3D IMAGING OF UNDERWATER OBJECTS USING MULTI-BEAM DATA

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One of the main applications of multi-beam sonars is high-resolution bathymetry measurement, as well as the detecting and imaging of underwater objects, such as shipwrecks. In order to ensure that the visual quality is good enough for the researcher to investigate the object in more detail, an approach relying on the construction of the three-dimensional model of an imaged object – e.g. consisting of nodes, edges and plane elements (facets) – is needed. Preceded by the short State-of-the-Art review, the applications of selected algorithms for three-dimensional seafloor-surface and underwater-object shape reconstruction have been presented. Two types of algorithms were investigated in the context of real-time application possibility; namely, raster height map, as well as 2D Delaunay triangulation. The presented preliminary results are promising both with respect to reconstructed 3D shape quality and to algorithm computational complexity, allowing for real-time mode applications.

INTRODUCTION

One of the main applications of multi-beam sonars is high-resolution bathymetry measurement, as well as the detection, measurement and imaging of underwater objects. Usually, multi-beam systems deliver data on seabed relief and underwater-object shape in the form of a geo-referenced file consisting of a cloud of points. These points are located in a three-dimensional space, XYZ, which can be used for the reconstruction of the original shape.

The process of measuring seafloor relief using multi-beam sonar may be summarised as follows. With the appropriate generation, acquisition and processing of signals in sonar, including beamforming (for more details, see e.g. [1]), the set of echo signals corresponding to a number of very narrow beams is received and recorded during a single ping. The beams are characterised by different transmission angles, which are localised in vertical planes perpendicular to the ship's track (Fig. 1).

For each beam – taking into account the pointing angle, as well as the time delay of the bottom echo return, and assuming that the model of acoustic-wave propagation in the water column is known (in the simplest case, the straight-line propagation with constant speed is assumed) – it is possible to calculate the (*x*, *y*, *z*) co-ordinates of the point where the beam meets the seabed surface. When the sonar is moving along the ship's track, collecting this data in consecutive pings, the result is a dataset that describes the shape of the bottom relief or underwater object in the form of a three-dimensional (*x*, *y*, *z*) point cloud.

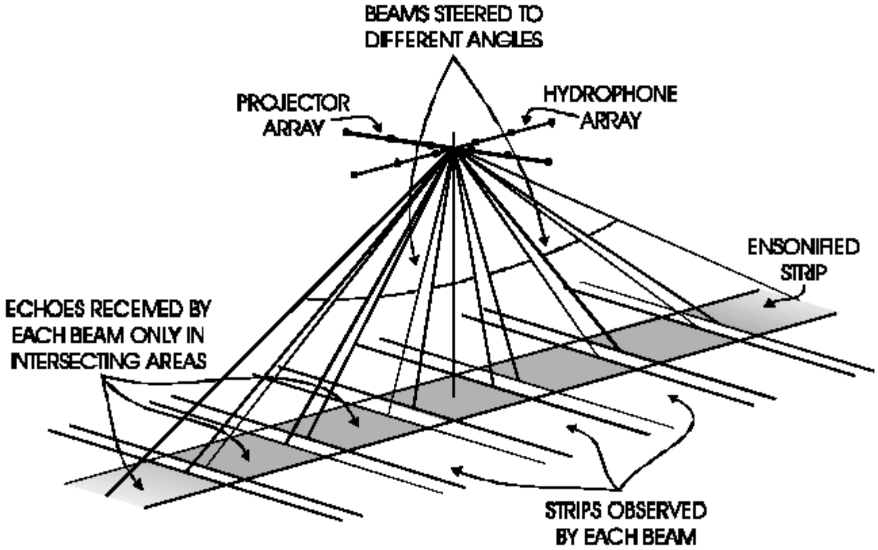

Fig. 1. Geometry of seafloor sensing by multi-beam sonar.

In the context of imaging underwater objects, the approach based on the visualisation of a point cloud as an unorganised set of points, and then generating the edges connecting the points in a trivial way (e.g. simply connecting the points corresponding to successive beams in one ping), does not provide satisfactory results. For instance, Fig. 2 presents a shipwreck point cloud transformed into a set of curves, where each curve corresponds to single-ping data.

