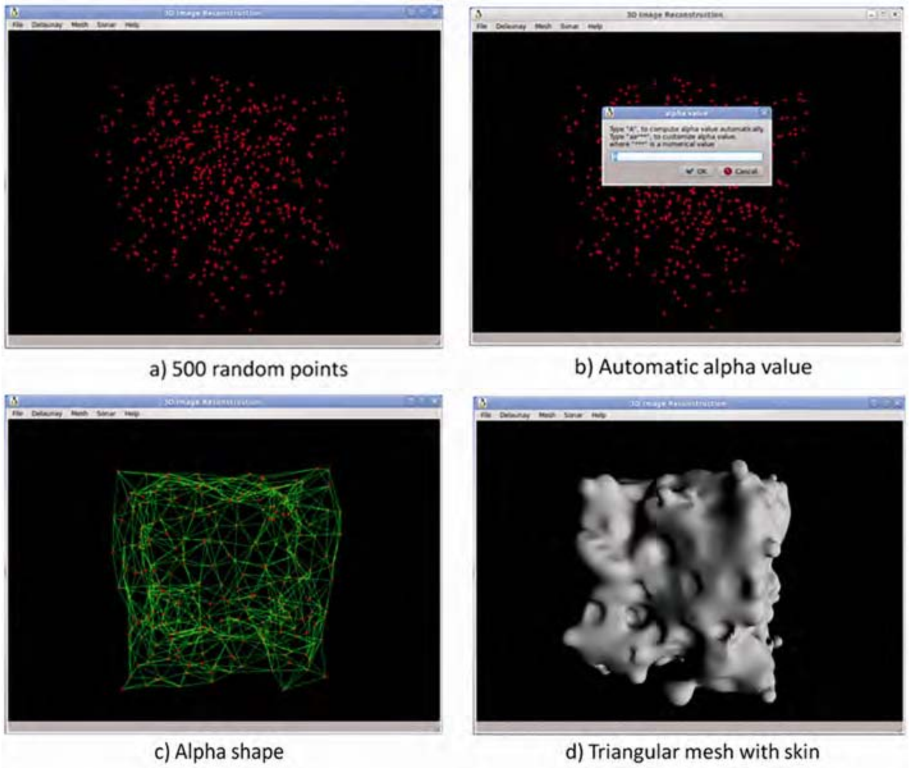


Fig. 7—Alpha shape and mesh

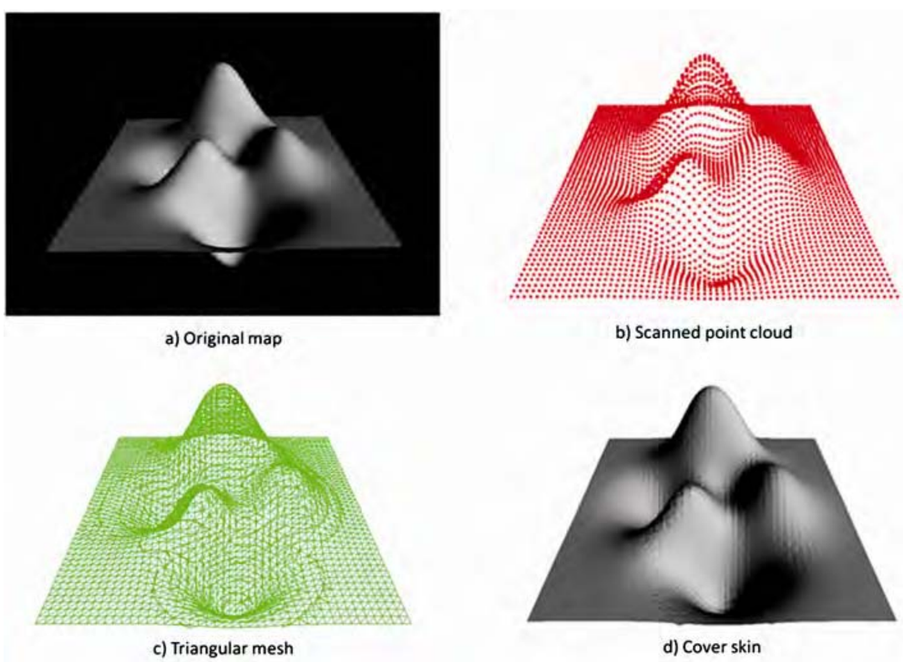


Fig. 8—3D seabed map reconstruction

**3D seabed map reconstruction**

The experiment shows the reconstruction of 3D seabed map. A simulated map is generated by the software as shown in Fig. 8a.

An AUV equipped with acoustic sonar suite traverses the entire map by employing the path following algorithm to obtain a set of point cloud data that is shown in Fig. 8b. In Fig. 8c, points are connected after applying triangular mesh, and the final reconstruction is accomplished in Fig. 8d after being covered the skin.

The above experiments illustrate two typical cases: closed surface and boundary surface. In the first experiment, random point cloud is used, which raises the difficulty of the reconstruction. The objective is to test the robust of our methodology, especially the realistically complicated seabed situation. In the second experiment, we try to reconstruct a simulated seabed map, which is a boundary surface. The objective is to test the robust of the methodology when the collection of data is not enough to construct a precise map. With these two experiments, it shows that proposed methodology can handle both of these two situations and successfully reconstruct 3D surface.

## Conclusions

In this paper, acoustic data collection by AUVs is briefly introduced, and the reconstruction of the seabed topography problem is studied in details. We have proposed a practical mesh method to achieve an accurate reconstruction of seabed surface from raw sonar records by adopting three different techniques: Delaunay triangulation, alpha shape and 3D triangular mesh. Based on the proposed method, the software is developed which permits to reconstruct 3D map based on the real sonar data obtained from AUV as well as the data generated by the simulator. With the experiments, the practical method demonstrates its robustness and effectiveness in 3D visualization of topography.

## Acknowledgements

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