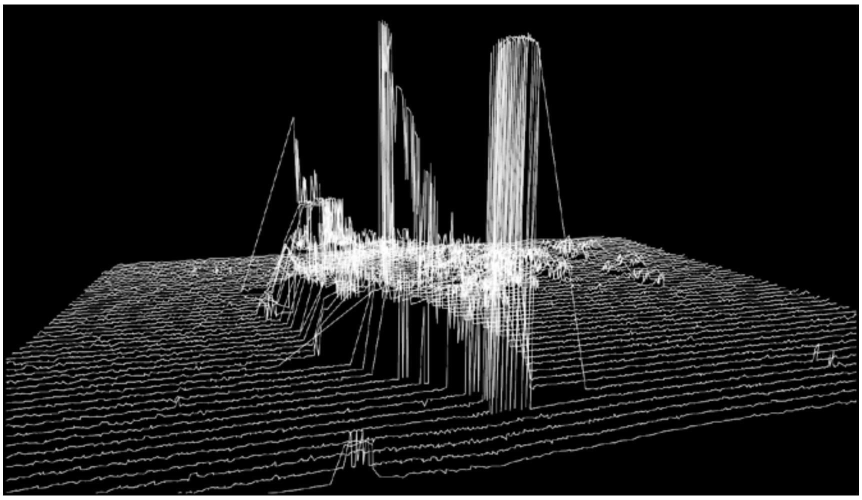

Fig. 2. A point cloud transformed into a set of curves, each corresponding to single-ping data; this is a typical method of displaying bathymetry data when searching for shipwrecks.

In order to obtain better-quality visualisation, which would allow the researcher, for example, to recognise more details and characteristic features of an investigated object, a more advanced approach is needed. This approach should rely on the appropriate construction of a three-dimensional model of an imaged object, e.g. consisting of such basic geometric elements as points (nodes), lines (edges) and plane elements (facets).

In this article, we will focus on the application of several methods for generating 3D models of underwater shapes using point clouds obtained by multi-beam sounding. Our primary goal is to find a method that would allow for automatic, real-time processing and the visualisation of underwater objects. This would allow for the implementation of the proposed solutions in operational mode, i.e. with the possibility of reconstructed shapes' visualisation almost immediately after acquiring the data during the sea measurements.

1. 3D SHAPE RECONSTRUCTION FROM MULTI-BEAM SONAR POINT CLOUD

The problem of reconstructing the accurate shape of an object from limited measurements has been discussed for many years, and a wide variety of methods have been proposed to solve it. For data obtained by multi-beam sonars, a straightforward solution is to create a digital elevation model based on a raster. This can be achieved by gridding the points and turning them into a height map. Another approach is to create a triangulated irregular network (TIN) [2]. One of the more popular methods for generating TIN meshes is the Delaunay triangulation algorithm. While this method works well in 2D, in higher dimensions it often produces additional faces with an undesirable shape [3]. One way of addressing this issue is to restrict the results to a reasonable subset of vertices that offer a satisfactory approximation of the original surface. A notable example is the Power Crust algorithm, which relies on constructing a Voronoi diagram from the set of input points, and using it as a determinant [4]. Another method of triangulating a point set is to cast it as a spatial Poisson problem. However, this solution requires that the input points are spatially oriented, meaning that the inward-facing normal of each point must be calculated in advance [5]. Another way of converting a point cloud into a triangulated mesh is to use a region-growing solution, such as the Ball-Pivoting method [6].

Many of the above methods have been tested for recovering 3D models of underwater areas of interest. However, they were used for surfaces where no large underwater objects, such as shipwrecks (see e.g. [7]), were present. What is more, due to their complexity, the methods based on the Power Crust algorithm or Poisson problem-solving approach, are not suitable for the real-time mode, which has been proved through performance testing [5].

In this paper, the preliminary results on using the following approaches are compared and discussed:

- producing the raster height map by adjusting the point cloud to regular grid;
- 2D Delaunay triangulation.

We did not perform any experiments with the use of the Ball-Pivoting algorithm, as its quality is heavily dependent on the parameters chosen by the user, which would have to be adapted for different areas by trial and error, making it unsuitable for automatic real-time visualization.

2. EXPERIMENTS AND RESULTS

In our experiments, we used the height map and the 2D Delaunay triangulation methods to convert two sample bathymetry datasets (non-organised point clouds) – obtained by multi-beam echo-sounder systems – into organised structures of points, edges and facets describing 3D shapes. Each file contains dozens of lists of points that represent an underwater region containing a single shipwreck; one list of points – or swath – corresponds to one pinging. Due to the presence of noise, each list may contain a different number of points. The datasets used in the investigation are shown in Fig. 3, seen from a convenient angle for human observers.

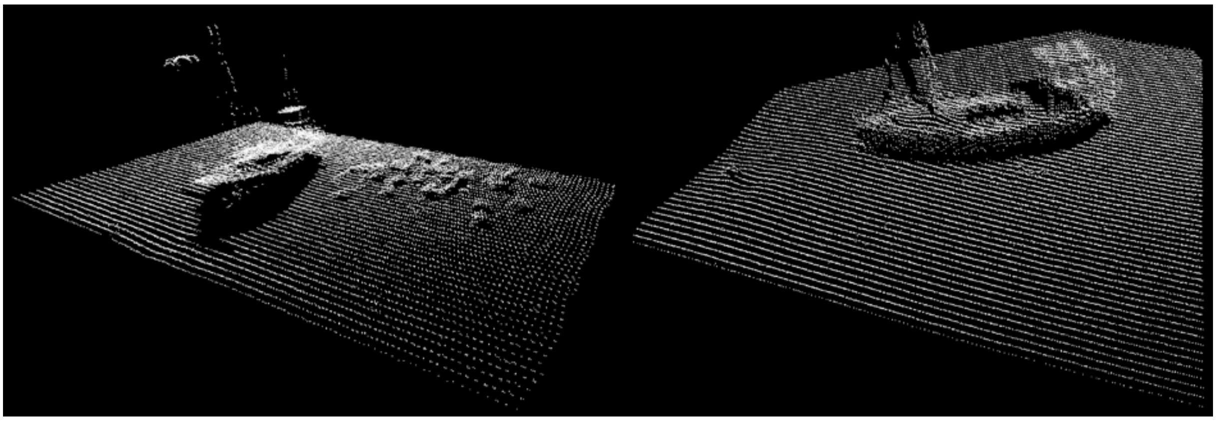

Fig. 3. Sample point clouds representing underwater regions with wrecks. The left part of the picture shows a low-resolution dataset containing a wreck of an unknown ship next to rocky terrain, while the right part of the picture shows a high-resolution dataset representing the Cleona shipwreck.

As stated before, our objective was to find a method that would create an automatic, real-time visualisation of the shape of underwater objects. The first method we applied was to turn each dataset into a grid, which was achieved by resizing the existing lists of points so that the number of points in list would be constant. The height of each point was calculated by linearly interpolating the proper values between the original points. We then triangulated these new point clouds by turning every four points into two triangles. From now on we will refer to this method as a “height map” technique.

The second method we tested was to use a 2D implementation of the Delaunay triangulation. In Fig. 4, we can see the results of both techniques when applied to the first dataset. We can see that both methods fail to preserve the shape of the bottom of the ship and merge it with the seafloor instead. When it comes to the seabed, the height-map technique gives positive results, but at the cost of losing some of the detail and increasing the overall number of points; the 2D Delaunay triangulation algorithm, however, preserves more details.

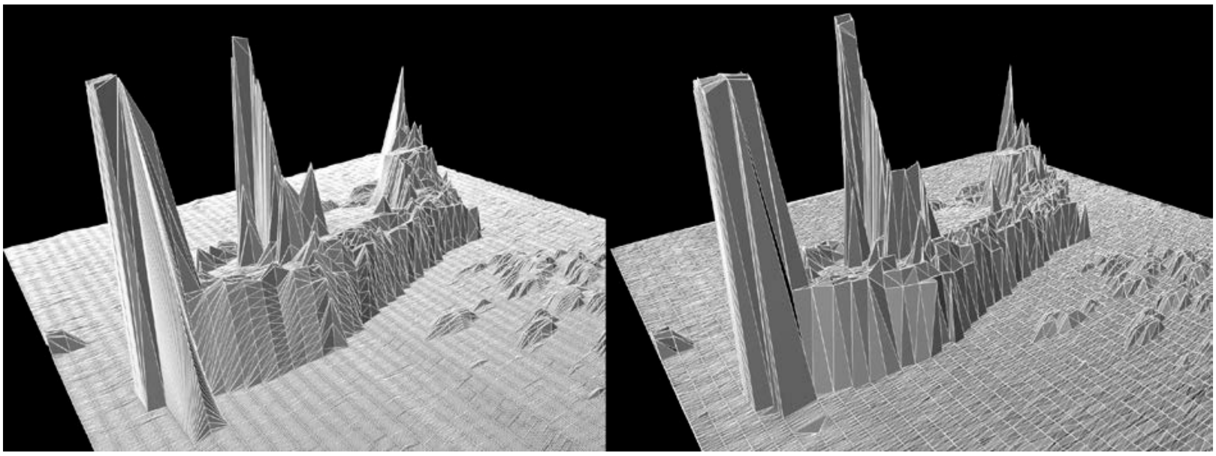

Fig. 4. Comparison of the height-map technique (left) and the 2D Delaunay triangulation (right) of the first dataset.

Fig. 5 presents the results of applying the same methods to the second dataset. The height-map technique, again, causes redundancy and loss of details. The 2D Delaunay triangulation method is better when handling the edges of the shipwreck. However, in this example, both methods perform very poorly in terms of replicating the irregular shape of the shipwreck.

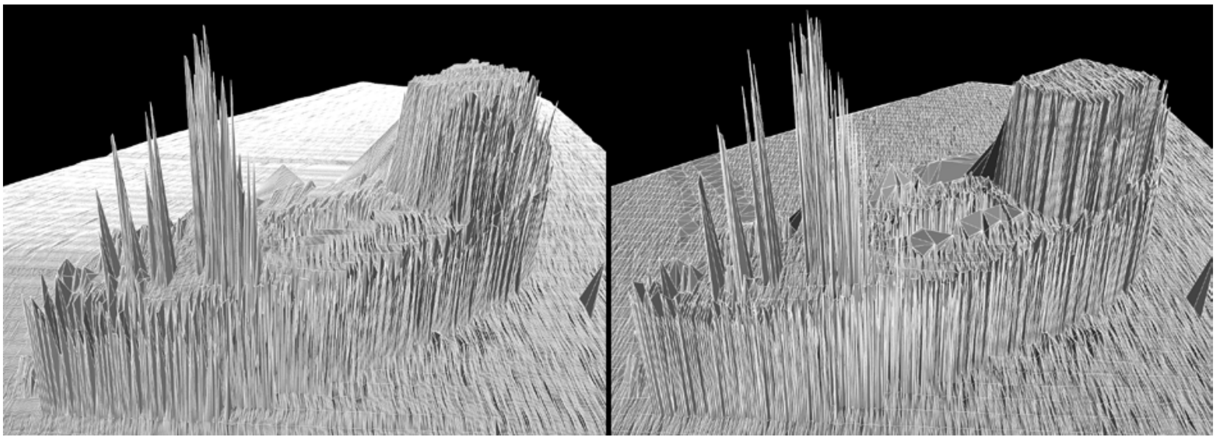

Fig. 5. Comparison of the height-map technique (left) and the 2D Delaunay triangulation technique applied to the Cleona shipwreck.

Tab. 1 summarises the running times of both algorithms and indicates that the height-map technique can be used for real-time applications, although its memory consumption is noticeably higher. The Delaunay triangulation method, despite its quality, is less suitable for this purpose.

Tab. 1. Results of algorithm performance testing.

Dataset	Unknown wreck	Cleona
Number of points used for testing	28504	28922
Number of points created by our implementation of the height-map method	30832	52910
Time required to compute height map (in seconds)	0.013	0.014
Time required to compute 2D Delaunay triangulation (in seconds)	0.401	0.364

3. CONCLUSIONS

Preceded by the short State-of-the-Art review, the application of selected algorithms for three-dimensional seafloor-surface and underwater-object shape reconstruction have been presented. Two types of algorithms were investigated in the context of real-time application possibility; namely, raster height map, as well as 2D Delaunay triangulation. The presented preliminary results on reconstructed 3D shape quality, as well as on algorithm computational complexity, show that the presented approaches are promising. Nevertheless, it is also clear that several improvements are needed at the current stage of the investigation.

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